M.L. “Bob” Emiliani

OTHER PUBLICATIONS

Technical Magazine Articles

1. “Bicycle Chains: Materials, Chain Wear, and Lubrication,” *Bike Tech*, Vol. 5, No. 1, Spring 1986, pp. 5-10.
2. “American Framebuilders: A Status Report,” *Bike Tech*, Vol. 4, No. 4, Fall 1985, pp. 9-13.
3. “Steel Frame Tubing: What Are the Differences?,” *Bicycle Guide*, Vol. 1, No. 1, Autumn 1984, pp. 83-88.
4. “Can Surface Finish Affect the Strength of Your Frame? Part III: Chrome Plating,” *Bike Tech*, Vol. 3, No. 3, June 1984, pp. 10-16.
5. “Anodized Rims are More Rigid,” *Bike Tech*, Vol. 3, No. 2, April 1984, p. 5.
6. “Can Surface Finish Affect the Strength of Your Frame? Particle Blasting, Part II,” *Bike Tech*, Vol. 3, No. 1, February 1984, pp. 1-6.
7. “Can Surface Finish Affect the Performance of Your Frames?,” *Bike Tech*, Vol. 2, No. 6, December 1983, pp. 5-9.
8. “Heat Treated Rims - Are They Worth The Money?,” *Bike Tech*, Vol. 2, No. 5, October 1983, pp. 1-7.
9. “The Metallurgy of Brazing, Part 4,” *Bike Tech*, Vol. 2, No. 2, April 1983, pp. 1-7.
10. “The Metallurgy of Brazing, Part 3,” *Bike Tech*, Vol. 1, No. 4, December 1982, pp. 6-11.
11. “The Metallurgy of Brazing, Part 2,” *Bike Tech*, Vol. 1, No. 3, October 1982, pp. 3-7.
12. “The Metallurgy of Brazing, Part 1,” *Bike Tech*, Vol. 1, No. 2, August 1982, pp. 1-4.
13. “Straight Talk on Steel,” *Bicycling Magazine*, Vol. XXIII, No. 6, July 1982, pp. 96-123.
14. “On Some Much-Misused Terminology,” *Bike Tech*, Vol. 1, No. 1, June 1982, pp. 9-11.
15. “Silver versus Brass Brazing,” *Bike Tech*, Pilot Issue, Vol. 1, February 1982, pp. 3-4.
16. “Reynolds versus Columbus versus the Framebuilder’s Torch,” *Bicycling Magazine*, Vol. XXII, No. 8, October 1981, pp. 92-97.

Israel and Hawaii: Should You be Cycling in These Sun Spots?

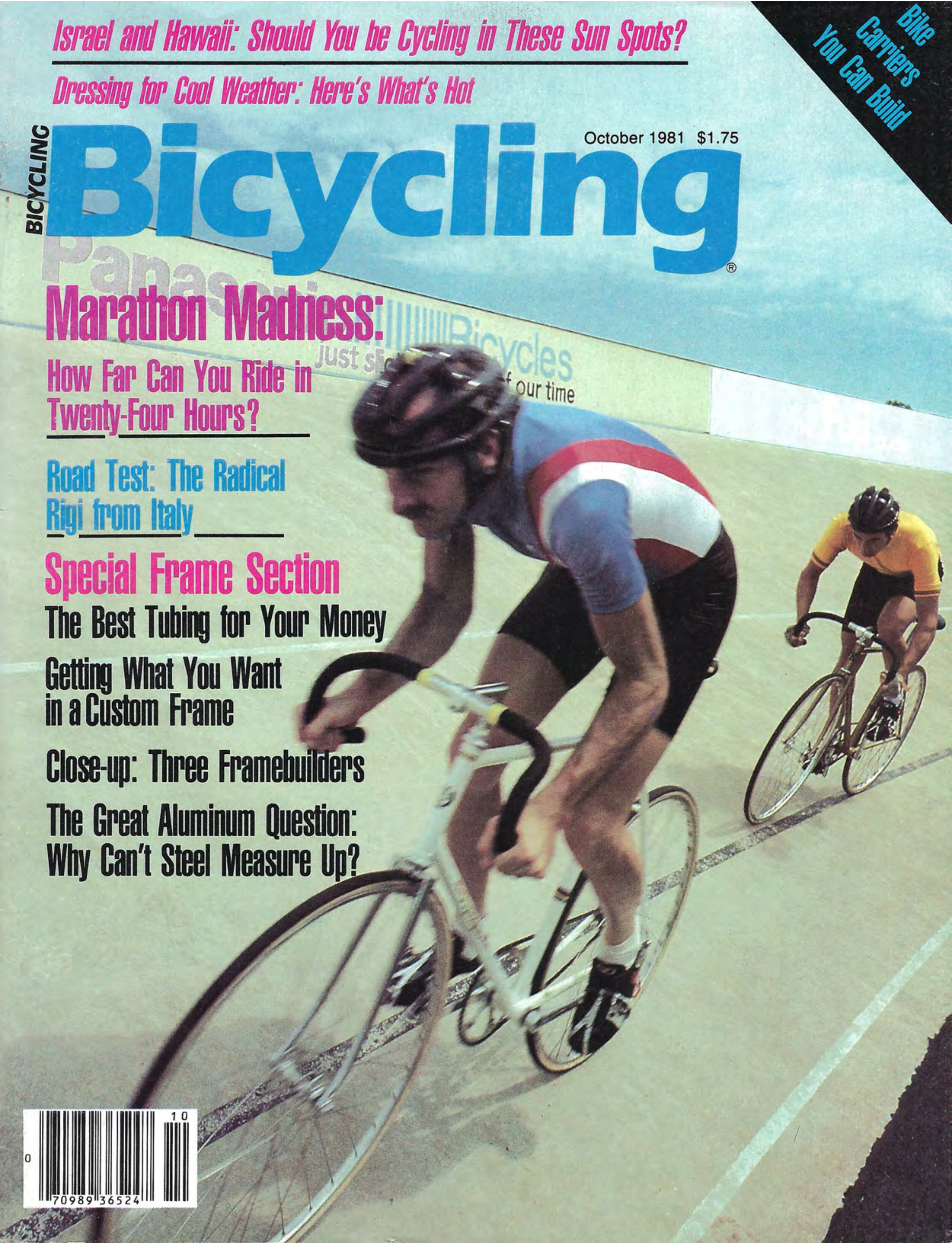
Dressing for Cool Weather: Here's What's Hot

Bike Carriers You Can Build

BICYCLING

Bicycling

October 1981 $1.75



Marathon Madness:

How Far Can You Ride in Twenty-Four Hours?

Road Test: The Radical Rigi from Italy

Special Frame Section

The Best Tubing for Your Money

Getting What You Want in a Custom Frame

Close-up: Three Framebuilders

The Great Aluminum Question: Why Can't Steel Measure Up?

0 70989 36524 10

America's Leading Bicycle Magazine

Bicycling®

Volume XXII, Number 8
September/October 1981

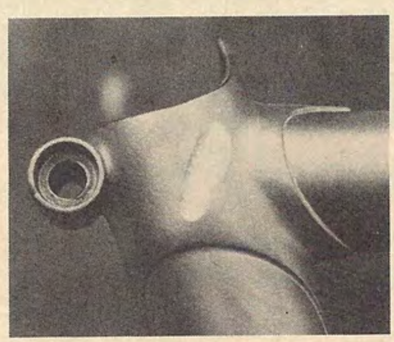
Incorporating Bike World® Magazine

FEATURES

ON THE COVER:
Round and round he goes . . . Curt Bond in practice for his world record-setting 24-hour marathon at Trexlertown, Pennsylvania. That's Rob Geisler, twice Junior State Champ, coming up behind.
COVER PHOTO BY SALLY ANN SHENK.

DEPARTMENTS

42
Dress the Part
Find cool weather comfort and style in this cyclewear for men and women.



68
Framebuilding
Your own custom frame — how to build it or have it built — plus much more about the framebuilder's art.

Reynolds versus Columbus versus the Framebuilder's Torch

What Happens When You Heat and Strain the Two Most Popular Brands of Tubing to the Point of Failure?

Mario Emiliani

Like most American framebuilders, I chose to assemble my frames with a low-temperature silver brazing alloy. I was following the conventional wisdom that the lower temperatures required to heat silver (as compared with brass brazing alloy) didn't hurt the tube's mechanical properties (tensile strength, yield strength, and ductility) as much as high-temperature brazing.

As I learned more about framebuilding, I began to question the American cycling community's insistence that overheating (brazing at temperatures beyond those the tubing manufacturer recommends) seriously reduces the mechanical properties of high-quality steel bicycle tubing. After all, European framebuilders don't use silver. They've been "overheating" tubes for years, with seemingly no ill effects. So why spend the extra time and money to silver braze a frame if overheating does not seriously affect the mechanical properties of the tubing?

I spent a great deal of time searching for published data that would substantiate the American claim. My search proved fruitless, so I decided to scientifically determine the effects of brazing on the mechanical properties of Reynolds 531 and Columbus SL cycle tubing. The experiment was the topic of my Bachelor of Science thesis in mechanical engineering, and was done at the University of Miami in fall 1980.

While there are many aspects to my findings, the most interesting conclusion is that overheating either Reynolds 531 or Columbus SL is not as serious as it has been thought to be.

ductility—ability of a material to deform permanently, without breaking, while under tension

hardenability—increasing a material's ability to be strengthened through heat treatments

impact loading—subjecting a material to sudden energy input (impact loading is the kind of stress for which impact strength is important)

impact strength—ability of a material to absorb energy without breaking

tempering—making a material more ductile through controlled heat treatment

tensile strength—maximum stress a material can withstand in tension

work hardening—increasing a material's strength by permanently deforming it

yield strength—stress level, in tension, at which a material becomes permanently deformed

TABLE 1

	Published Brazing Procedures[1,2]	
	Reynolds 531	Columbus SL
temperature	1562°F approximate	1292°F maximum
cooling	natural convection	natural convection
	Published Average Mechanical Properties[1,3]	
	531 as received	SL as received
tensile strength	112,000 psi	121,000 to 135,000 psi
yield strength	100,800 psi	107,000 psi
percent elongation[4]	10	10
	531 after brazing	SL after brazing
tensile strength	100,800 psi	—
yield strength	89,600 psi	—
percent elongation[4]	—	—
	Test Results	
	531 as received	SL as received
tensile strength	108,950 psi	97,140 psi
yield strength	98,850 psi	93,570 psi
percent elongation[4]	11.1	10.8
	531 after brazing at 1500°F for 5 minutes	SL after brazing at 1300°F for 5 minutes
tensile strength	122,520 psi	139,770 psi
yield strength	75,650 psi	66,380 psi
percent elongation[4]	15.6	18

1 TI Reynolds Limited, "Reynolds 531 Tubing Technical Data Sheet" 1976.
2 Columbus S.r.l., "INSTRUCTIONS FOR ASSEMBLING BICYCLING RACING FRAMES WITH TUBES 'COLUMBUS'". 1978.
3 Columbus S.r.l., "COLUMBUS special tubes for special bicycles". 1976.
4 Based on a two-inch gauge length.

TABLE 2 Chemical Composition of Reynolds 531 and Columbus SL

	Reynolds 531[1]	Columbus SL[2]
carbon	0.23% to 0.29%	0.22% to 0.28%
silicon	0.15% to 0.35%	0.35% max.
manganese	1.25% to 1.45%	0.50% to 0.80%
molybdenum	0.15% to 0.25%	0.15% to 0.25%
chromium	—	0.80% to 1.10%
sulfur	0.045% max.	0.035% max.
phosphorus	0.045% max.	0.035% max.

1 TI Reynolds Limited, "Reynolds 531 Tubing Technical Data Sheet" 1976.
2 Personal communications with Fabrizio Guissani, metallurgist with Columbus S.r.l., Milano, Italy.

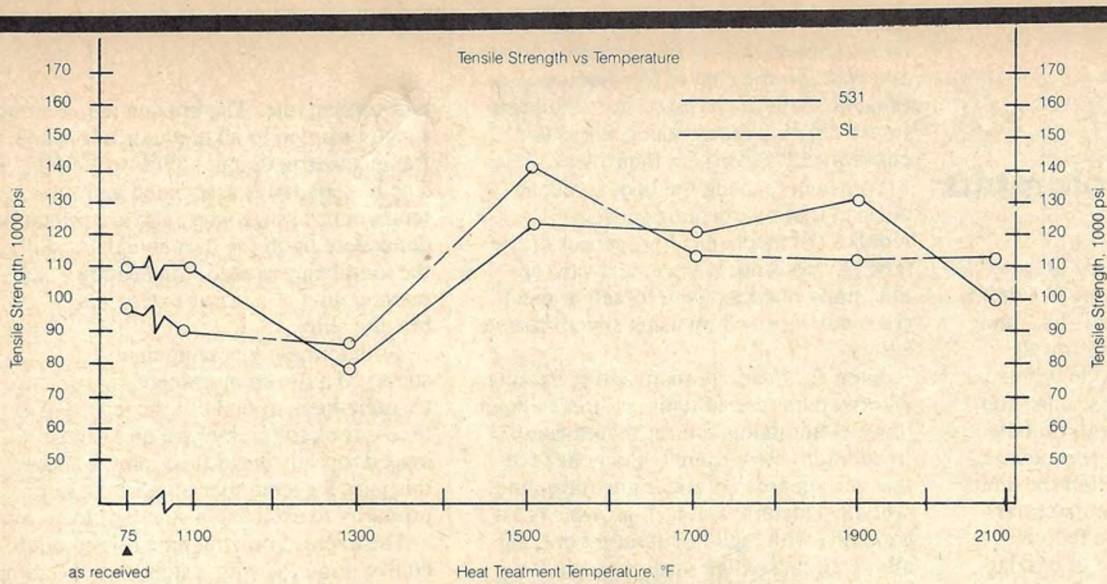


Figure 1: Graph of tensile strength versus heat treatment temperature for a brazing time of five minutes. The tensile strengths of Reynolds 531 and Columbus SL are reduced by low temperature brazing and increased by high temperature brazing.

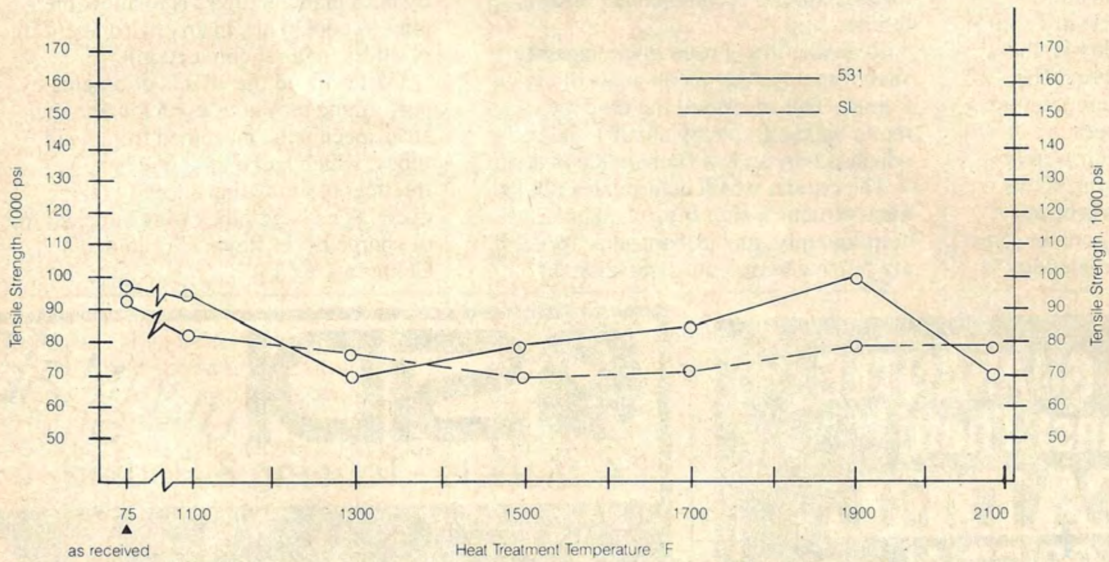


Figure 2: Graph of yield strength versus heat treatment temperature for a brazing time of five minutes. The yield strengths of both brands are also reduced by low temperature brazing and increased by high temperature brazing.

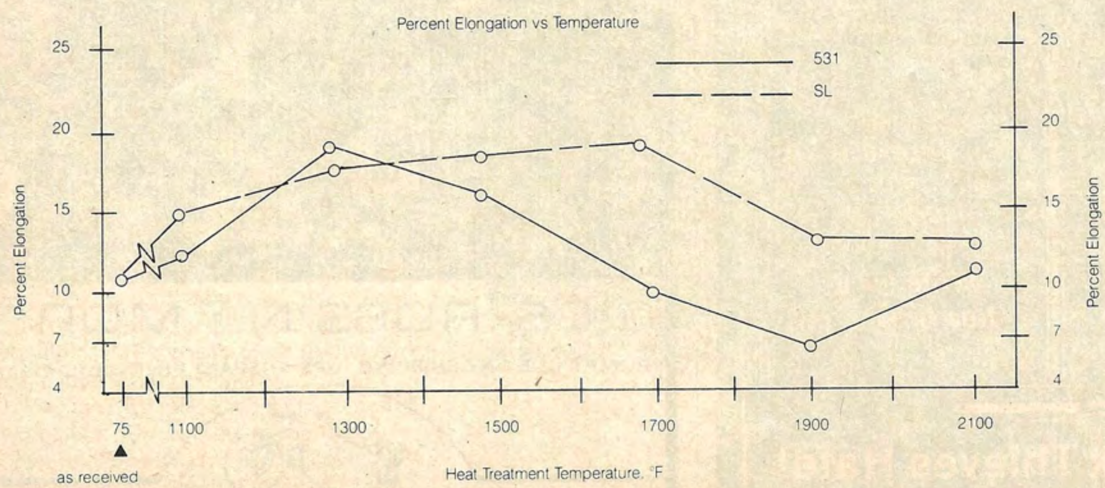


Figure 3: Graph of percent elongation versus heat treatment temperature for a brazing time of five minutes. Both Reynolds 531 and Columbus SL retain good ductility after brazing throughout the range of temperatures.

Reynolds vs. Columbus

I chose to test Reynolds 531 and Columbus SL (metallurgically, Columbus SL is the same as SP, PL, PS, KL, and Record tubings) because they are the most popular brands of bicycle tubing, and there was not time to test other top brands. Manufacturers of both brands publish data stating brazing procedures. If the framebuilder stays within the limits of these procedures, the manufacturers guarantee their tubes against failure.

The framebuilder's choice of brazing material is limited twice; first by the brazing alloys compatible with high-strength, low-alloy steels, and second by the maximum temperatures recommended by the manufacturers. These temperatures are given in Table 1.

The cheaper a brazing alloy is, the higher its melting temperature. (The technical term for melting temperature is liquidus — the lowest temperature at which the brazing alloy is completely liquid.) And expensive brazing alloys have lower liquiduses. This is because low-liquidus brazing alloys contain 35 to 55 percent silver, while high-liquidus alloys contain mostly inexpensive copper and zinc. So the cost of low-liquidus brazing alloys encouraged framebuilders to use high-liquidus brazing alloys and, consequently, overheat their tubes.

Somewhere along the line, someone decided that overheating seriously reduces the mechanical properties of the tube. As consumers became aware of this, framebuilders were forced to meet consumer demand by using silver brazing alloys.

Even so, there are many silver brazing alloys which melt at temperatures beyond those either manufacturer recommends. In addition, most framebuilders believe that certain areas of the frame (dropouts, seatstay clusters, and fork crowns) must be joined with high-temperature brazing alloys, because their viscous quality enables large gaps to be filled easily, and with little loss of strength. Therefore, these areas are overheated even on frames which otherwise follow manufacturers' recommended brazing temperature.

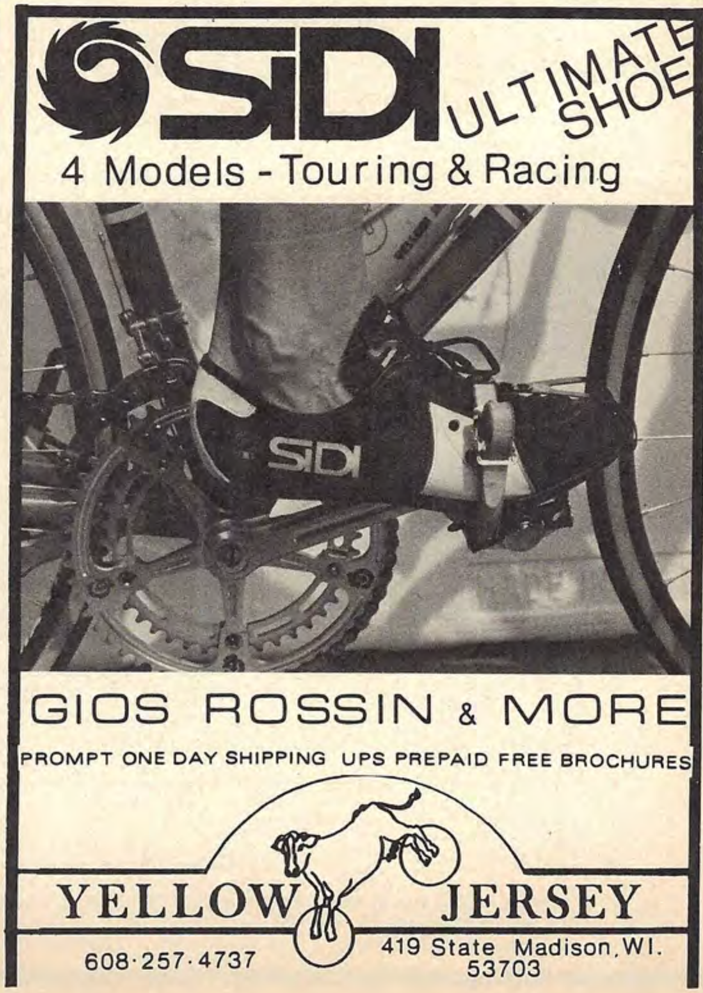
Realizing this, I used low-temperature silver brazing alloy on all areas of my frames. This increased the time it took me to build a frame by about 15 hours, which is why so few framebuilders do it.

The criteria which determine a tube's microstructure after brazing (and consequently, its mechanical properties) are brazing temperature, brazing time, and cooling rate. The brazing temperature range common to all methods of bicycle frame construction is 1200°F to 1900°F. The brazing times associated with this temperature range vary, and are primarily dependent upon the framebuilder's skill, the joint being brazed, the heating method, and to a lesser extent, the brazing alloy.

To determine a brazing time, I surveyed a dozen prominent framebuilders to find out the length of time it took to torch braze an average lugged top tube/head tube joint. I chose this joint for a number of reasons, but primarily to establish a standard to go by.

The average brazing time turned out to be five minutes, with a standard deviation of three minutes. These times include bringing the joint up to temperature and brazing at temperature. Cooling time is not included. The cooling rate specified by both manufacturers is to allow the joint to cool in air, in an environment free of drafts (natural convection).

I determined the effects of brazing by performing tensile tests on longitudinal strip specimens, machined from head tubes, which had undergone heat treatments simulating a torch brazing cycle. (The head tubes were supplied free of charge by TI Reynolds Limited and Columbus S.r.l.)



The heat treatment schedule was as follows: two 531 and two SL specimens were placed in an electric furnace, heated to 1100°F, kept at that temperature for five minutes, then cooled in air by natural convection. Another set of specimens was placed in the furnace, heated to 1300°F, and cooled in the same manner. This procedure was continued, in 200°F increments, up to 2100°F. The entire sequence was then repeated for brazing times of two and eight minutes. The brazing time was varied to see if it had any effect on either steel's mechanical properties.

Figures 1, 2, and 3 are graphical representations of the results of the tensile tests versus heat treatment temperatures and time. Only the data for a five-minute brazing time is presented here, but it is representative of what happens at two and eight minutes (I found that varying the brazing time had only a small effect). Since I performed two tensile tests at each time and temperature, I usually obtained a range of values. The data points in Figures 1, 2, and 3 represent the average of the range of values. Before I talk about the results of the test, it is necessary to say a few words about Reynolds 531 and Columbus SL as received (or before brazing).

The metallurgical differences between Reynolds 531 and Columbus SL are small. Table 2 shows the chemical composition of the two steels according to the manufacturers.

Much is made of the fact that Reynolds 531 is a manganese-molybdenum steel, while Columbus SL is a chromium-molybdenum steel. The reason these two steels are different lies in the methods each manufacturer employs to produce the tubes.

Adding about 1.35 percent manganese to a steel has the effect of slightly increasing its ability to be work hardened. Adding about 0.95 percent chromium to a steel has the effect of slightly increasing its hardenability. Thus, Reynolds 531 gains much of its strength from cold working, while Columbus SL gains much of its strength from heat treatments.

Table 1 shows the manufacturers' published data on the average mechanical properties of their tubes as received. Test results of Reynolds 531 and Columbus SL as received, also shown in Table 1, reveal that the average mechanical properties of Reynolds 531 are very close to that which the manufacturer publishes.

The average mechanical properties of Columbus SL, with the exception of percent elongation (percent elongation is a measure of a material's ductility; the greater the percent elongation, the greater the ductility), are lower than published data.

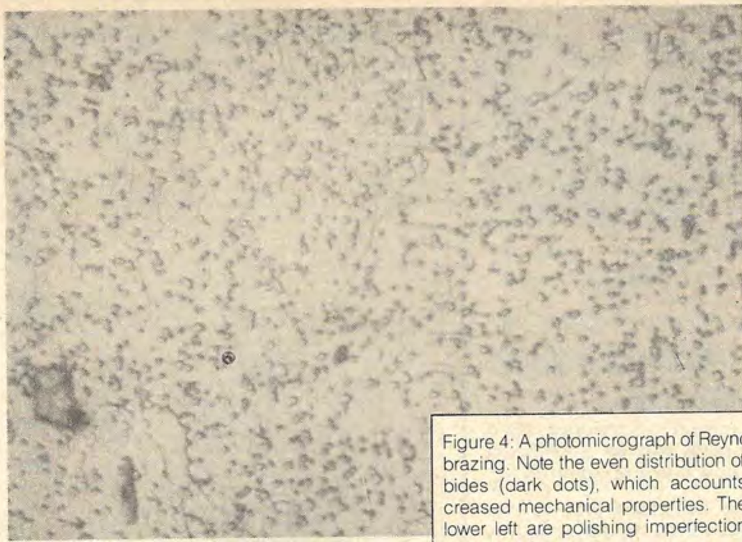


Figure 4: A photomicrograph of Reynolds 531 before brazing. Note the even distribution of spherical carbides (dark dots), which accounts for 531's increased mechanical properties. The dark spots at lower left are polishing imperfections. 1600 times magnification.

Mario Emiliani

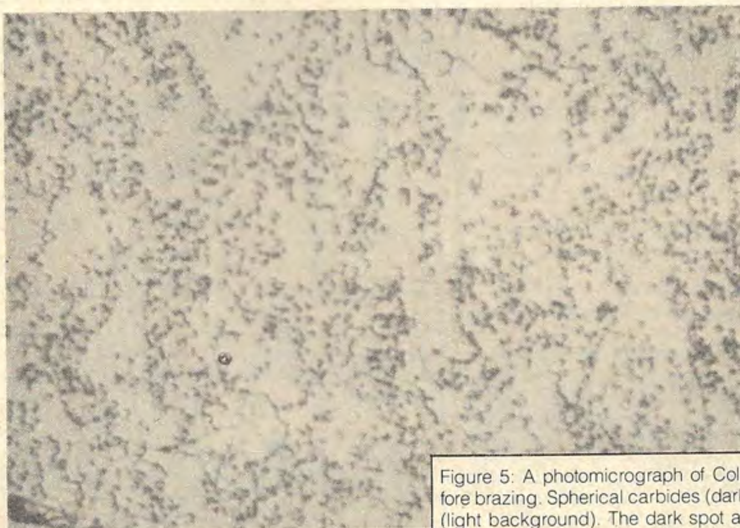


Figure 5: A photomicrograph of Columbus SL before brazing. Spherical carbides (dark dots) in ferrite (light background). The dark spot at lower left is a polishing imperfection. 1600 times magnification.

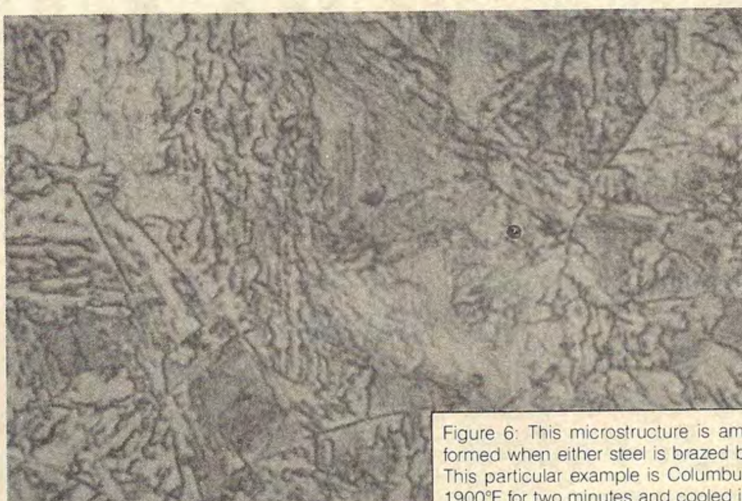


Figure 6: This microstructure is among the types formed when either steel is brazed beyond 1350°F. This particular example is Columbus SL heated to 1900°F for two minutes and cooled in air by natural convection. 1600 times magnification.

NOW!

Shining Mountain
Bicycle Maintenance Stand

Professional model saves you time, effort and energy! Makes your work easier, faster and more enjoyable.

- Stable, heavy-duty base.
- Vice rotates 360° to hold bike at the right angle, the right level for you.
- Replaceable plastic-coated vice jaw holds bike firmly without damaging finish.
- Height adjusts from 27" - 38".
- Vice has return spring so jaws open as you release pressure.

CHOOSE FLOOR OR BENCH MODEL

Inquire at better bike shops nationwide.
Money-back guarantee.

Shining Mountain Manufacturing Co.
P.O. Box 1321, 124 Old Corvallis Road
Phone 406-363-6699 Hamilton, MT 59840
Dealer inquiries invited

CLEMENT • SILCA • BELL • TAKARA • GRAB ON • GIOS • COOL GEAR • BROOKS • CANNONDALE • KIRTLAND • AVOCET • COLNAGO • S.B.I. • BLACKBURN • WOLBER • HURET • DETTO PIETRO • SUPER CHAMPION • CINELLI • T.A. • BETA BIKER (NEW) • TREK • CAMPAGNOLO • PHIL WOOD • SUNTOUR • MASI •

FREE FREIGHT
CONTINENTAL U.S.A.
MONEY BACK GUARANTEE

24hr. shipping on Visa, Mastercharge or M.O. Checks held 10 days.
Prices Subject to Change Without Notice - C.O.D. Fee - $2.00

All Blackburn products in stock - silver adj.	22.95
Cannondale Tire Bag (three zip pockets)	9.95
ALL OTHER CANNONDALE BAGS IN STOCK	
Cinelli, H-bars 64-66-65 (all sizes)	21.95
Bullseye sealed jockey wheels	17.95
Sugino B.B. Tool Set	16.95
Alloy w/bot. cage & clamp (alloy) silver, black, with bot..	4.95
Clear water bottle, Campagnolo imprinted	2.50
Avocet Saddles in stock 9.95 & up - call us	
Avocet Touring Shoes, new w/steel shank	32.95
Sugino Crank puller - fits Campy	6.95
Cyclo Rivoli chain tool	4.95
Wrights Leather Saddle (English Made)	11.95
Wolber Invulnerable 285 gram steel belted	29.95
Pacer 2000 Computer - speed-time-distance-cadence	149.00
T.A. Triple Crankset complete	109.95
Beta Biker Shoes (New Style)	18.95
Campagnolo N.R. Road Group	525.00
Campagnolo N.R. Brakeset	149.95
Gios Torino frameset	552.50
Masi framesets w/SR or Edco headset	695.00
Masi 58 cm super record equipped - silver/red	2195.00
OTHER FRAMESETS – BOTH TOURING & RACING IN STOCK	
Jackson riding shorts, acrylic w/velour	14.95
Jackson riding shorts, acrylic w/chamois (also others)	21.95
Black Bottom shorts, 60% wool w/chamois	29.95
Black Bottom leg warmers - 60% wool	18.95
Cycling Jerseys - 50% cotton/50% Poly. asst. colors	15.95
Trophy winter gloves, leather palms/fingers, red/orange/blue	18.95
100% Wool Jerseys, misc. colors	26.95
Detto Pietro T.D. Touring Shoe	39.95
Detto Pietro Art. 74 shoes w/adjustable cleats	42.95
Brancale Helmet	24.95
Huret Multito Cyclometer	9.95
Silca Floor Pump (The Best)	39.95
Silca Frame Fit Pump w/campy metal head	19.95
Two Wheeler Dealer T-Shirts (small-med-large)	5.00

FREE W/Mail orders only (good thru 9/30/81) - 1 clear Campy wat. bot. with $30. order. With $60 order - Cannondale seat bag (BO21) red/blu/yel.

TWO WHEELER DEALER
4406 WRIGHTSVILLE AVE.
WILMINGTON, N.C. 28403
TELEPHONE
(919) 799-6444

NEW! *Winter* Bata® biker™
"WINTOUR"
AVAILABLE NOW AT PARTICIPATING BIKE DEALERS
BATA SHOE CO., INC., BELCAMP, MD 21017 (301) 272-2000
Bata

MAIL ORDER Parts Catalog LOWEST Prices
FOR YOUR COPY SEND $2.00 TO
PEDAL PUSHER SKI & SPORT
P.O. BOX 82
HORSHAM, PA. 19044

Benotto...
50 Years of Experience,
7 World Championships.

Send $1.00 for our brochure which shows Benotto models and prices:

L.A. White, Jr., Inc.
1901 Medi-Park
Suite 1002
Amarillo, TX 79106

This result is confirmed by comparison of the photomicrographs of the two brands in their as-received condition (Figures 4 and 5). Figure 4 shows that Reynolds 531 has a more even distribution of spherical carbides (dark dots), whose function it is to reinforce the ferrite.

The first time I microscopically examined the as-received microstructures, I was very surprised (as were several metallurgists I consulted) to see spheroidized carbides. This microstructure is characteristic of low strength steels.

Reynolds 531 and Columbus SL are much stronger than their microstructures would indicate. As it turns out, a judicious combination of alloying, cold working, and heat treatment is responsible for their high strengths. Another interesting feature is that their as-received microstructures are ideal for steels which have to undergo further heat treatment (brazing or welding).

From Figure 1, it can be seen that the effect of brazing in the 1100°F to approximately 1333°F range significantly reduces the tensile strengths of both brands. This is because brazing in this range tempers the as-received microstructure. For all but one brazing temperature beyond approximately 1333°F, the average tensile strength of both brands is greater than their as-received values.

The purpose of brazing with low-liquidus silver alloys was to minimize the losses in mechanical properties encountered when brazing at higher temperatures. Unfortunately, there are sound metallurgical principles which state that this cannot be the case.

When any steel is heated beyond approximately 1333°F, it undergoes a transformation. If it is held at or above this temperature long enough, its mechanical properties can be altered upon cooling. Fast cooling will cause an increase in tensile and yield strength, but a loss of ductility. Slow cooling will reduce the tensile and yield strength, but increase the ductility.

The alloying element which most significantly affects this strengthening mechanism is carbon. The higher the carbon content, the slower the steel must be cooled to avoid strengthening to the point of brittleness. Reynolds 531 and Columbus SL have enough carbon so that cooling by natural convection results in an increase in tensile strength. Figure 6 is a photomicrograph representative of the type of structures formed.

When the forces applied to a bicycle frame are sufficient to induce permanent deformation, the frame is ruined. Since failure is determined by yielding, it is important for the tubing to retain a high yield strength after brazing. Figure 2 shows that the yield strength follows a trend similar to that in Figure 1. The yield strength increases with temperatures beyond the 1333°F point. Some values of yield strength may appear low, but I have calculated that they are satisfactory.

From Figure 3, you can see that tempering increases the ductility of both brands. In the temperature range where strengthening occurs, both brands retain good ductility. The ductility of Reynolds 531 at 1900°F is comparatively low, but would have to be below five percent to be considered unacceptable. Thus, the belief that brazing at high temperatures would reduce the tube's ductility to the point of brittleness is incorrect.

For the temperatures and times tested, Reynolds 531, in general, has higher tensile and yield strengths, but lower ductilities. This is because Reynolds 531 has a slightly higher carbon content than Columbus SL. The microstructures formed upon cooling from the 1333°F to 2100°F range (Figure 6) are characteristic of high strength brittle steels. But since both brands have sufficiently low carbon contents, the microstructures formed upon cooling have good mechanical properties.

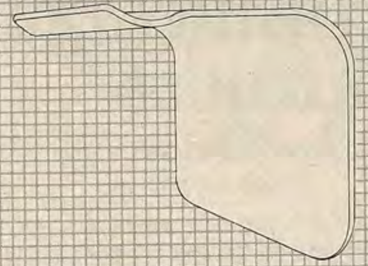
In addition, the microstructures temper upon cooling, thereby further improving their mechanical properties. Overheating is not the problem it has been thought to be. In fact, the cooling rate is the critical factor. It should never be faster than that achieved by natural convection, or the frame will surely fail.

My tests were unable to reveal the effects of high-temperature brazing on the fatigue strength of either steel, and I have also been unable to find adequate published data on these or similar steels. However, I am currently working on this problem. The only negative effect of microstructures such as in Figure 6 would be to reduce the impact strength of both steels. Impact strength may be an important consideration if road conditions are so severe that they subject the frame to high-impact loading.

While it now appears that it is acceptable to braze at temperatures beyond those the manufacturer recommends, it must be remembered that the guarantee will no longer be valid. Whether or not this is of any importance, as the European framebuilders have told us it is not, remains to be seen.

So after all this, which is a better tube: Reynolds 531 or Columbus SL? Neither one is significantly better than the other, and both are excellent. Matching the tubing gauges and tapers to the rider and use are far more important than any metallurgical differences I found.○

Introducing
THE BIKE SHELF

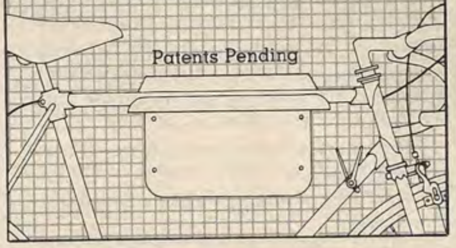


A safe and easy way to keep your bike indoors. Available in Birch, Walnut, or High Pressure Plastic finishes.

Satisfaction Guaranteed

For Information Write:
Eliasanne Research
1105 Park Street, N.E.
Washington, D.C. 20002

Patents Pending



Early Winters Brand New Outdoor Catalog
FREE

Take this opportunity to send for your free copy of the Early Winters catalog of unique outdoor gear.

The Early Winters Catalog is filled with high-quality, unusual outdoor equipment that'll lighten your load & help make your outdoor trips more enjoyable.
For your big, full-color copy packed with thousands of words of descriptive copy & scores of pictures, send this handy coupon or write today.

Early Winters, Ltd.
110-KV Prefontaine Pl. S., Seattle 98104

☐ Please send me your free color catalog of unique outdoor equipment filled with new & exciting items, most of which simply can't be seen or purchased anywhere else.

Name
Address
City/State/Zip

CUSTOM
·PRO BIKES
·FRAMESETS
·WHEELSETS
·RACE & TOUR
·16" — 33"
·FACTORY DIRECT
COLOR PHOTO - $1

MIURA Frameset $289

Send two stamps for a catalog
FASTAB CYCLES
Dept A 2706 S Glenbrook Garland TX 75041 214·278·0111

byKart Makes Bikes Useful

Use bicycles, mopeds in countless new ways. Add byKart, the great accessory: 3 cubic feet inside big (18" x 24" base) welded steel basket. Zinc plated, maintenance free. Unique tandem design puts load between rider and easy-rolling, heavy-duty tires. No tipping nor fishtailing. Never overloads bike. Trails perfectly; 3-way hitch attaches to any seatpost. Disconnects in seconds. Write byKart, P.O. Box 8373, Fountain Valley, California 92708. (C.O.D. any place in U.S.A.).

KALSØ earth shoe

MC & VISA Accepted

To order send shoe size and barefoot tracing and $65

STYLE 203
AMBER

or send 25¢ for mail order catalog of styles to:

Dept. BC8, P.O. 4084
Louisville, KY 40204

Go Sport LTD.
Importers of quality cycling products
Importeur
Sole U.S.A. distributors of
ALEX SPORT
cycle wear Belgium.
RIH SPORT
racing frames Holland.
Bata bikers in stock.
Campagnolo groups in stock.

dealer inquiries invited
319 E. 17th Avenue
Denver, Colorado 80203
(303) 839-1236

Bicycling Magazine's Newsletter for the Technical Enthusiast

BIKE • TECH

Aerodynamics • Mechanics • Physiology • Materials • Engineering

IN THE LAB

Volume 1 1982

PILOT ISSUE

IN THIS ISSUE

The Ultimate Titanium Frame?

As Stiff as Steel at Half the Weight

Fred DeLong and Crispin Miller

An accident in a brazing furnace and the two strange-looking bicycle frames that emerged have led Cecil Behringer and Pino Morroni to develop a promising new treatment for titanium bicycle frames. From the "victim" frames it appears that the treatment can approximately double the stiffness of a titanium frame. If the controlled version of the treatment works, it should create frames with the same stiffness as steel, at barely over half the weight. Moreover, since Behringer and Morroni's frames are lugged and brazed, they have no welds prone to soft or brittle spots. In short, these bikes may avoid both of the major problems of other titanium frames.

Behringer is now building a chamber to apply the controlled treatment, which hardens the inside and outside tubing surfaces by electrically implanting nitrogen atoms into the titanium. He is also building two frames to treat in it. These frames will be exhibited at the 1982 International Cycle Show in New York in February and the American Welding Society meeting in Kansas City in April.

Behringer is a metallurgical engineer from Edina, Minnesota, well-known for his expertise in metal-joining techniques for aircraft and spacecraft. He has also been active in bicycling for most of his life; he rode in six-day races in prewar days and learned framebuilding from "Pop" Brennan in 1936. A self-professed fanatic, he also builds portable steel velodrome tracks. Morroni, now of Rome, is known by many cyclists as the developer of wheels with spokes screwed straight into the hub flanges, avoiding the bend where fatigue causes breakage. He also makes special saddle frames, bottom brackets, and headsets, and is noted for his uncanny mastery of machining techniques. In their collaboration on bicycle frames, Morroni machines the titanium parts and Behringer joins and treats them.

The collaboration began in 1971 when Morroni, then living in Detroit, approached Behringer at a show there and suggested that they could build titanium bicycles. Behringer agreed, and they developed a system of lugs and brazing techniques to join high-strength titanium alloy tubing.

Other titanium frames had been made by inert gas welding, either of pure titanium or high-strength alloys, but the welding had detrimental effects. If this process was applied to high-strength alloys, it overheated them, necessitating heat treatment afterward that could distort the frame's alignment; and even with pure titanium, welding carried the risk of chemical embrittlement. Heated titanium is extremely reactive, and even if the welding region is shielded by streams of inert gas, any deflection of the gas stream by air currents allows atmospheric moisture, oxygen, and nitrogen to reduce the strength of the weld and make it brittle in spots.

Behringer took inert-atmosphere brazing techniques which were in standard industrial use for reactive metals and applied them to titanium bicycle construction. He heated the joints electrically or by quartz lamps in a furnace evacuated or filled with argon. The airtight furnace prevented any atmospheric contamination of the heated titanium.

But it did not protect the titanium from the furnace operator's mistakes. In 1973, when four of the frames were being brazed in a large furnace made available by a local factory, the process reached a stage at which the furnace was to be cooled by introducing cool argon. The operator used nitrogen instead.

When the furnace was opened, Behringer was horrified to find the frames covered with a gold and purple layer of nitrides. Two of them were so heavily encrusted with other reaction products as well that he considered them unusable (and still does). But two frames seemed to have possibilities, so he and Morroni assembled them as bicycles.

They happened to be not just all right, but the stiffest titanium frames Behringer and Morroni had ever seen. A scrap of tubing that had hung in the furnace along with them was tested and turned out to have approximately aluminum clamps. (Clamps of other materials could contaminate the titanium.) The brazing temperature for these joints is 1200°F and is held just long enough to wet the joint.

The sputtering process is to be done in an insulated furnace. The whole-frame-sized furnace is under construction (as of November 1981) but Behringer has done test runs on smaller parts. The part being treated is hung from a tungsten wire, and a large titanium plate is hung beside it; the plate acts as one electrode for the arc process and the part acts as the other.

The first step of the sputtering process is a cleaning procedure to ensure that the coating will be uniform. Surface oxides from handling must be removed. To accomplish this, the chamber is filled with argon and the charge — 20,000 volts — is applied in reverse polarity. This removes 1,500 to 2,000 angstroms of material. The chamber is then vacuum-pumped for a half-hour to remove the contaminants.

The charge is then applied in the proper polarity with a superimposed high-frequency alternating voltage. The part glows with a purple halo. Dry nitrogen is fed into the enclosure continuously to maintain 1 or 2 psi above atmospheric pressure as it is consumed. The high voltage dissociates it, and the nitrogen ions are carried in a plasma arc into the surfaces of the part, forming titanium nitride. The length of application time controls the depth of penetration. (The "accidental" frames have nitride layers about 1 or 2 ten-thousandths of an inch thick.) The electrical discharge heats everything to 600°F, but the temperature is uniform and causes no structural distortion.

In addition to the predicted stiffness increase, the process imparts a very hard surface and a uniform golden color. Behringer plans to run structural tests soon on the new frames and on test scraps processed with them. He hopes to have numbers on stiffness, strength, and fatigue resistance by early 1982. He's also testing the process on turbine blades for one of his aerospace clients. We'll publish the bicycle results when they become available.

Price for a frame? Not for sale. Behringer thinks someone could probably mass-produce them for $1,000 or so, but wants it to be someone else. "I wouldn't consider taking an order for less than $10,000. I like to make these things as sort of a test bed for my metallurgical techniques, but I'm not so sure titanium is the best thing to make bikes out of."

2

Malone Bradley

1 Track dropout of 6A1-4V titanium brazed with titanium-copper-nickel in vacuum.

2 Campagnolo titanium dropout brazed with titanium-copper-nickel in vacuum.

3 Titanium bottom bracket shell weight—87 grams. Each of the five pieces of the shell was hand-machined and then the shell was brazed together.

3

Silver vs. Brass Brazing

What Is the Real Strength Difference?

Mario Emiliani

What are the effects of brazing on the mechanical properties of Reynolds 531 and Columbus SL tubing? I answered that question in the September/October 1981 issue of *Bicycling* magazine. In turn, I received a number of critical letters which raised points I had not considered, including one about the strength difference between silver and brass brazing.

During torch brazing a temperature gradient is set up along the tube. The higher the brazing temperature, the farther back the gradient reaches. So if a high-temperature brazing alloy is used, the tube will be tempered (i.e. have significantly reduced tensile and yield strengths caused by exposure to temperatures between 1150°F and 1350°F) farther back, closer to the thinner unbutted section.

If this is the case, then the tube is weakened outside the lug, where it may not be thick enough to compensate for the loss of strength. Would it be possible to temper the tube beyond the butt using a high-temperature brazing alloy? In this case, the load the tube could support would be substantially reduced because the unbutted portion is usually very thin.

However, if a low-temperature brazing alloy were used, the tempered portion of the tube would be reinforced by the lug. My critics contend that the joint would be less prone to failure, and so they favor the use of low-temperature silver brazing alloys. I consider this hypothesis worth looking into. How far back a tube is tempered may be determined by testing actual brazed joints. Since I am not adept at brass brazing, I asked framebuilder Richard Sachs to braze one Reynolds 531 top tube/head tube joint[1] with a brass alloy (1630°F liquidus) and another Reynolds 531 top tube/head tube joint with a low-temperature silver alloy (1145°F liquidus). To have control over the experiment, the same tube lengths, tube gauges, and lug styles were used. The marked ends of the top tubes (short butt) were brazed into the lug.

To determine how far back the tubes had

[1]The tubes were supplied by SRC GROUP INC., Portland, Oregon.

been tempered, hardness tests were performed along the length of the top tubes (Figure 1). A Rockwell digital hardness tester was used on the 30-T scale (30 kg major load, with a 1/16-inch steel ball indenter). The 30-T hardness values were then converted to a diamond pyramid hardness (D.P.H.) values.

The conversions to D.P.H. were made so the yield strength of the tube could be determined using the equation

$$\text{yield strength} = \frac{\text{D.P.H.}}{3.6} (B)^n (1422), \text{ in psi}$$

where $B = 0.1$ and $n = 0.08$ for steel[2]. The results of the hardness tests are given in Table 1.

Table 1 shows a drop in hardness about 22 millimeters from the lug point for the brass brazed joint. The tube has been tempered at that place. Similarly, the silver brazed joint has been tempered up to at least 7 millimeters from the lug point. So it is true that high-temperature brazing tempers the tube farther back than low-temperature brazing. But is this something worth worrying about? It's impossible to say, since the stresses a top tube undergoes are unknown. Practical experience has shown that failures of properly brazed brass joints are very rare. However, I think that under the right loading conditions, the tempering could become a problem if the thickness of the butted section were less than 0.8 millimeters (21 gauge).

To determine if the tempered zones were beyond the butt, I split the tubes in half. They had a butted section 75 millimeters long, and a tapered section about 45 millimeters long. Thus, the tempered zones were well within the butted section in both cases (Figure 2).

I also received a bit of criticism over the heating procedure I used to simulate brazing in my initial studies. Table 2 is a comparison of actual brazing data from the experiment described in this article, and the data I presented in the September/October 1981 issue of *Bicycling*. As you can see, the data is in excellent agreement (less than 5% difference).

[2] J. R. Cahoon, W. H. Broughton, and A. R. Kutzak: *Metal. Trans.*, Vol. 2, July 1971, pp. 1979–1983.

Table 1

Distance From Lug Point, mm	Average D.P.H./Average Yield Strength, lb/in.² — Silver-Brazed Joint	Average D.P.H./Average Yield Strength, lb/in.² — Brass-Brazed Joint
2	213/69,980	255/83,779
7	198/65,050	257/84,436
12	281/92,321	268/88,050
17	283/92,880	251/82,465
22	286/93,965	215/70,637
27	290/95,280	277/91,010
32	284/93,307	285/93,635
37	292/95,935	299/98,235
42	298/97,910	297/97,580
47	294/96,593	299/98,235
52	299/98,235	308/101,192
57	306/100,535	310/101,850
62	305/100,206	307/100,865
100	306/100,535	307/100,865

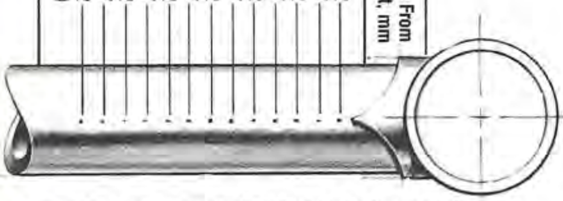


Figure 1: Top view of the top tube/head tube joint showing one set of hardness indentations.

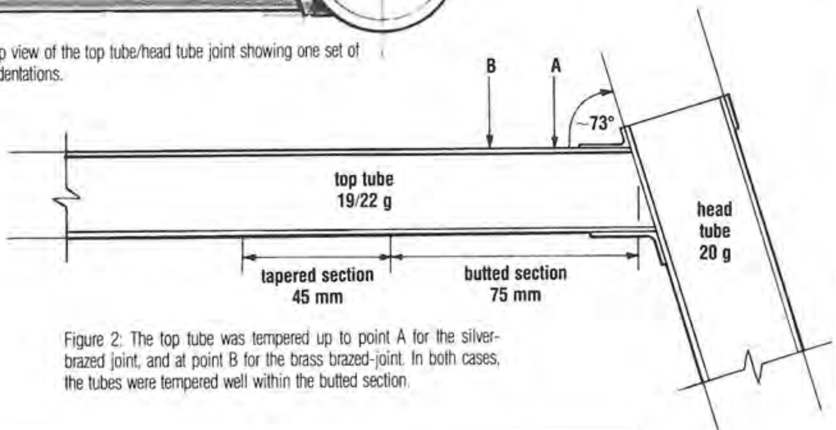


Figure 2: The top tube was tempered up to point A for the silver-brazed joint, and at point B for the brass brazed-joint. In both cases, the tubes were tempered well within the butted section.

Sandy Roth

Table 2

	531 after Brazing at 1300°F for 5 Minutes	531 after Brazing at 1700°F for 5 Minutes	Silver Brazed Joint 2mm from Lug Point	Brass Brazed Joint 2mm from Lug Point
Average Yield Strength, lb/in.²	66,670	87,370	69,980	84,683

Where the Information Is Lacking

David Gordon Wilson

Editor: Many of us know Wilson, a professor of mechanical engineering at Massachusetts Institute of Technology, for his innovations in bicycle technology such as the Avatar 2000 recumbent bicycle and the Positech brake (which, unlike the Avatar, has not yet been manufactured). We also know Wilson for his pleas for the bicycle industry to conduct more research. Here is Wilson's laundry list of neglected areas that need scrutiny.

To design vehicles which put less strain on the human body to propel, we need to do more research in the ergonomics of human power production, the aerodynamics of enclosed wheel-driven vehicles, the rolling resistances of tires, and the transmission efficiencies of alternative drives in actual working conditions. To design vehicles which are safer to use, we need to know more about the mechanics and biomechanics of various types of collisions and falls, and the friction of wet sliding surfaces. To use the new lightweight composites for construction, we need fatigue data taken in conditions of realistic loading.

To see that the necessary research takes place, we need to create a mechanism to fund that research. I'll present here some more detail on each of these topics and my proposal for funding research.

My list of topics is subjective and personal; other people would come up with their own lists. Although I present the areas of human power output and energy dissipation first, I consider the safety-related areas more important.

Ergonomics

Before the development of the sliding-seat rowing shell and the pedaled Michaux velocipede in the 19th century, most human power production was produced by straining mightily with arm and back muscles against a slowly yielding resistance, as in rowing galleys and in most agricultural work. The advantage of using muscles at a good impedance match with the load through the use of optimum leverage or gearing (Figure 1) led to the dominance of circular constant-velocity-ratio pedaling motions being used for cycles, and to sliding seats and long lightweight oars or sculls for racing boats.

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH T.M.

Bicycling Magazine's Newsletter for the Technical Enthusiast

Volume I, Number 1, June 1982 $2.00

IN THE LAB

Frame Rigidity

Crispin Mount Miller

How rigid is a bicycle frame? How much difference is there among different frames, and what are the consequences? Few other questions about frames intrigue cyclists as much as these, but good answers have seldom been available. Like many other aspects of bicycle engineering, frame rigidity is a subject that has been buried in folklore and mythology.

Some time ago we discovered that several people had independently thought of the same configuration for a frame rigidity testing jig. Among the people in this club were Gary Klein, Gary Fisher, John Schubert, and me. We were scattered around the bicycle industry and didn't all know each other, but we'd all wished for the same kind of machine.

A Different Kind of Machine

Our idea was to simulate riding stresses by loading a bicycle frame as a rider would — by pressing on the pedal — and then measuring how the frame deflected under the load. The frame would have to be supported in a realistic fashion, with dropouts and head tube not clamped rigidly in place, but allowed to move somewhat, as they do when a bike is ridden.

In this respect, our machine would differ from the few rigidity testing machines known to exist inside the bicycle industry. Most manufacturers test rigidity by clamping the frame down and poking sideways on the bottom bracket shell. This is adequate for some kinds of comparisons, but it doesn't address all the subtle questions that our pedaling load simulator would answer.

Building such a machine was too time-consuming and costly for any of us, but a cooperative effort made it possible. Gary Klein and John Schubert collaborated on a design over the telephone, and Klein built "Tarantula I" in his framebuilding shop. *Bicycling* magazine purchased the machine from Klein and it now sits in our bike workshop. We have done a few tests with the machine; in this article, I'll present an analysis of how and why the machine works and what questions it can answer for us.

Need to Isolate Results

The fundamental purpose of the machine's design is to apply loads to a frame in ways that resemble normal use, but to isolate the results: to sort out, from a bike's various deflections under load, what portion is due to deflection of the frame, and not of the wheels, drivetrain, or anything else.

To perform such measurements reliably, a testing machine must provide well-controlled, repeatable ways to do three things: support and hold the frame being tested; apply force with a known magnitude, location, and direction; and measure deflections of specific parts, in specific directions.

The support must be designed to minimize extraneous motion that would contaminate the readings. This machine's design accomplishes this principally by making all the supports many times as rigid as the object being tested, so that deflections of the supports are negligibly small; and also by arranging the support structure so that any deformations that do occur do not affect the measurements.

The principal support for the bicycle is a rail representing the ground, consisting of a steel pipe three inches in diameter and five feet long, three-dimensionally braced by several welded struts of smaller steel pipe.

The bicycle sits on this support rail on a pair of one-by-two inch steel pillars installed in place of wheels. These pillars are fastened to the bicycle frame's dropouts, not to the testing machine; at the bottom end they are simply notched to sit on the support rail. They simulate perfectly rigid wheels that have perfect traction (against lateral motion) on the ground. They are free, however, to move in certain limited ways (as rigid wheels would) so that they don't improperly restrain the motion of the frame itself.

The front pillar is equipped with a freely rotating "axle" at the top end and a "roller

IN THIS ISSUE

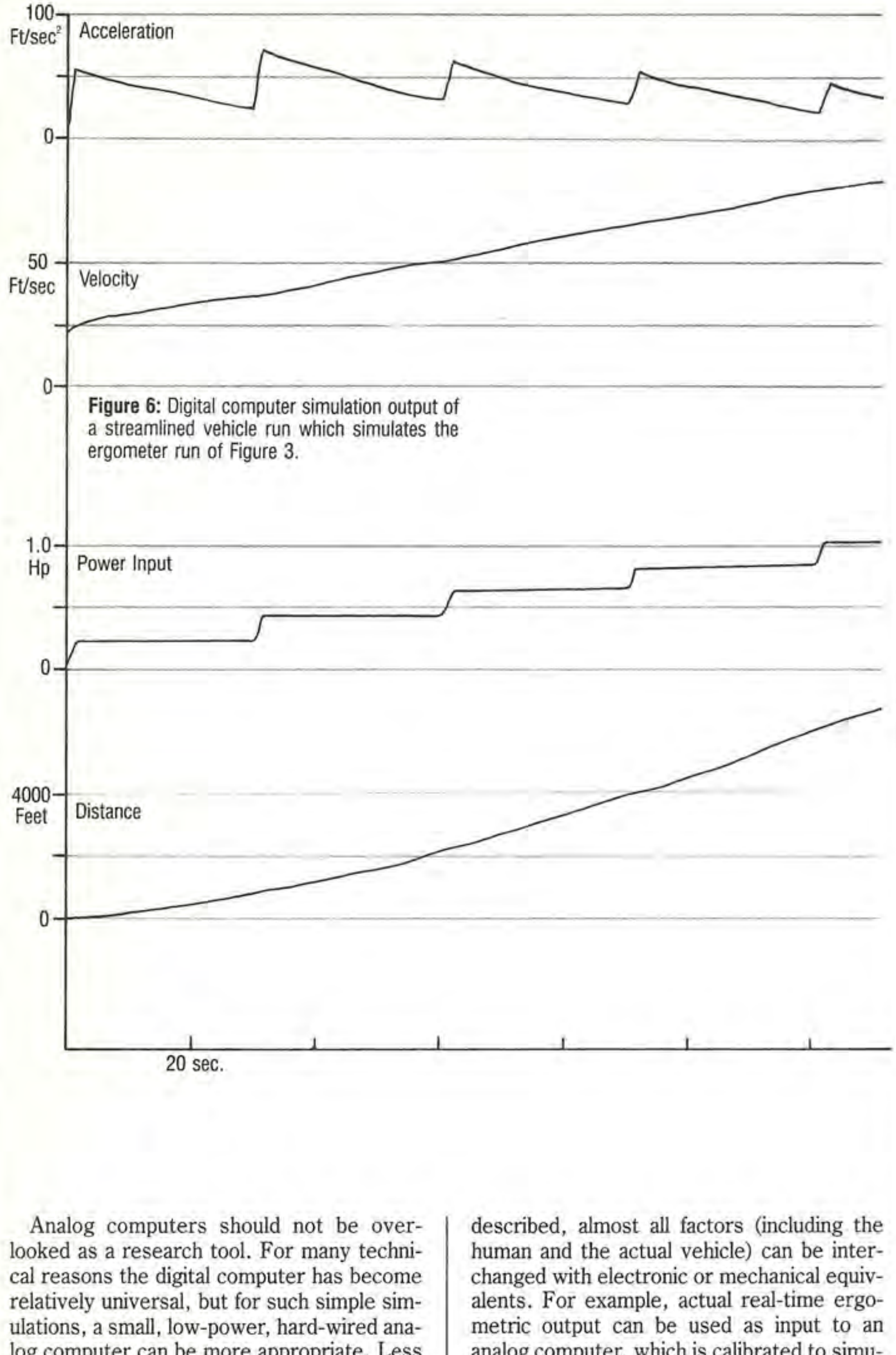


Figure 6: Digital computer simulation output of a streamlined vehicle run which simulates the ergometer run of Figure 3.

Analog computers should not be overlooked as a research tool. For many technical reasons the digital computer has become relatively universal, but for such simple simulations, a small, low-power, hard-wired analog computer can be more appropriate. Less than a few dozen electronic components are required, including a potentiometer for each of about five important variables. All of the necessary outputs can be plotted in real time just as the digital output shown in Figure 6. In fact, the device is similar to the previously described analog computer built to compute horsepower on an ergometer, and could be made small enough to fit in a pocket.

At this point, the research methodology has gone full circle. To perform a good simulation you need good drag and ergometric data, and to get good data you need a good lab simulator. A natural product of this situation is the full-scale simulator: given the mechanical and electronic hardware previously described, almost all factors (including the human and the actual vehicle) can be interchanged with electronic or mechanical equivalents. For example, actual real-time ergometric output can be used as input to an analog computer, which is calibrated to simulate any conceivable machine, and the output can be recorded in terms of speed or distance. In effect, this is what the previously described electronic feedback control motor/generator ergometer is — a programmable full-scale vehicle simulator. As a solution to the problem of finding acceptably flat and long courses on which to have speed championships, races could be held on such a machine. The only problem is the effort of determining appropriate drag coefficients for each competitor's vehicle.

**For more detail on all the tests and equipment mentioned here, see my book* Race Car Engineering and Mechanics *(Dodd Mead, 1976).*

On Some Much - Misused Terminology

Mario Emiliani

Editor: The folklore engineers of the bicycle world have traditionally abused a number of technical terms. Colloquial understanding of technical terms is sometimes so misleading that it becomes difficult for an enthusiast to understand a technical presentation. We hope this article will get us all speaking the same language and put an end to many common misunderstandings.

The following terms will appear frequently in Bike Tech. *Our contributing editor/metallurgist Mario Emiliani has defined all the terms and indicated some preferred terms along with the reasons why they're preferred.*

Most of these definitions are too difficult to remember if you don't work with them every day (yet another reason for you to save this issue of Bike Tech *for future reference). But this article is more than a dictionary; just reading through it and contemplating the definitions will help you understand a lot about how metals behave. And our future articles will rely heavily on this understanding.*

General Terms

Alloy - A mixture of two or more elements.

Ferrous Metal - A metal which contains mostly iron.

Steel - An alloy of iron and up to 2 percent carbon.

Plain Low-Carbon Steel - A steel which contains only carbon and manganese as intentional alloying elements.

Low-Alloy Steel - A steel which contains up to 5 percent total intentional alloying elements.

Microstructure - A metal's structure, which is usually visible only under a microscope after special preparation.

Rigidity - This term will always be used instead of "stiffness" when describing the ability of a frame, wheel, crankarm, etc., to resist deflections caused by pedaling. More about this when we get to the modulus of elasticity.

Hot-Drawing or Hot-Working - Deforming a metal at temperatures which depend upon the metal. These temperatures are usually above about one-half the metal's melting point. For steels, hot working takes place between about 1350°F - 2200°F. Hot working is used to make large dimensional changes in a component.

Cold-Drawing or Cold-Working - Deforming a metal at temperatures below about one-half its melting point. For steels, cold drawing can take place up to about 1350°F. The purpose of cold drawing is to increase the strength of the metal, and/or to refine the shape of a part to conform to close dimensional tolerances.

Terms Related to Testing

Force or Load - The effort needed to accelerate a mass, that is, pounds or newtons.

Stress - The force per unit area on an object; i.e., pounds per square inch (lb/in^2) or kilograms per square millimeter (kg/mm^2).

Strain - The amount a material deforms in the direction of a stress applied to it: stretching when tested in tension, compressing when tested in compression, or shear when tested in shear. Strain measurements are made on a portion of the test specimen called the gauge length. Strain is usually measured in terms of inches of deformation per inch of gauge length, or inches per inch (in/in). Shear strain is measured in terms of an angle.

Static - A state in which all the forces acting on a mass are in balance. Such a mass is said to be in equilibrium, or at rest. Many tests on materials are called static because the variations in testing parameters occur very slowly. A tensile test is considered a static test.

Dynamic - A state in which the forces acting on a mass are unbalanced, and vary continuously with time. An example of a dynamic test done on materials is a fatigue test.

Mechanical Properties - The tensile strength, yield strength, impact strength, fatigue strength, ductility, hardness, and modulus of elasticity of a material. Several of these properties (defined below) are illustrated graphically in Figures 1 and 2.

Tensile Strength - The maximum stress a material can withstand in tension. The tensile strength is Point 4 in Figures 1 and 2.

Yield Point - The tensile stress beyond which significant permanent deformation will take place. More accurately, it is the point at which the stress-strain curve begins to deviate from linearity. The line 0 to 1 in Figures 1 and 2 is the linear portion of the stress-strain curve, Point 1 being the yield point.

An important thing to remember is that Point 1 in Figure 1 is where *significant permanent yielding begins*. This is not to say that yielding doesn't occur at lower stresses - it does; it's just hard to detect.

Yield Strength - This is the stress at which a material exhibits a specified deviation from linearity. Some materials display a small dip in their stress-strain curves just beyond the yield point. The uppermost portion of the curve is taken as the yield strength. This is shown as Point 2 in Figure 1.

Some materials (including most of the high-quality steels used in bicycle tubing) don't exhibit a definite yield strength, so we have to arbitrarily define one. For these materials, the stress-strain curve doesn't dip after the yield point. The curve keeps rising smoothly.

To define a yield strength for these materials, we add a line to their stress-strain graphs, as seen in Figure 2. This line is parallel to the line 0-1 but offset 0.002 in/in to the right. The point at which this line intersects the stress-strain curve is taken as the yield strength (Point 3, Figure 2).

Ductility - The ability of a material to deform permanently without breaking. This property is usually measured by the percent elongation, which is the percent a material permanently deforms relative to a portion of its original length.

A material with a high percent elongation is termed ductile, while one with a low percent elongation is termed brittle. The value of percent elongation at which a material is considered ductile or brittle varies among materials, and depends on what the material is going to be used for. Ductility is influenced by cold working, heat treatments, and alloying elements.

Elastic Deformation - Strain which occurs between Points 0-1 in Figures 1 and 2. Materials stressed in this region will never take a significant permanent deformation.

Plastic or Permanent Deformation - Strain which occurs beyond Point 1 in Figure 1, or beyond Point 3 in Figure 2. Materials stressed in this region will take a permanent set.

Modulus of Elasticity or Stiffness - This property is a measure of a material's ability to resist deformation by stresses below its yield strength. It varies considerably among materials, but is fairly constant for particular metals. For example, the moduli of elasticity of steel, titanium, and aluminum are 30 million lb/in^2, 17 million lb/in^2, and 10 million lb/in^2, respectively. These values don't vary appreciably regardless of alloy content, heat treatment, or mechanical working.

The word stiffness, as applied to the modulus of elasticity, should never be confused with the rigidity of bicycle frames. They are two entirely different things. The rigidity of a bicycle frame varies, and depends upon the inside and outside diameters of the tubes and the geometry of the frame. The modulus of elasticity is independent of material dimensions.

The modulus of elasticity, customarily called "E," is found by determining the slope of the linear portion of the stress-strain curve (see Figures 1 and 2).

Hardness - A material's resistance to plastic deformation, usually measured by making an indentation in the material. Hardness tests are good indicators of a material's tensile and yield strength, and have the added attraction of being easy to do.

Impact Strength - The amount of energy needed to break a material. If a material can absorb a lot of energy and deform plastically, the material is said to be "tough."

Fatigue - Failure of a component due to the application of repeating stresses. Fatigue failures are progressive, in that the repeating stresses must be applied enough times that they create cracks large enough to cause failure.

Fatigue Strength - The maximum stress a material can withstand for a specified number of cycles without failure. For this term

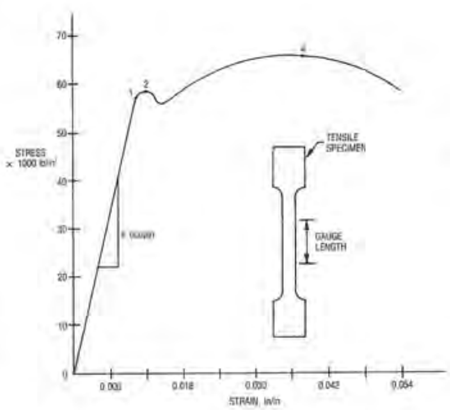


Figure 1. A typical stress-strain curve for plain low-carbon steels. Point 1 is the yield point; Point 2 is the yield strength; Point 4 is the tensile strength; and E is the modulus of elasticity. 0 to 1 is the linear portion of the stress-strain diagram.

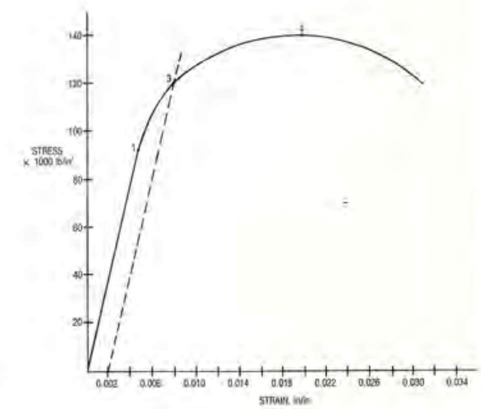


Figure 2. A typical stress-strain curve for high-strength steels and aluminum alloys. Point 1 is the yield point. The intersection of the dotted line and the stress-strain curve, Point 3, is the yield strength of 0.002 in/in strain. Point 4 is the tensile strength.

to mean anything, both the stress level and the number of cycles must be stated.

Fatigue Limit - The maximum stress level a material can withstand for 10 million cycles without failure. Only a few metals, most notably steels, exhibit a fatigue limit.

Slip - The process by which plastic deformation occurs. Slip is simply rows of atoms sliding over each other due to shear stresses.

Terms Related to Brazing

Brazing - A process which joins metals by heating them to a suitable temperature, then introducing a non-ferrous filler metal (the brazing alloy). The filler metal has a liquidus above 840°F, but below the solidus of the base metals. (Only non-ferrous metals have such a low liquidus.) A characteristic of brazing is that the filler metal is drawn into close-fitting surfaces by the phenomenon of capillary attraction.

Base Metals - The metals which are joined together.

Liquidus - The lowest temperature at which a metal is liquid. Sometimes a component of a metal melts first, leaving the remaining metal still solid or slushy. Liquidus refers to the lowest temperature at which the *entire* alloy is liquid.

Solidus - The highest temperature at which a metal is completely solid.

Silver Brazing Alloy - This term is preferable to silver solder since soldering is a completely different joining process. The confusion between soldering and brazing occurs because the upper temperature limit of soldering is near the lower temperature limit of brazing (around 840°F).

Silver Brazing - This term will be used instead of silver soldering for the above reasons.

Brass Brazing Alloy - This term is preferable to "bronze brazing alloy" because there aren't any bronze brazing alloys. Some brazing brasses (alloys of copper and zinc) contain about one percent tin, and as a result people called them bronzes. In 1978 the American Welding Society recognized that "bronze" was misleading, and changed its filler metal specifications to "brass" where applicable.

Brass Brazing - This term will be used instead of bronze brazing for the above reasons.

Heat-Affected Zone - A region of base metal adjacent to the area joined, whose mechanical properties are altered by the heat.

Overheating - Most people use this term, as it applies to the joining of bicycle frames, to refer to a supposed impairment of the steel's mechanical properties due to excessively high heat. Usually, excessive heat is thought of as temperatures beyond those recommended by the tube manufacturer. But tests I have done show that high-quality bicycle tubing can withstand temperatures much higher than the manufacturers recommend, with (apparently) few ill effects (see *Bicycling*, September/October 1981).

Overheating is a term more accurately applied to the brazing alloy than the steel. Brazing alloys have a narrow range of temperatures at which they can be used successfully. If the brazing temperature is higher than the upper limit of this range, constituents of the brazing alloy will become volatile and burn off. Because of the locally high pressure created when the brazing alloy is overheated, some of the brazing alloy is driven between the grains of the steel. This can weaken the steel. In addition, burning the brazing alloy will alter its chemical composition, which in turn may affect the strength of the joint.

Natural Convection - The way brazed bicycle joints are cooled. It's simply to let the joint cool by itself in still air at room temperature.

Welding - Joining two metal objects by heating them to a temperature which allows the base metals to fuse together without the need for filler metal. Often, though, a filler metal (welding rod) is used.

Terms Related to Heat Treating

Heat Treatment - Controlled heating and cooling of a metal to obtain certain mechanical properties. Time is a very important factor when heat treating metals.

Annealing - A general term describing a heat treatment designed to soften (and consequently, weaken) a metal. Variations of this term are used to describe the extent to which the metal is softened.

Normalizing - A heat treatment for ferrous alloys which involves heating the metal above about 1350°F, then cooling it in air by natural convection (usually to room temperature). This is the heat treatment given to steels brazed at temperatures beyond about 1350°F.

Tempering - A heat treatment used to make a metal tougher. This is done, for example, by heating a steel to between approximately 1100°F and 1350°F for a period of time. This is the heat treatment given to steels brazed at temperatures below about 1350°F. The time period depends on the specific alloy and on the thickness of the object (thicker pieces take longer for the center to reach temperature).

Grain Size - Metals are made up of many microscopic crystals called grains. The grain size of a metal determines its mechanical properties; the grain size is determined by alloying, and heat and mechanical treatments.

BOOK REVIEW

Fahrradtechnik: *A Very German Approach to Bicycle Engineering*

John S. Allen

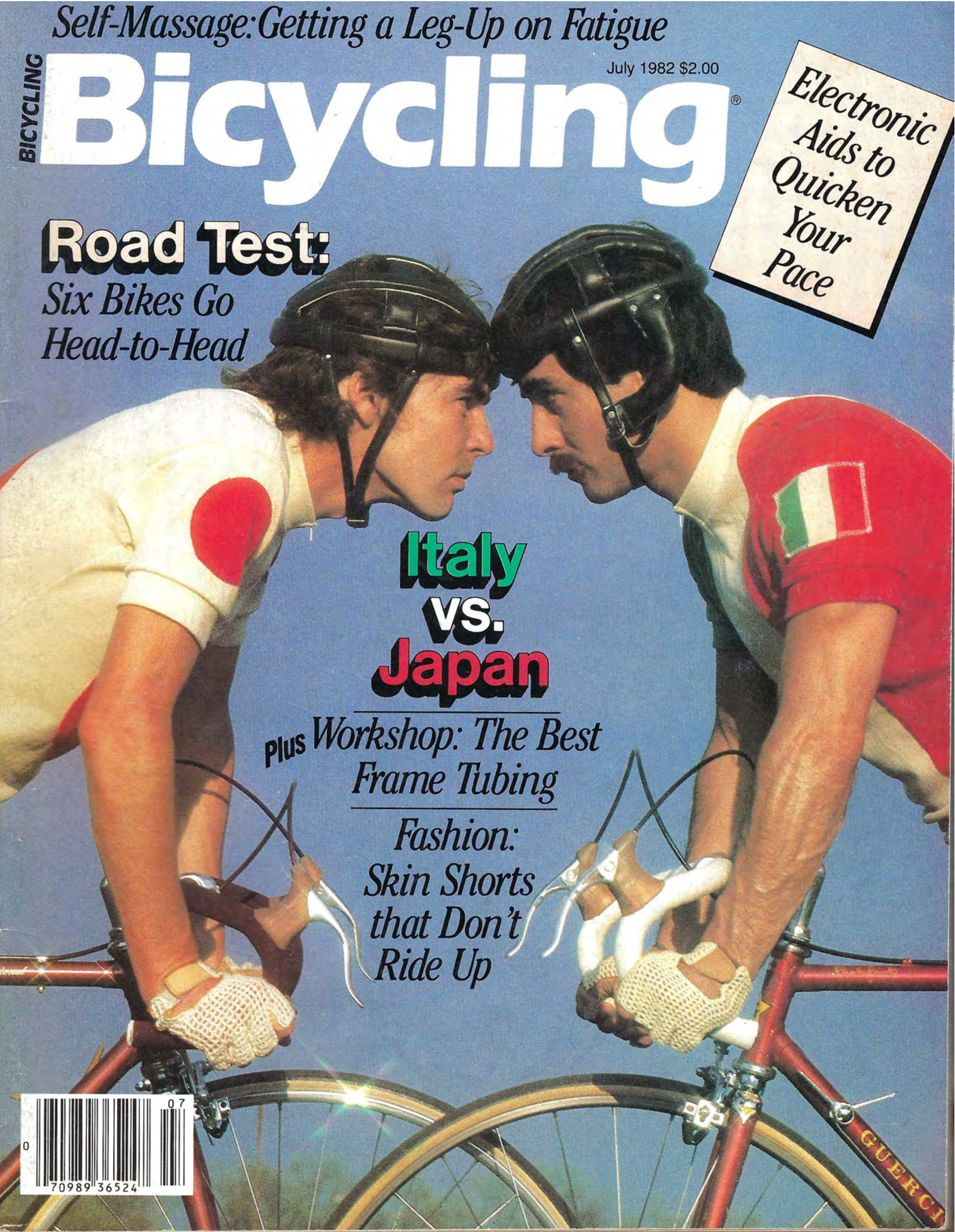
Fahrradtechnik: Konstruktion, Fertigung, Instandsetzung (Bicycle Engineering: Design, Fabrication, Assembly and Adjustment); by Siegfried Rauch and Fritz Winkler. (Bielefelder Verlaganstalt KG, Bielefeld, Federal Republic of Germany, 1980) 306 pages, 263 illustrations.

This book belongs on the shelf of any person who takes an active interest in the subjects covered in its title. The many illustrations convey considerable information even if you don't speak German: if you want more information, use the illustrations as your table of contents and find a German-speaking person to translate.

Both authors have worked as engineers in major bicycle manufacturing firms in Germany and Holland. The emphasis of the book reflects their experience. The third of the book on materials, design considerations, and techniques related to mass production of bicycle frames is quite thorough, but the other two-thirds on components is less complete.

The book brings together, and relates to bicycles, much information that is usually found only in general engineering manuals: tables of different types of steels with their compositions and properties; a look at the geometry and stress relationships in welded and brazed joints; and a survey of welding and brazing materials and techniques. The book includes many engineering drawings, with dimensions, of frames and frame parts, gleaned directly from the drafting departments of major German bicycle manufacturers. Such drawings are not available to the public anywhere else, as far as I know. They give an unparalleled insight into major bicycle manufacturers' design decisions and into the manufacturing process.

The authors demonstrate a strong understanding of materials science and manufacturing technology. This strength is evidenced by their discussion of frames and the manufacture of handlebars, stems, machine-built wheels, and some other bicycle parts. There is a substantial but appropriately cautious discussion of the present and future uses of plastics and other synthetic materials in bicycle construction.


Self-Massage: Getting a Leg-Up on Fatigue
BICYCLING
Bicycling®
July 1982 $2.00
Electronic Aids to Quicken Your Pace
Road Test:
Six Bikes Go Head-to-Head
Italy vs. Japan
Plus Workshop: The Best Frame Tubing
Fashion: Skin Shorts that Don't Ride Up
07
0 70989 36524
GUERCI

Contents *Bicycling July 1982* *Volume XXIII, Number 6*

Cover photo by Sally Ann Shenk

Fitness

Features

The Workshop

Departments

Bicycling Magazine, Inc. is a wholly owned subsidiary of Rodale Press, Inc. Robert Rodale, Chairman of the Board; Robert Teufel, President; Marshall Ackerman, Executive Vice President; David Widenmyer, Treasurer. Editorial contributions about equipment, repairs, touring, and health are welcome. Send inquiry or write for guidelines. Include a stamped, self-addressed envelope for return of unused material. Submission of the manuscript which includes all drawings, sketches, photos and other artwork, to Bicycling Magazine is the author's warranty that the material is in no way an infringement upon the rights of others and that the material may be published without additional approval.

Bicycling (ISSN 0006-2073) is published by Bicycling Magazine, Inc. 33 E. Minor St., Emmaus, PA 18049 Phone (215) 967-5171. Subscription rate: United States, one year $12.97; two years $24.00 (Canadian add $3.00 per year; other foreign add $6 per year). Single copy price, $2.00. Second class postage paid at Emmaus, PA 18049 and at additional mailing offices. In Canada, second class postage paid at Laval, Quebec; return to: 49 Westmore Dr., Rexdale, Ontario M9V 4M3. Bicycling is published monthly March through August, bimonthly September through February. Copyright by Bicycling Magazine, Inc. 1982. **Postmaster: Send address changes to Bicycling, 33 E. Minor St., Emmaus, PA 18049.**

The Workshop

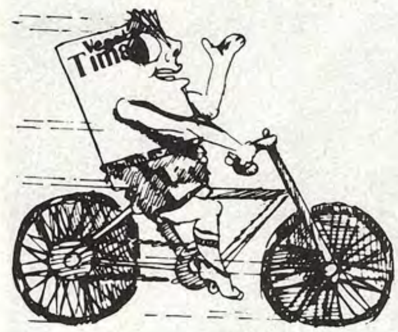
Straight Talk on Steel

Bicycling's Metallurgist Peels Away the Myths and Advertising Hype, and Tells You the Facts About Your Frame's Tubing

Mario Emiliani

Steel is the most popular bicycle frame material ever used. It is inexpensive, readily available, easy to work with, strong, and light. Other materials such as plastic, aluminum, graphite, titanium, wood, aluminum-graphite composites, and aluminum-boron composites have been used, but only aluminum and aluminum-boron composites have been long-time

WE GO FULL CYCLE



VEGETARIAN TIMES covers the distance . . . between good nutrition and good eating. And the connecting "link" is low cost.

Three good reasons to invest in **VEGETARIAN TIMES,** a magazine for every health-conscious American . . . vegetarian, partial vegetarian, or just thinking about it.

Read about great health, great food, great ideas, and how to get there with a magazine that is newsworthy, entertaining and informative.

Issue after issue will provide you with better ways on how to spend less to be healthy and live well.

Ride with a winner. Fill out the coupon below and pedal it to the nearest mailbox.

VEGETARIAN TIMES-BY
41 East 42 Street, N.Y., NY 10017

Published monthly

( ) 1 Yr. $20 ( ) 2 Yrs. $36
( ) 3 Yrs. $50

( ) Check Enc. ( ) VISA
( ) Mastercard ( ) Bill Me

Credit Card # ____________
Exp.Dt. ____________
Name ____________
Address ____________
City ______ State ____ Zip ______

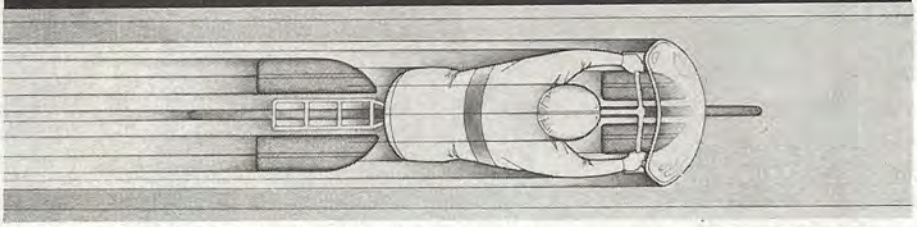
If you've ever wondered what the real differences between your Columbus SL bike and your neighbor's Ishiwata 022 bike are, now you know: you have lighter fork blades and stays, but a heavier steering column. This table shows that many tube sets are quite similar, but also that a few surprising differences exist.

Table 1: Gauges and Weights of Seamless Tube Sets[5,6,7]

Brand	(thickness in millimeters)								Set Weight (grams)
	Head Tube	Top Tube	Down Tube	Seat Tube	Fork Blades	Chain-stays	Seat-stays	Steering Column	
Columbus Record	0.8	0.5	0.5	0.5	0.9	0.5	0.5	2.5/1.65	1,610
Columbus KL	0.8	0.7/0.5/0.7	0.7/0.5/0.7	0.7/0.5	0.9	0.5	0.5	2.5/1.65[A]	1,670
Columbus PL	0.8	0.6	0.6	0.6	1.0	1.0	0.7	2.5/1.65	1,840
Columbus SL	1.0	0.9/0.6/0.9	0.9/0.6/0.9	0.9/0.9	0.9	0.7	0.7	2.5/1.65[A]	1,925
Columbus PS	1.0	0.71	0.71	0.71	1.05	1.05	1.0	2.5/1.65[A]	2,255
Columbus SP	1.0	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7	1.05	1.0	1.0	2.5/1.65[A]	2,295
Columbus Aelle	1.0	0.8	0.8	0.8	1.05	0.9	0.9	2.3/1.65	2,345
Ishiwata 015	0.7	0.6/0.4/0.6	0.6/0.4/0.6	0.7/0.4	1.0/0.8[B]	0.55	0.6	2.2/1.6[A]	1,595
Ishiwata 017	1.0	0.7/0.4/0.7	0.7/0.4/0.7	0.7/0.4/0.7	1.0/0.8[B]	0.8	0.6	2.2/1.6[A]	1,855
Ishiwata 019	1.0	0.8/0.5/0.8	0.8/0.5/0.8	0.8/0.5	1.0	0.8	0.6	2.2/1.6	1,990
Ishiwata 021	1.0	0.9/0.55/0.8	0.9/0.55/0.8	0.9/0.6	1.0	0.8	0.8	2.2/1.6	2,065
Ishiwata 022	1.0	0.9/0.6/0.9	0.9/0.6/0.9	0.9/0.6	1.0	0.8	0.8	2.2/1.6	2,185
Ishiwata 024	1.0	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7	1.2	0.8	0.8	2.2/1.6	2,360
Ishiwata 0245	1.2	1.2/0.85	1.2/0.85	1.0	1.2	1.0	1.0	2.7/1.6	2,794
Ishiwata 0265	1.2	1.2/0.85/1.2	1.2/0.85/1.2	1.2/0.85	1.2	1.0	1.0	2.7/1.6	2,805
Ishiwata Magny V	1.0	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7	1.0	0.8	0.8	2.5/1.6	3,290
Ishiwata Magny X	1.0	0.9/0.6/0.9	0.9/0.6/0.9	0.9/0.6	1.0	0.8	0.8	2.5/1.6	3,190
Reynolds 753[C]	0.9	0.7/0.3/0.7	0.8/0.4/0.8	0.7/0.3	1.0/0.5[B]	0.6	0.4	2.3/1.5	1,760
Reynolds 531 SL	0.9	0.7/0.5/0.7	0.8/0.5/0.8	0.7/0.5	1.0/0.5[B]	0.6	0.5	2.3/1.5	1,995
Reynolds 531	0.9	0.8/0.5/0.8	0.9/0.6/0.9	0.8/0.5	1.0/0.5[B]	0.8	0.9	2.3/1.5	2,140
Reynolds SMS	0.9	0.8	0.8	0.8	1.0	1.0	0.9	2.3/1.5	2,700
Super Vitus 980	1.0	0.8/0.5/0.8	0.9/0.5/0.8	0.8/0.5	1.0	0.8	0.6	2.5/1.6[A]	1,805
Vitus 181	1.0	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7	1.2	0.9	0.8	2.5/1.6	2,241
Tange Champion Pro	1.0	0.6/0.3/0.5	0.6/0.3/0.6	0.6/0.3/0.6	0.9	0.6	0.6	2.5/1.6[A]	1,600
Tange Champion No. 1	1.0	0.8/0.5/0.8	0.8/0.5/0.8	0.9/0.6/0.9	1.0	0.8	0.8	2.5/1.6[A]	1,960
Tange Champion No. 2	1.0	0.9/0.6/0.9	0.9/0.6/0.9	0.9/0.6/0.9	1.0	0.8	0.8	2.5/1.6[A]	2,050
Tange Champion No. 3	1.0	1.0/0.7/1.0	1.0/0.7/1.0	0.9/0.6/0.9	1.0	0.8	0.8	2.5/1.6[A]	2,130
Tange Mangaloy 2001	1.0	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7/0.85	1.0	1.0	0.9	2.1/1.6	2,270
Tange Hi-Ten #101	1.2	1.2/0.9/1.2	1.2/0.9/1.2	1.2/0.9/1.2	1.2	1.0	1.0	2.7/1.6	2,710
Tange Hi-Ten #102	1.2	1.2/0.9	1.2/0.9	1.2/0.9	1.2	1.0	1.0	2.7/1.6	2,630

[5]*This information was compiled from the sales catalogue of each manufacturer.*
[6]*Multiple entries denote butted tubing; for example:*
0.9/0.6/0.8 denotes triple butting
0.9/0.6/0.9 denotes double butting
0.9/0.6 denotes single butting
0.9 denotes plain gauge
[7]*There are variations in gauges of some tubes presented here, but they are usually special order items. Also, most manufacturers offer chainstays, seatstays, and fork blades in a choice of outside diameters.*
[A]*These steering columns have helical reinforcements to increase their torsional (twisting) rigidity.*
[B]*These tubes are plain gauge.*
[C]*Reynolds 753 is made to French specifications only.*

SLICKER IS QUICKER.



TOURING IS MORE FUN WHEN IT'S MORE EFFICIENT.

Easy-going, easy-packing, easy-handling, Tailwind is the ultimate touring system. The front panniers actually reduce drag and pedaling effort. Modular packing puts more into a smaller, slimmer volume. Tailwinds keep weight close to the bike and properly distributed fore and aft. $89 front, $99 rear.

Tailwind

The ZZIPPER T is the most effective streamlining device ever developed for bicycles with good handling and ultra light weight. User tested over 3 million road miles, the ZZIPPER T provides a noticeable performance boost; a difference you can feel! $69 postpaid.

Yes, send me more information.

NAME

STREET ADDRESS

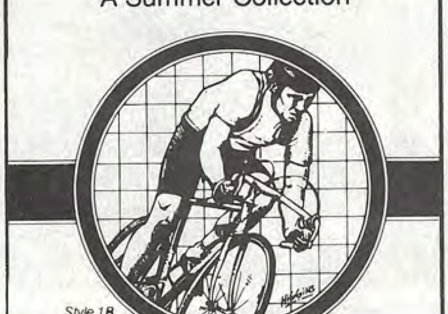
CITY

STATE ZIP

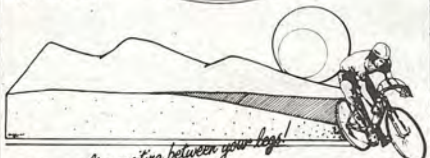
ZZIP DESIGNS
458 Thayer Road, Bonny Doon, CA 95060
Phone (408) 425-5147

ZIPPER ROAD FAIRINGS

SPORTGRAPHICS
presents
A Summer Collection



Style 1B
three color design



Style 3B
three color design

Original art silk-screened on high quality 100% preshrunk cotton. Adult sizes: S, M, L, XL. Tan, Kelly Green, Lt. Blue, Dk. Blue, Gold, Red. Immediate delivery. Money back quarantee if you don't love these shirts. $7.95 ea. 4 or more $6.95 ea. Add $1.50 per shirt P&H. Free brochure with order.

Send check or money order to:
SPORT GRAPHICS Dept. B 1
2620 N. Farwell Ave.
Milwaukee, WI 53211
WI Res. Add 5% Sales Tax

Name
Address
City State Zip
Style Qty Size Color
Style Qty Size Color
Style Qty Size Color
Style Qty Size Color
Style Qty Size Color

The Cornucopia Project

A *fresh* look at our food system.

Our food system—the farming, processing, shipping, and storing—clearly needs to be reexamined. That's what THE CORNUCOPIA PROJECT is all about. We hope to develop interest in and collect information about ways that the U.S. food system can be reorganized to circumvent a food crisis.

We hope this project will be a forum of ideas for improving our food system, where you can learn about policies and practices controlling the food system, and how you can influence them.

THE CORNUCOPIA PROJECT doesn't profess to have any "pat" answers. Our goal is to develop a working dialogue with people from every region of the country, and by sharing ideas and experiences, map out together a new, more sensible direction for our wayward food system.

For more information, please write: Robert Rodale, THE CORNUCOPIA PROJECT, Rodale Press, Emmaus, PA 18049.

commercial successes. Even those two require special assembly techniques and equipment, and are therefore very expensive.

Because of all the positive aspects of steel, there are many varieties of tubing available. Just go into any bicycle shop and take a look at all the different tube identification decals there. They say things like "COLUMBUS," "1020," "4130," "REYNOLDS 531," and "ISHIWATA CrMo 022," to name a few. If you're like most people, you're probably wondering what all these decals mean, and how they affect you as the consumer.

The purpose of the tube identification decal is twofold. First, it indicates a level of metallurgical quality which the consumer can depend on. Second, it is an indication of the weight of the tube set (in most cases). It was a good idea for the tube manufacturers to devise a system like this, but the problem is that they rarely tell anyone what these things mean. The consumer then usually ends up getting this information from salespersons, who in most cases are no better informed than the consumer.

Unfortunately, most of what the people associated with cycling "know" about steel is imprecise or wrong. That's because nobody who is in a position to influence the customer has ever bothered to check and see whether his information is correct. This has been going on for such a long time that most people now believe the bogus information.

Sorting out the good information from the bad requires a strong knowledge of the science and engineering of metals, called *metallurgy*. Until now, there hasn't been a metallurgist interested enough in writing about bicycles to challenge the old ideas. This article, and others to follow, will try to help clear up the many myths and misconceptions about steel bicycle tubing.

Welded Seamed Tubing

There are two varieties of steel bicycle tubing: seamed and seamless. *Seamed tubing* starts out as a flat strip of plain low-carbon steel of constant thickness (straight or plain gauge). It is put into tubular form by a series of rolling operations, then flash welded along its length (Figure 1). Because the edges are forced together during welding, a characteristic seam results.

Plain low-carbon steels are not very strong, and as a result the tube must be thicker to withstand a given force. This is why frames made from seamed tubing

You can set the pace by wearing it...

pace™

Technologically engineered cycling clothing.

For complete color catalog and list of dealers in your area, send .50 (refundable with first order) to:

Custom Athletic Wear
5285 Production Dr.
Huntington Beach, Ca. 92649
(714) 891-8716

Dealer inquiries invited

Revolutionary New Tube

Makes Clinchers Ride Like Sew-Ups!!

imp' air® latex

Made by a unique latex extrusion process:
- Improves performance
- More puncture resistant
- Retains riding pressure for days

Dealer inquiries welcome:
RB DISTRIBUTING
418 W. Fifth St.
Reno, NV 89503
(702) 323-1225

The Workshop

weigh a lot and feel unresponsive or "dead."

Cold-Drawn Seamless Tubing

Since seamless tubing is manufactured by a different process, the steel it is made from can be much higher in quality. A *seamless tube* starts out as a solid bar (called a billet), which is pierced hot by a pointed mandrel while being pulled by rollers (Figure 2). It is then hot-rolled until it has the approximate desired dimensions. After that, the tube-to-be is annealed and dipped in a mild acid to remove scale (iron oxides). It is now ready to be *cold-drawn* to its final dimensions. This is done by placing a different mandrel in the tube and pulling it through a die several times (Figure 3).

Hot-Drawn Seamless Tubing

There is another, less expensive way to produce seamless tubes. This process usually utilizes low-alloy steels instead of plain low-carbon steels. The tube is flash welded and then *hot-drawn* through a die to flatten and eliminate the seam.

At this point, you have a tube whose seam is still visible under a microscope, because the microstructure in and immediately around the flash weld looks different from the rest of the tube's microstructure. To make the microstructure uniform throughout, the entire tube is given a heat treatment. So the end product is a tube which has no seam visible to the naked eye, and none visible under the microscope, and thus is a seamless tube.

The highest quality seamless tubes are *butted.* These tubes have a constant outside diameter, but a varying inside diameter. Tubes are butted because the stress in a frame is highest at the ends where the tubes are joined. Butting enables tubes to be lighter by removing steel from the middle of the tube, where the stress level is not as great.

Tubes are butted by placing a mandrel shaped like the desired inside dimensions of the tube into the tube. Both together are pulled through a die, so the inside of the tube assumes the shape of the mandrel. The mandrel is then removed simply by forcing it out of the tube. The reason why the tube doesn't deform permanently when this happens is that steel behaves elastically up to its yield strength. The steel tube stretches as the mandrel is forced out, but all the stretching is within steel's elastic limits. So when the mandrel is removed, the tube just springs back into the proper shape.

FREE CATALOG of quality clothing & accessories for cycle touring & camping.

Sturdy, dependable panniers. 8 oz. super K-Kote nylon parapac, teardrop shaped, 1700 cu. in capacity. Front or rear use. 2 zippered compartments per side. High quality — reasonable price. **$42.00** Master Charge, Visa & C.O.D. orders accepted by phone.

BIKING EXPEDITION DESIGNS, INC.

(603) 428-7500
PO BOX 547, HENNIKER, NH 03242
Operating bicycle camping & hosteling trips in U.S., Canada & Europe since 1973.

Bullseye pulleys
- *low friction*
- *improved shifting*
- *sealed bearings*

Bullseye
DURHAM BICYCLES
418 South Varney Street, Burbank, CA 91502
(213) 849-1300 • 849-1309

$2.00 buys you the brand new, complete

HANDBOOK OF CYCLING — 81

INCLUDING:

Pictures, prices and description of the leading brands of bicycles. Complete parts manual. Custom frames and wheel building. Clothing, shoes, helmets, etc.

FLYING DUTCHMAN, LTD.
YOUR BICYCLE SPECIALIST
Dept. "K," P.O. Box 20352
Denver, Colorado 80220
(303) 333-2449 333-2914

— Videocassette —

BICYCLE MAINTENANCE AND REPAIR

More than a manual or a book, this videotape shows you, step-by-step, how to keep your bicycle in top condition. Prepared and presented by experts in cycle care, it covers each component system (wheels and tires, brakes, derailleurs, power train, bottom bracket, and headset) from maintenance check through complete overhaul. Program running time is 1 hour 10 minutes.

Presenter: Carolyn Sweers
Technical Consultant: Ron Bois, RRB Cycles

Available on VHS or Beta (please specify) at $49.95* (plus $2.00 shipping and handling) from:

GOLDSHOLL ASSOCIATES
420 Frontage Road, Northfield, Ill. 60093
*Illinois Residents add 5% Sales Tax

Pro Sport

NR Group with S R chainrings and S L pedals........................$465.00
Above Group with purchase of Gios frame............................ 445.00
GIOS frame and fork.................... 499.00
SIDI titanio leather...................... 69.00
SIDI Confort............................ 46.00
Weinmann Concave A 124.............. 17.50

Send $2.00 for 1982 catalog

"Your one-stop source for all your cycling needs"

Visit our retail store at
1073 S. Pearl St. in Denver
PRO-SPORT, P.O. Box 9758,
Denver, CO 80209 (303) 777-0487

FOLDING BICYCLE

"IT GOES WHERE YOU GO"

MONTAGUE FOLDING BICYCLE

WRITE --
3042 NEWARK ST.N.W
WASHINGTON,
D.C. 20008

NETWORK OF LOCAL DISTRIBUTORS.

INTERNATIONAL PRO BIKE SHOP

BIKE MAINTENANCE STANDS

Our design allows full access to all parts of bicycle from both sides. Securely holds all sizes of bikes. Features sturdy 4 point base.

PRO I — uses foot operated pedal mount/release system; repair shop quality with heavy duty tubing **$96.50**
PRO II — uses wingnut-secured, coated J-bolt release; excellent for home use, shop display, etc. **$42.95**
PRO III — new folding-leg version of Pro II, folds down for convenient transport and storage **$49.95**
TOOL TRAY **$8.95**
WHEEL TRUE STAND **$27.95**

• Shipping Stand $5; Tray or Jig $2 •

Prompt mail-order service. Catalog $3.00. Send $1.00 along with name and address to get on our "SPECIALS" mailing list. Dealer inquires invited.

859 East Franklin St. Centerville, OH 45459
Call Pete DiSalvo (513) 433-6687

BAY RIDGE BICYCLE WORLD
Home of ***TEAM BROOKLYN***

8916 3rd Avenue
Brooklyn, NY 11209
212-238-1118

Brooklyn's Only Complete Pro Shop

- PRO - CUSTOM - TOURING -

Clearance Special

Campy Nuovo Record Gruppo......................$435.00

with any:
Guerciotti, Columbus SL..... 475.00
Rossin, Columbus SL........ 495.00
Raleigh, Red Team Pro-531.. 425.00
Viner, Columbus SL.......... 375.00

Complete Bikes Built and Shipped FREE.

Complete Stock on all Pro Equipment

Write for special catalogue and prices.

The Workshop

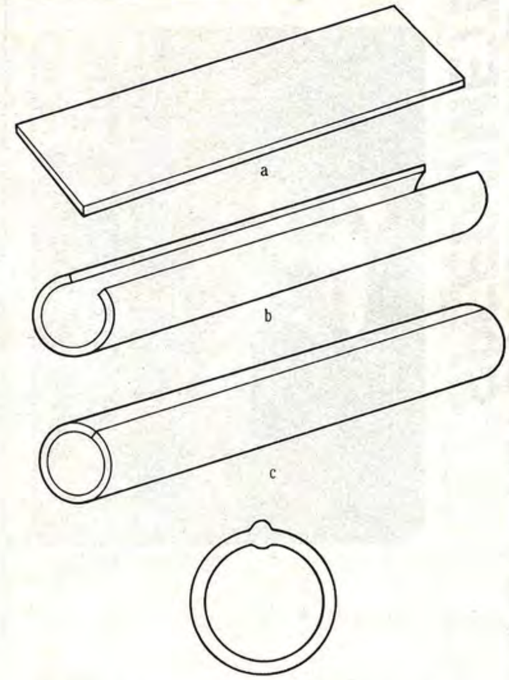
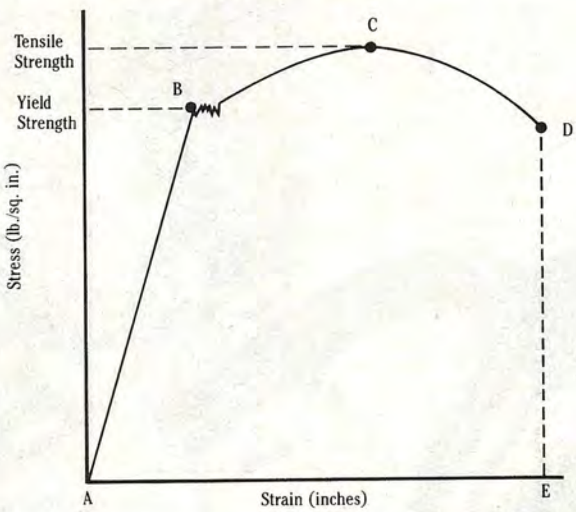


Figure 1: A seamed tube starts out as a flat strip which is rolled into tubular form, then welded together. Because pressure is applied when the tube is joined, a characteristic seam results (the bulge in "d" is exaggerated for clarity).



The above diagram is called a stress-strain curve, and is found by tensile-testing a material. This particular curve shows how ductile steels behave when they are stressed to failure. When a steel tensile specimen is stressed, it exhibits a range where it behaves elastically. That is, the deformations (called strains) produced by stressing the steel can be negated by simply removing the load. Steels behave elastically up to their yield point; from point A to point B on the stress-strain diagram. Point B is where permanent deformation, or yielding, first takes place, and is called the yield strength. After a steel has yielded, it can still be stressed more. The maximum stress the steel can withstand is given by point C, the tensile strength. Once. this maximum stress has been reached, the steel specimen can no longer carry the load and fails, point D. The total strain at failure, point E, is the amount the specimen has stretched. This value is used to determine the steel's ductility, as measured by the percent elongation.

George Retseck

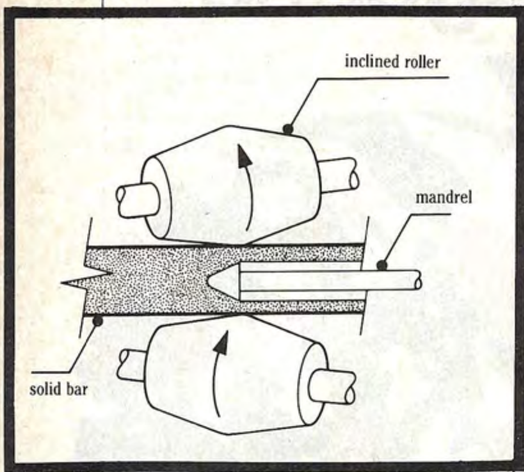
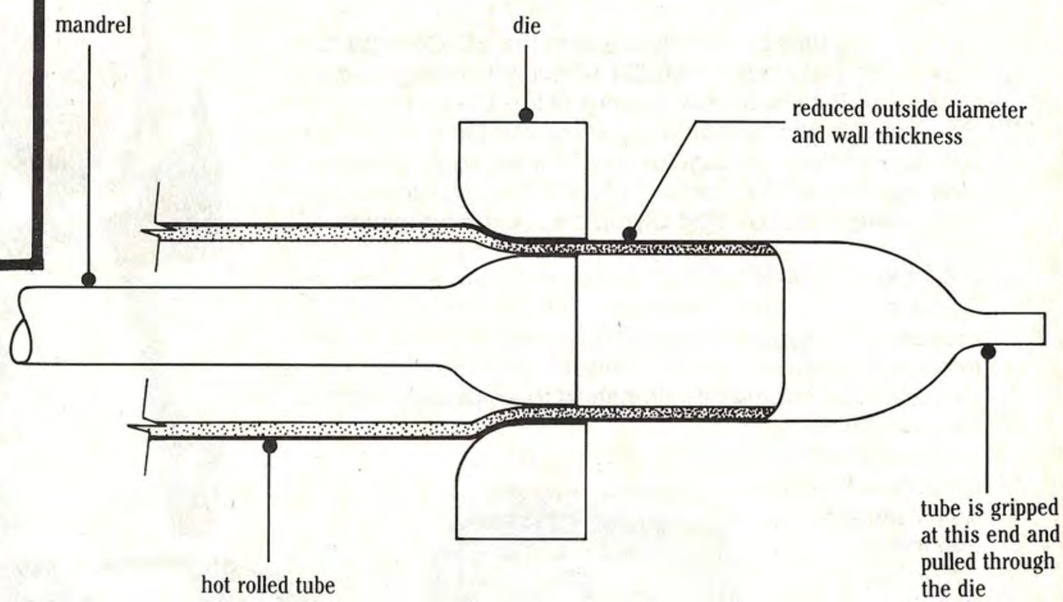


Figure 2: The hole is put into a seamless tube by hot-piercing the solid steel bar with a pointed mandrel. The inclined rollers pull the solid bar along, while also limiting the amount it can deform.

Figure 3: After the tube has been hot-rolled to approximate dimensions, the final step is cold-drawing. This reduces both the outside diameter and wall thickness of the tube.



Triple Butting

There are three different types of butted tubing: single, double, and differential (or triple). *Single-butted* tubes are thicker at one end only, *double-butted* tubes are thicker at both ends, and *differential-butted* tubes have ends of varying thickness (Figure 4).

Let me spend a moment explaining the tube identification decals found on some butted frames, because they can be quite misleading. Consider the decal on my frame, for example. It says "GUARANTEED BUILT WITH REYNOLDS 531 BUTTED TUBES FORKS & STAYS." Many people think *all* the tubes are butted when, in fact, they are not. What the decal means is that all the tubes are made out of REYNOLDS 531 steel, the top and down tubes are double-butted, the seat tube and steering column are single-butted, and the head tube, fork blades, chain, and seatstays are straight gauge (Figure 4).

This butting arrangement is standard for all top-quality butted tube sets. However, there are minor differences among the various manufacturers. Some Japanese seat tubes are double-butted. Table 1 is a list of the gauges and weights of all the top-quality seamless tube sets usually imported into this country.

As you can see, the tube sets come in a variety of weights. This is to accommodate the various rider weights and riding conditions. When buying a bicycle where there is a choice in tube sets, take care to make sure it is right for you. Table 2 is an *approximate* guideline to help you choose.

"Hi-Ten?"

Many tube identification decals say things like "Hi-Ten" or "Alloy Steel," and aren't much use to the buyer because their meaning is so general. Other decals offer more precise information, but to understand them you must be familiar with the American Iron and Steel Institute (AISI) numbering system.

In this system, four numbers are used to identify steels. The first pair of numbers indicates the type of steel and the

Cycle Goods THE HANDBOOK OF CYCL-OLOGY®

Revised New 10th Edition For '82

The Complete Catalog and Service Manual. Featuring the largest and most complete selection in parts, tools, clothing and accessories. All at lowest average prices. Internationally known for Quickest service.

Over 175 illustrated pages with the most completely detailed technical section and cross reference section available anywhere. Replacement parts as well as complete assemblies available with no minimum. Ranging from coaster and 3-speed parts to commuting, touring, and racing specialties. Hundreds of brand names available, with new tandem and frame building sections. A must for *all* cyclists.

—Send For Yours Now— Check •Money Order •Charge

Now Only! **$3.00** Catalog Price Refunded With $30.00 Order

ORDER TOLL FREE 1-800-328-5213

9 am to 6 pm Mon-Fri • For Minnesota and Technical Info: 612/872-7600

WIDEST SELECTION – LOWEST PRICES – HARD TO FIND COMPONENTS

OMAS
"Big Sliding" Sealed Hubsets
- Art. 101/C Steel 36 hole .... **$79.95 pr.**
- Art. 101/T Titanium 36 hole .... **$109.95 pr.**

"Gran Prix" Hubsets
- Art. 1000 36 hole ..... **$59.95 pr.** (Specify 5 or 6 speed)

"Big Sliding" Headsets
- Art. 120 (Eng. or Ital.) Gold, Red, Blue, Silver, or Black **$34.95**

MODOLO
- Professional Brakeset... **$118.95**
- Kronos Brake Lever Set.. **$52.95**
- Kronos Shift Lever Set... **$10.50**

AVOCET
Mod. I Hubset **$44.95**
Mod. II Hubset **$69.95**
Mod. I Pedal **$21.95**
Mod. II Pedal **$44.95**
Mod. III Pedal (platform) .. **$44.95**
Complete Avocet Line in Stock —

AVOCET SADDLES
- Touring I Men's and Women's ... **$19.95**
- Touring II Men's and Women's ... **$26.95**
- Touring III Men's only **$36.95**
- Racing II "T" Men's only **$29.95**

CONCOR SADDLES
- Super Leggero **$29.00**
- Profil **$34.00**

CHAINS
- SEDIS — SEDISPORT (fits Ultra-6!) **$6.00**
— Prestige Sedis. (Same as Sedisport but plated. Specify Gold or Silver) **$11.00**

HELMETS
(specify forehead circumference)
- NEW — BELL Tourlite .. **$42.50**
- BELL Standard **$28.95**
- PROTEC Firefly **$36.95**
- SKID-LID (yellow or white).................. **$44.95**

SPECIALTY ITEMS
- Kryptonite K-4 Lock **$23.00**
- Citadel Lock **$23.00**
- Sutherland's Manual **$32.50**
- Zefal HP Pump **$9.50**
- Bullseye Pulleys **$15.95**

Z ZIPPER FAIRING **$49.95**

CAR CARRIERS
- NEW! Zulu Rack......... **$34.95**
- Adjust-a-porter III **$19.95**
- NEW! Folding Adjust-a-porter .. **$23.00**
- La Pre Alpina .... **$95.00** Base with 2 quick release units.

REDWOOD TOURING SHORTS
- (Lt. Blue or Tan) **$25.50**

PACK SPECIALS
(Big Savings on all Models)
KIRTLAND PANNIERS (Red, Blue, Yellow); Early Warning (Blue, Yellow) **Std. — E.W.**
S/T-2 Pannier
2120 cu. in ..... **$100.00 — $113.00**
C-600 Pannier
1476 cu. in........ **$65.00 — $69.00**
Commuter Pannier
2175 cu. in........ **$55.00 — $62.00**
Wanderer Pannier
1476 cu. in........ **$52.00 — $56.00**

KIRTLAND HANDLEBAR BAGS
(Red, Blue, Yellow) **Std. — E.W.**
S/T Elite
675 cu. in......... **$65.00 — $68.00**
X/T Elite
470 cu. in......... **$45.00 — $49.00**
C-900
660 cu. in......... **$52.00 — $59.00**
C-300
380 cu. in......... **$37.00 — $40.00**
Wanderer
600 cu. in......... **$35.00 — $39.00**
Courier
905 cu. in......... **$31.00 — $35.00**

KIRTLAND SEAT BAGS
(Red, Blue, Yellow) **Std. — E.W.**
Seat Bag I
100 cu. in.......... **$8.50 — $10.00**
Seat Bag II
270 cu. in.......... **13.00 — $15.00**
Seat Bag III
335 cu. in......... **$19.50 — $23.00**

CANNONDALE PANNIERS
B041 Overlands (Red, Bl, Sil, Bk)
2500 cu. in. **$67.00**
B040 Whistles (Red, Bl, Yel)
2000 cu. in. **$54.00**

CANNONDALE HANDLEBAR BAGS
B037 Trestle (Red, Bl, Sil, Bk)
675 cu. in. **$36.00**
B027 Chugger (Red, Bl, Yel)
525 cu. in. **$27.00**
B017 Casey (Red, Bl, Yel)
420 cu. in. **$16.00**

CYCLE PRO TOURING BAGS
Cycle Pro Panniers (Red, Blue) 1770 cu. in. **$42.50**
Cycle Pro Deluxe Bar Bag (Red, Blue) 648 cu. in. **$28.75**
Cycle Pro Seat Bag (Red, Blue) 270 cu. in. **$7.50**

ECLIPSE PANNIERS
(Red, Blue, Orange)
Free Slide-Mount Add On Kit
Professional 2120 cu. in. .. **$105.00**
Standard 1850 cu. in. **$75.00**
Superlite 1017 cu. in. **$60.00**
Nomad 1150 cu. in......... **$35.00**

ECLIPSE HANDLEBAR BAGS (Red, Blue, Orange)
Professional 610 cu. in..... **$60.00**
Standard 568 cu. in. **$45.00**
Nomad 511 cu. in. **$28.00**

CANNONDALE TOURING SHORTS
- (Specify Men's or Women's cut, and Dk. Blue or Camel) .. **$26.75**

CYCLING SHORTS (specify waist)
- PROTOG SHORTS 100% Superwash wool ... **$32.00**
- SERGAL SHORTS
  Cotton **$16.95**
  Lycra **$25.50**
  Wool................... **$28.50**

THE BICYCLE WHEEL
Demystifies your wheel knowledge!
......**$7.95**

HANDCRAFTED WHEELS
Our Wheel Craftsmen welcome custom orders, and build lasting, sturdy wheels. Call for Custom Wheel prices.

TIRES
- Clement Criterium Seta 240 gr **$29.00**
- Clement Campionato Del Mundo 290 gr **$28.00**
- Clement Super Condor 270gr **$13.00**

CAMPAGNOLO TOOL KITS
- Reduced Kit........... **$1250.00**
- Full Kit................ **$1599.00**
- Campagnolo components still at May ad prices. Call for details.

CYCLE PRO GLOVES
- Top quality, leather with knit back.................. **$9.75** Specify sm, med, lg, x-lg.

CANNONDALE GLOVES
Highest quality, check our price (Specify palm circumference) **16.95**

SHOES
- VITTORIA SUPER PRESTIGE The Record breaking shoe used by Lon Haldeman. Finest shoe available. Sz. 38-47 ...... **$69.00**

NEW! Patrick "Cyclo" Touring Shoe Racing Performance, Touring Comfort
Sz. 38-52.................. **$47.00**

NEW 1982 Guerciotti Framesets
- Columbus SL, Aero Cast Crown, Brazeron Campy front derailleur, Super Record Headsets: Specify Metallic Red or BMW Blue Sizes 47-63 cm **$625.00**
- Bob Jackson Super Tourist (531 SL) .... **$425.00 w/headset**
- Guerciotti (Columbus) . **$475.00**
- Specialized Touring (Sequoia) **$375.00**
- Specialized Racing (Allez) **$475.00**

ALL ITEMS SHIPPED IN 24 HOURS
Call us for items NOT listed! 612-872-7600
LARGEST SELECTION ANYWHERE! SHIPPING $3.00 GROUND UPS
WHEEL SHIPPING $6.00

Cycle Goods, 2735 HENNEPIN AVE. S. MINNEAPOLIS, MN. 55408

VISA

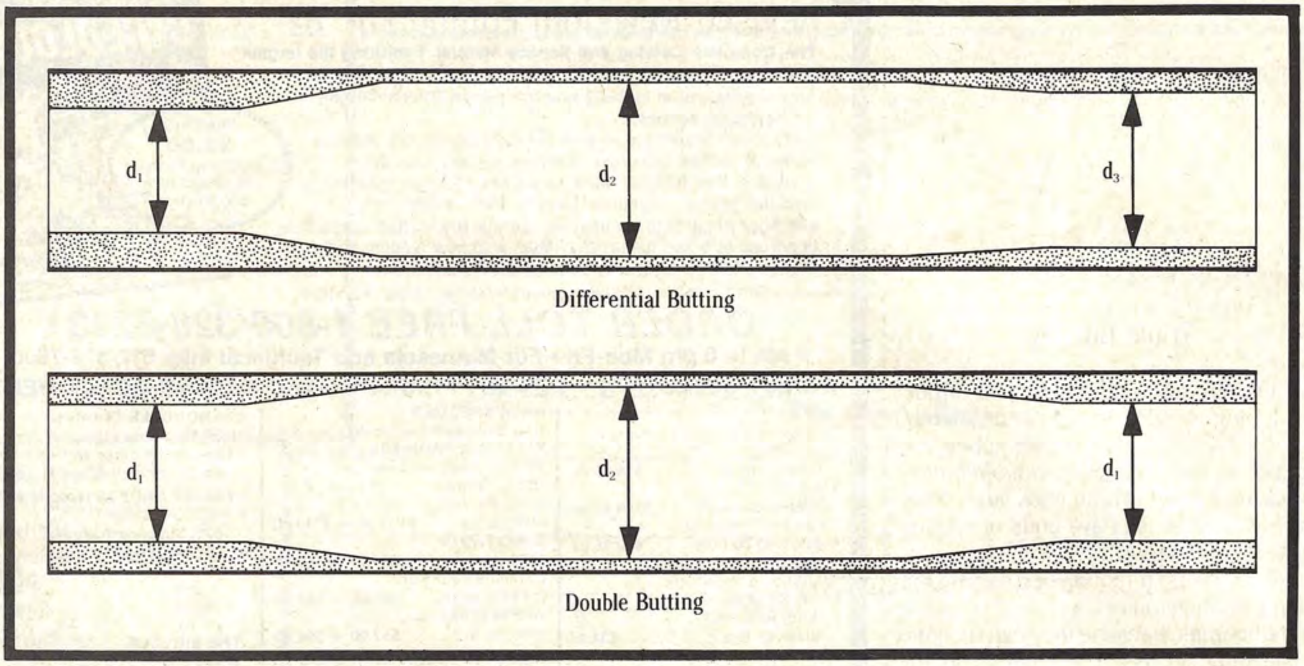


Figure 4: The butts and tapers are exaggerated for clarity.

Continued on page 110

Featherweight your feet

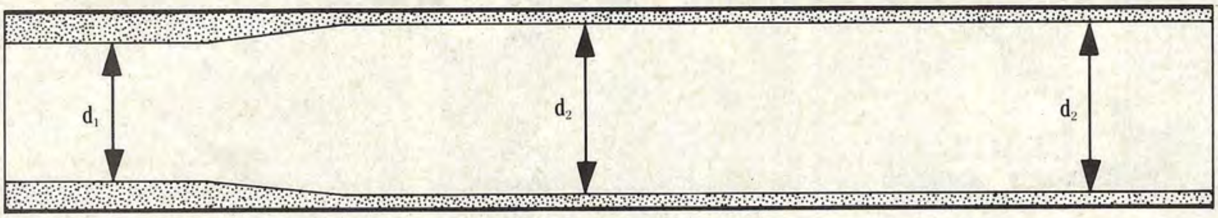
The Brancale shoe made of kangaroo leather is a mixture of Italian tradition and novelty.
The high quality materials combined with experience assure a soft, confortable fit.

Technical characteristics:

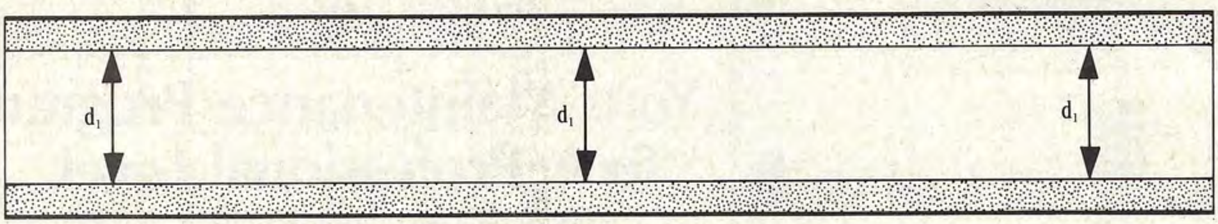
The kangaroo leather uppers and buffalo leather double soles are sewn together, with a steel reinforcement plate and adjustable nylon cleats attached.
Available in sizes 36 to 47, including half sizes.

brancale sport s.a.s.
27029 Vigevano ITALIA.
C.so Torino, 93 - Tel. (0381) 75033

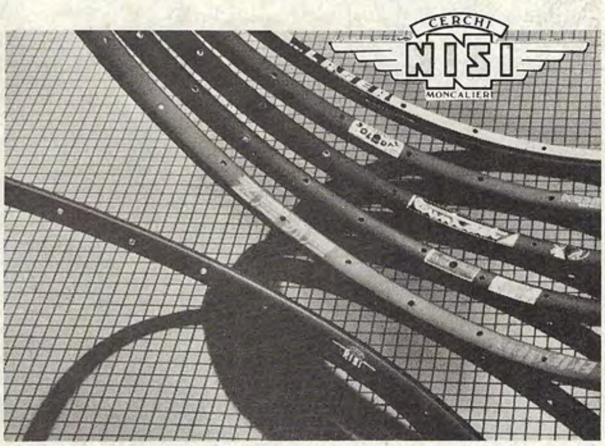
Continued from page 108



Single Butting



Plain Gauge



ALL RIMS AVAILABLE IN HEAT TREATED ONLY.

PISTA SPECIAL ....230 and 280 Grams
SLUDI ....290 and 320 Grams
SOLIDAL ....350 Grams
CONTACH ....350 Grams
LASER ....400 Grams
EKIP ....410 Grams

24, 28, 32 and 36 hole.

DEALER INQUIRIES INVITED.

Neel & Katz INC. **EXCLUSIVE DISTRIBUTION**

EAST OF THE ROCKIES:
2135 WESLEY ST.
EVANSTON, ILLINOIS 60201
312 • 864 • 5095

WEST OF THE ROCKIES:
1200 SOUTH ROCK BLVD., #13
SPARKS, NEVADA 89431
702 • 356 • 0367

WHEN IT COMES TO THE FINEST IN CYCLING HELMETS...

WE'RE NOT PLAYING GAMES!

WITH YOUR HEAD OR YOUR POCKETBOOK!!

Each ***HannaPro*** helmet comes with years of designing, tooling and manufacturing experience. ***HannaPro***'s high impact hard shell is made of hand laminated fibreglas (for maximum protection). It's cool and lightweight and features a self-adjusting (one size fits all) head suspension band. It's also washable and replaceable. The liner is shock absorbing. Expanded polystyrene quick release helmet straps. Visor snaps installed. TWO-YEAR GUARANTEE Free replacement if involved in an accident. Once you wear it you'll buy it 'cause it feels so good — and we'll feel better too, 'cause your head is in our hat.

SUGGESTED RETAIL $34.95

And that's no joke! Get maximum head protection at an affordable price.
SEE YOUR BICYCLE DEALER TODAY

HannaPro • SALES AGENT

CYCLE COMPONENTS • P. O. BOX 4363 • FULLERTON, CA 92634

amount of major alloying element(s). The second pair of numbers indicates the average carbon content in hundredths of one percent. In a 4130 steel, the "4" means it is a chromium-molybdenum steel; the "1" means it contains a total of about one percent chromium and molybdenum; and the "30" means it contains an average of 0.30 percent carbon. Table 3 is a list of AISI steels commonly used for bicycle tubing.

All seamed tubing and even some seamless bicycle tubing are made from plain low-carbon steels. These steels contain only carbon and manganese as intentional alloying elements (as in all steels, there will also be impurity levels of phosphorus, sulfur, and a few other elements left over from processing).

The highest quality seamless bicycle tubing is made from low-alloy steels. These are steels which contain no more than five percent total intentional alloying elements. Certain elements are added to steels to increase their strength; some are more effective than others. Carbon, for example, is a very potent and inexpensive strengthener of iron.

Too Much Carbon

The strength of steel increases with in-

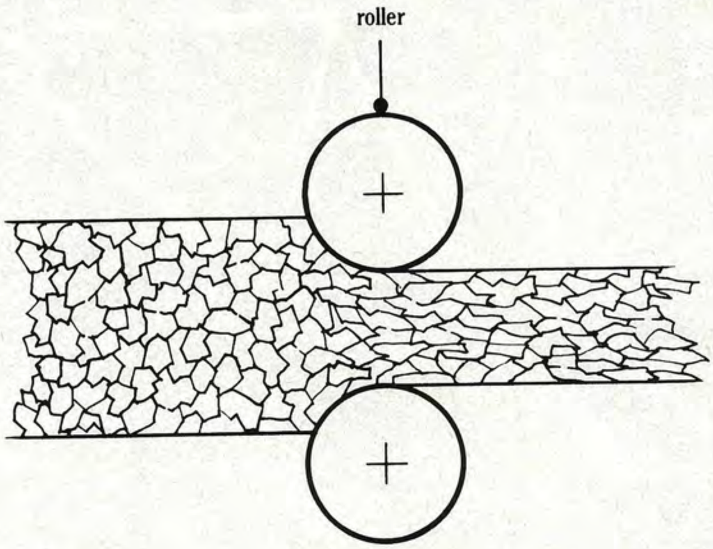


Figure 5: Steel is made up of many microscopic crystals called grains. When a steel is cold-worked, the grains become squashed. This increases the strength of the steel. Diagram exaggerated for clarity.

RIDE TOMORROW TODAY

Rossin

FRAMES, BICYCLES AND ACCESSORIES.

Neel & Katz INC.

EXCLUSIVE DISTRIBUTION

EAST OF THE ROCKIES:
2135 WESLEY ST.
EVANSTON, ILLINOIS 60201

WEST OF THE ROCKIES:
1200 SOUTH ROCK BLVD., #13
SPARKS, NEVADA 89431

STEWART
HUNT
CYCLES

P.O. BOX 7678
RENO, NEVADA
89503

SEW-UP TIRE SPECIAL		
(Mix for 5 Quantity Price)		
Clement Silks and Cottons		
(Crit., Paris-Roubaix, Del Mundo	**$28.95**	**$26.95/5**
Criterium Cotton	**25.95**	**- 23.95/5**
Condor	**9.95**	**- 8.95/5**
Continental - Simply the Best 240gm.		**42.00**
Vittoria CX or C6 Cotton	**29.95**	**- 27.95/5**
Vittoria CX Silk	**31.95**	**- 29.95/5**

Campagnolo Groups NR	**$425.00**
Campagnolo Groups SR	**479.00**
Rigida 13-20 Rims	**20.00/pr.**
Modolo Brakes (All Colors)	**99.00**
Aero Shorts (Better than any other on the market or your money back)	**30.00**

C.O.D./VISA/M.C. (PREPAID W/MONEY ORDER — 5% DISCOUNT)
FREE SHIPPING ! ! **(702) 323-4900**

creasing carbon content up to about 0.8 percent. However, steels with carbon contents greater than 0.4 percent are not suitable for use as bicycle tubing because, depending on the heat treatment, they either won't be ductile enough or strong enough (these terms are defined further on).

Several other elements are also used in steel. When the following ones are present in percentages greater than those given below, they are considered intentional alloying elements: manganese, 0.5 percent; silicon, 0.35 percent; chromium, 0.2 percent; molybdenum, 0.06 percent; niobium, 0.01 percent; nickel, 0.25 percent; and vanadium, 0.01 percent. These alloying elements can strengthen steel in two ways: they can dissolve in the iron or they can form carbides.

Chromium, manganese, silicon, and nickel strengthen by dissolving in iron. The dissolved elements act as obstacles which inhibit movement within the crystalline structure of the steel. Since movement is restricted, a greater force is needed to deform the steel permanently.

Carbides

Carbon, niobium, chromium, vanadium, manganese, and molybdenum strengthen by forming carbides. *Carbides* are extremely strong compounds of iron, carbon, and any of the above alloying elements. Carbide compounds exist within the crystalline structure of the steel and strengthen it by forming obstacles similar to dissolved elements. But carbides are much more effective at inhibiting movement between groups of atoms. As a result, a much greater force is needed to deform the steel permanently.

Another trick used to strengthen a steel is to *cold-work* it. The process involves decreasing the grain size of the steel by physically deforming it (Figure 5). Cold-working is a very effective means of increasing the strength of a steel, and produces tubes with very close dimensional tolerances.

By judiciously combining the effects of dissolved alloying elements, carbides, and cold-working, a very strong steel can be made. If a tube is made of high-strength steel, its wall thickness can be reduced, and the frame weighs less. In addition, the frame feels much more responsive. Thus, low-alloy steels have a number of advantages over plain low-carbon steels. Table 4 provides the chemical compositions of the top-quality seamless tubes.

The strength of a material is represented by its tensile and yield strengths. The *tensile strength* is the maximum stress a material can withstand in tension. The *yield strength* is the stress, in tension, at which a material exhibits significant permanent deformation. Of the two, the yield strength is the more important, since it is the lowest stress which will ruin a frame. Thus, it is nice to have a high yield strength, especially after brazing — a feature that only the low-alloy steels have.

Ductility is the ability of a material to deform permanently without breaking. This property is usually measured by the *percent elongation*, which is the percent a material stretches relative to a portion of its original length.

A material which has a high percent elongation is termed *ductile*, while one with a low percent elongation is termed *brittle*. The percent elongation a material must have to be considered ductile varies among materials, and depends upon what the material is going to be used for. For steel bicycle frames, a percent elongation of five percent or greater before and after brazing is required.

The mechanical properties of the top-quality seamless tubes, before and after brazing, are given in Table 5. However, I question most of the data provided by the manufacturers. In tests I ran on Columbus SL before brazing, I found the manufacturer's data on the tensile and yield strengths to be high by 24 percent and 13 percent respectively.[1] This isn't a big deal since Columbus SL is still very strong and will be able to do the job as well as equivalent quality tube sets. But I do believe this kind of misinformation to be common.

Strength Losses?

For a long time there has been quite a bit of controversy over what happens to the strength of low-alloy steel tubes after brazing. Most people believed that brazing at temperatures beyond about 1500°F resulted in serious losses in strength and ductility. Because of this, many framebuilders decided to use more expensive brazing alloys which melt at lower temperatures.

To resolve this controversy, I ran some tests on Reynolds 531 and Columbus SL after brazing.[1] These tests showed that the rationale for using low-temperature brazing alloys was incorrect. In fact, my results were almost opposite to the tra-

[1]*See* Bicycling, *October 1981, pp. 92–97.*

Table 2: Recommended Tube Weights for Various Uses

Tube Set Weight (grams)	Rider Weight (pounds)	Frame Size (centimeters)	Riding Conditions
1,595–1,670	80–125	up to 55	Record attempts and time trials on very smooth surfaces
1,670–2,000	125–150	48–59	Time trials, road races, and criteriums on normal surfaces, and pursuit.
2,000–2,300	160–200	59–65	Road racing, criteriums, and general riding on all surfaces; also sprints and touring
more than 2,300	more than 200 or all weights	all sizes	General riding and racing

Tube set weights are based on uncut tubes. Since the tubes are cut to size before being assembled into a frame, tube set weights aren't an exact indicator of the weight of the final frame. Also, the weights of the lugs and bottom bracket shell aren't included.

ditional opinion. Low-temperature brazing (1150°F–1350°F) results in substantial losses in tensile and yield strengths. (Even so, the tube is still more than strong enough.)

But high temperatures are not nearly so bad for the tube as they have been thought to be. My tests for brazing at temperatures above 1350°F showed that the after-brazing tensile strength of the tube is usually greater than its before-brazing value, and the yield strength, although lowered, is still high. In addition, the tubes retain a ductility greater than seven percent elongation throughout the range of brazing temperatures (1150°–1950°F).

However, torch brazing at temperatures around 1600°F does have one proven negative effect.[2] During brazing a temperature gradient is set up along the length of the tube. The hotter the brazing temperature, the farther back the gradient reaches. So somewhere along the length of the tube, it will be exposed to the temperatures which weaken it the most (between 1150°F–1350°F).

What makes this a problem is that the weakened portion of the tube is about two centimeters outside the lug. Thus the lug can't do the job it's supposed to do — reinforce the joint. In practice, this isn't anything to worry about since the butted section is usually thick enough to compensate for the loss of strength. But under certain riding conditions, the tube could fail if the thickness of the butted section were less than about 0.8 millimeter (21 gauge).

[2]*See "Silver vs. Brass Brazing" by Mario Emiliani,* Bike Tech *pilot issue, January 1982.*

Hot Brazing Alloys

The after-brazing data given by the manufacturers is of limited practical value, since it reflects the methods they used. In reality, brazing procedures vary considerably among builders. For instance, many framebuilders pay little attention to the manufacturer's recommended braz-

Table 3: AISI Steels Used for Bicycle Tubing

10XX	plain carbon steels (up to 1% manganese)
15XX	plain carbon steels (1%–1.65% manganese)
20XX	nickel steels (up to 0.5% nickel)[8]
21XX	nickel steels (1%)[8]
31XX	nickel (1.25%)–chromium (0.65%) steels
41XX	chromium (0.5%–0.95%)–molybdenum (0.12%–0.25%) steels

XX denotes carbon content in hundredths of one percent

[8] *20XX and 21XX are not AISI steels, but they are found so frequently on moderately-priced framesets that their intended meaning is worth explaining here.*

ing temperature. They tend to use the brazing alloy which they are accustomed to working with, or one which is economical. In some cases, these brazing alloys melt at temperatures beyond which the tubes are guaranteed by the manufacturers. Furthermore, the length of time it takes to braze the joint and any variations in the cooling rate will affect the after-brazing mechanical properties of the tubes. Usually, these variations in brazing technique don't cause a problem. After all, most frames don't break. But a few exceptions are breakage-prone. So keep these things in mind when you read the data in Table 5.

All Brands Are Similar

To the untrained eye, there appear to be large differences among the various brands of tubes. But if you look closely at Tables 4 and 5, you will notice that all the low-alloy steels are quite similar. The same is generally true of the plain low-carbon steels. These similarities are no accident. Because of the rigors a bicycle frame must endure, there is only a handful of steels that can be used. So all of the advertising you see promoting the differences among brands of tubing is largely hype.

The mechanical properties of a steel depend upon its microscopic structure (or microstructure); specifically, upon the type of microstructure and the size of the grains. Steels used for bicycle tubing have the microstructure shown in either Figure 6 or Figure 7. These were chosen because given the proper grain size, they offer the best combination of strength and ductility.

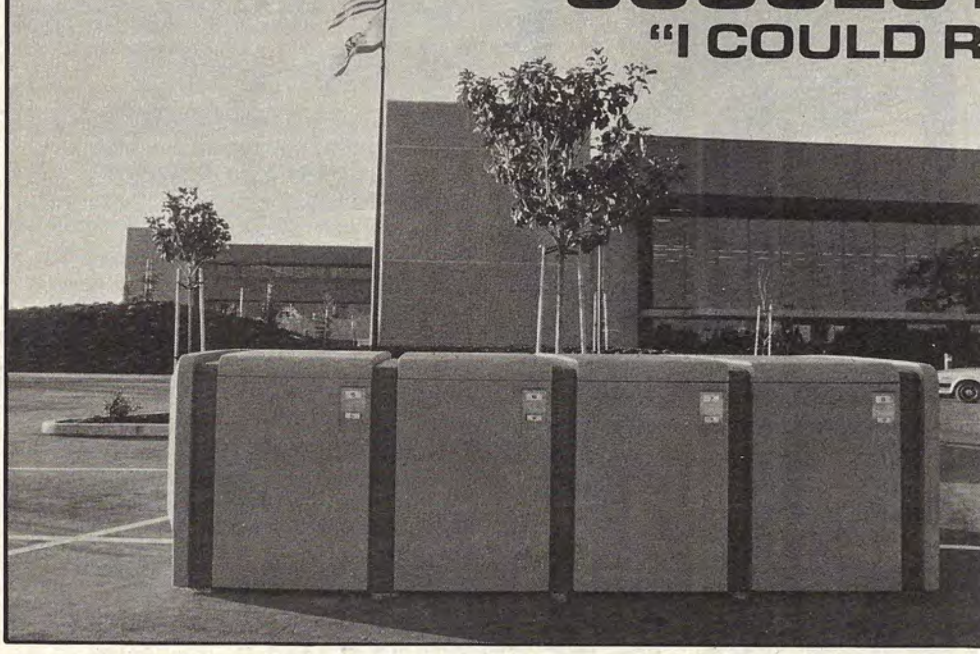
The plain low-carbon steels must have the microstructure shown in Figure 6 to have enough strength, but the low-alloy steels can have either. Table 5 also lists the type of microstructure each of the various brands has.

Rarely Discussed

There are a few other material properties that are as important as the previous three, but they are rarely discussed by anyone. They are the impact strength, fatigue strength, and stiffness.

Impact strength is a measurement of the amount of energy needed to break a material. Window glass, for example, has a low impact strength. It only takes a light tap from a hammer to break it. Lead, on

SUGGESTION BOX:
"I COULD RIDE MY BIKE!"



EMPLOYER/EMPLOYEE BENEFIT OF THE EIGHTIES
- SECURITY AND WEATHER RESISTANCE INCREASE BICYCLE RIDING.
- HEALTHEIR EMPLOYEES INCREASE PRODUCTIVITY.
- TWELVE BIKES OCCUPY THE SPACE OF ONE CAR.
- UP TO A 35:1 RETURN IN DIRECT EMPLOYEE SAVINGS.

Recent Installations
Hewlett-Packard (shown)
Getty Oil
Rutgers University
Dept. of Energy
Butterworth Hospital

CYCLE SAFE ®

Cycle-Safe Division
Philip Johnson Corporation
326 Terminal St., S.W.
Grand Rapids, Michigan 49508 (616) 452-8747

iku tire drive speedometers

this lightweight tire-drive is in use by over a 1,000,000 bicyclists

- fits any wheel size.
- whispering quiet in action
- stainless steel fastening clip
- self lubricating gears
- highly accurate
- well designed for easy cleaning

MODEL NO. 300 260/266 diameter 3¼"

184 GRAMS

iku quality products from holland, on the road in more than eighty countries!

CHROMIUM PLATED

RACING MODEL

MODEL NO. 250/256 diameter 2¼"

MODEL NO. TT 210/216 diameter 2¼"

184 GRAMS

156 GRAMS

Sole U.S.A. Distributor

ANDREW FISHER CYCLE Co. Inc.

23 EAST 26th. STREET, NEW YORK, NY 10010

NEW BIKE MOTORS

- 200 Miles Per Gallon
- 2 HP Motor
- Fits Almost Any Bike
- Easy Installation
- Motor Cycle Type Clutch And Throttle
- Better Brackets And Controls Than Competitors
- Does Not Interfere With Pedaling
- Fast Delivery

$169

$9.00 for delivery in Continental USA

Write or call for a free brochure or order from this ad. We have the best prices on top quality front and rear drive bike motors.

NORTHERN HYDRAULICS
P.O. Box 1221 Dept. BC7
Burnsville, MN 55337
612-894-8310

What's the best way to travel in remote areas? The Mountain Bike goes anywhere. Silently.

Balloon tires. 18 speeds. 28 lb.
Frames built by Tom Ritchey

Send $1.00 for Catalog
Mountain Bikes
Box 405
Fairfax, CA 94930
(415) 456-1898

CANADIAN ROCKIES

5 days to 2 weeks • Luxurious Mountain Lodge Tours • Support Vehicle • Home-Cooked Meals

Box 895, Banff, Alberta Canada T0L 0C0
403-762-3477

Rim Wrap™

Let's Wrap!™ with A Rim Tape that HOLDS ITS SEAL!

RND CO BOX 153
GLENCOE, ILL. 60022

BICYCLE TOOLS !!

(Free Catalog)

If you plan to do any repair work...you need our catalog. We carry the largest selection of Bicycle Tools found anywhere. Park, Var, Campi, Kingsbridge, B.R., HKC, and more! Each tools function is well described and illustrated. Dealers may inquire! Send $1 for 1st Class mailing. Write or call:

THE THIRD HAND
990 Park St. Dept. 22 Ashland, Oregon 97520
(503)482-1750

the other hand, has a much higher impact strength. For a material to have a high impact strength, it must combine a high yield strength with a fair amount of ductility. The steels used for bicycle tubing usually meet these requirements before and after joining. Exceptions to this occur when steels containing more than 0.3 percent carbon are welded, and when steels containing more than 0.4 percent are brazed. When these steels are cooled in the usual way[3] after joining, they suffer a loss in impact strength which could be dangerous in certain riding conditions.

The *fatigue strength* of a material is the maximum stress level it can withstand without breaking for a specific number of cycles of loading and unloading. As the stress level increases, the number of cycles the material can withstand decreases. A bicycle frame is stressed cyclically by each revolution of the pedals, and by road shocks and vibrations. Thus, the fatigue strength of the steel would seem to be an important consideration.

The most important factors determining the fatigue strength of a material are its tensile strength and the presence of stress raisers. For steels, the higher the tensile strength, the higher the fatigue strength. So you would expect the low-alloy steels to have the greater fatigue resistance.

Stress Raisers

Stress raisers are discontinuities which alter the stress distribution in a material. They are produced by irregularities such as voids, holes, grooves, or notches. Stress raisers are bad things to have, because they can raise the local stress level to well beyond the yield strength of the material. Repeated application of the stress can then lead to premature failure of the part.

On a bicycle frame, there are many potentially damaging stress raisers. Namely, they are the "points" on lugs, bottom brackets, fork blade reinforcements, bridge reinforcements, and some styles of fork crowns, in addition to any sharp-angled cutouts these components may have. Other sources of stress raisers are porosity in the brazing alloy, and foreign substances in the steel (both of which are unavoidable to various degrees). Under the right conditions, any of these discontinuities can lower the fatigue strength of the steel. It's interesting, but not too surprising, that the top-quality frames suffer

[3] *The "usual way" is to let the joint cool by itself in a room free of drafts.*

Table 4: Chemical Compositions[9]

These figures indicate that high-quality steel alloys used in bicycle tubing are usually quite similar. Note, for example, how tiny the differences are among the three chrome-moly steel alloys that fall under the AISI 4130 designation.

Brand	% carbon	% silicon	% manganese	% molybdenum	% chromium	% phosphorus	% sulfur	% other	AISI #
Columbus Record, KL, PL, SL, PS, SP	0.22–0.28	0.35 max.	0.50–0.80	0.15–0.25	0.80–1.10	0.035 max.	0.035 max.	—	4130
Columbus Aelle[E]	—	—	—	—	—	—	—	—	—
Ishiwata 015, 017, 019, 021, 022, 024	0.28–0.33	0.20–0.35	0.40-0.60	0.15–0.25	0.80–1.10	0.035 max.	0.04 max.	—	4130
Ishiwata 0245, 0265	0.08–0.13	—	0.30–0.60	—	—	0.04 max.	0.05 max.	—	1010
Ishiwata Magny V	0.10	0.29	1.40	—	—	0.019	0.005	0.042 niobium 0.05 vanadium 0.022 aluminum	—
Ishiwata Magny X[D]	—	—	—	—	—	—	—	—	—
Reynolds 753, 531SL, 531	0.23–0.29	0.15–0.35	1.25–1.45	0.15–0.25	—	0.045 max.	0.045 max.	—	—
Reynolds SMS[E]	—	—	—	—	—	—	—	—	—
Super Vitus 980 Vitus 181	0.22 max.	0.50 max.	1.50 max.	0.10 max.	0.15 max.	—	—	0.15 nickel	—
Tange Champion Pro, No.1, No.2, No.3	0.30	0.23	0.49	0.16	0.84	0.014	0.003	—	4130
Tange Mangaloy 2001	0.08	0.03	2.23	—	—	0.015	0.07	—	—
Tange Hi-Ten	0.17	0.13	0.50	—	—	0.022	0.006	—	1017

[9] *This information was compiled from the sales catalogue of each manufacturer and from personal communications.*

[D] *Proprietary information.*

[E] *Not available.*

PBS Limited Offer TOURING SALE

Order by mail or toll free 1-800-334-5471
(In N.C. call 1-919-933-9113)

Order now! Get ready for touring. Performance Bicycle Shop offers you unbelievable prices on Cannondale equipment. Of course, all sales carry the PBS "100% Guarantee" of complete satisfaction or return the product for your money back.

	Sale Price	Sugg. Retail
32-1037A Handlebar Pack, 675 cu. in., Red, Blue, Silver, Black	$35.35	$49.50
32-1017A Handlebar Pack, 420 cu. in., Red, Blue, Yellow	$14.25	$19.95
32-1021A Seat Pack, 215 cu. in., Red, Blue, Yellow	$ 7.15	$ 9.95
32-1026A Tire Sock, 70 cu. in., Red, blue, Silver, Black	$ 7.15	$ 9.95
32-1045A Rack Pack, 400 cu. in., Red, Blue, Yellow	$10.75	$14.95
32-1041A Rear Pannier, 2500 cu. in., Red, Blue, Silver, Black	$67.85	$95.00
32-1040A Whistles Rear Panniers, 2000 cu. in., Red, Blue, Yellow	$53.50	$75.00
32-1042A Front/Rear Panniers, 1420 cu. in., Nylon Pack Cloth, Red, Blue, Yellow	$39.75	$55.00
32-1043A Front/Rear Panniers, 1420 cu. in., Nylon Cordura, Red, Blue, Silver, Black	$46.75	$65.00
32-2020A Blackburn Rear Pannier Rack (Brake Mount) Silver	$18.95	
32-2010A Blackburn Front Pannier Rack (Brake Mount) Black	$21.50	
32-2040A Blackburn Front Pannier Rack, Silver	$17.95	
32-2030A Blackburn Front Pannier Rack, Black	$20.50	

Add $2.75 for UPS Shipping/N.C. residents add 4% sales tax.

☐ **Yes, send me your FREE Color Catalog**

VISA

Name ______

Address ______

City/State/Zip ______

Performance Bicycle Shop, Inc.
1126 Sourwood Dr./P.O. Box 2741/Chapel Hill, N.C. 27514

MasterCard

THE ULTIMATE TOURING SHORT

Comfort and great looks. Redwood Cycling Apparel has taken a special machine washable blend of cotton, polyester and lycra fabric and created an attractive cycling short that stretches and moves as you ride. Our unique terry-lined seat eliminates uncomfortable seams and bulkiness. Large side pockets and elastic waistband are convenient for casual riding and touring.

Dealer inquiries invited:
Mail orders send 50¢ for catalogue.
Write: Redwood Cycling Apparel
1593 G St. Arcata, CA. 95521
(707)822-8021

Redwood Cycling Apparel
1593 G STREET ARCATA CA 95521

MAKERS OF QUALITY BICYCLE CLOTHING

Just as the steel alloys used in different brands of tubing are similar (as shown in Table 4), the mechanical properties of the different brands fall within a narrow range.

Table 5: Mechanical Properties[10]

Brand	Before Brazing			After Brazing (at recommended brazing temperature)			Recommended Brazing Temperature	Before Brazing Microstructure
	Tensile Strength lb/in²	Yield Strength lb/in²	% Elongation	Tensile Strength lb/in²	Yield Strength lb/in²	% Elongation		
Columbus Record, KL, PL, SL, PS, SP	121,000–135,000	107,00	10	—	—	—	1290°F max.	Figure 7
Columbus Aelle[E]	—	—	—	—	—	—	~1560°F	Figure 7
Ishiwata 015, 017, 019, 021, 022, 024	113,200	—	5	109,200	—	6	~1560°F	Figure 6
Ishiwata 0245, 0265	85,200	—	10	48,500	—	50	~1560°F	Figure 6
Ishiwata Magny V	99,500–114,000	—	—	84,600–96,900	—	—	~2000°F	Figure 7
Ishiwata Magny X	106,600–121,000	—	—	90,600–102,900	—	—	~2000°F	Figure 7
Reynolds 753	168,000	134,000	8	—	—	—	1200°F max.	Figure 7
Reynolds 531 SL, 531	112,000	100,800	10	100,800	89,600	—	~1560°F	Figure 7
Reynolds SMS	71,700	—	—	—	—	—	~1560°F	Figure 6
Super Vitus 980 Vitus 181	121,000	99,500–107,000	10	—	—	—	~1560°F	Figure 6
Tange Champion Pro, No.1, No.2, No.3	129,500	—	10	98,400	—	12	~1560°F	Figure 7
Tange Mangaloy 2001	111,300		6	95,700	—	17	~2000°F	Figure 7
Tange Hi-Ten	71,800	—	9	62,000	—	39	~1560°F	Figure 6

[10] *This information was compiled from the sales catalogue of each manufacturer, and from personal communications.*

[E] *Not available.*

MUSCLOR (France) European massage creams formulated for post ride rub down (No. 1), warm up rub (No. 2), & for protection from the cold (No. 3). FDA approved.

ASSOS (Swiss) Swiss tailoring & materials produce the ultimate skinsuits, shorts, thermal suits, booties. Worn by '81 World Road Champion Freddy Maertens. Expensive but worth it.

CONCOR (Italy) Supercorsa, Max & Profile Aero saddles are fabricated from the finest materials, in modern design. Proven in European Professional races. Concor saddles are durable, affordable, and now available for racing and touring in USA.

GIPIEMME (Italy) Hubs, bottom brackets, chainsets, seat posts, tools, frame building materials. Italian technology and tradition in cycling.

Climbing steep gradients, sprinting for the finish line, touring the outback, all demands a harmony approached through the innovative use of technology to increase performance and reliability.

Every Thing has its own Harmony & Proportion, Two Inferior Qualities in it. For its reality is its Imaginative Form.

Annotations to Berkeley's "Siris," W. Blake

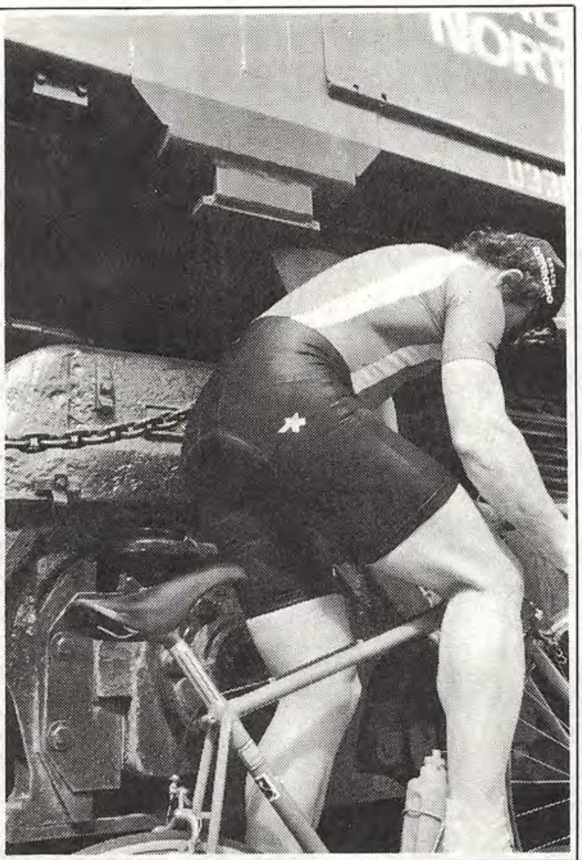


Photo: Bruce Freeman

***IMPORTED BY* SRC GROUP INC.**

For full product information and name of local dealer, please send large self addressed stamped (37¢) envelope to SRC GROUP INC., 530 N.W. 9th Ave., Portland, OR 97209. Dealers: phone Andy Newlands or Bruce Freeman at (503) 225-0136.

the least from fatigue failures. There are many reasons for this, all of which need some looking into.

For many people it is very important that their frame be efficient; that is, the frame should not deflect much during pedaling, so that most of the riders energy goes toward producing forward motion. The name chosen for a frame's resistance to lateral deflection was "stiffness." This is an unfortunate choice, because there is a material property called stiffness. And because the two are similar, there is a lot of wrong information about them. To avoid any confusion in this discussion, I will refer to the "stiffness" of bicycle frames as "rigidity."

A material's *stiffness,* or modulus of elasticity, is its ability to resist deformation by stresses up to its yield strength. The stiffness of steel is 30,000,000 lb./sq. in., and does not change regardless of carbon content, alloy content, cold-working, or heat treatment. So if I take two different steels of equal cross-sectional area and stress them the same amount (below their yield strengths), they will deform the same amount.

Rigidity

The *rigidity* of a steel bicycle frame varies, and depends upon the inside and outside diameters of the tubes, and the frame geometry. Since the outside diameters of bicycle tubes are pretty much standard,[4] the inside diameter (or thickness) and frame geometry are the important variables.

The thicker the tube, the more rigid it is (since there is more metal there). But the steel still has the same stiffness (30,000,000 lb./sq. in.), because although the cross-sectional area has increased, the load required to deform it the same amount increases proportionally.

To illustrate the point, imagine someone holding one end of a ten-foot long piece of 1-inch x 1-inch wood parallel to the ground. You would see that the free end deflects considerably (for example, the wood isn't very rigid). If the person then held a ten-foot long piece of 2-inch x 2-inch wood parallel to the ground, you would see that the free end deflects much less. So by increasing the cross-sectional area, the rigidity is increased.

[4]*The exceptions being tubing made to French specifications, which has slightly smaller outside diameters (this includes Reynolds 753). Also, fork blades, and chain- and seatstays, come in many different outside diameters and tapers.*

Figure 6: This is a photomicrograph of the kind of microstructure plain low-carbon steels have, and is also the type many low-alloy steels have. The dark islands are clusters of carbides, while the light areas are primarily iron. Note the individual crystals, or grains, which make up the steel's structure (800 times magnification).

By changing the geometry of a frame, its rigidity can be changed, too. Shortening a tube increases its rigidity, while lengthening a tube decreases its rigidity. If this isn't obvious to you, let's modify the above example. Again, notice the deflection caused by holding the same piece of 1-inch x 1-inch wood parallel to the ground. Now cut the wood in half, and notice how much less it deflects. By cutting the wood in half, its rigidity has been increased, but its stiffness is unchanged (because stiffness does not depend on length).

So if everything were equal (tube gauges, tapers, frame dimensions, lugs, etc.), a frame made out of Reynolds 531 would have the same rigidity as a frame made out of Columbus SL or any other steel.

Which Is Best?

I suppose what you really want to know is which brand of low-alloy steel tubing is best. Well, there isn't any one brand; there are several.

Columbus Record, KL, PL, SL, PS, and SP; Reynolds 753, 531 SL, and 531; and Tange (pronounced Taan-gay) Champion Pro, No.1, No.2, and No.3 all have the

PEDAL PUSHER SKI & SPORT

1. CYCLING JERSEY—SHORT SLEEVE—3 POCKETS—ACRYLIC $12.95
2. CITADEL SUPER LOCK $14.95
3. SUNTOUR ALPINE FREEWHEEL 14-38 . $12.95
4. SUNTOUR ALPINE REAR DERAILLEUR $14.95
5. SUNTOUR SUPERBE PRO SEALED PEDALS $47.85
6. SUNTOUR NEW WINNER ULTRA SIX FREEWHEEL 14-19 .... $19.95
7. SUNTOUR NEW WINNER ULTRA SEVEN FREEWHEEL (STATE SIZE) $22.95
8. REGINA CX FREEWHEEL SIX SPEED 13-18 . . . 13-21 .... $24.95
9. SUGINO MAXY/MIGHTY TRIPLE CRANKSET 34-44-52 .... $59.95
10. REG ALLOY WATER BOTTLE CAGE . . $ 2.95
11. CANNONDALE WATER BOTTLE W/HOLDER (VELCRO) .... $ 8.45
12. ACRYLIC SEAT COVER—RACIN OR TOURING .... $ 3.95
13. CRC BRAND CYCLING SOCKS—2 PR. .... $ 5.95
14. WEINMANN ALL-WEATHER BRAKE SHOES—PR .... $ 1.75
15. CANNONDALE PANNIERS—OVERLANDS—RED, BLUE, SILVER, EBONY $66.95
16. CANNONDALE PANNIERS—WHISTLES—RED, BLUE, YELLOW $59.95
17. CANNONDALE FT. CARRIER—SILVER . . . ADD $2.00 FOR BLACK . . . $20.50
18. CANNONDALE REAR CARRIER—SILVER . . . ADD $2.00 FOR BLACK . . . $22.95
19. CANNONDALE RAIN PONCHO $28.75
20. CANNONDALE FRONT BAG—CASEY—RED, BLUE, YELLOW $16.95
21. CANNONDALE FRONT BAG—CHUGGER—RED, BLUE, YELLOW $28.95
22. CANNONDALE FRONT BAG—TRESTLE—RED, BLUE, SILVER, EBONY $38.95
23. CANNONDALE REAR BAG—TOOT .... $ 8.95
24. CANNONDALE REAR BAR—SIGNAL . . $12.50
25. CANNONDALE REAR TIRE SOCK BAG—RED, BLUE, SILVER, EBONY . . . $ 8.45
26. LEATHER PADDED CYCLING GLOVES—P-S-M-L-XL-J .... $ 8.95
27. CRC BRAND WIND SHELLS—S-M-L . . $19.95
28. CRC BRAND SS JERSEY—WOOL BLEND—STATE SIZE & COLOR PREFERENCES $29.95
29. ZEFAL HP PUMP W/UMBRELLA CLIP—FITS SCHRADER & PRESTA . . $ 8.70
30. ZEFAL HP FRAMEFIT PUMP—STATE FRAME SIZE .... $ 8.95
31. ZULU BIKE RACK $34.95
32. MIRRYCLE BIKE MIRROR .... $ 5.95
33. ZEFAL PLUS FOOT PUMP $34.95
34. SEDISPORT CHAIN . . . ½" x 3⁄32" .... $ 4.99
35. SUNTOUR CYCLONE MK II REAR RACING DERAILLEUR $26.50
36. SUNTOUR CYCLONE MK II REAR TOURING DERAILLEUR $28.50
37. SUNTOUR CYCLONE MK II FRONT DERAILLEUR $16.50
38. SUNTOUR MICRO-LITE SHIFT LEVER SET $15.50
39. TRUNK MOUNT CAR RACK $19.95
40. ROOF MOUNT CAR RACK $44.95
41. CHRISTOPHE LEATHER BLACK OR WHITE TOE CLIP STRAPS .... $ 2.95
42. CHRISTOPHE TOE CLIPS—STATE SIZE .... $ 4.50
43. WEINMANN CONCAVE RIM—STATE SIZE—ALLOY $14.95
44. CAMPAGNOLO 8MM OR 10MM SEAT TUBE BINDER BOLT .... $ 4.85
45. BAILEN HELMET—ADULT OR CHILDREN'S—WHITE ONLY $42.50
46. TROXEL PAC-2 CHIL/CARGO CARRIER $38.95

SEND OR CALL IN ORDERS TO:
PEDAL PUSHER SKI & SPORT,
455-57 EASTON ROAD, HORSHAM, PA. 19044
PHONE: 215-672-0202 OR
PEDAL PUSHER SKI & SPORT,
2038 COTTMAN AVE., PHILADELPHIA, PA 19149
PHONE: 215-342-6188

ORDERING INFORMATION:
PAY BY VISA, MC, AM. EX., CHECK OR M.O. — ADD SHIP. & HANDL. CHARGES AS PER CHART BELOW. MIN. ORDER—$15.00
$15 TO $50 — $3.75
$50. TO $75. — $4.75
ABOVE $75.00 — $5.75

Finest and most complete Bicycle Parts Catalog available.
BEST PRICES!!
Please send $1.00 for postage and handling.

PEDAL PUSHER SKI & SPORT

Figure 7: This is the kind of microstructure many low-alloy steels have. The carbides are the dark dots, while the light areas are primarily iron. Individual grains aren't visible in this picture. Notice how the appearance of the carbides differs from that in Figure 6. (800 times magnification).

type of microstructure shown in Figure 7. Ishiwata 015, 017, 019, 021, 022, and 024; Super Vitus 980, Vitus 181, and Tange Mangaloy 2001 are the low-alloy steels which have the type of microstructure shown in Figure 6. There are some differences between the two microstructures, but none that are significant. For the most part, they are just two different ways of making a strong and ductile tube. In spite of what you have heard, all of the above brands are excellent, and any one can be used to make a frame of superior quality.

A few "new" steels have come onto the market recently to fill the void between plain low-carbon steels and high-priced low-alloy steels. They are Ishiwata Magny V, Ishiwata Magny X, and Tange Mangaloy 2001. These steels were designed for use mainly in automated framebuilding operations, but the manufacturers hope non-automated framebuilders will use them, too.

According to the manufacturers, the tubes' features include: before- and after-brazing mechanical properties comparable to low-alloy steels; the tubes are less prone to corrosive attack by the acids used to clean frames after joining; and they can withstand the temperatures associated with automated brazing (around 2000°F).

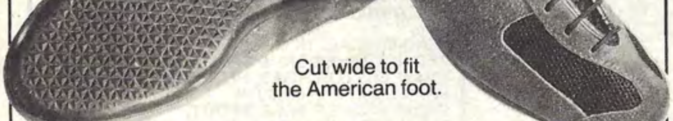
You need a stiff sole and good ventilation.
You also need to be able to walk!

The Rivat name, your assurance of quality.

Rigid one-piece rubber sole with walking heel disperses pedal pressure while it cushions your foot.

Nylon mesh uppers, reinforced against wear & tear with suede leather.

Distinctive diamond tread grips the pedal without restricting foot position.



Cut wide to fit the American foot.

The Rivat 'Touring' Shoe
So you can be comfortable off the bike too.

DEALER INQUIRIES INVITED.

sba
SECURITY BICYCLE ACCESSORIES
Dept. RB-6, P.O. Box 247
Hempstead NY 11551

baleno
BALENO CURRENT SPORTWEAR
Dept. BI-6, P.O. Box 15633
Seattle WA 98115

RIVAT Z.I., rue Jacquart 26100 Romans, France Telex 345279 RIVAT

THE MOST COMFORTABLE SHORTS MONEY CAN BUY!

Try on a pair of Torelli bib shorts made of our cotton lycra or spandex. The first thing you will notice is — no waistband! No constricting elastic, or bulky drawstring. Go for a ride in Torelli bib shorts. Feel the marvelous comfort of our soft cotton velour chamois. Wear your bib shorts under your jersey — they'll look just like regular shorts to everyone else, but you will know the comfortable difference.

Try Torelli bib shorts — the spandex shorts with the built-in suspenders!

TORELLI ©

Torelli Imports
P.O. Box 3163
2388 E. Las Posas Road
Camarillo, CA 93010
(805) 484-8705
Dealer inquiries invited

The remaining steels listed in Table I, Columbus Aelle (pronounced A-L), Ishiwata 0245, Ishiwata 0265, Reynolds SMS, and Tange Hi-Ten, are the plain low-carbon steels. They are all about equal in quality, although Columbus Aelle is quite a bit lighter than the rest.

Steel is a great material to make bicycle frames out of, but like anything, it has its liabilities and limitations. Light steel frames (tube sets that weigh less than about 2,000 grams) are not as durable as heavier frames. They get dinged and dented very easily and can be ruined by a misplaced framebuilder's file. And as I said before, these frames aren't very rigid.

Another thing to worry about is rust; not just on the outside of the tubes, but on the inside. To braze successfully, flux (a substance which helps the molten brazing alloy flow better) has to be used. If it isn't completely removed after brazing, it can corrode through the tubes.○

I would like to thank the following persons for their help in supplying the information given in Tables 1, 4, and 5: Ed Blank, The Cycle Factory; Jeff Davis, Campagnolo USA; Tom Field, TI REYNOLDS LTD.; Fabrizio Giussani, COLUMBUS S.r.l.; Bob Read, Trek Bicycle Corp.; John Temple, TI Sturmey-Archer; and John Uhte, Shimano Sales Corp.

alloy—*a mixture of two or more elements*

annealing—*a general term describing a heat treatment designed to soften (and consequently, weaken) a metal*

cold-drawing or cold-working—*deforming a metal at temperatures which depend upon the metal. For steels, cold-drawing can take place up to about 1350°F*

ductility—*the ability of a material to deform permanently without breaking*

fatigue strength—*the maximum stress a material can withstand for a specified number of cycles without breaking*

flash welding—*a process which fuses two metals together by applying an electric current between mating surfaces. This process is similar to spot welding in that no filler metal is used*

heat treatment—*heating and cooling a metal under controlled conditions to obtain specific mechanical properties*

impact strength—*the amount of energy needed to break a material*

low-alloy steel—*a steel which contains up to five percent total intentional alloying elements*

plain low-carbon steel—*a steel which contains only carbon and manganese as intentional alloying elements*

mechanical properties—*the tensile strength, yield strength, impact strength, fatigue strength, ductility, and hardness of a material*

microstructure—*a metal's structure which usually is visible only under a microscope after special surface preparation*

steel—*an alloy of iron and up to two percent carbon*

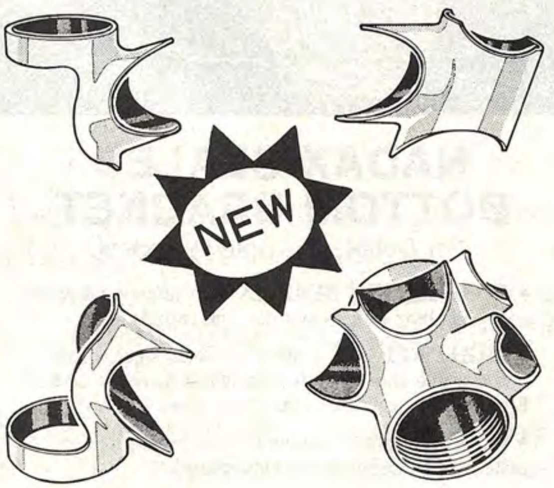
stress—*the force per unit area; i.e. lb./sq. in.*

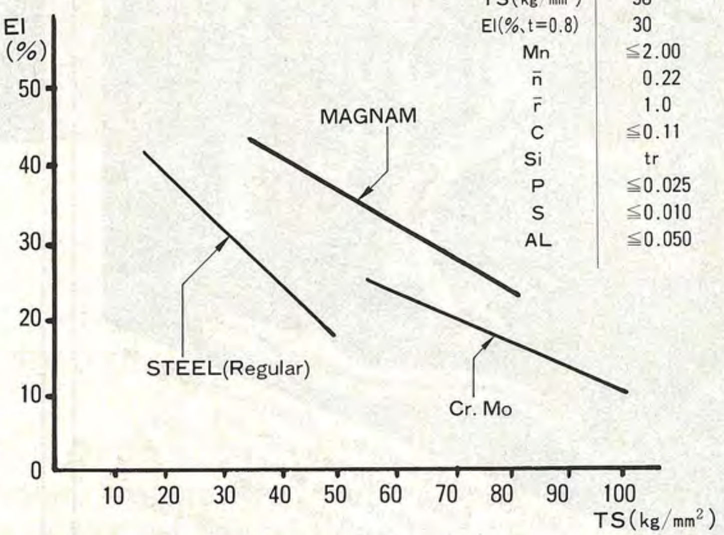
temperature gradient—*a gradual transition from a low temperature at one side of a region to a high temperature at the other*

tensile strength—*the maximum stress a material can withstand in tension*

yield strength—*the minimum tensile stress required to produce significant macroscopic deformation*

MAGNAM the Quality short point lugs





YP(kg/mm²)	34
TS(kg/mm²)	58
El(%,t=0.8)	30
Mn	≦2.00
n̄	0.22
r̄	1.0
C	≦0.11
Si	tr
P	≦0.025
S	≦0.010
AL	≦0.050

NIKKO SANGYO CO., LTD.

No. 14-23, 4-chome Shiratori, Katsushika-ku, Tokyo, Japan.
Tel.: (601) 4166-9 Telex: 262-2305 NKLUGS

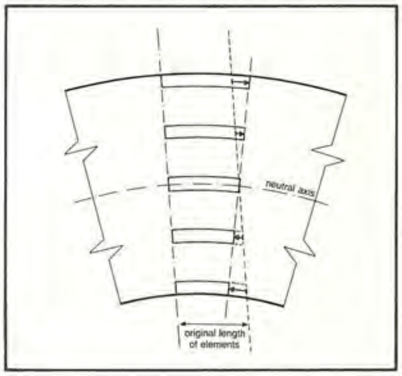
Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH T.M.

Bicycling Magazine's Newsletter for the Technical Enthusiast

August 1982 Volume I, Number 2, $2.00

IN THIS ISSUE



MATERIALS

The Metallurgy of Brazing, Part 1

Mario Emiliani

Have you ever wondered what you're doing when you braze two metals together? What makes them stick? Why is a well-brazed joint so strong when the filler metal is so weak? What factors affect the strength of the joint, and how sensitive are they?

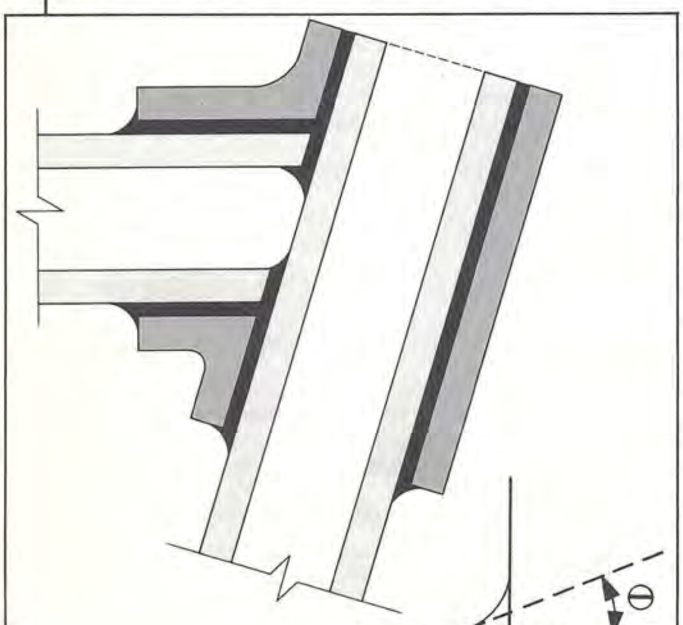
Brazing isn't a difficult skill to learn, and it's not even really necessary to know much about it to produce a well-brazed frame. But knowing a few details of the process can only help you produce more consistently sound joints, and satisfy your curiosities. "The Metallurgy of Brazing" is a series intended to thoroughly explain brazing. The above questions are but a few that will be answered in this series.

History of Brazing

It's difficult to say when brazing was invented, let alone who invented it. Brazing, like most other manual arts, was something handed down from generation to generation. Apparently nobody thought enough of brazing to document it, or perhaps documentation would have led to a loss of one of the world's first trade secrets. In any event, its origins are a mystery.

The earliest examples of brazing are found in jewelry and other types of adornment from about 2,500 years ago. Pieces of pure gold were joined together using lower-melting alloys of gold and silver.

About 900 years ago, when it was discovered that zinc was a separate metal, brazing with brass filler metals became popular. It was through the use of these filler metals that the term "brazing" came about. Originally, the process of joining metals using lower-melting brass filler metals was called "brassing." Through the centuries, this term evolved to the word "brazing."



Effect of wetting on brazing alloy penetration.
A: good wetting; low contact angle; full penetration.

Definitions

Before we continue, we must go over a few definitions. Brazing is a process which joins metals by heating them to a suitable temperature, then introducing a non-ferrous filler metal. The filler metal must have a liquidus* *above* 840°F (450°C), but below the solidus of the base metals. The filler metal is distributed through the joint by capillary attraction.

Soldering is the same as brazing, except the non-ferrous filler metal has a liquidus *below* 840°F (450°C). Because a few silver brazing alloys melt at very low temperatures, and because silver brazing was originally termed hard soldering, silver brazing is usually referred to as silver soldering. The difference in liquidus between a brazing alloy and a soldering alloy has so crucial an effect on the nature of the joint that the term silver soldering should never be used when referring to silver brazing.

(There are several factors that contribute to this difference; most of them are too complex for a brief description. One major factor, though, is simply that soldering alloys are generally much weaker than brazing alloys, and this difference is reflected in the strength of the joint.)

Welding differs from brazing and soldering in that the base metals are melted, and capillary attraction isn't a factor. Welding may or may not use a filler metal, depending on the process.

Braze welding, as the name implies, is akin to both brazing and welding. The similarities are (to brazing) that the base metals aren't melted, and (to welding) that the filler metal (which may be ferrous or non-ferrous) isn't distributed by capillary attraction. An example of braze welding is two pieces of steel which are joined by simply building up a brass fillet betwen them as in a lugless frame joint. Thus, the strength of the joint depends upon the strength of the fillet.

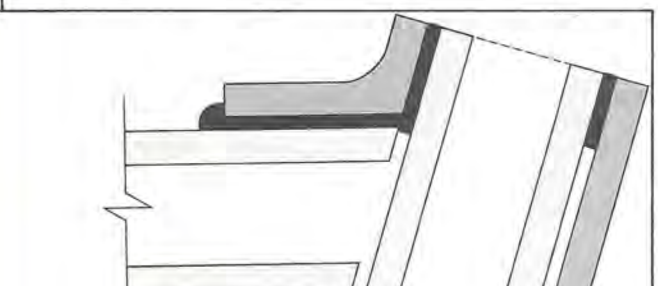
I'm sure you are all well acquainted with the definition of brazing, but I bothered to define soldering, welding, and braze welding, with hopes of giving you a better understanding of what brazing is by comparing it with other joining processes. The differences should help clarify the important factors in brazing.

**See* Bike Tech, *June 1982 for definitions of liquidus, solidus, etc.*

Adhesion Theory

What makes one substance stick to another? Nobody really knows. It's not even known why ordinary Scotch® Tape sticks to paper, plastics, glass, or anything else it sticks to. The whole science of adhesives is very complex. Chemists and chemical engineers spend a great deal of time experimenting with thousands of substances, to see if any of them have uses as adhesives. It's very time-consuming trial-and-error work, but the payoff can be enormous — just look at all the adhesives in the hardware store.

Since nobody knows how adhesives work, there are a number of theories around to explain it. The trick in making things stick together is to develop very intimate contact between mating surfaces. The sticky stuff on Scotch® Tape is a very viscous liquid which bonds readily to a cellophane backing. When the tape is pressed onto a favorable surface, the air is squeezed out and the viscous liquid fills up all the microscopic gaps on the surface. This creates such intimate contact that atomic forces between the viscous liquid and the surface (and between the liquid and the cellophane) can form a "mechanical bond." This bond accounts for most of the tape's holding ability.



B: poor wetting; high contact angle; incomplete penetration.

The strength of the bond depends largely upon the degree to which the viscous liquid displaces air, and fills up the gaps on the surface. The more gaps that are filled, the stronger the bond is going to be. To illustrate the difference the amount of contact makes, lightly attach one end of a piece of tape to a relatively smooth, flat surface, and pull the tape parallel to the surface. It should take only a light tug to shear the tape from the surface. Now attach another piece of tape to the surface, rub the contact area with your fingernail, and pull. You'll agree, it takes a much larger force to shear the tape off. In fact, if you do the experiment on a rigid surface (like a desk top), the tape will fail, not the joint. This is an example of mechanical bonding.

In mechanical bonding, secondary atomic forces called Van der Waals bonds are what give a joint its strength. These bonds are due to the electrostatic attraction between the nuclei of one molecule and the electrons of another. The forces generated by Van der Waals bonds vary according to the distance between molecules and the type of molecules. So depending on these factors, anything from extremely weak joints to relatively strong joints can be made.

Another type of bonding is chemical bonding. In this case, much stronger primary atomic forces form the bonds, enabling joints of very high strength to be made. Brazing, soldering, and welding are joining operations which form primary bonds of a type called metallic bonds.

Metallic bonds, as the name implies, are characteristic of metals. These are the bonds which hold metals together and give them their unique properties; i.e., high electrical and thermal conductivity, ductility, shiny appearance when polished, etc. These bonds form when atoms with easily detachable electrons come so close together that their electrons can circulate freely between the atoms. Thus the negatively charged "sea" of electrons in a metal crystal holds the positively charged metal ions securely in place.

During brazing, metallic bonds are formed due to extremely intimate contact between the filler metal and base metals. In addition, there is always some degree of alloying between constituents of the base metals and filler metal. This action also forms metallic bonds. While it is these bonds that allow the filler metal to adhere strongly to the base metals, the strength of the joint depends upon several other factors as well. These factors will be discussed here and in subsequent articles.

There are several other theories of adhesion, but chemical adhesion is the one most likely to explain how liquid metals bond to solid metals. For this reason, I will not attempt to explain the other theories.

Wetting

A factor critical to whether or not an adhesive sticks is its ability to wet the material to which it's applied (called the "adherend"). Wetting is a substance's ability to spread, and consequently become intimate with a

BIKE TECH: EXECUTIVE EDITOR Crispin Mount Miller • EDITOR John Schubert • EDITOR-AT-LARGE John S. Allen • COPY EDITOR Kathy Fones • CONTRIBUTING EDITORS Frank Berto, Fred DeLong, Mario Emiliani, Richard Jow, Gary Klein, Dr. David Gordon Wilson • CHAIRMAN Robert Rodale • PRESIDENT Robert Teufel • PUBLISHER James C. McCullagh • ART DIRECTOR John Lenaas • CIRCULATION MANAGER Pat Griffith

• BIKE TECH is published bimonthly by Rodale Press, Inc., 33 E. Minor St., Emmaus, PA 18049. Subscription rates: $11.97 yearly, $13.97 Canada, $15.97 other foreign. Single copy $2. Inquire about bulk rates. *Copyright ©1982 by Rodale Press, Inc. All rights reserved.*

BIKE TECH application to mail at second-class postage rates is pending at Emmaus, PA 18049.

BIKE TECH may not be reproduced in any form without the written permission of the publisher.

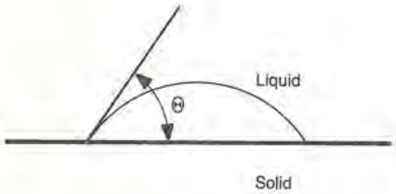


Figure 1: The angle θ is one way of measuring how well a liquid wets a solid surface. As the angle decreases, wetting increases.

surface. Wetting ability depends on the relative magnitude of two variables: the adhesion between the liquid and the surface (due to attraction between molecules of the liquid and molecules of the solid); and the cohesion of the liquid (due to its molecules' attraction for each other). In other words, wetting depends on whether a liquid sticks more tightly to itself or to something else.

A measure of how well a liquid wets a solid is the contact angle θ. Figure 1 shows a drop of liquid that has come to rest on a surface. The angle formed between the surface and a line tangent to the drop is high, which means the liquid isn't wetting the surface very well. The lower the contact angle, the better the wetting. For example, if Figure 1 shows how a water drop acts on the surface of a newly waxed car, then the wax is a barrier to wetting.

All metals are covered by oxide films, which form when a metal is exposed to an environment containing oxygen. You can clean oxides off, mechanically or chemically, but immediately a new oxide layer will start to form. The thickness and tenacity of the oxide layer depends upon the metal and the environmental conditions. Oxides are barriers to wetting because their atoms are bonded ionically. A characteristic of ionic bonding is that there aren't any free (or easily detachable) electrons, which are a prerequisite for forming metallic bonds. Thus, all oxides must be removed if wetting is to take place.

The easiest way to remove oxides is to chemically treat either the liquid or the surface. For brazing either mineral fluxes or gaseous atmospheres are used. Since most bicycle frames are brazed with mineral fluxes, I will forego discussion of protective gaseous atmospheres (although the principle is the same).

It was once believed that molten fluxes increased the wetting ability of brazing alloys (and therefore the bonding) by reducing the alloys' surface tension. All liquids have a surface tension, measured as the force per unit length on a surface, which opposes expansion of the surface area. Surface tension results from the cohesive forces between adjacent molecules of the liquid. Its origin can be visualized in the following way: Imagine a molecule in the middle of a stationary drop of water. This molecule's relation to its nearest neighbors is symmetrical in all directions, and therefore the forces acting on the molecule are the same on all sides. Now imagine a molecule at the free surface of the drop. This molecule isn't being pulled equally from all sides; there's a force pulling it inward that isn't opposed by any force pulling it outward. This means that every molecule on the surface is under a constant force tending to pull it inside the drop (Figure 2). As a result the surface exhibits a tension, and will contract at any opportunity.

But to affect the alloy's surface tension, the flux would have to change the cohesion, and to do this it must dissolve in the brazing alloy. Experiments were done to verify this, and it turned out that fluxes were virtually insoluble in molten brazing alloys. So how does flux enable the brazing alloy to flow better?

Flux is a chemical consisting mostly of fluorides, chlorides, and borates. When applied to a metal in paste form and heated, the water boils off leaving the flux crystals attached to the metal's surface. Upon further heating, the flux melts, wets the metal, and becomes chemically active. During this "active" period, the flux dissolves and absorbs contaminants (primarily oxides) on the metal's surface, and prevents further oxidation of the metal by coating it.

So now the surface of the base metal is essentially free of all oxides, and the brazing alloy has no difficulty in wetting it when introduced. After a while, the flux becomes saturated with oxides from the base metals, brazing rod, oxygen in the air, and torch flame (if an oxidizing flame is used), and is no longer effective. One should complete the brazing operation before this happens (or add more flux).

So the flux doesn't reduce the surface tension or cohesion of the molten brazing alloy; instead it enables good adhesion by cleaning the metal's surface.

Wetting agents can be added to improve wetting, but they must be soluble in the liquid. About 28 years ago, a program was undertaken to develop brazing alloys that didn't require flux, either mineral or gaseous. The brazing alloys were to be made self-fluxing and airproof by alloying them with small amounts of powerful deoxidizers. In addition, it was hoped that the deoxidizers would reduce the surface tension of the brazing alloy.

The results were that the brazing alloys

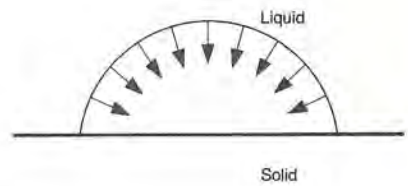


Figure 2: The arrows indicate the direction of surface tension forces. These forces tend to make the droplet contract, thus assuming a spherical shape.

containing the strongest deoxidizers (lithium, magnesium, aluminum, etc.) exhibited improved wetting on steel, but diffusion of atmospheric oxygen through the molten brazing alloy was fast enough to oxidize the base metal. Thus the molten brazing alloy wet the base metal well, but only if the brazing time was very short. Some elements, such as copper, actually increased the diffusion rate of oxygen.

It was also discovered that small additions of nickel or tin might make the molten brazing alloy impervious to diffusion of atmospheric oxygen. As it turns out, this endeavor found use, but only in specialty applications such as jet engine components. Bicycle builders still have to use fluxes.

In view of all this, the importance of using the proper mineral flux is obvious. A good mineral flux should have the following properties:

1. Melt at temperatures below the melting point of the brazing alloy.
2. Completely wet the base and filler metals.
3. Reduce, dissolve, and absorb oxides.
4. Protect the base metal from oxidation during heating.
5. Be displaced by the molten brazing alloy when liquid.
6. It must not run off the base metal, leaving areas open to oxidation.

All six points are important, but the fifth one has special significance. Molten brazing alloy pushes flux out of its way as it's sucked into the joint. If the flux is too viscous, flow of the molten brazing alloy will be impeded. Thus, there will be many areas where the brazing alloy didn't wet the base metals, and the joint strength will be reduced significantly. Fortunately, most, if not all, commercial fluxes meet the six requirements.

It's commonly believed that the criterion for a liquid metal to wet a solid metal free of oxides is that the two metals must be soluble and form an alloy at their interface. This isn't true; wetting will occur if the surface tensions are favorable. Specifically, the surface tension of the solid must be greater than the sum of the liquid and solid/liquid interface surface tensions.

While alloying between the filler and base metals occurs to some degree in most cases, it isn't essential to the forming of a good metallic bond. A good flux will clean the metals so well that metallic bonds are easily formed (provided the surface tensions are favorable). Alloying at the interface usually occurs because at brazing temperatures, it's easy for filler metal atoms to diffuse into the base metal (and vice versa). (Alloying is different from the phenomenon called "brass inclusion" sometimes found in bicycle frames, which is generally harmful, as will be discussed in a subsequent part of this series.)

The degree of alloying at the interface depends upon the brazing temperature, brazing time, composition of the base and filler metals, and how well the flux removes oxides. Sometimes it's possible to have alloying at the interface which has a deleterious effect on the joint strength. For example, when steels are brazed with silicon-bearing brazing alloys, the iron and silicon form FeSi (iron silicide). This is a strong but brittle compound called an "intermetallic." If sufficient silicon is present in the brazing alloy (greater than about 0.2%), the FeSi formed at the interface will greatly reduce the strength of the joint.

Other alloy combinations can also produce similar reductions in joint strength. Fortunately it's been determined, by experimentation and/or trial and error, which combinations of metals produce efficient bonding without extensive formation of intermetallics. These favorable combinations are what eventually end up on the market. But remember, not all brazing alloys are compatible with all base metals. I'll say more about that in Part 2.

Topics of succeeding installments will include:

Compatibility of fluxes and filler metals with bicycle tubing and lugs — capillarity; formation of intermetallic compounds; brass inclusion.

Strength of joints (tensile, yield, impact, fatigue); the role of defects in joints.

Strength of steel tubes after brazing — annealing and hardening; temperature gradients versus length of butt in tube.

Proper framebuilding procedures.

DESIGN CRITERIA

Tubing Rigidity

Its Relation to Size Is Dramatic – But Often Misunderstood

Crispin Mount Miller

Many mechanical effects follow equations that contain power functions — something in the equation will vary with the square or cube, for instance, of something else. These variations are often dramatic, so people quote them a lot. Unfortunately, though, the quotes are often taken out of context.

A prime example is the effect of diameter on frame tubing. Some people will say that a tube's rigidity is proportional to the square of its diameter; some will say to the cube; and some will say to the fourth power (and, of course, some people will shun the dramatic exponents and say it's a simple direct proportion). To design any new kind of frame in a rational way, you need to know: which is it?

Some people also will quote the same relationships not for a tube's rigidity, but for its strength. Are strength and rigidity the same thing?

As it happens, most of these assertions can be correct (or approximately so), depending on the assumptions you make. Strength and rigidity are different properties though and they often vary in different ways.[1] I'll start with examples in which some of the proportions quoted above *are* correct, and then I'll go into more detail about why rigidity and strength work as they do. Finally I'll discuss a few of the implications for frame design.

Bending and Twisting

The first step of the description is to specify the kind of strength or rigidity in question. There are four common types, corresponding to the four common ways of applying a load: axial, flexural, torsional, and shear. Axial loading is lengthwise tension or compression; flexural is bending; torsional is twisting; and shear loading tends to move portions of the object crosswise past one another, similar to a stack of cards pushed sideways.

For bicycle frames the important types of rigidity are flexural and torsional.[2] Strength is rarely a problem in normal use but could be of greater concern in modified designs; again the important types would probably be flexural and torsional. (Strength does affect a frame's ability to survive an accident, of course, and the loading to be withstood in accidents seems to be mostly of a bending type.)

The following examples, then, are for flexural and torsional loading. (Conveniently, the rigidities against these two types of loading always change by equal ratios for tubing; and the strengths also change by equal ratios, but not by the same ones used for the rigidities. For example, if a change in tube design increases the flexural rigidity by 10 percent, the torsional rigidity also increases by 10 percent.) The hidden variable that lets all the different exponents be correct is, of course, the tubing wall thickness. Here are four possible permutations:

A. If both the diameter and wall thickness are multiplied by some number — call it k — then the rigidity increases by a factor of k^4 and the strength by a factor of k^3. (Meanwhile the weight for a given length increases by a factor of k^2.)

B. If the diameter is multiplied by k but the wall thickness is not changed, the rigidity increases by a factor of approximately[3] k^3 and the strength by a factor of approximately k^2. (Weight increases by a factor of approximately k.)

C. If the diameter is multiplied by k but the wall thickness is *divided* by k (so that the weight remains approximately the same) the rigidity increases by a factor of approximately k^2 and the strength by a factor of approximately k.

A fourth example is worth mentioning, even though (or because) it doesn't involve a diameter change:

D. If the diameter stays constant and the wall thickness is multiplied by k, the flexural and torsional rigidities increase by approximately the simple factor of k, and so does the strength (and the weight). For any frame design that uses standard lugs and fittings, of course, this is the only change available.

Deducing from these examples, an approximate rule of thumb would appear to be that rigidity depends on the product of the wall thickness and the cube of the diameter; and strength depends on the product of wall thickness and square of diameter.

As we'll see, this rule is a useful approximation, reasonably accurate for thin-walled tubing, but it leaves the reasons (and the exact magnitudes of change) a mystery. Also, common sense dictates that examples *B* and *C* must encounter some sort of limit.

The reasons do take some careful thought, but they aren't very complex (and they equip you to find the limits and the exact values). I'll discuss rigidity first, and then add one more consideration that will explain strength.

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

October 1982 $2.00

Volume 1, Number 3

SPECIAL REPORT

The View from Japan

Gary Fisher

The country, we Americans often think of as Japan, Incorporated is an unlikely king of manufacturing excellence. In the U.S., we're used to plentiful raw materials and cheap real estate on which we build sprawling factories. But in Japan, raw materials are at a premium — 98 percent are imported — real estate is several times as expensive as it is where I live (none-too-cheap Marin County, California), and Japan has had to rebuild its manufacturing base from the ground up in the years since World War II.

But, as we all know, Japan has triumphed. The extra cost of buying from abroad simply pressures the Japanese to be inventive and cost-efficient.

I got to see this firsthand earlier this year, when Tom Ritchey and I traveled to visit a number of Japanese manufacturers. We made the trip to encourage component manufacturers to make components better suited for our off-road bicycle business (Ritchey MountainBikes). Our buying power is small, but we were welcomed as the pioneers of a new cycling activity.

The bicycle market is flat this year in Japan, Europe, and the United States, and both Shimano and Ishiwata were producing car parts (transmission, differential, and drive shaft parts) when we visited. Herein lay the reason for our warm welcome; they need to stay abreast of trends to keep their factories running, and no one wants to be the last company to spot a new market. They all look at Shimano's success in BMX — which started in the United States and has since spread to become a lucrative worldwide fad — and this makes them especially eager to stay abreast of U.S. trends. They're willing to pay an inordinate amount of attention to off-road bikes because they can see them becoming popular worldwide as BMX has done.

Representatives of our trading company served as interpreters, guides, and appointment secretaries for us. They introduced us to the awesome pace of Japanese business: long, tightly scheduled days with intense discussions.

Almost without exception, the people we spoke with genuinely wanted to understand how our bikes were used, and they wanted to know how to make their products better suit that use. This was a welcome change from the typical American attitude of, "It's a toy, why take it seriously?" The Japanese were much more open with us, in a cooperative spirit, than most American manufacturers have been. (I'm told that the president of one major U.S. manufacturer has ordered his employees, "Don't ride those things around in the parking lot; we have enough problems already without you going and finding more.")

So our hosts listened intently to lengthy explanations of off-road riding, of how our designs have evolved broken bike by broken bike, and of where component designs could be improved. They spoke in metric terms, but they used U.S. names and numbers for metallurgical processes.

Extensive Lab Testing

Generally, they knew very little about what off-road riding is like. For example, they thought there was no place to go off-road riding anywhere in Japan, but Tom and I quickly found several appropriate trails on a hill outside of Kobe. They thought off-road riding was an outgrowth of BMX, and we explained to them that it was more related to touring.

These people don't ride bikes (I suspect it's because their long hours at work preclude it), and Japan has a very limited domestic enthusiast cycling market. Thus, they can't test equipment the way Italians do, which is to have a professional team use it in race conditions. The country has millions of cyclists riding hundred-dollar fat-tire single-speed commuter bikes, but that won't do for testing of high-quality products. These factors leave only one option: extensive lab testing.

Our first stop was in Tokyo at Nitto, the handlebar manufacturer, and even this company with its limited product line had many interesting things to show us. Nitto personnel told us that Japanese are now using seamed chrome-moly steel tubing. They like it — they've failure-tested it, and it com-

IN THIS ISSUE

ity," *Bike Tech*, June 1982) with the addition of cylinders pushing back the fork to simulate front brake action.

Most impressive, though, is a complete robot bike rider, made up of cylinders for muscles and weighing about the same as a person. The robot rides on rollers with built-in bumps. Attached to all these machines are computers and chart recorders. Testing like this gives more positive answers about longevity. The engineers at National are keen on stringent testing; every bike must pass 100 percent of the time.

The Japanese bicycle industry standards book very much outclasses our U.S. Consumer Product Safety Commission rules, not to mention the BMA/6 self-imposed rules that preceded them. The book is readily available within the Japanese industry, and it's a very useful guideline on how to make a well-built bicycle. It includes plenty of the kind of information that U.S. manufacturers are forever calling "proprietary." It goes down to such minute detail as the amount of elongation and adhesion you would want on both cloth and synthetic handlebar tapes. I recommend this book to anyone who wants to build high-quality bicycles.

Our last visit was with Tange, makers of tubing and forks. A tour of the fork manufacturing plant revealed — again — quick and good manufacturing processes. A brass insert is placed in the fork crown before the straight chrome-moly blades are lightly pressed in. The fork joins others on a conveyer which takes the fork past ring torches. The penetration is excellent; misalignment is corrected on an automatic straightening machine. Then the fork is raked and sent on to another straightening machine. These straightening machines handled six forks at a time, and did the job as fast as they could be loaded. We had Tange build 300 forks for us. That was less than a day's work.

The Japanese are manufacturing in huge numbers; we expected that. What impressed us were the big investments in high technology and the dedicated management and work force behind the technology. I've seen large manufacturers here in the United States, and the state of the art in bicycle design and execution are all right here, but the question is, can we combine high volume production with the product quality our buyers have come to demand? The Japanese have.

MATERIALS

The Metallurgy of Brazing, Part 2

Filler Metal Characteristics

Mario Emiliani

Not all filler metals are suitable for use in bicycle frame brazing. A filler metal must satisfy several conditions, some having to do with its own physical behavior such as its solidus and liquidus temperatures, and some having to do with its chemical interaction with the base metals. One way that several of these qualities become important is by their effect on the capillary flow that enables the filler metal to penetrate the joint. This installment will describe the implications of some of these qualities, with a detailed description of capillary attraction as context for several of them.

Both silver-based and copper-zinc (brass)-based brazing alloys (filler metals) are commonly used to join bicycle frames. All are known by a string of letters which is their American Welding Society (AWS) designation. Fourteen of the more widely-used alloys are listed in Table 1, along with two fluxes compatible with each.

Of the nine silver-based alloys, each has advantages and disadvantages. Low melting temperature, narrow melting range,* and nice flowing characteristics are the advantages of BAg-1, BAg-1a, and BAg-3. The low melting temperatures save both time and energy. BAg-2 and BAg-2a contain less silver and are therefore less expensive. However, they have wider melting ranges.

All five of these alloys have a potential health hazard: they contain appreciable amounts of cadmium. The cadmium fumes

Table 1: Filler Metals Commonly Used on Bicycle Frames

Filler Metal[1]	Average Chemical Composition,[2] %												Other Elements	Solidus, °F	Liquidus, °F	Brazing Temperature Range, °F	AWS Flux
	Ag	Cu	Zn	Cd	Ni	Sn	Fe	Mn	Si	P	Pb	Al					
BAg-1	45	15	16	24	—	—	—	—	—	—	—	—	0.15	1125	1145	1145-1400	3A, 3B
BAg-1a	50	15.5	16.5	18	—	—	—	—	—	—	—	—	0.15	1160	1175	1175-1400	3A, 3B
BAg-2	35	26	21	18	—	—	—	—	—	—	—	—	0.15	1125	1295	1295-1550	3A, 3B
BAg-2a	30	27	23	20	—	—	—	—	—	—	—	—	0.15	1125	1310	1310-1550	3A, 3B
BAg-3	50	15.5	15.5	16	3	—	—	—	—	—	—	—	0.15	1170	1270	1270-1500	3A, 3B
BAg-4	40	30	28	—	2	—	—	—	—	—	—	—	0.15	1240	1435	1435-1650	3A, 3B
BAg-5	45	30	25	—	—	—	—	—	—	—	—	—	0.15	1250	1370	1370-1550	3A, 3B
BAg-6	50	34	16	—	—	—	—	—	—	—	—	—	0.15	1270	1425	1425-1600	3A, 3B
BAg-7	56	22	17	—	—	5	—	—	—	—	—	—	0.15	1145	1205	1205-1400	3A, 3B
RBCuZn-A	—	59	Bal.[3]	—	—	0.63	—	—	—	—	0.05	0.01	0.5	1630	1650	1670-1750	3B, 5
RBCuZn-C	—	58	Bal.	—	—	0.95	0.73	0.26	0.09	—	0.05	0.01	0.5	1590	1630	1670-1750	3B, 5
RBCuZn-D	—	48	Bal.	—	10	—	—	—	0.15	0.25	0.05	0.01	0.5	1690	1715	1720-1800	3B, 5
RBCuZn-E	—	50.5	Bal.	—	—	—	0.1	—	—	—	0.5	0.1	0.5	1595	1610	1610-1725	3B, 5
BCuZn-F	—	50.5	Bal.	—	—	3.5	—	—	—	—	0.5	0.1	0.5	1570	1580	1580-1700	3B, 5

[1] *"B" designates an alloy as a brazing alloy; "R" means that it can also be used for braze welding. "Ag," "Cu," "Zn" indicate principal ingredients.*
[2] *Ag = silver, Cu = copper, Zn = zinc, Cd = cadmium, Ni = nickel, Sn = tin, Fe = iron, Mn = manganesee, Si = silicon, P = phosphorus, Pb = lead, Al = aluminum.*
[3] *Bal. = Balance*

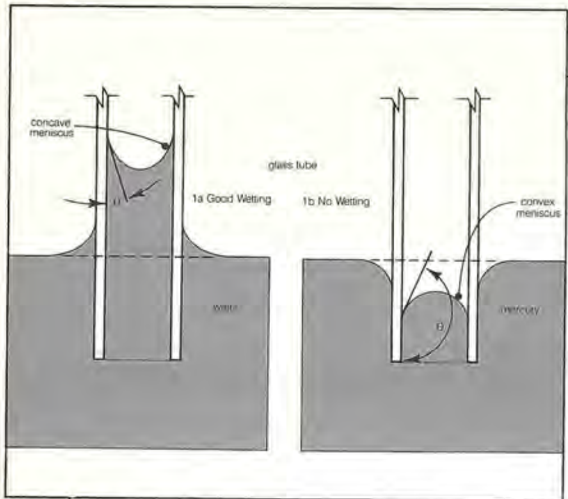


Figure 1: If adhesion between the liquid and tube is greater than the cohesive forces of the molecules, capillary attraction (or wetting) occurs as in 1a. If cohesion is greater, capillary attraction won't take place. Notice that the contact angle Θ in 1a is much less than in 1b.

formed during brazing can be lethal, so these filler metals should be used only if there is excellent ventilation.

There are cadmium-free silver brazing alloys — BAg-4, BAg-5, BAg-6, and BAg-7 — but they exchange the freedom from cadmium fumes for higher melting ranges. Thus, it's important to be sure the brazing temperature is 50-100°F above the liquidus of the filler metal. If it is not, some constituents of the brazing alloy won't be melted entirely. This can affect the strength of the joint, in addition to making it more difficult to achieve good penetration of the joint (since the viscosity of the not-fully-molten filler metal is high).

The RBCuZn-type filler metals are very popular (especially with Italian framebuilders) because they cost much less than silver brazing alloys (at today's prices, BAg-1 costs 50 times more than RBCuZn-C). But they too have drawbacks; these copper alloys contain large amounts of zinc, which is a very volatile metal. If the filler metal is overheated, zinc fumes will form. This will cause filler metal inclusion (penetration among grains) in the tube or lug, and/or porosity in the filler metal.

Small amounts of silicon are added to two of the brasses listed in Table 1 to reduce the fuming tendencies of zinc. Hence, RBCuZn-C and RBCuZn-D are better known as "low fuming brass" and "low fuming brass, nickel" respectively.

In addition to alloying techniques, there is a torch-handling trick that will minimize zinc fumes: use a neutral or oxidizing flame (excess oxygen) when torch brazing. This creates a thin layer of oxide on the surface of the molten filler metal so zinc can't escape as easily, but your flux won't last as long.

**An alloy's melting range is the range of temperatures between its solidus (highest fully-solid temperature) and its liquidus (lowest fully-molten temperature).*

Many framebuilders have sentimental favorite filler metals. One example of this is Sifbronze #1, which is made in England. But Sifbronze #1, like many other foreign and domestic brand-name filler metals, conforms to an AWS specification. Instead of ordering Sifbronze #1 from across the pond, it's much easier to buy the equivalent RBCuZn-A, which is readily available at your local welding supply store.

The copper-based filler metals listed in Table 1 are usually referred to as bronzes, but that's a misnomer. Bronze is an alloy of copper and tin (95%Cu-5%Sn, for example) which doesn't contain any other major intentional alloying elements. Two of the CuZn filler metals in Table 1 don't contain any tin, and they all contain large quantities of zinc. Thus, these filler metals aren't bronzes.

RBCuZn-D (which is the same as Sifbronze #2) contains an average of 10% nickel, and therefore has a silvery appearance. This filler metal is frequently called "nickel silver," but as you can see from Table 1 it doesn't contain any silver. A better name for this alloy is "white brass."

For a number of reasons, a framebuilder may choose to use a couple of different filler metals on a frame. It might be advantageous to braze the dropouts in with a filler metal that's easy to build up; RBCuZn-C for example. However, it's been my experience that every joint on a frame can be brazed successfully with even the most fluid of filler metals, BAg-1.

While most commercial fluxes conform to the AWS Specification given in Table 1, some brand-name fluxes are proprietary compositions which the manufacturers believe work as well or better. As long as the flux is compatible with the filler and base metals, any commercial flux should work well. I haven't seen an exception yet.

Whenever you braze, even if it's with cadmium-free filler metals, always have good ventilation. Constant exposure to fumes from filler metals and fluxes will surely lead to serious health problems.

Capillary Attraction

By definition, the two things that make brazing different from other joining processes are that temperatures lie between 840°F and the solidus of the base metals, and that the molten filler metal is distributed through the joint by a force called *capillary attraction*.

A capillary is usually thought of as a small tube with a very small inside diameter. When applied to brazing, a capillary is simply two solid surfaces which are close enough together so that capillary attraction can occur.

If you immerse a small, clean glass tube into a favorable liquid (such as water), you will notice that the liquid travels up into the tube and also up along the outside of the tube, but not as high. You will also notice that the surface of the liquid inside the tube is concave. This curved surface is called a meniscus, and its presence means that the liquid is wetting the solid.

Another way of looking at this is that the adhesive forces between the liquid and tube are greater than the cohesive forces among the liquid molecules. Thus wetting occurs; and since wetting results in a low contact angle, the meniscus is concave. Figure 1 shows examples of concave and convex meniscuses.

Capillary attraction occurs by the following sequence: when a glass tube is immersed, a thin film of liquid runs up the sides of the tube, creating a concave meniscus (see Figure 2a). The surface tension of this concave surface exerts an upward force and a difference in pressure; the pressure at point A is less than that at point B, so the liquid flows into the tube. It flows until it reaches a height where the resulting column of liquid compensates for the pressure difference; that is, when the liquid reaches point C the pressure at A will be equal to the pressure at point B (see Figure 2b).

The same thing happens when a lugged frame joint is properly brazed together: some molten brazing alloy coats the inside of the lug and the outside of the tube, and sets up an imbalance of forces which sucks the filler metal into the joint. The filler metal will keep going into the joint until equilibrium is reached.

The magnitude of the pressure difference, called ΔP, depends on three variables: the surface tension of the liquid, γ; the contact angle, Θ; and the distance between surfaces, d (see Figure 3). Written as an equation,

$$\Delta P = \frac{2\gamma \cos \Theta}{d}$$

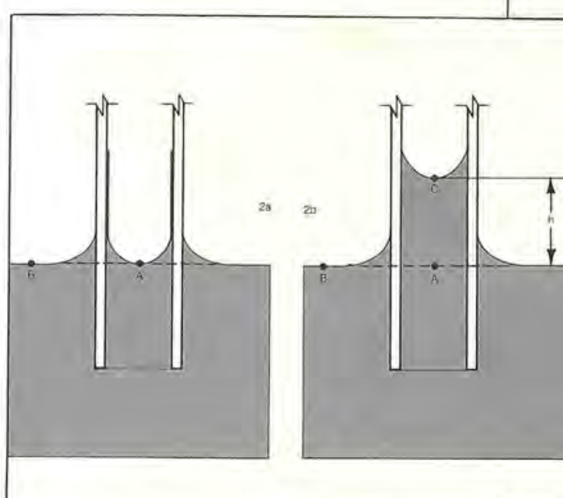


Figure 2: The moment the tube is immersed, a thin film of liquid travels up its walls (2a). This causes a difference in pressure which makes the liquid rise to a height h, so that the pressures are again balanced (2b).

George Retseck

Liquid metals such as molten brazing alloys have high surface tensions, between three and ten times as great as water. From the above equation, it's clear that a high surface tension is a prerequisite to having a high ΔP.

If a joint is cleaned and fluxed properly prior to brazing, most molten brazing alloys compatible with low-alloy and plain carbon steels form a contact angle approaching zero. As Θ approaches zero, the cosine of Θ approaches 1. Thus, the cos Θ term does not significantly affect ΔP for a well-prepared joint.

As the distance between solid surfaces decreases, ΔP increases — but up to a point. Very small clearances won't allow the filler metal through. Conversely, if d increases, ΔP decreases, and capillary attraction isn't as strong. This is one reason why the AWS recommends joint clearances between 0.002-0.005 inches for both silver and copper brazing alloys; larger or smaller clearances will result in poor capillary attraction.

For bicycle frame brazing, there is a high γ, low Θ, and small d. Thus if no problems arise (like de-wetting of the flux or filler metal, burning of the brazing alloy which may change γ, or joint clearances outside the range of 0.002-0.005 inches), capillary attraction will be close to the maximum possible value. For example, if we have a joint as in Figure 3, and assume that at 1740°F RBCuZn-C has $\gamma^* = 0.0031$ lb_f/in; $\Theta = 5°$; and $d = 0.004$ inches; ΔP turns out to be 1.54 psi (or 0.0106 N/mm^2). Thus, there is a pressure of 1.54 psi pulling the molten filler metal into the joint.

The viscosity of brazing alloys is also an important factor. As the brazing temperature increases, the viscosity of the filler metal decreases. Thus, the filler metal becomes more fluid, and is able to penetrate

**G.M.A. Blanc, et al.,* Welding Journal, *Vol. 40, #5, p. 214-s.*

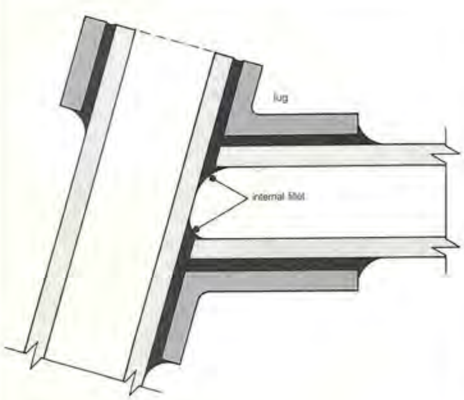


Figure 5: The lack of an internal fillet may be due to changes in filler metal composition. By the time the brazing alloy reaches the miter, its liquidus may be high enough to solidify it.

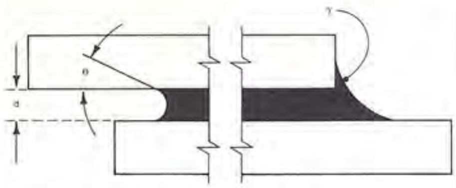


Figure 3: the magnitude of capillary attraction depends on three variables: γ, Θ, and d. When brazing bicycle frames, γ is high, Θ is low, but d can vary considerably.

the joint more easily. But remember, filler metals should never be overheated.

Up to now I've talked about capillary attraction without discussing one important factor — flux. *Most framebuilders and manufacturers use mineral rather than gaseous fluxes.* Until the filler metal is applied, the gap between lug and tube contains molten flux, which would appear to be an obstacle to capillary flow. What happens to the molten flux when the filler metal is introduced?

The capillary attraction between the base metal(s) and molten filler metal is much greater than the capillary attraction between the base metal(s) and flux. Thus, the molten filler metal simply displaces the flux to areas outside of the joint. For a lugged joint, the flux ends up either on the periphery of the lug, or inside the mitered tube (i.e., the tube whose end is open inside the joint).

The viscosity of mineral fluxes can have profound effects on the quality of the joint. As the viscosity of the flux increases, the ability of the filler metal to push the molten flux out of the way decreases. A joint brazed with too viscous a flux will not be bonded completely. Fortunately most if not all commercial fluxes compatible with steels aren't viscous enough to cause extensive problems.

Figure 6: These flower-like crystals were found in the fork crown joint of a well-known production Italian racing frame. The filler metal is an (R)BCuZn-type, and the base metal is Columbus SL. The average diameter of the crystals is about 0.00085 inches (magnified 240 times).

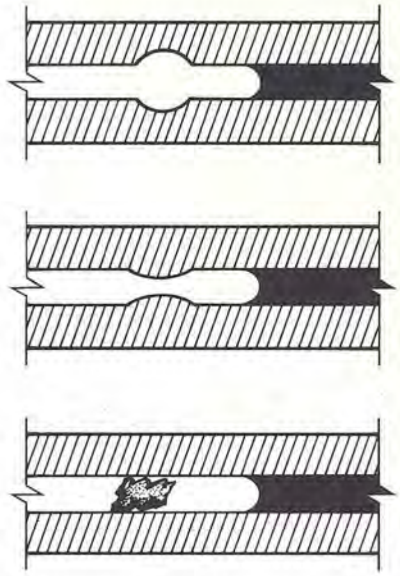


Figure 4: Capillary dams can be caused by sudden increases in clearance, sudden decreases in clearance, and foreign material lodged in the gap. Too many of these dams will result in a poorly bonded joint.

Capillary Dams

Most joints on a bicycle frame don't have uniform clearances. There is usually a range of clearances, from zero inches to sometimes as large as 0.025 inches or larger. Before the use of investment cast components became widespread, lugs, bottom brackets, and fork crowns were either sandcast, stamped, forged, or bulge formed. These aren't precision manufacturing methods, so the tube to component clearance always varied. Furthermore, unless you were a large framebuilder, it was hard to find these components in the required angles. Lugs and bottom brackets usually had to be bent to the desired angles. This would worsen an already poor clearance situation.

Investment cast components are now used by many framebuilders. These are made to very close tolerances, so initial variations in clearance aren't as big a problem. However, these components sometimes have to be bent to the proper angles, too. Clearances can also be affected by misdirected files, uneven filing, and the like.

Variations in joint clearance can cause capillary dams, which are barriers to capillary attraction. Capillary dams are caused by four situations: sudden increases in clearance; sudden decreases in clearance; foreign substances; and a change in composition of the brazing alloy. Figure 4 shows three of the four situations.

When the molten brazing alloy meets a sudden increase in joint clearance, capillary attraction (ΔP) decreases. In other words there is a pressure drop, so the flow slows down while the dam gets filled. Once it is filled, the brazing alloy can continue to penetrate the joint. However, if the joint is vertical so that the filler metal must flow against gravity, a large increase in clearance will stop the flow because it creates too low a ΔP to lift the filler metal. If filler metal can't be introduced elsewhere to reach the rest of the joint, it may help to change the orientation of the joint so that gravity aids the flow.

Sudden decreases in joint clearance cause a brief increase in capillary attraction when the filler metal first reaches them, but act as bottlenecks afterward, so the rate of flow past them decreases. If a constriction is too small, the rate of flow past it may be so slow that the joint won't get filled in a reasonable time. Adding more filler metal elsewhere around the joint may be necessary to complete the joint.

If the clearance is zero, the filler metal won't be able to get through at all. Either the filler metal must go around the dam, or more filler metal must be added elsewhere. Either way, there is a spot where bonding doesn't take place.

In all framebuilding shops, there is quite a bit of dirt and metal filings around. It's very easy for some of this stuff to end up between a lug and a tube to create a capillary dam. If the foreign substance is large enough, bonding won't occur because the filler metal can't get through.

Changes in Composition

Capillary flow can cease during brazing because the composition of the filler metal in the joint changes. At brazing temperatures, the thermal energy is high enough that the filler metal dissolves some of the base metal. This can raise the liquidus of the filler metal, so that it solidifies before complete penetration of the joint is achieved. To finish the joint more filler metal will have to be added elsewhere, or the temperature of the joint must be raised (but not so high that it overheats the filler metal).

A case in point is lugged joints which have been brazed with (R)BCuZn-type filler metals. I've examined many of these joints from top-quality frames, and found that rarely is there a fillet inside the joint (see Figure 5). I suspect that since the filler metal composition changes, it solidifies before penetration is complete (either that or the joint isn't hot enough). The framebuilder, noticing that capillary attraction has stopped, figures the job is done (as anyone would). In practice, lugged frames seem to have a large safety factor, so not having a complete fillet obviously isn't critical.

The amount of iron dissolved depends on the chemical composition of the brazing alloy, and especially its liquidus. The higher the liquidus, the more iron will be dissolved. That's why incomplete filleting is usually more common in brass-brazed joints. The filler metals listed in Table 1 dissolve anywhere from 1/2% to 4% iron.

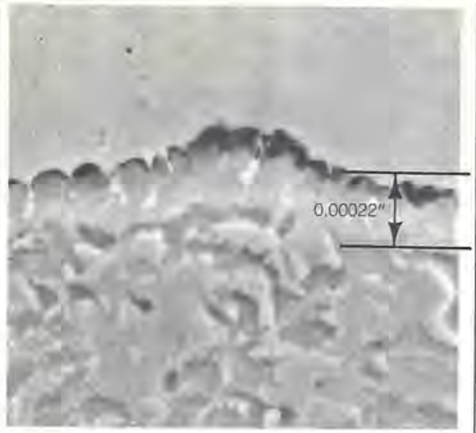


Figure 7: This is a Scanning Electron Photomicrograph of the alloying which can take place at the filler metal-base metal interface. The region above the interface is RBCuZn-A filler metal, while the region below the interface is Reynolds 531 tubing. The average thickness of the intermetallic layer is 0.00022 inches. This photo was taken from the head tube joint of a custom frame built by a well-known American framebuilder (magnified 1550 times).

When a frame brazed with RBCuZn-A gets in an accident and needs a new tube, the joints to be dismantled have to be heated well above 1650°F (the original liquidus of RBCuZn-A). This can cause extensive filler metal inclusions in the lug and adjacent tube because zinc fumes are likely to form. This makes brass-brazed frames more difficult to repair than low-temperature silver-brazed frames.

Figure 8: This photo, from the fork blade-dropout joint of another custom American frame, shows that filler metal inclusion doesn't affect just brass-brazed frames. The arrows point to areas where BAg-1 has entered the grains of Reynolds 531. The maximum depth of the inclusions is only about 4.5% of the thickness of the tube. Overheating the brazing alloy will result in much deeper filler metal inclusions (magnified 240 times).

The brazing time isn't as great a factor as filler metal composition or liquidus. For a fixed brazing temperature, the filler metal dissolves about as much base metal as it can in a minute or so.

The elements responsible for dissolving steel appear to be copper and zinc. Since these elements are present in all filler metals listed in Table 1, dissolution of some of the base metal can't be avoided. Provided the joint is filled with brazing alloy, changes in filler metal composition don't seem to adversely affect the mechanical properties of the joint. Figure 6 shows what copper-rich iron crystals look like in a frame joint brazed with (R)BCuZn-type filler metal.

Brazing should always take place 50°F-100°F above the liquidus of the filler metal, then, for the following three reasons: it ensures that the filler metal is completely liquid; it reduces the viscosity of the filler metal; and it will offset the effect of changes in filler metal composition.

Intermetallics

During brazing there is usually some degree of alloying at the interface between filler metal and base metal. Figure 7 shows what this alloying looks like on a frame brazed with RBCuZn-A. It's not necessary to have an alloy form at the interface to develop a strong bond; pure silver is virtually insoluble in iron at its brazing temperature, yet extremely strong joints can be made.

Some filler metal-base metal combinations can lead to the formation of intermetallic compounds at the interface. These are strong but usually brittle compounds which, because they are brittle, can affect the strength of the joint.

An example of the formation of a brittle intermetallic is the formation of iron silicide when brasses containing over 0.25% silicon are used to braze steels. This compound can form in sufficient amounts to impair the mechanical properties of the joint. Furthermore, when this intermetallic forms, the reaction involved gives off enough heat to locally melt the steel (it's an exothermic reaction).

When a joint containing sufficient amounts of iron silicide is stressed, failure is likely to occur at the brittle interface. Conversely, joints which don't contain large amounts of harmful intermetallics are much stronger, and when tested to failure, they fail midway between the joined surfaces.

Another example occurs when steels are joined with BCuP filler metals (copper-phosphorus brazing alloys that contain a minimum of 5% phosphorus). At brazing temperatures, the phosphorus combines with iron to form the brittle intermetallic iron phosphide.

Other harmful intermetallics can form if silver is alloyed with over 30% zinc or over 20% tin (i.e. 65% Ag-35% Zn, or 70% Ag-30% Sn). Notice that none of the filler metals listed in Table 1 contain large amounts of elements which can significantly affect the mechanical properties of the joint.

Filler Metal Inclusions

During brazing it's inevitable that some filler metal finds its way between the grains of the base metal, even if the filler metal isn't overheated. This happens because grain boundaries are less stable than the grains, and therefore more prone to attack. This phenomenon is commonly called "brass inclusion," but it can happen with any brazing alloy. Thus, a better name would be "filler metal inclusions."

If brazing is done in the temperature ranges given in Table 1, it's extremely unlikely that filler metal inclusions will be extensive enough to significantly affect the mechanical properties of the joint. But if the filler metal is overheated, inclusions will be present to a much greater depth. A deep filler-metal inclusion disrupts the continuity of the steel, and can affect the strength of the joint, especially if the frame tubes are extremely thin like those found in Columbus Record or Tange Pro tubesets. Figure 8 shows filler metal inclusions in a frame joint.

Surface Finish

Prior to brazing, the surfaces of the base metals on a frame can have a variety of surface roughnesses. They can be filed, sandblasted, sandpapered, etc., or some combination of these. Surface finish can affect the strength of the joint because it will influence capillary attraction.

Fine scratches aren't a problem if they are parallel to the flow of filler metal. In fact, they can even speed filling of the joint. This can be very helpful, especially when brazing with brass filler metals. Scratches perpendicular to flow can create capillary dams if they are deep enough. In practice, frame joints aren't usually rough enough to cause problems. Furthermore, dissolution of the filler metal by the base metal will smooth out fine scratches.

After reading the first and second parts of this series, you're probably becoming uncomfortably aware that a lot can go wrong during brazing. But do these problems significantly affect the mechanical properties of the joint? We'll find out in Part 3.

Part 3 of The Metallurgy of Brazing will cover tensile, yield, impact, and fatigue strengths in joints, and the role played by defects. Subsequent installments will cover the strength of steel tubes after brazing, annealing and hardening, temperature gradients versus the length of the tube's butt, and proper framebuilding procedures.

INDUSTRY TRENDS

ISO Develops International Bicycle Standards

Fred DeLong

What is ISO, and how did ISO become involved with bicycles?

ISO, the International Standards Association, is composed of the national standards organizations of 86 countries. Its 1,900 technical committees in various fields have developed almost 4,000 international standards, which facilitate world trade, reduce costs to consumers, and promote interchangeability worldwide. Committees have dealt with measurements and measuring, nut and bolt dimensions, computer language, and automobile safety requirements, to name a very few subjects.

In 1968, the International Organization of Consumers' Unions, International Center for Quality Promotion, and International Labeling Center petitioned the ISO to initiate work on standards for bicycles. National member bodies voted to take up this suggestion, and the ISO commissioned its technical committee TC/149. At its first meeting, in March 1973, two subcommittees were established. SC/1 studies bicycle construction and safety; SC/2 studies parts interchangeability.

The standards organizations of 14 countries participate fully in the work of the committee. Sponsoring companies and organizations in the individual countries, and some individual delegates, see to the funding, including the ISO's costs; provide laboratory workers and equipment to perform needed tests; and send representatives to meetings. Nine additional nations send observers. Minutes of the meetings and resolutions approved are sent to the standards organizations of all ISO member nations. The United States is a full participant through its standards organization, the American National Standards Institute (ANSI).

Nations have drawn on bicycle engineering experts, consumer representatives, government safety organizations, and transportation and standards representatives to recommend and review standards for the ISO committee. Additional experts were drawn in for consultation when necessary.

Working groups of each ISO subcommittee delve into the details of each particular subject (such as braking requirements or freewheel threading). Once agreement is reached, findings are brought to the full subcommittee for discussion. When consensus is reached, a proposal, called a Draft International Standard (DIS) is written. The central ISO council in Geneva, Switzerland, then transmits this standard to the standards organizations of member nations for discussion, approval, disapproval, or comment.

Comments are transmitted back to the ISO and to all participating countries. Differences are ironed out either by mail, or in the case of larger problems, through further investigation. When 75 percent of nations voting on a standard have approved it, it is proclaimed as an ISO international standard.

ISO standards are voluntary in many countries and do not prohibit continued use of previous standards or inhibit new design and innovation. As technology, manufacturing procedures, and requirements change, standards can be revised if needed.

Fred DeLong is an ANSI delegate to the ISO TC/149.

A Look at the Standardization Process — and Its Impact

John S. Allen with Fred DeLong

Fred DeLong has described the work of the ISO in developing standards for bicycles and bicycle parts. I will attempt now to draw some conclusions about the impact of the ISO's work on the bicycle industry and on bicycle users.

Three entirely different types of standards apply to bicycles: standardization of markings; of fit and threading; and of safety requirements. Each has a different type of impact.

Standardization of markings is the establishment of a uniform way of indicating which parts fit or do not fit each other, are interchangeable or not. The most dramatic example in the bicycle industry has been the Universal Tire Marking System which now finally makes it possible to compare sizes of tires and rims from different countries. Under previous systems, tires and rims of different sizes might have the same marking (for example, the Schwinn and British 26 × 1 3/8-inch sizes), while tires and rims of the same size might have different markings (for example, the Canadian 28 × 1 1/2, British 28 × 1 5/8, and French 700 × 38C tires, which all fit the same rim). Standardization of markings is of unquestionable benefit to bicycle

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast TM Reg.

December 1982 Volume 1, Number 4 $2.00

IN THIS ISSUE

AERODYNAMICS

Testing for Aerodynamic Drag: A New Method

Crispin Mount Miller

In pursuit of better testing of the Zzipper fairings and Tailwind aerodynamic panniers he makes and sells, Glen Brown has been developing a new aerodynamic drag testing technique this year. The new technique requires only the addition of one piece of equipment to his existing downhill coasting test rig.

The new method offers an accuracy of one percent (of total drag for a standard bicycle); compensates automatically for variations in slope (a major problem for most coasting tests); and uses self-contained on-board instruments whose total cost is less than $400.

The new instrument is a single-axis accelerometer. Rather than deducing the drag force from terminal speed or rates of change in speed data, Brown's method takes direct measurements of inertial effects on the bicycle and rider.

The automatic correction for slope considerably simplifies the extraction of results. In other coasting tests the slope of the road must be known exactly so that the record of speed change can be corrected for the propelling or retarding effect of gravity. But to the accelerometer the slope is irrelevant: what it measures (see box) is not simply change in speed, but deviation from pure inertial motion.

Pure inertial motion can be thought of as a one-dimensional counterpart of "free fall" (which generally requires three dimensions). An accelerometer in free fall will always read zero, and so will a single-axis accelerometer in free inertial motion along the accelerometer's axis.

Rearward Acceleration

On level ground the accelerometer reads simple change in speed after all: since pure inertial motion would be constant speed, the deviation (which happens because of drag) is the rearward acceleration that occurs as the bike coasts to a stop.

But on a downhill slope, pure inertial motion includes gravitational acceleration (as free fall does) and therefore would give ever-increasing speed. In this case, the deviation is the *loss* of acceleration as drag limits the speed to a terminal speed. In both cases, though, the accelerometer gives a reading proportional to the drag.

(To be rigorous, there is one small difference between the slowing-down case and the downhill case. The rotational inertia of the wheels makes the effective inertial mass, that determines the level-ground slowing-down reading, slightly different from the gravitational mass that determines the downhill terminal-speed reading. Since bicycle designs usually minimize wheel inertia, the resulting error is only one or two percent for the pure level-ground case, and proportionally less for situations approaching a steady terminal speed. The data can be corrected if the approximate rate of change in speed is known, but for tests run near terminal speed, as Brown now does them, the error is negligible.)

Brown uses the technique principally for comparative evaluations of the drag effects of various accessories on a standard bicycle, though he has also tested one human-powered streamliner (Jim Gentes's, sponsored by Blackburn and SunTour) with it.

Brown estimates that the new method's precision — roughly one percent of total drag, for a standard bike — is about the same as that of his previous drag-testing method (reading terminal speed, to the nearest 0.1 mph, for a bike coasting downhill). However, product of foot force and foot speed. But if one is comparing seated spinning to slower pedaling *standing up* (as many riders climb hills), the question is less clear-cut, because a standing rider usually applies much more force to the pedals. (The very highest power outputs, of course — sprints — are done by spinning *and* standing up.)

For any power output sustainable for longer than a minute or two, the rider probably can either sit or stand, so the question really is which is more efficient — which one is less work for a given net output? At moderate, long-term output levels, sitting is presumably more efficient, since, as Wilson points out, riders don't choose to ride standing up all day. But is this also true at higher outputs?

To resolve this question we need *two versions* of Figure 2: one for riders seated and one for riders standing up. How would the "standing" line compare to the "sitting" one? Certainly all the cadence graduations would be shifted to the right (since the greater foot force would place any given cadence at a higher power level); and the right end, representing all-out sprints, would be farther out than the maximum sitting-down power; but where would the "standing" line have its efficiency peak? And — most important — would any of its right end show higher efficiency than the sitting line?

At any rate, most fast riders spin on level roads — so what does happen on a hill?

Some of us install whatever cogs we have to, and keep on spinning. But many racers stay in gears in the fifties and methodically stand up to climb the hill.

They could install lower gears. Why don't they? Is it habit, from having learned to ride on bikes that didn't have them? For successful racers, that seems unlikely. Is it a tactical preference to keep the gear intervals narrow for the sake of high-speed riding on the flat, and just grin and bear the hills?

It might be because of a decision to work harder during hill climbs than on the flat. It's always important to minimize the amount of time you spend below your chosen pace, because going faster (to compensate) costs more energy than you saved by going slow. But hills are an especially emphatic case of this rule.

At level-riding speeds, because air drag is important, going slower does save some energy per mile. But gravity offers no such relief when you climb a hill; in fact, it may even cost you more energy if you spend longer straining at it, since it costs some energy just to spend time with your muscles tense.

If a "Figure 2" for standing riders would show higher efficiency than the sitting one at high power outputs (even the first Figure 2 is still hypothetical, remember) then this — the choice to work harder — would be a good reason to stand up on hills.

Or there may be no good reason, as Wilson suspects; or there may be one that neither of us has thought of. Does anyone know? *Crispin Mount Miller*

MATERIALS

The Metallurgy of Brazing, Part 3

Strength of Joints

Mario Emiliani

In the first two parts of this Series, I've concentrated on the microscopic aspects of brazing. In this part, I'll examine some properties of brazed joints from a large-scale perspective. The topic of this part is the strength of brazed joints, and the factors which affect them.

Tests to Determine Mechanical Properties

Many tests have been devised to measure the properties of materials. For all of them, there is a tradeoff between specific simulation of one particular structure (which enables accurate prediction of that structure's performance) and standardization (which enables comparison of one test with many others). Since relatively few tests have been made (or published, anyway) specifically on bicycle frame joints, this article will report on the results of standardized tests, while noting their limitations.

One of the first tests performed on a material when someone wants to know its basic mechanical properties is the tensile test. However, a tensile test subjects the test specimen to a very unrealistic loading situation: it is simply pulled from both ends until it fails. In reality, most if not all load-supporting members are subjected to a variety of stresses from many different directions; a situation called combined loading.

Combined Loading

Perhaps there is no better example of this than bicycle frames. Frames are subjected to many different types of stresses, which are very difficult to duplicate in the laboratory. While the tensile test gives useful ball-park numbers, the tensile strength, yield strength, and ductility of a material under combined loading may be much lower than in the pure tensile loading applied by the test. Safety factors are always used when designing parts under stress; this is one reason why.

Similarly, the fatigue, impact, and shear strength data of brazed joints presented here are from tests that did not accurately represent the types of stresses a bicycle frame "sees." Furthermore, the test specimens were usually not shaped like bicycle frame joints. While the tests and test specimens are idealized, however, they do give data on the specific alloys used in bicycle frame construction. Thus, they are excellent starting points, and a great deal of information can be gathered from them.

Unfortunately, there seems to be no data even vaguely relevant (to bicycles) on yield strength or ductility. I've never been able to

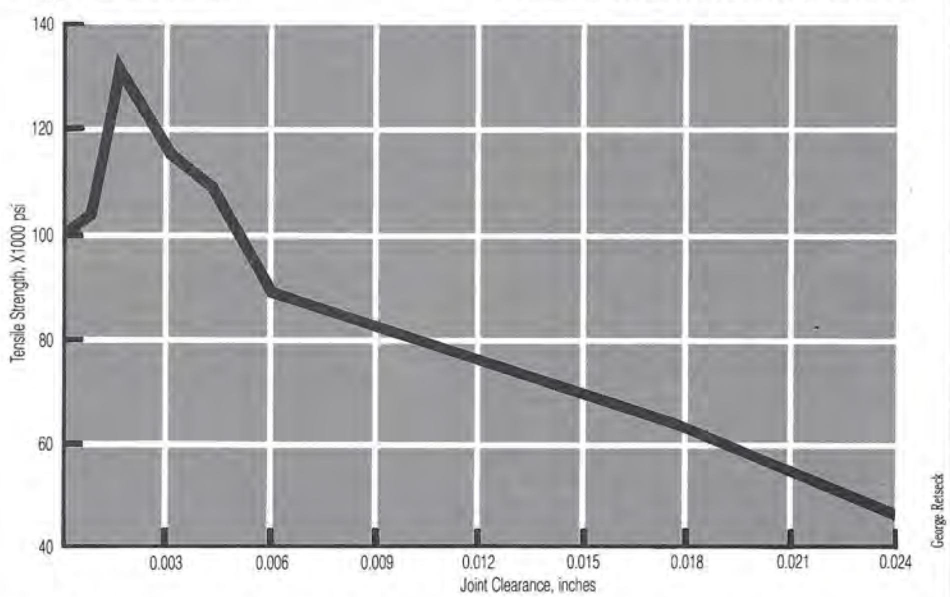


Figure 1: While a joint clearance of about 0.0015 inches produces the strongest possible joint for the conditions in which the joints were brazed, the joint is still very strong for clearances up to 0.005 inches. However, the maximum tensile strength shown here won't be the same for frame joints, since frame tubing isn't as strong as the base metal used in these tests (from C.D. Coxe and A.M. Setapen, *Welding Journal* vol. 28, no. 5, p. 462; by permission of American Welding Society *Welding Journal*).

find anything published on these properties for any brazed joints whose materials (specific alloys used) resemble those of bicycle frame joints. This is quite a pity since a lot of work was done determining the tensile strength of brazed joints, and it would have taken very little effort to collect yield strength and ductility data during those tensile tests. Thus, this discussion will have to be limited to the tensile, fatigue, impact, and shear strength of brazed joints.

Throughout this part, it's assumed that filler metals and base metals are compatible, the surfaces of the base metals are smooth, and the joint is cooled by natural convection. These are reasonable qualifications, since most frames are built under these conditions anyway, and it greatly simplifies analyzing the more relevant factors that affect joint strength.

Factors Affecting the Strength of Brazed Joints

For a given filler metal, there are five factors that determine how strong a brazed joint can be:

1. Joint clearance
2. Strength of the base metals
3. Voids in the filler metal
4. Quality of the metallic bond
5. Geometry of the joint

I include the fifth factor just to remind the designer to avoid stress concentrations in the joint. Although many potentially damaging stress raisers exist in bicycle frames, they don't normally have any effect. Thus, I won't discuss the fifth factor further.

The remaining four factors have different effects on the mechanical properties of the joint, so no broad generalizations can be made. Instead, I will discuss the four factors individually as they pertain to the tensile, fatigue, impact, and shear strengths.

Tensile Strength

To my knowledge, the relation of tensile strength to joint clearance has never been determined for steels brazed with brass filler metals. However, extensive work has been done with steels and silver brazing alloys. While this doesn't exactly mirror the ways all frames are made, it still provides useful information. Furthermore, the mechanical properties of brass-brazed joints probably parallel those of silver-brazed joints fairly closely, because in many cases the type of filler metal isn't a factor.

• Effect of joint clearance — Forty-three years ago, researchers at Handy and Harman (well-known manufacturers of brazing filler metals and fluxes) undertook research to determine the optimum joint clearance for butt-brazed specimens (a butt-brazed joint is made of two bars placed end-to-end and brazed together). This classic work appears in that company's publications *The Brazing Book* and *Brazing Technical Bulletin No. T3*. The data from this research can be plotted as a curve of tensile strength versus joint clearance (see Figure 1).

This research used torch-brazed specimens of 18-8 stainless steel (18 percent chromium, 8 percent nickel), which had a before-brazing tensile strength of 160,000 psi (and about the same after brazing). The specimens were deoxidized with a mineral flux, and the filler metal was BAg-1a.

The curve shows that optimum joint clearance is about 0.0015 inches. This is probably very close to the optimum clearance (though a different strength would result) for brass- or silver-brazed bicycle frame joints too, since the brazing procedures are the same. (The optimum clearance depends on how the joint is brazed. For example, good bonds can be achieved with smaller clearances by using gas fluxes instead of mineral fluxes.)

While it's certainly desirable to braze at the optimum joint clearance, it's just not practical when building frames. It's all but impossible to achieve uniform clearances on frame joints, so why waste the time?

I'm sure someone is thinking that it is worth the time because the joint will be as strong as possible. Well, take another look at Figure 1. You'll notice that the tensile strength of the joint is 100,000 psi or greater for clearances between 0.001-0.005 inch.

Thus, while an optimum clearance exists, it's not necessary — for all practical purposes the joint is strong enough, even with 0.005 inch clearance. So in terms of framebuilding practice, a slip-fit is all that's required to produce very strong joints.

Small and Large Clearances

Figure 1 also shows what happens to the tensile strength of the joint at very small and very large clearances. Joint clearances less than 0.001 inch reduce the tensile strength of the joint because capillary dams begin to prevail, resulting in many unbonded areas.

Beyond 0.005 inches, the tensile strength of the joint again decreases. This is due to an increase in flux inclusions, poor capillary attraction, and a general increase in defects since thick joints have a statistically greater chance of containing more defects.

As the joint thickness approaches 0.024 inches or more, the tensile strength of the joint approaches the tensile strength of the filler metal; about 50,000 psi. Thus, large buildups of filler metal at seatstay clusters, for example, are probably not much stronger than the tensile strength of the filler metal itself (all the filler metals listed in Table 1 of Part 2 of this series, published in the October issue of *Bike Tech*, have tensile strengths of about 50,000 psi in the as-cast condition).

The optimum joint clearance in Figure 1 yields a tensile strength of 135,000 psi. You may have heard that clearances beyond about 0.003 inches in silver-brazed joints result in substantial reductions in the joint's tensile strength, but the same is not true for brass-brazed joints. This is hard to believe since the tensile strengths of both filler metals are about the same. Anyway, Figure 1 shows that the tensile strength does drop off rapidly, but so what? The joint may still be strong enough.

For instance, suppose the seat tube/top tube joint is stressed to a maximum of 25,000 psi. Then the tensile strength of the joint need only be about 40,000 psi. If this were the case, then the joint clearance could be very large. Unfortunately, nobody has ever determined the stress distribution in frames, or a tensile strength versus joint clearance curve applicable to frames.

In the second part of this series, I spoke

Types of Stresses in Frame Joints

This issue's brazing article deals extensively with tensile strength of brazed joints (among other topics) and this raises an important question: why should bicycle framebuilders care about tensile strength? The answer is easily overlooked.

At first, it might appear that the joints of a lugged bicycle frame are stressed only in shear. Since the tubes are enclosed in the sleeves of the lugs, one might assume that a joint would fail only if a tube slides out of it (or twists within it), and such a failure occurs by shearing of the filler metal.

It would follow from this that the tensile strength of the brazed joint would be irrelevant, and so would be the results of fatigue and impact tests that measure strength with tensile loadings (as most of them do, although it's possible to test a specimen for fatigue or impact strength under shear loading).

However, this reasoning overlooks another type of stress that occurs in lugged joints, when they bear bending moments: when a moment begins to spread the angle that two tubes form at their intersection, the spreading of the angle tends to lift the lug away from the surface of each tube, in the region inside the angle. Thus the brazed joint receives a tensile stress.

As it happens, this type of loading is very important, because it occurs in the most heavily loaded joint in the frame: the bottom bracket. (It also occurs in the head tube joints.) Every pedal stroke tends to pull one end (or the other) of the bottom bracket shell away from its side of the seat tube. I once had a cheap handbuilt frame (with poorly bonded joints) that failed there.

Crispin Mount Miller

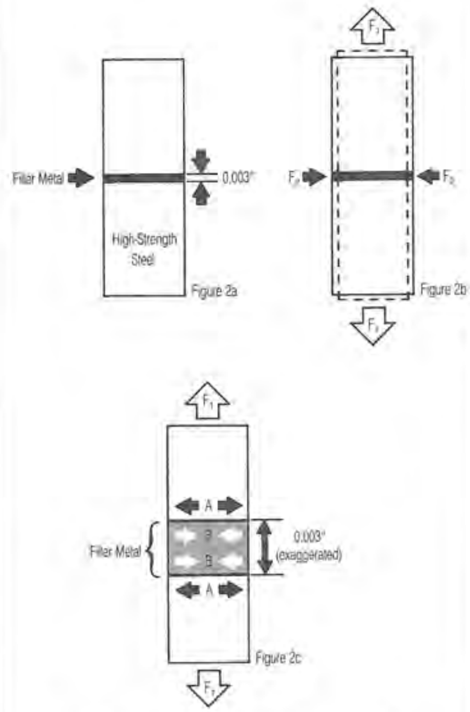


Figure 2: The tensile strength of a butt-brazed joint is two to three times as great as the tensile strength of the filler metal because the steel bars don't allow the filler metal to yield.

about the importance of having joint clearances between 0.002-0.005 inches to ensure adequate capillary attraction, and to help avoid capillary dams. This, simply put, is the overriding factor. The above clearances will virtually guarantee a strong joint (as experience has proved), without having to worry about an optimum clearance. All that's necessary is to take reasonable care when preparing the joint: degrease the tube, clean it well with sandpaper (inside the tube too, if you expect to get a fillet of filler metal in there), wipe the tube off with a clean cloth, and flux the joint prior to brazing. This will also ensure the formation of good metallic bonds.

• Strength of the base metals — A very important factor in determining the tensile strength of the brazed joint is the tensile strength of the base metal. The tests used to produce Figure 1 utilized a stainless steel with a tensile strength of 160,000 psi before and after brazing. With all other things constant (brazing time, brazing temperature, joint clearance, etc.), the tensile strength of the joint increases as the tensile strength of the base metals increases.

Since steels like Reynolds 531, Tange Champion, Columbus SL, etc. have lower tensile strengths (on the order of 110,000 psi before brazing, and roughly the same after brazing), the tensile strength of their brazed joints will be less, at any given clearance, than that shown in Figure 1. Just how much less is hard to say, since no tests have been performed.

As I've shown in the September/October 1981 issue of *Bicycling*,[1] the tensile strength of bicycle steels varies considerably depending on what temperature they are exposed to during brazing. Obviously, this too will affect the tensile strength of the joint.

By now you may be wondering why the tensile strength of brazed joints can be 2-3 times as great as the tensile strength of the filler metal. The reason lies in how the stress is distributed in and around the joint.

Figure 2a shows two high-strength circular steel bars that have been butt-brazed together with a compatible filler metal. The thickness of the joint is small, say 0.003 inches. When the rod is pulled in tension by the force F_1, it must elongate. This also forces the diameter of the rod to decrease proportionally. Thus the forces F_2 act radially inward to make the rod thinner, as shown by the dotted lines in Figure 2b.

Soon the rod is stressed to the yield point of the filler metal, but the steel bars aren't near their yield point yet. And since the steel bars are so close together, they simply prohibit the filler metal from contracting enough to yield. Figure 2c shows the situation: the forces which resist F_2 are greater at "A" than at "B", so the filler metal isn't allowed to yield just yet. As the stress increases, the forces at "A" and "B" become equal, and the filler metal begins to yield. Eventually the joint fails, usually near the yield strength of the base metals.

0.001 Inch

The thinner the joint clearance, the greater the ability of the steel bars to prohibit yielding of the filler metal. Theoretically, as the joint clearance becomes infinitely thin, the tensile strength of the joint approaches the tensile strength of the bars. But as we all know, clearances less than about 0.001 inches result in joints with many voids. Thus, the tensile strength of the bars can't ever be reached (at least by the methods used to build bicycle frames).

Conversely, as the joint clearance gets large, the steel bars aren't as effective at restraining the filler metal. Eventually the steel bars won't have any effect, and the joint will fail at the tensile strength of the filler metal.

• Voids — Small quantities of flux, called flux inclusions, can be trapped in the filler metal upon solidification. Structurally they are the equivalent of voids, and are obviously detrimental because they disrupt the continuity of the filler metal, and can reduce the area bonded.

To a degree, flux inclusions are unavoidable. However, their occurrence can be minimized by brazing within the temperature ranges given in Table 1 in Part 2. This ensures that all the flux is molten and can be readily displaced by the molten brazing alloy.

Flux within the joint that has been saturated with oxides is more difficult to displace, so keeping the brazing time to a minimum will help. Another trick is to make the filler metal flow in the direction of gravity. Since frame joints contain a range of clearances, the filler metal can't possibly flow uniformly. Gravity will help smooth out the flow, and hence help the filler metal displace the molten flux more effectively.

Figure 3 shows porosity in a frame joint caused by overheating the filler metal. This too will reduce the bonded area, as well as produce stress raisers within the filler metal. Unlike flux inclusions, the porosity shown in Figure 3 is avoidable, but it is not uncommon.

• Quality of the bond — It's no surprise that if the base metals aren't properly cleaned and fluxed, the metallic bond isn't going to be good. This will affect not only the tensile strength, but every other mechanical property as well; and it will affect them long before any of the other three factors becomes relevant. In this part, it's assumed the joints are properly prepared, so that the bond has little or no effect (i.e., the joint fails midway between the metals joined).

With this assumption, there are only three things left which might damage the metallic bond: flux inclusions, porosity caused by overheating the filler metal, and de-wetting of the flux (i.e., failure of the flux to stay on all parts of the surface). The third factor is a common occurrence which can be avoided by simply buying a better flux, or by applying more flux.

Flux inclusions are usually unavoidable, so some of them are bound to lie at the filler metal/base metal interface. This, of course, will impair the quality of the bond by reducing the area bonded. Porosity has the same deleterious effect.

Fatigue Strength

The fatigue strength of bicycle frames has long been sought-after information. But, sad to say, nobody has ever produced any data that's worthwhile because everyone's tests have been so unrealistic. The loads a frame "sees" are very complicated, and aren't even roughly simulated by standard fatigue test equipment. This being the case, we'll take a look at some simplified tests performed on butt-brazed specimens.

• Effect of joint clearance — Figure 4 shows graphs of applied stress (in bending only) versus the number of cycles (of applied stress) to failure, commonly called S-N curves. In Figures 4a and 4c, the base metal is AISI 1020 steel, while the base metal is AISI 4140 steel in the remaining two figures. The before-brazing tensile strengths of the 1020 and 4140 steels are 64,000 psi and 164,000 psi respectively. Both these steels

[1] *Mario Emiliani, "Reynolds vs. Columbus vs. the Framebuilder's Torch,"* Bicycling, *September/October 1981, pp. 92-97.*

Mario Emiliani

Figure 3: This photo is from the top tube/head tube joint of a well-known Italian racing frame. The porosity in the joint was caused by overheating the filler metal, an (R)BCuZn-type. If enough of these voids are present, the mechanical properties of the joint will be impaired.

are similar or identical to steels used to make bicycle frames.

The joint clearance is 0.001 inches in Figures 4a and 4b, and 0.010 inches in Figures 4c and 4d. The base metals were deoxidized with mineral flux and oxy-acetylene torch-brazed using BAg-1. Thus the materials and procedure used to braze the specimens are the same as those used in constructing many frames.

Notice that in all the figures, the curves become parallel to the "cycles" axis at about 22,000 psi (while they vary from this value by 10 or 15 percent, in the context of fatigue tests these variations are very small). This stress is called the fatigue limit, and it means that the joint can survive stresses at or below this level for an infinite number of cycles. So it appears that within the range of clearances tested the joint clearance has little or no effect on the fatigue limit.

Joint clearance does appear to have a minor effect on fatigue strength.[2] The fatigue strength at one million cycles in Figures 4a and 4b is about 32,000 psi, while the corresponding fatigue strength in Figures 4c and 4d is about 26,000 psi. But it's hard to say whether the difference in fatigue strength is statistically significant, since only nine tests were performed per curve. Furthermore, the joint clearance in Figures 4c and 4d is twice as large as the maximum recommended by the American Welding Society (AWS); if the joint clearance were 0.005 inches, there probably wouldn't be a statistically significant difference. So the bottom line is that if the joint clearance is within that recommended by the AWS, the joints should have close to the maximum fatigue strength.

• Strength of the base metals — The difference in before-brazing tensile strengths of the base metals is quite large, but the four curves all give practically the same fatigue limit. Thus, the before- and after-brazing tensile strength of the base metal doesn't significantly affect the fatigue limit (as long as it's higher than about 21,000 psi).

The fatigue strength does not seem to depend on the strength of the base metals either, because Figure 4a is very similar to Figure 4b, and Figure 4c is very similar to Figure 4d.

• Voids and quality of the bond — The soundness of the joint is the single most important factor determining its fatigue strength. The fewer the voids, the greater the fatigue strength.

Defects such as porosity (Figure 3) and flux inclusions act as stress raisers, which can locally magnify stresses to well beyond the yield strength of the filler metal. Soon cracks begin to form, and because they too act as stress raisers, the cracks continue to grow. Eventually the joint will fail.

It's very difficult if not impossible to produce joints absolutely free of voids by the methods used to join frames. Even so, I've never seen a brazed joint fail by fatigue. Perhaps there is an inherently large safety factor which helps the joints tolerate voids.

Fatigue failures outside the joint do occur, however. These failures usually occur in the heat-affected zone, and are invariably next to a lug point or other obvious stress raiser. While realistic fatigue data would be nice to have, this problem could be avoided through better construction techniques and/or design: thin the lug tips in critical areas, use a different lug design, or use a heavier gauge tube.

Impact Strength

Bicycle frames are often subjected to large

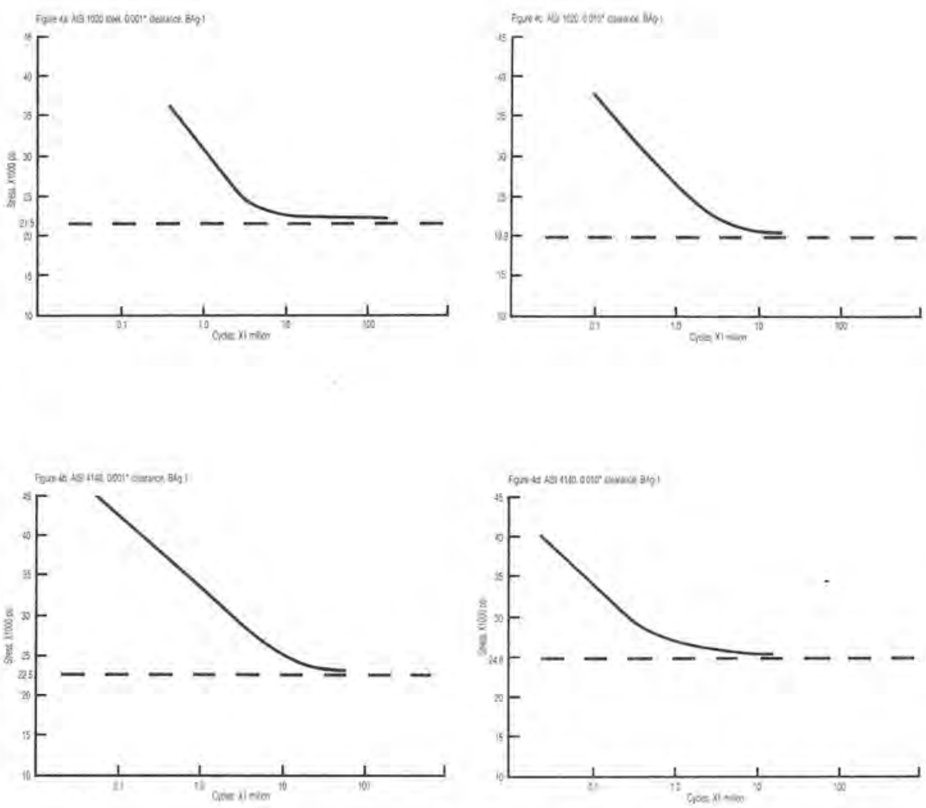


Figure 4: Both the fatigue limit and fatigue strength are not significantly affected by the tensile strength of the base metals. However, the fatigue strength is influenced by the joint clearance, while the fatigue limit isn't. Voids will reduce the fatigue strength of the joint because they act as stress raisers (from C.H. Chatfield and S. Tour, *Welding Journal* vol. 37, no. 1, pp. 37s-40s; by permission of American Welding Society *Welding Journal*).

[2] *The stress which a specimen can sustain for a given number of loading cycles; the number of cycles must be specified.*

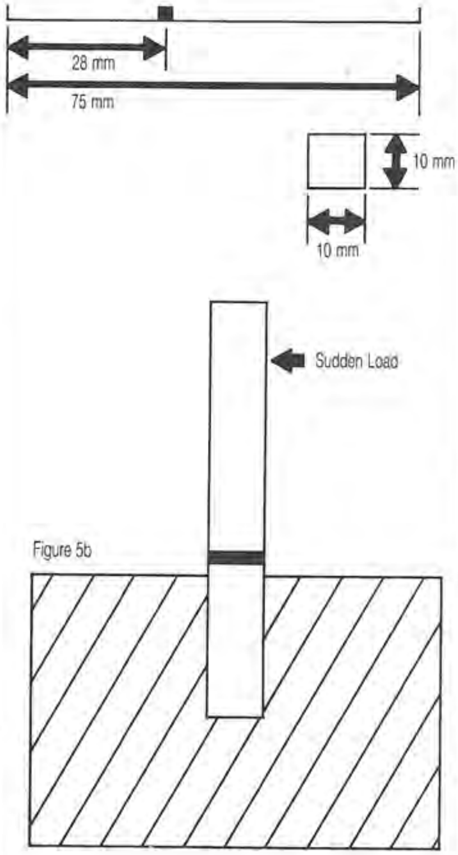


Figure 5: A standard impact specimen is made by butt-brazing two steel bars with dimensions shown in Figure 5a. In Figure 5b the short end of the specimen is held rigidly while a sudden load is applied, usually by a massive swinging pendulum (from "Tentative Methods for Notched-Bar Impact Testing of Metallic Materials," ASTM Designation E23-56T).

forces for very brief periods; riding over large bumps and potholes, for example. These types of forces are called impact loads, and the impact load needed to break a material is called its impact strength. Values of impact strength are usually given in foot-pounds, and indicate the amount of energy that a test specimen of the material can absorb before it breaks.

The impact strength of a material varies depending on the geometry of the test specimen. To ensure that everyone's impact data are comparable, there are standard specifications for test specimen geometries. Standard impact test specimens are notched so that the specimen is guaranteed to fail (in other words, the notch tests a material's ability to withstand the effects of a defect under impact loading). Brazed-joint specimens, however, need not be notched, since the filler metal acts as a weak spot. The data presented here are for un-notched brazed specimens. Figure 5 shows what a brazed impact specimen looks like, and how it's loaded to failure. As a rule of thumb, the minimum acceptable impact strength is about 15 foot-pounds for test specimens of joint types being considered for brazed frameworks.

• Effect of joint clearance — The effect of joint clearance has been investigated, but so few data points were taken that it's not worth discussing. Besides, the following factors have been shown to be more critical.

• Strength of the base metals — A pair of impact tests, with base metals of high-strength steel and soft iron, showed a dramatic difference in a way one might not expect.

The tests were performed on butt-brazed specimens of AISI 4140 steel, whose before-brazing tensile strength was approximately 150,000 psi and ductility approximately 10 percent, and Armco Iron (iron with a maximum of 0.02 percent carbon), whose respective properties were approximately 50,000 psi and 40 percent. The filler metal was BAg-1a, and the joint clearance was 0.002 inches.

The results were that the joints brazed in 4140 steel absorbed an average of 1.7 foot-pounds of energy, while the joints brazed in iron had an average impact strength of 39.9 foot-pounds.[3]

The joints brazed in iron absorbed 23 times more energy because the iron's tensile strength was low, close to that of the filler metal. Thus the filler metal was strong enough to make the iron permanently deform a lot — and large plastic deformation is the name of the game in impact testing because (for a given yield strength) the more a material deforms, the greater its impact strength. The joint in steel, however, had a very low impact strength because the steel was much stronger than the filler metal, and as a result didn't deform much.

Let's assume that the after-brazing tensile strength of frame tubes is 95,000 psi. This is much higher than the tensile strength of any filler metal, so you'd expect the impact strength of frame joints to be fairly low. But most frame joints have large laps (i.e., the portion of the lug which overlaps the tube). These tests didn't take this into account; but another test did.

AISI 4140 steel bars and rings brazed together with BAg-1a, having a radial joint clearance of 0.002 inches, a lap of 0.375 inches, and a bond area of 0.474 square inches, produced average tensile impact strengths of 88 foot-pounds.[4] Since most frame joints have considerably more lap and bonded area than this (a long-point Prugnat seat lug without cutouts provides about 1.75 square inches of bond area to the top tube, for example), their impact strengths must be quite high. This is proved by experience, since we've all ridden over big bumps without any problem (sometimes to our surprise). It's probably the lap on frame joints which produces the "inherently large safety factor" so important to this and other mechanical properties.

• Voids and quality of the bond — Once again, these factors prove to be very important. Voids have a pronounced effect during impact loading because the rate of stressing is so high. In a given length of time, cracks will travel much farther in an impact test than in a tensile test.

Shear Strength

When a bicycle hits a bump, the top tube/head tube joint is stressed in tensile shear (i.e., the top tube wants to pull out of the lug). During a sprint, the down tube "feels" torsional (twisting) shear stresses. Both joints, of course, are under the influence of other types of stresses as well.

Shear tests in tension produce different results from shear tests in torsion, because the mode of deformation in and around the joint is different. Nobody has ever done comprehensive tests using just one type of shear. Consequently, the data given below is a mix of the two.

• Effect of joint clearance — Figure 6 shows plots of shear strength versus joint clearance for circular steel shafts brazed 0.78 inches into steel rings. It's not known whether the specimens were tested in torsional shear or tensile shear. The before-brazing tensile strength of the steel was about 64,000 psi, and the filler metals used are shown on the curves. The brazing procedure is also not specified.

The curves show that the shear strength of the joint depends upon the filler metal, and there is an optimum joint clearance (which I hope you're not too concerned with). These curves are similar to Figure 1 in that there is a drop in strength at either end of the curves.

The shear strengths for RBCuZn-D are quite a bit higher than those for the other two filler metals, possibly because nickel, copper, zinc, and iron form an intermetallic at the interface. This strong intermetallic may affect the stress distribution in a way similar to how the steel bars prohibit yielding of the filler metal in a tensile test. But don't get too excited by what the curve shows; since the brazing procedure wasn't specified, the same high shear strengths may not exist in frame joints.

Since most frame joints have laps, the effect of joint area must also be considered. The joint area influences the shear strength of the joint in a way similar to Figure 6: when the joint area is small, about 0.5 square inches, the shear strength of the joint is

[3] *C.D. Coxe and A.M. Setapen,* Welding Journal, *Vol. 28, No. 5, pp. 462-466.*

[4] *H.A. Smith and P.A. Koerner,* Welding Journal, *Vol. 25, No. 3, p. 190-s.*

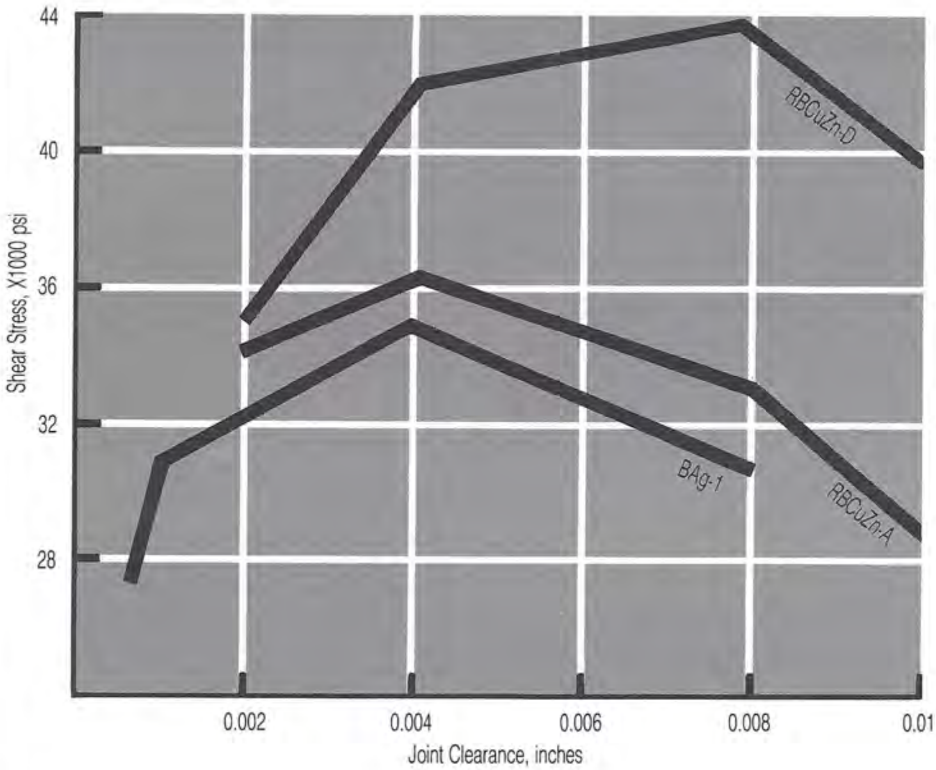


Figure 6: The maximum shear strength occurs at clearances considerably greater than the maximum tensile strength in Figure 1; yet another reason why it's not worthwhile to try and achieve a uniform clearance in frame joints (from J. Colbus et al., *Welding Journal* vol. 41, no. 9, p. 415s; by permission of American Welding Society *Welding Journal*).

around 40,000 psi. As the joint area gets larger, to around two square inches, the shear strength is about 28,000 psi.[5]

When the lap, and consequently the joint area is small, the joint quality is usually very good. Hence the joint strength is high. But as the lap increases, the shear strength of the joint (per unit area) drops partly because the quality of the bond is reduced. The other factor which makes longer laps weaker (for their size) is that beyond a certain length, the stress isn't distributed uniformly along the lap. The shear stress becomes concentrated at the ends of the lap, while the center-portion of the lap doesn't support any stress. Figure 7 shows this situation.

In practice, joint failures due to shear stresses only are extremely rare on lugged frames, although shear stresses are probably a contributing factor in fatigue failures. In any event, it's not necessary to modify current framebuilding practices to improve the shear strength of joints.

• Strength of the base metals — The shear strength of brazed joints is much less dependent on the tensile strength of the base metal when tested in torsion than when tested in a tensile test. Armco Iron and AISI 4140 steel (having tensile strengths of 50,000 psi and 135,000 psi respectively) brazed with BAg-1a produced shear strengths of 36,000 and 43,000 psi respectively.[6] This is not a big difference. Thus, while the after-brazing tensile strength of the tube may vary considerably, the shear strength of the joint (in torsion) doesn't.

• Voids and quality of the bond — There's nothing left to say about this that wouldn't be redundant, except that bicycle framebuilders should use paste fluxes. Paste fluxes minimize voids and improve the bond quality because they provide better coverage of the metal when molten. Furthermore, paste flux isn't blown away by the flame as easily as are powdered fluxes prior to becoming liquid.

[5] *J. Colbus, et al.*, Welding Journal, *Vol. 41, No. 9, p. 415-s.*

[6] *See footnote 3.*

Summary

By now I'm sure you're aware that voids and bond quality are the key factors in determining the mechanical properties of brazed joints. Thus, the framebuilder should always remember these requirements for good joints: use a good paste flux, prepare the joint properly, maintain joint clearances between about 0.002 and 0.005 inches, and employ good brazing technique (i.e., don't overheat the filler metal or spend too long making the joint, etc.).

In the final part of this series, I'll discuss what happens to the tubing during brazing, why tubing manufacturers recommend specific temperature ranges, and why many framebuilders choose to ignore this advice.

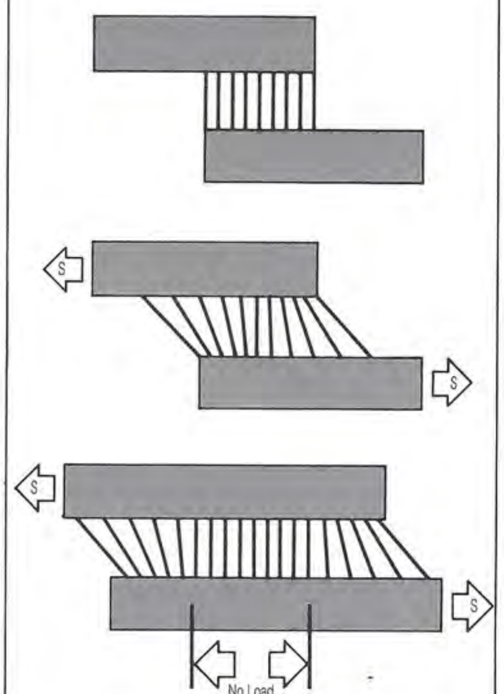


Figure 7: (Top) The parallel lines between the plates represent the filler metal in an unstressed state. (Center) When a shear stress S is applied to a lap whose joint area is small, the stress is distributed evenly throughout the joint. (Bottom) When the joint area increases, a portion of the lap in the center doesn't carry any load. Thus, lengthening the lap doesn't guarantee a stronger joint simply because the bond area is greater. (from H.R. Brooker and E.V. Beatson, *Industrial Brazing*, Butterworth Group, Seven Oaks, England, 1975).

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

TM Reg.

April 1983 Volume 2, Number 2 $2.00

Materials

The Metallurgy of Brazing, Part 4

The Effect of Temperature on Steels

Mario Emiliani

No discussion of the metallurgy of brazing would be complete without discussing the effect of brazing temperatures on the base metals. Not too surprisingly, this effect on the base metals will affect the strength of the joint — Part Three of this series (*Bike Tech*, December 1982) detailed a few mechanical properties which depend strongly on the after-brazing strength of the base metals — but brazing metallurgists have usually neglected to consider the question.

To understand the effect of temperature, it's important to understand a few things about steels.

Steel

By definition, steel is simply an alloy of iron and carbon, but other elements are usually added to help remove impurities (by combining with them and floating away in the slag) or to produce specific physical properties. For example, a minimum of 0.25 percent manganese is added to all steels to help remove sulfur and oxygen, while large amounts of chromium and nickel may be added to improve corrosion resistance (about 10 percent for some stainless steel alloys). But for the moment, neglect other elements and consider iron alloyed with just carbon.

Iron can be strengthened in many ways, but the simplest way (and one of the most effective ways) is to add carbon. Carbon is virtually insoluble (i.e., won't dissolve) in iron at room temperature; instead, it combines chemically with some of the iron atoms to form a strong but brittle intermetallic compound called *iron carbide*. This compound is also known as Fe_3C, since it is made up of three iron atoms per carbon atom. The carbide exists as a distinct substance or "phase" within the iron, in particles (hereinafter called "carbides") whose size and shape vary depending on the steel's history of heat treatment(s).

Figures 1 and 2 are examples of what carbides look like in high-quality steel bicycle frame tubing. With the exception of Reynolds 753, all frame tubing has the type of microstructure shown in either Figure 1 or Figure 2.[1]

The presence of iron carbide is fundamental to the strengthening of steels (except most stainless steels, which work differently), because the carbides inhibit microscopic deformations. Steel is made up of many crystals called *grains*, each made up of ordered arrays of iron atoms. Permanent deformation in metals under stress occurs through microscopic deformations called *slip*, in which layers of atoms within a grain slide past each other.[2] If the stress is high enough, slip is extensive, and macroscopic yielding occurs. Carbides act as obstructions within the slippage planes, and enable the metal to bear more stress before it yields.

The ability of carbides to inhibit slip depends upon their size, shape, and distribution. If the carbides are large spheres spaced far apart, the steel will be weak and ductile since the carbides aren't effectively reinforcing the weak and ductile iron. But if the carbides are small and close together, slip can take place only over very small distances.

[1] *See "Straight Talk On Steel" by Mario Emiliani,* Bicycling, *July 1982, pp. 96-123.*

[2] *See "What Is Fatigue?" by Richard Brown,* Bike Tech, *Vol. 1, No. 3, pp. 12-13.*

IN THIS ISSUE

FROM THE EDITOR

With this issue, *Bike Tech* completes its first year of publication. This past year, we were proud to publish Mario Emiliani's authoritative series on The Metallurgy of Brazing and Paul Van Valkenburg's series on Getting the Numbers Right (in HPV testing). We covered the designs of practical and impractical recumbents, structural analysis of frames and frame rigidity testing, the work of the International Standards Organization, advanced repair techniques, and more.

Our next six issues promise to improve on this. You'll be reading the results of an exhaustive dynamic test of bicycle frame flex while the bicycle is ridden on rollers, accompanied by a theoretical analysis of what percentage of your energy you could expect a frame of a given rigidity to swallow. We have an authoritative answer to the exercise physiologists who tell us we ride better at cadences our bodies can't tolerate, a thorough report on a year's analysis of frame stiffness with our "Tarantula" testing machine, test results on the metallurgy of heat-treated rims, an analysis of bicycle steering and balancing which is more thorough than others you've read (here or elsewhere), and an impressive catalog of design faults in today's brakes.

Negotiations are under way to bring you the results of destructive strength tests of bike frames, a how-to series on framebuilding, and reports from engineers at the world's most respected companies.

Needless to say, we think you'll find the next year's issues even more rewarding and valuable than this year's.

John Schubert

BIKE TECH

Executive Editor
Crispin Mount Miller

Editor
John Schubert

Editor-at-Large
John S. Allen

Contributing Editors
Frank Berto
Fred DeLong
Mario Emiliani
Richard Jow
Gary Klein
David Gordon Wilson

Chairman
Robert Rodale

President
Robert Teufel

Publisher
James C. McCullagh

Circulation Manager
Pat Griffith

Copy Editor
Kathy Fones

Art Director
John Lenaas

BIKE TECH (ISSN 0734-5992) is published bimonthly by Rodale Press, Inc., 33 E. Minor St., Emmaus, PA 18049. Subscription rates: $11.97 yearly, $14.97 Canada, $17.97 other foreign. Single copy $2. Inquire about bulk rates. Copyright ©1983 by Rodale Press, Inc. All rights reserved. POSTMASTER: Send address changes to *Bike Tech*, 33 E. Minor St., Emmaus, PA 18049. *Bike Tech* application to mail at second-class postage rates is pending at Emmaus, PA 18049. *Bike Tech* may not be reproduced in any form without the written permission of the publisher.

This results in a much stronger steel.

Thus it's no coincidence that high-quality frame tubes have the microstructures shown in Figures 1 and 2, since this carbide size and distribution provides the best combination of strength and ductility (Reynolds 753 is a special case, which I'll discuss shortly).

Figure 1: This is the type of microstructure top-of-the-line Ishiwata and Vitus tubings have, and is also the microstructure that plain low-carbon steels have. This microstructure consists of grains of iron (light areas), and carbide platelets embedded in iron (dark areas). Magnified 400 times.

Figure 2: This is the type of microstructure top-of-the-line Tange, Columbus, and Reynolds tubings have (except Reynolds 753). It consists of small spheres of carbides (dark dots) embedded in iron (light background). Notice how fine the dispersion of carbides is. There is no significant difference in mechanical behavior between this microstructure and the one shown in Figure 1 — they're just two different ways of making a strong and ductile steel. 400 times.

The strength of non-stainless steels increases with increasing carbon content, because more carbides are present to inhibit slip. But beyond about 0.8 percent carbon, the strength of steels levels off because the additional carbide adds no effective reinforcement to the iron. Moreover, there is so much brittle carbide present that the steel is no longer useful for many applications, especially bicycle frame tubes; and if these high-carbon steels are brazed beyond about 1400°F, conventional air cooling may make the steel even less ductile. Thus, steels used for frame tubes won't contain more than about 0.4% carbon.

Strained Bonds

Most high-quality steels used to make frame tubing also contain one or more of the following alloying elements: manganese, chromium, molybdenum, nickel, vanadium, and silicon. Table 1 lists the chemical compositions of several well-known brands of steel tubing. These elements help strengthen steels two ways: first, chromium, molybdenum, and vanadium combine with iron and carbon to form compounds called chromium carbides, molybdenum carbides, and vanadium carbides (though they contain iron as well). These carbides strengthen steel in the manner previously mentioned. Second, manganese, chromium, molybdenum, nickel, vanadium, and silicon strengthen steels because they have varying degrees of solubility in iron.

When an element such as chromium is added to steel, it assumes a position within the crystalline array of iron atoms (ignore for now that chromium also forms carbides). However, since a chromium atom is slightly larger than an iron atom, the ordered array of iron atoms is disrupted in the vicinity of the chromium atom. Figure 3a shows this situation: the shaded circle represents a chromium atom surrounded by iron atoms, while the lines between atoms represent atomic bonds. The bonds near the chromium atom are curved, which means they are strained (distorted) slightly. Strained atomic bonds increase the *internal energy*[3] of the crystal and make it harder to initiate slip. Thus the steel is a bit stronger. Similarly, a manganese atom is smaller than an iron atom, so it too strains the ordered array of iron atoms (Figure 3b). Thus, adding elements which are soluble in iron creates more obstacles, and makes the steel stronger.

The strength of steels can also be influenced by mechanical processing such as cold

[3] *Internal energy is the sum of kinetic and potential energies of all the atoms in a metal. The strength of most metals at room temperature depends primarily on their atoms' potential energy; so by convention the term "internal energy" is used in this context to refer to potential energy and not kinetic energy, whose effects complicate the issue. Potential energy of a crystal depends on the attractive and repulsive forces between atoms, and is increased by irregularities in the ordered array of atoms.*

working. This process is used extensively to shape steels at temperatures below about 1400°F. All high-quality frame tubes are cold-drawn at various times during fabrication. Large increases in strength are attainable because cold working produces large numbers of defects in each crystal (or grain) which raise its internal energy. (Defects are places in the grain where the ordered array is severely disrupted. Like other distorted bond patterns, they act as obstacles to slip.)

A final method used to influence the strength of steels is *heat treatment*. This is controlled heating and cooling of a steel to produce specific mechanical properties. Some heat treatments will strengthen steels by producing more obstacles (raising each crystal's internal energy), while other heat treatments will soften steels by reducing the number of obstacles (reducing each crystal's internal energy). If a heating operation remains at temperatures so low that no mechanical properties are altered, it isn't called a heat treatment. Heat treating is obviously central to a discussion of brazing temperature effects, so I'll discuss it in detail shortly.

The trick to strengthening steels, then, is to produce an optimum number, size, shape, and distribution of different types of slip obstacles by alloying, mechanical processing, and/or heat treatment.

Some of these techniques cost money; top-quality frame tubes are more expensive than lower-quality tubes (for example, AISI 1020 steel tubes) for several reasons. While steels like those listed in Table 1 don't contain large amounts of alloying elements, they do contain enough to increase the cost of the steel. Chromium and molybdenum are two alloying elements which are very costly because they are mined in foreign countries, demand for them is high, and they are getting scarcer every day.

Low-alloy steels (a designation which includes all bicycle tubing steels) are subjected to a series of heat treatments to produce a very fine dispersion of carbides. This requires more time and energy than would normally be spent on plain low-carbon steels.

Since high-quality frame tubing is usually very thin, extra care has to be taken to ensure that it has the proper before-brazing microstructure and very few imperfections. Thus the reduced safety factor caused by thinner tubes demands better quality control. These are just a few reasons why low-alloy frame tubes cost more.

Table 1: Chemical Compositions of Selected Frame Tubings

Brand	%carbon	%silicon	%manganese	%molybdenum	%chromium	%phosphorus	%sulfur	%other	AISI #
Columbus Record, KL, PL, SL, PS, SP	0.22-0.28	0.35 max.	0.50-0.80	0.15-0.25	0.80-1.10	0.035 max.	0.035 max.	—	4130
Ishiwata 015, 017, 019, 021, 022, 024	0.28-0.33	0.20-0.35	0.40-0.60	0.15-0.25	0.80-1.10	0.035 max.	0.04 max.	—	4130
Reynolds 753, 531SL, 531	0.23-0.29	0.15-0.35	1.25-1.45	0.15-0.25	—	0.045 max.	0.045 max.	—	—
Super Vitus 980 Vitus 181	0.22 max.	0.50 max.	1.50 max.	0.10 max.	0.15 max.	—	—	0.15 nickel	—
Tange Champion Pro, No. 1, No. 2, No. 3	0.30	0.23	0.49	0.16	0.84	0.014	0.003	—	4130

This information was compiled from the sales catalog of each manufacturer and from personal communications.

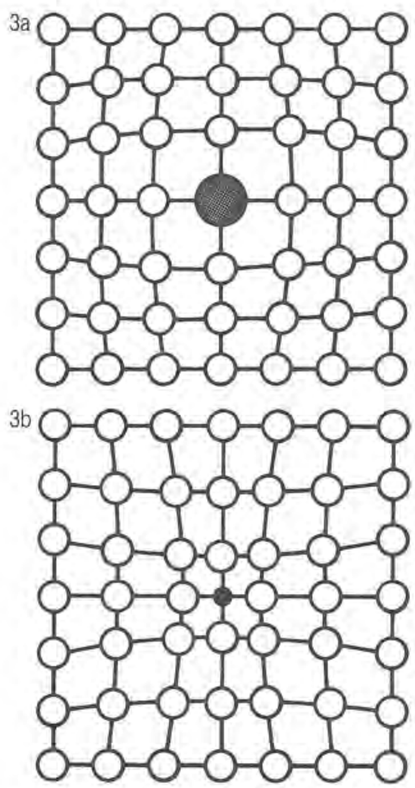


Figure 3: Adding elements which are capable of dissolving in iron at room temperature strains atomic bonds due to the difference in diameters of the atoms. This helps block slip. (From: Marc H. Richman, *An Introduction to the Science of Metals*, Ginn Custom Publishing, MA (1967), p. 303, by permission).

Heat Treatment

Brazing involves an input of heat which affects the base metals, and is therefore a heat treatment. The extent to which the base metals are affected depends upon the nature of the steel (i.e., alloying, prior heat treatments, amount of prior cold work, etc.), as well as on the brazing temperature, brazing time, and cooling rate.

The temperature at which steel frame tubes are brazed can be split into two groups: temperatures below about 1400°F, and temperatures above about 1400°F. The exact dividing temperature depends on the steel's chemical composition; the 1400°F value given here is for AISI 4130 steel, a steel used extensively for top-quality frame tubing (see Table 1). We'll assume that all high-quality frame tubes exhibit a similar threshold temperature. This isn't a bad approximation, since the chemical compositions of the steels listed in Table 1 are very similar to each other (if not exactly the same).

Brazing temperatures are divided into these two broad categories because vastly different things happen to steel in these temperature ranges. This difference will strongly influence the mechanical properties of the tube after brazing.

When the tubes listed in Table 1 are brazed below about 1400°F, they are exposed to a heat treatment which *tempers* the steel. Tempering is normally used to soften (i.e., weaken) steels which may be excessively strong and brittle for a particular application. However, tempering is also what happens when frame tubes are joined using a number of the silver brazing alloys listed in Table 1 of Part 2, (*Bike Tech,* October 1982).

High-quality frame tubes are alloy steels, whose microstructures are not stable, and have some degree of crystal deformation from cold working left in them before brazing. Thus these steels have a high internal energy, which they tend to reduce whenever they can. But they can't do it without some help, and what tempering does is provide this help:

Heating increases the vibration of atoms within the metal, so that atoms and crystal defects become mobile and diffuse through the crystal until they reach positions of lower energy. Specifically, carbon collects in larger and more widely separated carbide particles, while crystal defects link up and annihilate each other. This results in fewer obstacles to inhibit slip, so the metal becomes weaker and more ductile.

Heat treatments depend on both time and temperature, so if the temperature is increased, the tempering time can be reduced. For example, to achieve a certain hardness in a steel one could heat-treat at 1100°F for three hours or 1300°F for one hour. Increasing the temperature increases the diffusion rate, so the heat-treating time can be reduced.

Figure 4a

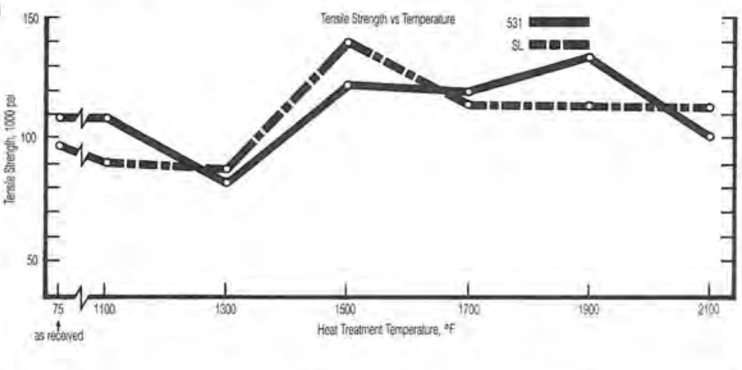


Figure 4b

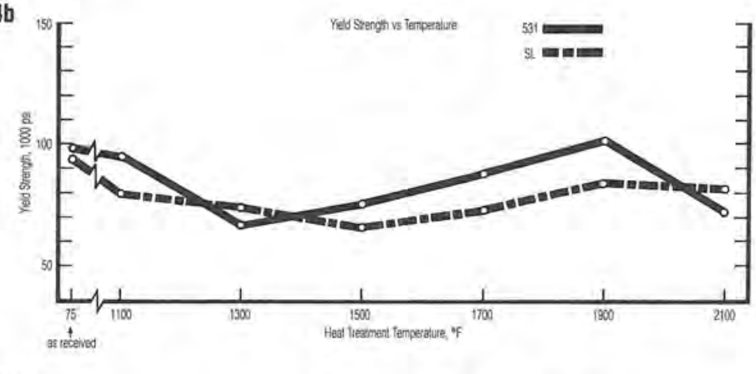


Figure 4c

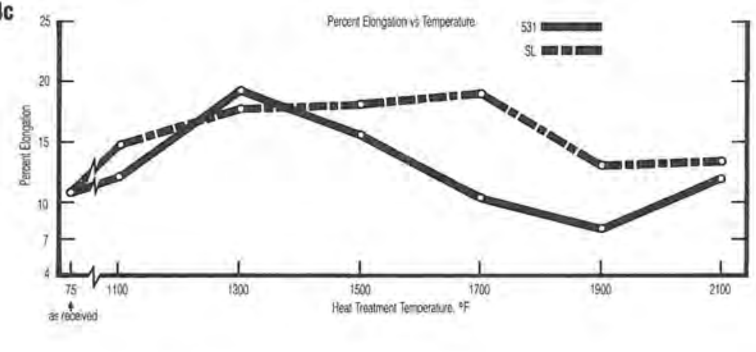


Figure 4: These curves, for a heat treatment time of five minutes, show what happens to the three basic mechanical properties of Reynolds 531 and Columbus SL tubing after tempering and normalizing heat treatments. Throughout the ranges of temperatures, the tubing remains strong and ductile.

Reynolds & Columbus

Figure 4 shows the result of an experiment performed to determine the effect of tempering temperatures on the tensile strength, yield strength, and ductility of Reynolds 531 and Columbus SL. For each curve the heat treatment time was five minutes, and the tube specimens were cooled in air by natural convection. The time of five minutes represents an average time to braze an average top tube/head tube joint.[4]

Figures 4a and 4b show a marked decrease in tensile and yield strength as the tempering temperature increases up to 1300°F. In addition, there is a large increase in ductility. Note that since tensile tests were performed on specimens heat-treated at certain temperatures only, the lines connecting the dots indicate general trends only; they shouldn't be used to interpolate mechanical properties for heat treatment at intermediate temperatures where tensile tests weren't performed.

A case in point is the Columbus SL line connecting the 1300°F and 1500°F data points. The maximum tempering temperature for Columbus SL is about 1400°F. So if a specimen were heat-treated at that temperature for five minutes, there would be a further drop in strength, and an increase in ductility, before a reversal of these trends at 1500°F. What happens to the tubes at temperatures beyond 1400°F will be discussed shortly.

As Figure 4 shows, the strength of the tubes drops, sometimes significantly. So the question arises, are the tubes strong enough after tempering, especially if brazing is performed at 1400°F for longer than five minutes? Certainly the strength of the tubes will be *comparatively* low, but experience has proved that this isn't a problem.

The cooling rate is often a very important factor in heat treatments. But when the heat treatment is a tempering one, the cooling rate isn't critical. A steel could be quenched in water without significantly affecting the temper. If the steel is slow-cooled, some further tempering will result. However, brazed frame joints should never be cooled faster than the rate attained by natural convection in air, even if faster quenching won't affect the temper much. The reason for this is that faster cooling creates stresses high enough to crack the filler metal, because the base and filler metals contract at different rates.

New Structure

When frame tubing is brazed beyond about 1400°F, something entirely different happens to the steel: the crystal structure of the iron begins to change. The new arrangement of iron atoms allows carbides to dissolve into

Table 2: Mechanical Properties of Selected Frame Tubings (Before Brazing)

Brand	Tensile Strength, lb/in²	Yield Strength, lb/in²	%Elongation	Recommended Brazing Temperature
Columbus Record, KL, PL, SL, PS, SP	121,000-135,000	107,000	10	1290°F max.
Ishiwata 015, 017, 019, 021, 022, 024	113,200	—	5	~1560°F
Reynolds 753	168,000	134,000	8	1200°F max.
Reynolds 531 SL, 531	112,000	100,800	10	~1560°F
Super Vitus 980 Vitus 181	121,000	99,500-107,000	10	~1560°F
Tange Champion Pro, No. 1, No. 2, No. 3	129,500	—	10	~1560°F

This information was compiled from the sales catalog of each manufacturer.

their component elements, iron and carbon, because the spaces between the iron atoms become larger, and carbon atoms can fit into them. As a result, single carbon atoms cease to be bonded with iron atoms as carbides, and become free to move through the crystal structure of the iron.

Between about 1400°F and 1510°F, the iron is a mixture of the two crystal structures; only part of it has changed. It only takes a small amount of the new crystal form to hold all of the carbon, though, so all the carbides can dissolve in this temperature range. However, the carbon can't distribute itself evenly yet, because the grains of iron that remain in the old form won't admit it.

Above 1510°F, all of the iron is arranged in the new crystal structure, and the carbon atoms can diffuse to become homogeneously distributed throughout the steel.

As in the case of tempering, this process is time- and temperature-dependent. Carbides won't dissolve right away; the amount of time it takes depends on how massive the metal is and on the temperature. Since bicycle frame tubing is very thin, the time to completely dissolve and disperse all carbides will be on the order of one or two minutes at 1600°F.

When the iron in steel is transformed, either partially (1400°F-1510°F) or completely (1510°F-2500°F), the cooling rate becomes a critical factor in determining the steel's strength.

When a steel above its transformation temperature (for instance, AISI 4130 heated to 1600°F) is cooled very slowly to 1500°F, some of the iron atoms begin to reposition themselves into their room-temperature arrangement. When the temperature reaches 1400°F and almost all the iron is back in room-temperature form, carbides must begin to form because carbon is practically insoluble in this structure. If the slow cooling continues, larger carbides grow by diffusion at the expense of smaller ones (which are less stable), until eventually the temperature becomes too low to permit further diffusion. The result is a steel which is very weak and ductile, because there aren't many obstacles against slip in it. This type of heat treatment is called *annealing.*

If a piece of AISI 4130 is held at 1600°F for a while, and then quickly cooled by tossing it into a bucket of cold water, a very strong steel results. At 1600°F, all the carbides are dissolved. When the steel is quenched in water, the iron atoms want to position themselves in their room temperature arrangement. But they are unable to do so because the carbon atoms are in the way; the cooling rate is so fast that the carbon atoms don't have time to diffuse out and form carbides. The steel so treated is extremely strong because its atoms are arranged in a state of very high strain (presenting many obstacles to interfere with slip). Such a heat treatment, called *hardening,* would probably be followed by tempering to restore ductility, but at the expense of some strength, by forming a small amount of carbide.

Table 2 shows that Reynolds 753 is considerably stronger than the other steels, but only slightly less ductile. That's because the manufacturers heat-treat the steel the following way: the tubing is heated to somewhere above 1400°F, then cooled very quickly to trap carbon atoms. At this point the steel is very strong and brittle, and can't be used for frame tubing. So the steel is tempered (probably in several steps) to form some carbides (i.e., heated to make the carbon atoms mobile, so that some diffuse out to form carbides), which puts less strain on the arrangement of iron atoms. Consequently the steel is weakened a bit, but some carbon atoms still remain trapped. This is what gives Reynolds 753 its high strength and good ductility, which enables the tubes to be much thinner than other bicycle tubes.

Annealing and hardening use two extremes of cooling rates, and produce two extremes of strength in a steel. Cooling rates between these two extremes will produce steels of intermediate strengths, because the cooling rate dictates the size, shape, and distribution of carbides (or the lack of carbide, if the steel is cooled quickly from above 1400°F).

One example of an intermediate cooling rate which can be quick enough to trap some carbon atoms is air cooling. When frame tubes are exposed to temperatures above about 1510°F and then cooled in air by natural convection, the heat treatment that has been performed is called a *normalizing* heat treatment.

This type of treatment is what occurs in the brazing of many bicycle frame joints. When tubes are brazed with brass, or with some of the higher-melting silver alloys, at least a portion of the iron will be transformed; and the usual way to cool frame joints is in air, by natural convection. This cooling rate is fast enough to produce tensile strengths greater than the tube's before-brazing values (see Table 2). Similarly, while the after-brazing yield strength of the tubes is generally lower than the before-brazing yield strength, it is greater than that achieved by tempering at lower brazing temperatures. Figures 4a and 4b show this to be the case. Figure 4c shows that the ductility generally decreases.

Note that the data points for each curve at the 2100°F heat treatment temperature reveal trends opposite to what I've just said. That's because at very high brazing temperatures, the grains of steel grow very large in short periods of time; and the larger the

[4] *See "Reynolds versus Columbus versus the Framebuilders Torch" by Mario Emiliani,* Bicycling, *September/October 1981, pp. 92-97.*

grain size, the weaker and more ductile the steel will be. So there is obviously a trade-off here: the higher the brazing temperature (beyond 1400°F), the less time it takes for the grains to grow to a size which negates any increase in strength that might be achieved from a normalizing heat treatment. In fact, when this happens, the heat treatment is no longer considered a normalizing heat treatment.

Figure 5 shows a common microstructure form when Reynolds 531 is brazed at 1700°F for five minutes, then cooled in the usual way. This microstructure represents a state of slightly higher internal energy than that shown in Figures 1 or 2, because the cooling rate was fast enough to cause additional strain in each grain. The mechanical properties which correspond to Figure 5 can be seen in Figures 4a, 4b, and 4c.

Something I haven't discussed yet is how tempering and normalizing heat treatments affect the fatigue and impact strength of the tubing (not the joint!). Figure 4 shows that no matter what the brazing temperature, the tubing remains strong and ductile. This fact,

Figure 5: Reynolds 531 brazed at 1700°F for five minutes and air-cooled. This microstructure represents a slightly stronger steel than that shown in either Figure 1 or 2, since air cooling is fast enough to trap some carbon atoms in the room temperature arrangement of iron atoms. Magnified 400 times.

with a few others too lengthy to explain, implies that the tubing will have adequate or more-than-adequate impact and fatigue strength to do the job. Experience taught framebuilders this a long time ago.

When I first published the information contained in Figure 4, however, some readers weren't convinced. As they pointed out, torch brazing creates a temperature gradient along the tubes: every temperature between room temperature and the brazing temperature is represented somewhere along the tube.

Temperature Gradients

The higher the brazing temperature, the farther back the tubes the gradient reaches. So if a high temperature brazing alloy like RBCuZn-A were used, one would expect the tubes to be tempered farther back than if BAg-1 were used. But this means that the tube will be weakened outside the lug, where it may not be thick enough to compensate for the loss of strength. Furthermore, is it possible to temper the tube beyond the butt, where the tube is even thinner? I looked into this problem, and came up with some interesting results.

Since I am not adept at brass-brazing lugged frame joints, I asked framebuilder Richard Sachs to braze a Reynolds 531 top tube/head tube joint[5] with a brass brazing alloy (1630°F liquidus), and another Reynolds 531 top tube/head tube joint with a silver brazing alloy (1145°F liquidus). To control the experiment, we used the same tube gauges, tube lengths, and lug styles in both joints. The ends of the tubes brazed into the lugs were the marked ends, i.e., the short butts.

To determine how far back the tubes had been tempered, I performed hardness tests along the length of the top tubes. One set of hardness indentations appears in Figure 6a, but actually at least three hardness tests were taken at each distance and averaged. A Rockwell digital hardness tester was used on the 30-T scale (30 kg major load, with a 1/16-inch steel ball indenter).

[5] *The tubes were supplied by SRC GROUP INC., Portland, Oregon.*

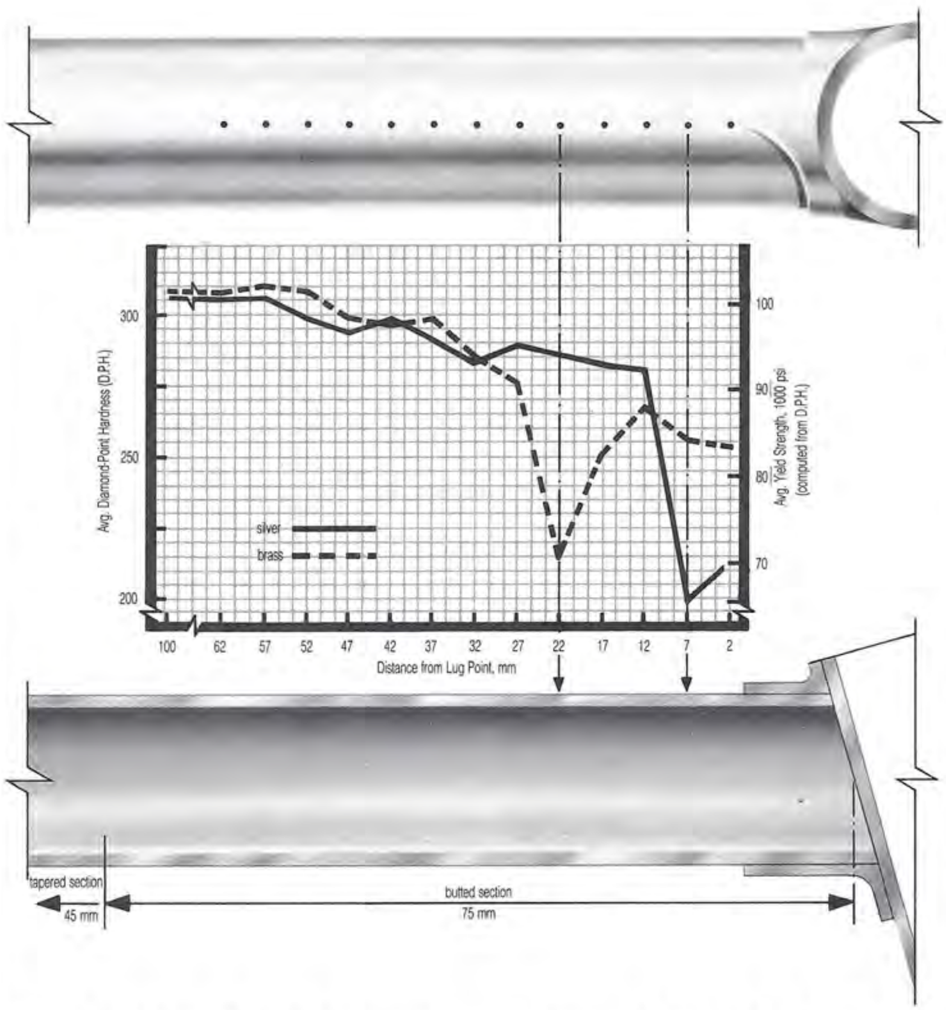


Figure 6: Test for the effect of temperature gradient on tube strength

a: Top view of the top tube/head tube joint showing one set of hardness indentations.

b: Results of the hardness tests: strength as a function of distance from the lug.

c: The top tube was tempered up to point A for the silver-brazed joint, and at point B for the brass-brazed joint. In both cases, the tubes were tempered well within the butted section.

The 30-T hardness values were then converted to diamond pyramid hardness (D.P.H.) values, so that the yield strength of the tube along the gradient could be determined using the equation

$$\text{yield strength in psi} = 395\ (\text{D.P.H.})\ (B)^n$$

where $B = 0.1$ and $n = 0.08$ for steel.[6] The results of the hardness tests are plotted in Figure 6b.

Figure 6b shows a drop in hardness about 22 millimeters beyond the lug point for the brass-brazed joint. It is at this point that the tube has been tempered. Similarly, the silver-brazed joint has been tempered up to at least seven millimeters beyond the lug point. So it is true that brass-brazing tempers the tube farther back than silver brazing (when silver brazing is performed below about 1400°F).

To determine whether the tempered zones were beyond the butt, I split the tubes in half and looked. They had a butted section 75 millimeters long, and a tapered section 45 millimeters long. Thus, as Figure 6c shows, the tempered zones were well within the butted section in both cases.

Is the tempering something to worry about? Probably not. Though the stresses a top tube undergoes aren't known, practical experience has shown that failures of properly brazed brass joints are very rare. However, under some loading conditions tempering beyond the lug could become a problem if the butted section were too thin. This would make brazing extremely light tubesets like Columbus KL, Ishiwata 015, Reynolds 753, and Tange Champion Pro beyond 1300°F a high-risk proposition. In fact, this is the only reason why TI Reynolds requires that Reynolds 753 be brazed with BAg-1a (it's surprising that they don't specify BAg-1 instead, since its liquidus is slightly lower and it's less expensive).

Table 3 shows values of yield strengths as determined by Figure 4c and by the hardness test data. As you can see, the data are in excellent agreement, with less than a five percent difference.

[6] *Cahoon, J.R., et al., Met. Trans., Vol. 2, July 1971, pp. 1979-1983.*

Table 3

	531 after Brazing at 1300°F for 5 Minutes	531 after Brazing at 1700°F for 5 Minutes	Silver-Brazed Joint 2mm from Lug Point	Brass-Brazed Joint 2mm from Lug Point
Average Yield Strength, $lb/in.^2$	66,670	87,370	69,980	84,683

Recommended Brazing Procedures

Tubing manufacturers provide framebuilders with instructions on how to braze their tubes. This information varies slightly among manufacturers, but it typically reads as follows:

1. Maintain joint clearances between about 0.002 and 0.005 inches.
2. Use a filler metal that melts at about 1560°F (see Table 2 for each manufacturers recommended brazing temperature).
3. Clean the tubes well.
4. Oxyacetylene torch-braze with a neutral flame.
5. Use a paste flux compatible with the filler and base metals.
6. Avoid overheating the filler metal.
7. Braze in a well ventilated area, but avoid drafts.
8. After brazing, cool in air by natural convection.

If the instructions aren't followed, and someone can prove it, the tube guarantee is no longer valid. Framebuilders normally pay close attention to these guidelines, with one notable exception: the brazing temperature.

Columbus wants their high-quality tubing to be brazed at temperatures no higher than 1292°F because they feel that higher temperatures (beyond 1400°F) will cause enough grain growth to weaken the frame significantly. As we all know, many framebuilders, especially the Italians, don't pay any attention to this advice. They regularly braze their Columbus frames with brass brazing alloys.

They have two reasons for this: one is simply to save money, and the other is that brass brazing results in about the same small number of failures as silver brazing. Thus, to many framebuilders it's just not worth the extra money to use silver brazing alloys. Furthermore, they've determined the results of Figure 4 by experience — that brass-brazed frames are strong and ductile — and that these frames last a long time.

It's interesting that Tange Champion tubing has the same chemical composition and microstructure (Figure 2) as the Columbus tubings listed in Table 1, yet Tange recommends using a filler metal that melts at about 1560°F. Apparently Tange isn't so concerned with the amount of grain growth that might occur at this temperature in the time it takes to braze frame joints.

Concluding Remarks

After reading these four articles, you've seen that there is much more to brazing than meets the eye. It's a very complicated subject which I hope I've been able to explain thoroughly and effectively. But despite brazing's complicated nature, it's a relatively simple operation to perform. All that's required to produce sound joints is a little common sense and some practice. I hope this series of articles has given you some insight into some of the lesser-known aspects of brazing, to help you produce more consistent joints.

But even if framebuilders understand everything I've included in this series and have decades of experience making frames, frame failures will still occur. This is simply the result of numerous factors which are unavoidable during brazing, such as voids. All it takes is one void in the right place to cause failure.

Frame failures can also be the result of many factors not related to brazing. For instance, the tubing could have the wrong microstructure or a large defect not picked up in quality checks, a lug may have a crack in it not visible to the framebuilder, there may be rust in the tubes, or maybe the framebuilder just had a bad day — it happens.

It's unfortunate that most consumers of high-quality frames have an inordinately high regard for framebuilders, because this has led to the perception that their frames should never fail. Then when a frame does fail, it's considered a very bad reflection on the framebuilder. Perhaps this reasoning is the result of the price people must pay for a good frame. After all, $400-$800 is a lot of money, so it's easy to see why people expect a frame to last 10, 20, or 30 years.

But the fact is that frames do fail, even ones constructed by the so-called "masters." I've spent a great deal of time trying to get failed frames from American builders to analyze, and have been successful only twice. Builders are very reluctant to give frames to me because they fear I'll publish their names with my results — which would be bad for business. Because these frames could teach us a lot, and because naming names serves no purpose — what happens to one framebuilder happens to many — the photos shown in this series don't reveal the framebuilder or manufacturer. No matter how skilled the framebuilder is, some very small percentage of frames will fail for one reason or another. This shouldn't result in a negative opinion of a competent framebuilder.

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

October 1983

Volume 2, Number 5 · $2.00

SPECIAL REPORT

"Heat-Treated" Rims — Are They Worth The Money?

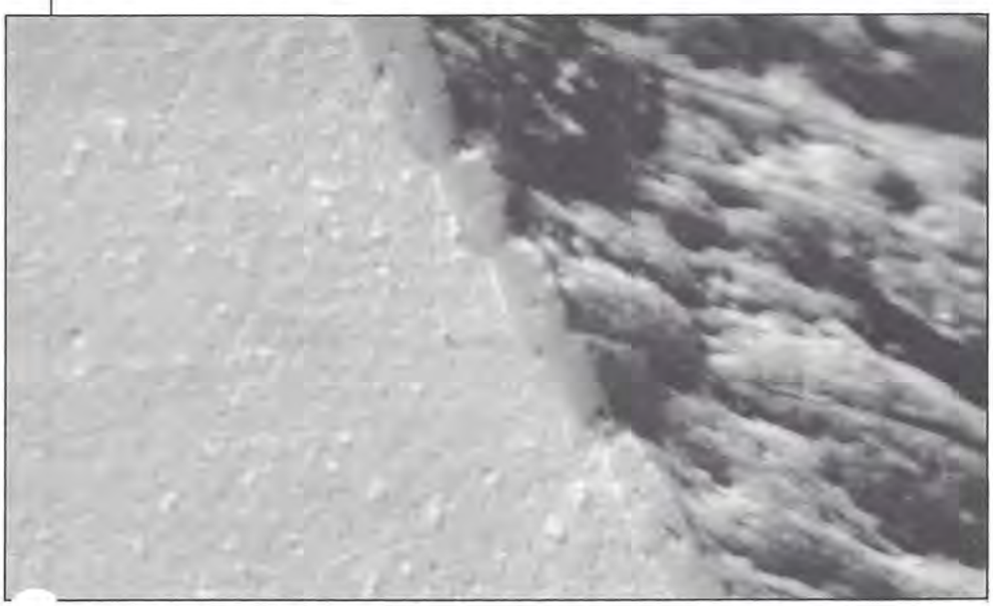
Mario Emiliani

In the early to mid-70s the fad in cycling was to minimize weight. Aluminum and titanium bolt kits replaced factory-equipped steel bolts, components were drilled out, frames were made from the lightest tubing, and wheels were as light as possible.

Recently, however, more emphasis has been placed on efficiency and durability. Frames have become heavier, home-drilled chainrings, seatposts, and brake levers are rarely seen, and the search for more durable wheels has seen the introduction of what are popularly called "heat-treated" rims.

These rims are much more expensive than ordinary rims, so I decided to find out why. What I discovered was that the so-called heat-treated rims I tested aren't heat treated, and they aren't much better than ordinary rims.

Rims, as we know, must endure a brutal environment. The constant pounding from bumps and potholes can lead to out-of-true wheels, flat spots, and dents. And the added weight that tourists carry can worsen the situation. Good wheels can be expensive and, even with regular maintenance, the rims can lead very short lives. Stronger rims are the sensible solution to more durable wheels.



A close look at a "heat-treated" rim reveals a hard-anodized layer over soft aluminum. 500 times magnification.

IN THIS ISSUE

FROM THE EDITOR

Changing of the Guard

This issue of *Bike Tech* is the last one in which Crispin Miller will have a direct managerial hand. Crispin is leaving us for the Massachusetts Institute of Technology — a place that's "like taking a drink from a fire hose," he tells us — where he will pursue an assortment of advanced degrees in mechanical engineering. Should the fire hose run dry, he'll reappear on these pages with the analytical articles which bear his distinctive style.

Replacing Crispin as executive editor is Doug Roosa, whom we plucked from a physics teaching job at Greenville Technical College in Greenville, South Carolina. Doug has also worked on the design of a high-temperature solar energy collector and storage device, on passive solar techniques, editing and production work of an annual 56-page astronomical calendar, and, oh, yes, seven years as moped and bicycle mechanic at the Great Escape bicycle shop in Greenville. We're glad to have found him.

Doug inherits a job which has come a long way in less than two years. Crispin has given *Bike Tech* a high level of credibility — typified, I think, by Shinpei Okajima's article in the August 1983 issue, in which he gave such a thorough presentation of Shimano's research and development in biomechanics, and by Mario Emiliani's article in this issue, in which rigorous chemical analysis dispels a lot of folklore about expensive aluminum rims.

Doug and I will be working hard to bring you more of the same. We hope you will find it as valuable as we do.

John Schubert

BIKE TECH

Executive Editor *Doug Roosa*
Editor *John Schubert*
Editor-at-Large *John S. Allen*
Contributing Editors *Fred DeLong*, *Mario Emiliani*, *Gary Klein*, *David Gordon Wilson*
Editor Emeritus *Crispin Mount Miller*
Chairman *Robert Rodale*
President *Robert Teufel*
Publisher *James C. McCullagh*
Circulation Manager *Pat Griffith*
Copy Editor/Proofreader Patricia Peltekos
Art Director *John Lenaas*

BIKE TECH (ISSN 0734-5992) is published bimonthly by Rodale Press, Inc., 33 E. Minor St., Emmaus, PA 18049. Subscription rates: $11.97 yearly, $14.97 Canada, $17.97 other foreign. Single $2. Inquire about bulk rates. Copyright ©1983 by Rodale Press, Inc. All rights reserved. POSTMASTER: Send address changes to *Bike Tech*, 33 E. Minor St., Emmaus, PA 18049. *Bike Tech* application to mail at second-class postage rates is pending at Emmaus, PA 18049. *Bike Tech* may not be reproduced in any form without the written permission of the publisher.

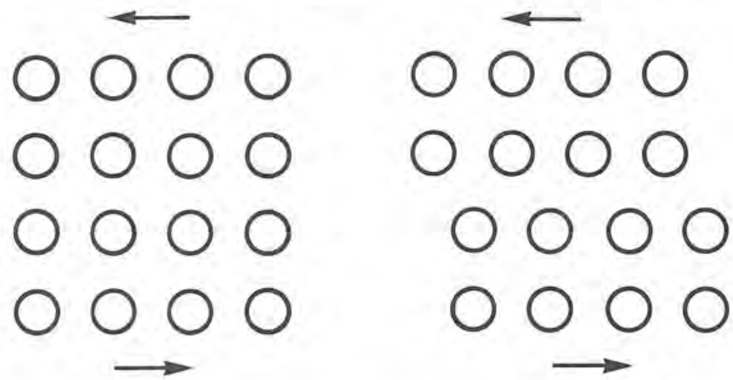


Figure 1: When sufficient stress is applied to a metal, rows of atoms slide past each other. If slip can be interfered with, the metal will be stronger.

In 1978 Mavic introduced their Special Service des Courses (SSC) rim to the European racing circuit. It was used by professional teams on some extremely rough courses with excellent results. Everyone praised the rim, which somehow became referred to as "heat-treated."

The rim was quickly copied by other European rim manufacturers — so was the price. Everyone I've talked to who rides "heat-treated" rims loves them. They say the rims don't dent easily and rarely need truing. Some won't ride anything else.

While these rims appear to be very good, is their increased performance worth their high price? And is their better performance due to heat treatment(s)? The latter question is very important because it is the basis upon which these rims are bought.

To determine whether "heat-treated" rims are really heat treated (as many are advertised to be by importers and bike shops) I hardness tested four rim samples and had them analyzed for chemical composition. The "heat-treated" rims in these tests were a Mavic SSC, a Nisi Ekip, and an Ambrosio Synthesis. A Fiamme Red Label was also tested; it was used as a standard for comparison. Table 1 lists the weights and retail prices of these rims. The SSC and Ekip were chosen because they are the most expensive regular cross section (non-aero) tubular rims. The Synthesis was chosen because it is more modestly priced, and the Red Label because it is an inexpensive ordinary rim. Additionally, these rims were selected because they are popular and highly regarded. The Ekip and Red Label rims tested were new, while the Synthesis and SSC had been ridden.

Heat Treating

Heat treating is a metallurgical term used to describe controlled heating and cooling of a metal for specific periods of time to obtain certain mechanical properties.[1] Thus, heat treatments can be used to strengthen or weaken a metal depending on the desired mechanical properties. Metallurgists normally apply the term "heat treatable" only to those aluminum alloys which can be strengthened by heat treatments.[2]

Whether or not an aluminum alloy is heat treatable depends upon its chemical composition. Of the seven aluminum alloy series from which rims can be made, only three are heat treatable for increased strength. These grades are aluminum-copper (2XXX)[3], aluminum-magnesium-silicon (6XXX), and aluminum-zinc (7XXX).

Table 1

	Weight Per Rim, grams	Retail Price, per pair
Mavic SSC	395	$196
Nisi Ekip	410	$133
Ambrosio Synthesis	410	$65
Fiamme Red Label	360	$25

Metals are made up of many crystals called grains, and each grain consists of a three-dimensional array of atoms. The atoms are arranged in a specific order which varies depending upon the type of metal. When sufficient stress is applied to a metal, a few rows of atoms slide past each other. This microscopic movement is known as *slip*. Figure 1 illustrates this situation.

If even greater stress is applied, more rows of atoms will slip past each other causing the metal to *yield;* that is, the metal un-

[1] *Mechanical properties are measures of a material's response when stressed.*
[2] Metals Handbook, *Vol. 2, 9th Ed., 1979, p.28.*
[3] *The first digit indicates the alloys series (e.g., aluminum-copper, etc.), the second digit indicates the degree to which impurities were controlled, and the third and fourth digits identify the different alloys in the series.*

dergoes a noticeable amount of permanent deformation.

To inhibit yielding, pure metals can be alloyed with one or more elements to produce a visibly distinct compound, or second phase, within the metal (see Figure 2a). A proper arrangement of second-phase particles within the base metal impedes the slip. This results in a stronger metal. The optimum size, shape, and distribution of second phase particles is controlled by heat treating.

To illustrate how heat-treatable aluminum alloys are strengthened, take the case of aluminum alloyed with 4 percent copper. Proper heat treatment produced an even distribution of zones where aluminum atoms have been replaced by copper atoms. These zones typically consist of 10 to 50 copper atoms. Since copper atoms are smaller than aluminum atoms, the bonds holding these atoms together are highly strained. This results in a stronger metal because it's more difficult to initiate slip through a region of strained atomic bonds. Figure 2b shows how heat-treatable aluminum alloys are strengthened by the strain between atomic bonds.

To strengthen a heat-treatable grade of aluminum, it must first be heated to a temperature high enough (~950°F) to dissolve the second phase. Fast cooling of the metal (by immersion into water, for example) traps the second-phase atoms within the aluminum matrix. If you were to look at the aluminum under a microscope at this point you'd see only grains of aluminum because the second-phase atoms have been dispersed into the aluminum matrix. In this form, the aluminum is not much stronger (i.e., not much more slip resistant) than pure aluminum, but this atomic arrangement is not stable, and if the newly quenched alloy is left at room temperature for a few weeks, the second-phase atoms will migrate and group into small particles. As this microscopic dispersion progresses, the aluminum gains strength.

Second Phase

The process of forming small zones of second-phase atoms after cooling from high temperatures is known as *aging*. Aluminum is a peculiar metal in that room temperature provides enough thermal energy for atoms to move about. Most other metals possessing unstable structures can be left at room temperature for thousands of years without any change in properties. Aging at room temperature is called *natural aging*.

If the aluminum is aged at higher temperatures (~350°F), it will reach full strength in shorter time. This is called *artificial aging*.

Tests must be performed to determine the times and temperatures required to produce *peak aging* (maximum strength) for the various heat-treatable aluminum alloys, because improper heat treatment will result in either *overaging* or *underaging*. Improper aging results in less-than-maximum strength because bonds between the aluminum and

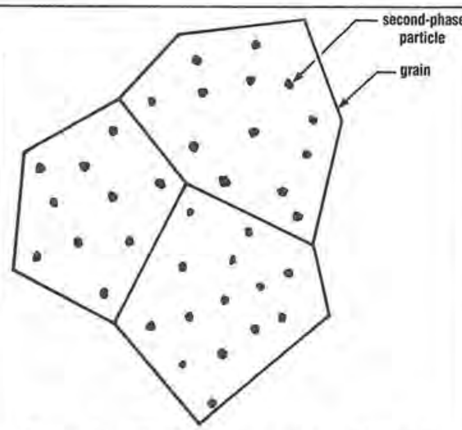


Figure 2a: Alloying pure metals with small amounts of other metals can produce a visibly distinct compound called the second phase. When viewed under a microscope at low magnification, second-phase particles can appear as spheres embedded within grains of the pure metal.

second-phase atoms are not as highly strained.

Now let's make some general observations on what heat-treated rims might be, and what they really are. When something is made stronger, its thickness can be decreased to save weight. This is an engineering rule of thumb. Saving weight on wheels is a smart thing to do because it's much easier to accelerate and maintain speed with lighter wheels. So one might expect that a benefit to be gained from genuine heat-treated rims would be less weight and better performance compared to heavier non-heat-treated rims.

The Mavic SSC, Nisi Ekip, and Ambrosio Synthesis, three of the most expensive "heat-treated" rims, each weigh approximately 400 grams. The Fiamme Red Label, a rim known for its durability, weighs only 360 grams. Four-hundred-gram rims are going to be durable whether they're heat treated or not. Odd, isn't it, that in this top-of-the-line selection of "heat-treated" rims, none are even as light as an ordinary Fiamme Red Label!

Anodizing

Perhaps to distinguish it from all other rims at the time of its introduction, the Mavic SSC was *anodized* dark gray. Anodizing is simply controlled corrosion of a metal. A thick oxide film is grown by placing the rim in an electrically conducting liquid (called the electrolyte) maintained at a certain temperature (~70°F), and imparting a specific amount of current (called the current density) on the rim. Depending on the conducting liquid, its temperature, and the current density, the oxide layer can appear silvery or various shades of blue, bronze, or gray. The oxide layer formed is porous and must be

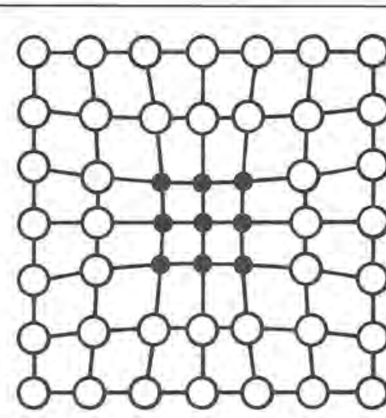


Figure 2b: Representation of strained atomic bonds created when a second-phase particle forms in the base metal.

sealed to preserve the finish. One way of doing this is to place the rim in boiling water for 15 to 30 minutes. Silvery oxide layers can be dyed various colors by placing them in dye baths prior to sealing.

The oxide film formed by anodizing differs from many other oxides in that it adheres well to its aluminum substrate—unlike rust (iron oxide) which flakes off easily. If the anodized layer is grown and sealed properly, it's highly resistant to corrosion. For example, most inexpensive aluminum rims aren't anodized and require periodic polishing to maintain an attractive appearance. Thus, rims are anodized for improved corrosion resistance, improved surface finish, and to provide a distinctive appearance.

Most so-called heat-treated rims have a special "hard-anodized" surface. This anodizing process differs from ordinary anodizing in that the temperature of the electrolyte is lower (~40°F), and the current density is higher. This process can add an extra $10 to $20 to the price of each rim because of the extra energy and handling costs, but it produces a much thicker and harder oxide layer. The extra expense for a colored rim that doesn't need polishing is worthwhile in the eyes of many riders.

Figures 3a to 3d are scanning electron micrographs of the rims tested showing the thickness of their oxide layers. The Red Label rim, Figure 3d, is not anodized, but it has a very thin oxide layer (not visible) formed naturally by exposure to oxygen in the air.

Misinformed

Since Mavic SSC rims are dark anodized and supposedly heat treated, many consumers have the false notion that all dark anodized rims are heat treated. This association is further strengthened when the rim is scored with a file to provide a rougher surface for tubular tire glue to adhere to. In doing this, it's impossible not to notice that these rims are more difficult to file than ordinary rims.

But it's assumed these rims are harder to file due to heat treatment. Well, the rim is harder not because it has been heat treated, but because it has been hard anodized. The oxide layer formed by hard anodizing is harder and more brittle than the aluminum from which it was grown because atoms in the oxide layer are bonded differently. If you get past the oxide layer, you'll find that the aluminum files as easily as in ordinary rims.

The manufacturers of "heat-treated" rims have engaged in a bit of creative marketing by simply not explaining their product. They make no claims, in print, that their rims are heat treated. Rather, some use buzz words which can sound like their rims have been heat treated. "Durex," used by Ambrosio, is a good example, which sounds like "more durable" or "harder." However, something of a disclaimer is also on the Durex decal. It says, in small letters, in Italian, "machio depositato allumag monocellulars." Translation: Durex is our trademark for aluminum anodizing.

So the job of informing consumers is left to salespersons who get their information from importers who get their information from company reps talking in heavily accented English.

Hardness Tests

The hardness of a metal is related to its strength; the harder the metal, the stronger it is. If the SSC, Ekip, or Synthesis were heat treated for added strength, they would be harder than the Red Label rim. To investigate this assertion, I first removed the oxide layer from all the rims by sanding from 240-600 grit. I then performed hardness tests on a Wilson Digital Hardness Tester using the 30-T scale (30 kilograms major load with a 1/16-inch diameter steel ball indenter). The 30-T hardness data was converted to Diamond Pyramid Hardness (DPH) so the yield strength of the rims could be calculated using the equation

$$\text{yield strength (in psi)} = 377\ (\text{DPH})\ (B^n)$$

where B = 0.1 and n = 0.06 for aluminum.[4] The results are given in Table 2.

Table 2

	Average Rockwell 30-T Hardness	DPH	Yield Strength, psi
3004, fully annealed	~5	~30	10,000
Mavic SSC	58.2	111	36,450
Nisi Ekip	42.5	81	26,600
Ambrosio Synthesis	45.5	86	28,240
Fiamme Red Label	49.0	92	30,210

From the hardness numbers and corresponding values of yield strength, it's obvious that the Ekip and Synthesis rims could not have been heat treated for increased strength. It is possible, though, that they were subjected to improper heat treating (i.e., over- or underaging). The SSC is significantly stronger than the other rims, but is this due to heat treating? To clarify this situation it is necessary to examine the chemical composition of these rims to determine if they are even heat treatable.

Chemical Composition

Samples of all the rims were sent to a company specializing in metallurgical testing to determine their chemical compositions.[5] The results are given in Table 3.

As mentioned earlier, the heat-treatable grades of aluminum are the 2XXX, 6XXX, 7XXX series. However, all rims tested were made from an aluminum-manganese alloy (type 3004). These alloys can't be heat treated! Since these rims aren't heat treated, they will herein be referred to as "hard-anodized" rims.

The yield strength of the Ekip, Synthesis, and Red Label are all approximately equal, but the SSC is significantly stronger. This discrepancy can't be due to heat treatment, since the 3XXX series of aluminum alloys can't be strengthened this way. If the chemical composition of the SSC varied greatly from the other rims, then that might account for some of the difference. But as Table 3 shows, there is little difference between the SSC and the others. Some other factor must be responsible for the SSC's superior strength.

Cold Working

Cold working is a very effective method of strengthening metals. For example, take a spoke and bend it 45°. Then get a good grip and try to bend it the opposite way. You'll notice that the spoke bends in a different place.

Cold working is simply permanent deformation of a metal at temperatures below

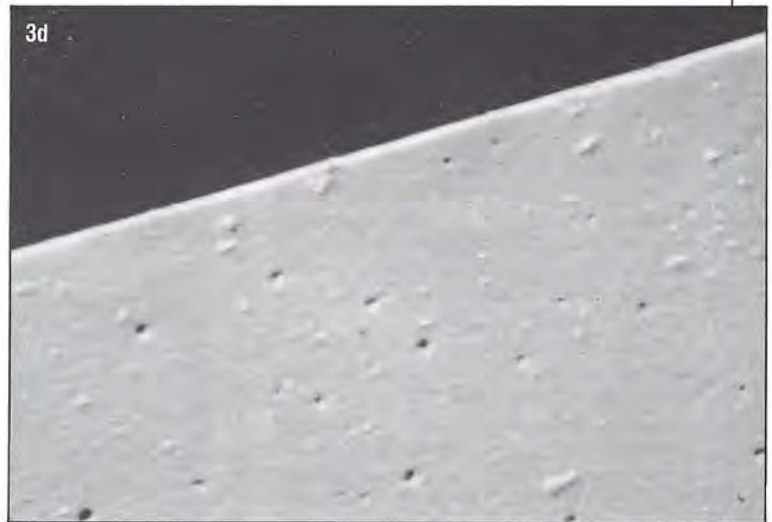


Figure 3: The hard-anodized layers of the SSC (3a), Ekip (3b), and Synthesis (3c) are 0.014-0.026-millimeter thick. The Red Label rim (3d) is not anodized. 500 times magnification.

about one-half its melting point. The spoke has been cold worked when it is bent to the point where it takes a permanent set. The principle by which metals are strengthened when cold worked is the same as that for heat-treatable aluminum alloys — millions of regions are created where atomic bonds are strained.

Cold working distorts the grains of a metal, so it's apparent (after special preparation) when a metal has been cold worked. Figure 4 is a schematic diagram showing what grains look like before and after cold work. The SSC rim tested had elongated grains indicative of a large amount of cold work (see Figure 3a). Thus, the large difference in strength between the SSC and the other rims is due to cold working.

While cold working can increase the strength of a rim, there is a simultaneous loss in ductility (the ability of a metal to deform permanently without breaking — a desirable property for wheel rims). Thus, once a rim is near its final shape, it may be helpful to remove some or all of the strengthening effects of cold working to make it more durable. This is done by heating the rim to about 500°F for a period of time — a process known as *annealing*. After annealing, the grains of the metal appear less distorted. The range of yield strengths given in Table 2 show that each manufacturer has a slightly different way of making rims. Some cold work more and anneal less, while others do the opposite.

[4] *Cahoon, J.R., et al.,* Met. Trans., *Vol. 2, July 1971, pp. 1979-1983.*

[5] *Consulting Chemists of Florida, Inc. Tampa, FL. Testing was done in conformance with National Bureau of Standards.*

Stress Raisers

Whenever a load-bearing structure is designed it is important to distribute stresses evenly. Thus, care is taken to minimize the presence of discontinuities called *stress raisers*. Stress raisers are produced by irregularities such as file marks, machining marks, keyways, cracks, etc., and should be avoided because they can raise the local stress to well beyond the yield strength of the metal. When this happens small cracks develop. Repeated application of the load causes the cracks to grow until the part fails. This type of failure is called *fatigue failure*.

In addition to showing the thickness of the oxide layer, Figure 3b also shows its surface appearance. Notice how irregular it is.

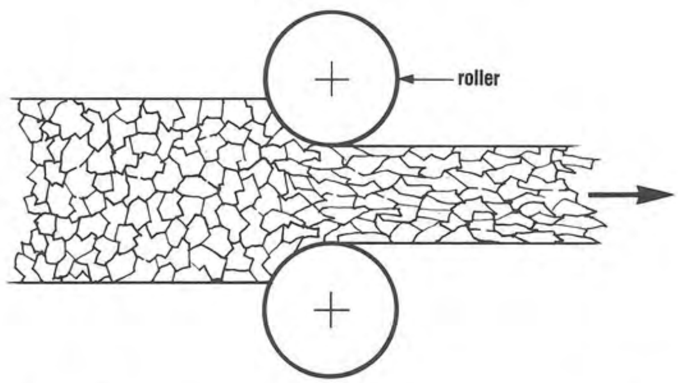


Figure 4: The grains of a metal devoid of cold work will be approximately the same size in all three dimensions. It's obvious when a metal has been cold worked because its grains are elongated.

Table 3 Chemical Composition, %

	Manganese	Magnesium	Iron	Copper	Silicon	Zinc	Aluminum	Alloy Type
Mavic SSC	1.22	0.98	0.51	0.18	0.17	0.10	balance	3004
Nisi Ekip	1.28	1.10	0.48	0.23	0.26	0.17	balance	3004
Ambrosio Synthesis	1.30	1.09	0.53	0.21	0.26	0.13	balance	3004
Fiamme Red Label	1.26	1.15	0.54	0.21	0.23	0.14	balance	3004

There are numerous pits which can act as stress raisers. If the applied stress is high enough (due to rider weight, spoke tension, road conditions, etc.), cracks can initiate and propagate into the aluminum causing rim failure.

The highest stress on a rim is going to be at the spoke holes. Since the mechanical properties of the hard-anodized layer differ from the aluminum, it will stretch at a different rate when the rim is stressed in tension. This can crack the oxide layer thereby forming stress raisers.

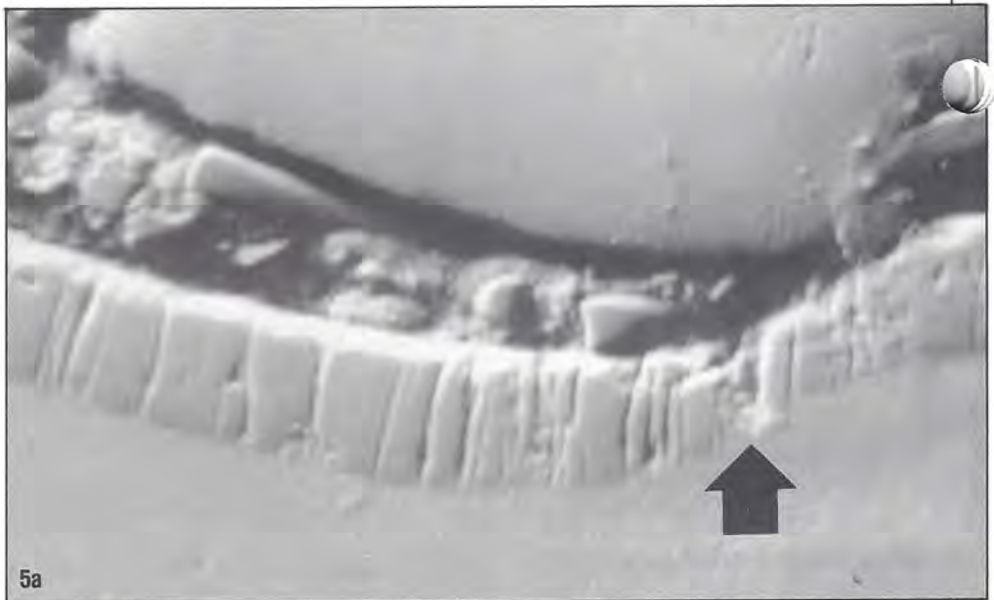
I took a look at cross sections of the SSC and Synthesis rims (the ones which had been ridden) at the spoke holes to see if there were any cracks in the oxide layer and/or aluminum. I did not find any cracks in the aluminum, and the only cracks in the oxide layer were beneath the ferrule where it contacted the rim. These cracks were formed when the ferrule was attached to the rim. Figure 5a shows the cracked oxide layer, while Figures 5b and 5c show its location on the rim.

Thus, there is the potential for failure of hard-anodized rims because of the brittle oxide coating. Ordinary anodizing produces a softer and thinner oxide layer which should not act to instigate cracking (although ordinarily anodized rims have been known to fail in this same manner). I've heard of many failures of hard-anodized rims, but have not been able to examine any to determine the role of the oxide layer. Clearly this aspect needs further investigation because wheel failure at any speed can cause serious injury.

Conclusion

Most rims are manufactured in such a way that they receive a large amount of cold working and therefore must be annealed. So technically, the term "heat treated" could be applied to the rims I tested. But the aluminum industry normally applies this term only to aluminum alloys that can be strengthened by heat treatment(s) and, clearly, the Mavic SSC, Nisi Ekip, and Ambrosio Synthesis are not made from these alloys. While the manufacturers have not made any false claims, neither have they stepped forward to erase the misconception held by importers, salespersons, and consumers that these rims are stronger because of heat treatment. Whether this deception is intentional or not, I cannot say; but I wonder what other justification the manufacturers have for the high prices they charge for their rims.

All these rims perform well. The manufacturers have been in the business a long time and know how to make a strong and durable rim. But these rims are strong and durable for the same reasons that the Fiamme Red Label is—they are cold worked and annealed, and they are heavy. They differ from ordinary rims only in that they are hard anodized. While this surface finish is attractive, evidence suggests that if it cracks, it may in-



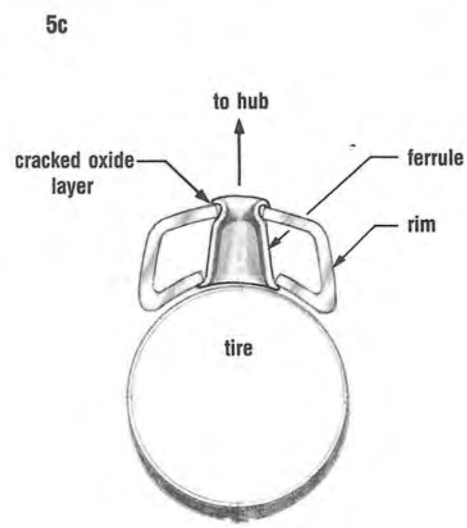


Figure 5: A cross section of the Synthesis rim at the spoke hole showed the oxide layer was cracked where the ferrule contacted the rim (Figure 5a, 500 times magnification). The cracked oxide layer is arrowed in Figure 5b (50 times magnification). Figure 5c is a schematic diagram showing the cross section investigated.

stigate rim failure. This seems a high price to pay for pretty rims.

As an afterthought, I obtained a Mavic GP-4 hard-anodized rim ($58/pair) to see how its hardness compared to the Mavic SSC. Surprisingly, the GP-4 is as hard as the SSC. So, the only difference I can find between these rims is the color of the anodized layer and the decals.

Matrix Rims Are Heat Treated

To my knowledge no European or Japanese rims, hard anodized or otherwise, are heat treated. However, Tru-America Corporation of Marshall, Wisconsin, does make actual heat-treated rims called Matrix™ rims. Three different types of clincher rims are currently available. These rims are made from aluminum alloy 6063 heat treated to a yield strength of 31,000 psi, which is a little stronger than a Fiamme Red Label. Their ductility is better than a Mavic SSC. The cost of these rims is competitive with ordinary clincher rims.

Tubular Matrix™ rims will soon be available. Current prototypes are made with the same 6063, and their price will be competitive.

But if the strength of these rims is going to be comparable to a Red Label, then what is the advantage of heat treating? For similar strengths a heat-treated rim will be more ductile than an ordinary rim. This is a desirable property, because if you hit a pothole you'd rather have the rim dent instead of break. But the significance of ductility is overstated here, because most ordinary rims are only a few percentage points less ductile than heat-treated rims, and ordinary rims perform very well.

Something is amiss here. If the strength and ductility of ordinary rims and heat-treated rims remain comparable, then the reason to heat treat any rim remains in question. Surely, the idea of reducing rim weight while maintaining strength and durability cannot be realized.

There are, however, other aluminum alloys that can be used to make rims. Alloy 6070 is a good example. It has good workability, it can be heat treated to a yield strength of 51,000 psi, and its ductility at this strength is better than that of most ordinary rims. Rims made of this alloy could certainly be lighter and still be as strong as the rims available today.

Mario Emiliani

I would like to thank the following companies for supplying the rims used in this article: Bicycle Parts Pacific; Lee Katz and Co., Inc.; SRC Group, Inc.; and Wheelsmith Fabrications, Inc. Special thanks to Eric Hjertberg of Wheelsmith for his valuable insight into the rim business.

INVENTIONS

The Bent Crank: Chronology of an Idea

Harvey Sachs

Each year, the bicycle industry produces dramatic and radical advances in technology. One of the most startling of these was the P.M.P. "bent" crank, which outdid even the Gear-Tel for originality. Harvey Sachs, best known for his active leadership in East Coast tandem events, predicts what the future holds for P.M.P. in the following special report:

1981: P.M.P., a small Italian firm, bursts on the scene with the revolutionary "bent" crank, featuring a 90-degree bend in the crankarm. The "L-shaped design increases the pedal's propulsion power and lessens energy dispersion on the downstroke," according to the manufacturer's literature.

1981: The British magazine *Cycling* issues a set of P.M.P. cranks to an unnamed first category Surrey roadman for road testing. "Whatever the theories, in practice our roadman tester felt the P.M.P. cranks offered an advantage — and surely that is the true criterion," *Cycling* reported. The roadman himself said, "At low pedaling speeds, dead center seemed to be removed."

1982: P.M.P. cranks are the talk of the New York trade show. Not many orders, but lots of talk . . .

Editor's note: from here, author Sach's chronology dissolves from well-documented factual reporting to crystal-ball speculation.

1983: Polish Olympic team purchases 20 pairs (mostly 205-millimeter, equivalent to 170-millimeter "old-style" cranks).

1983: Soviet Olympic team commissions study by East German Sports Academy to determine extent of functional advantage of new bent cranks. To cover bets, Soviet applied mathematician carries out extensive analysis (256 pp of equations) to optimize shape.

1984: Miyata introduces Shimano BX aerodynamic bent cranks with concave pedals to match. Availability is restricted, and interest is intense.

1984: U.S. Olympic team fails to find sponsor for additional cost of either Shimano or P.M.P. cranks; enters Olympics feeling very discouraged.

1984: Polish national team uses P.M.P. cranks only for climbing stages, relying on the Surrey Roadman's report that they "helped me keep a steady rhythm particularly when sitting back in the saddle and climbing hills."

The P.M.P. crankarm has no moving parts — just a longer piece of metal "to allow greater ease on the upstroke."

1985: Bikecology, Lickton's, and Bike Nashbar introduce the components to American amateurs — at $178, plus rings. Delivery time, 6-8 months.

1985: Richard Jow gives equivocal evaluation in *Bicycling* — but uses nice test jig.

1986: Huret joins forces with Maillard to introduce patented recurved (S-shaped) crank for track bikes. Claimed to give equally significant advantage when sprinting or standing. Helicomatic design gives rapid disassembly with a single lightweight wrench (supplied), and recurved design makes it easy to convince the user that the arms are really 180 degrees out of phase.

1988: Polish Olympic team uses straight hollow titanium cranks. Soviet team, on basis of 256 pp. analysis, bolstered by information from East German Sports Institute, introduces the CCCP bent crank — bent to the left instead of the right, of course.

1989: Bikecology sells their only three pairs at warehouse sale for $37 per pair. Bike Nashbar offers remaining three (right only, 43/54, 205 millimeter, Italian thread) for $78.

1992: USCF's famed Elite Athlete Program completes study on the most efficient pedaling motion in the history of cycling; concludes that P.M.P. cranks are the way to go. Purchases the last available P.M.P. cranks at collectors' item prices (rumored to be $500+ per set). Technical Director Ed Burke is ecstatic. Other equipment sponsors (Campagnolo, SunTour, etc.) are perturbed by large cash outlay.

2013: MIT engineering professor finds P.M.P. crank in back room of The Bicycle Exchange, and carries out strain tests to see if it really did make a difference.

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

December 1983 Volume 2, Number 6 $2.00

TEST RESULTS

The Roval Wheel: How Much Faster?

Pierre Hugaud

This article originally appeared in the French cycling journal Le Cycle, *of which Pierre Hugaud is the editor. Michel Belly, a Canadian framebuilder, translated the article into English and relayed it to* Bike Tech.

When the Paris Cycle Show convened in 1977, aerodynamics was not yet a bicycling buzzword. Shimano's aerodynamic components and the oval tubing of Tange and Reynolds were still ideas on the drafting board. At this show, a precursory aerodynamic design made its debut: Claude LeHanneur, a French engineer, introduced the Roval aerodynamic wheel. Significantly different from a standard wheel, the Roval has a contoured hub, a narrow, deep-section rim radially spoked together with oval spokes, and nipples recessed into the rim (See Figure 1). By departing from the traditional lacing patterns and paying close attention to the cross sectional profiles of the wheel's components, LeHanneur succeeded in designing a more aerodynamically efficient wheel.

Changing Speeds

An analysis of a rolling bicycle wheel's aerodynamics is complex because the wheel is both spinning in the air and moving through it. Also, each part of the wheel has a different drag coefficient, and the velocities of all points on the wheel are constantly changing with respect to the ground, or the still air.

If a bicycle is cruising at 30 km/h, then its

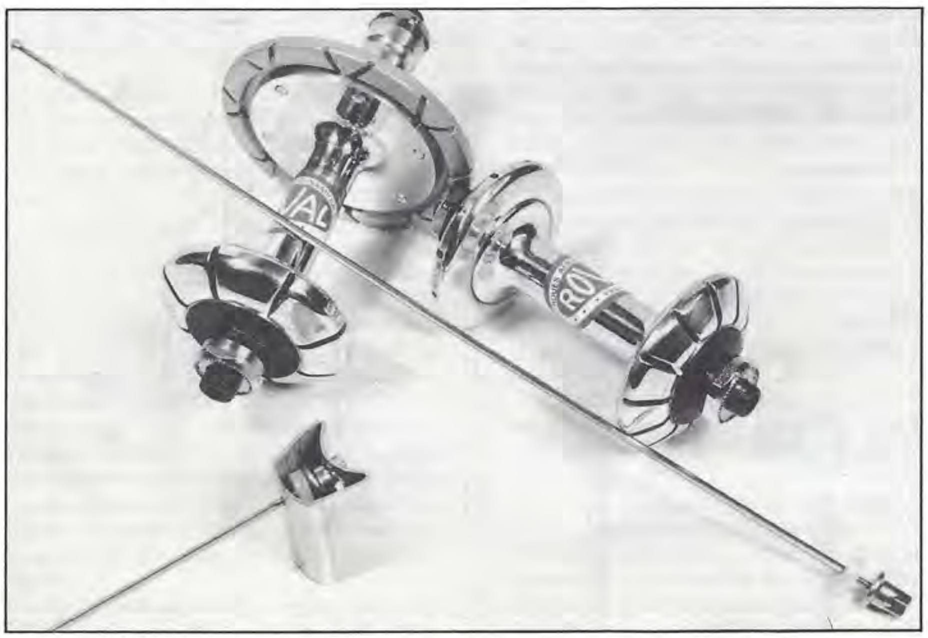


Figure 1: Main components of a Roval wheel.

IN THIS ISSUE

Can Surface Finish Affect the Performance of Your Frames?

Mario Emiliani

This is Part 1 in a series of new articles exploring how different surface finishes can affect the performance of bicycle frames.

The surface finish on a bicycle frame is necessary both for durability and aesthetics. A good paint job protects the steel tubing from rust and enhances a frame's looks.

But the application of paint is the final touch in the frame's production. What's underneath the paint really determines how well and how long a frame's finish will last. It's very important that the framebuilder prepare the surface properly before applying the paint.

Unfortunately, one of the traditional methods of surface preparation—particle blasting—can actually degrade the frame's structural integrity by removing metal from the tube surfaces and/or initiating microscopic stress raisers that can generate cracks in the tubes. So we have the unhappy situation where in an effort to finish a frame for durability, the builder may actually shorten its life and compromise its performance by the most widespread of finishing techniques—particle blasting.

Surface Finish of Tubes

Steel tubes, as supplied to custom framebuilders and manufacturers, appear to be quite smooth. But a closer look will show numerous surface irregularities formed during fabrication. Figures 1a and 1b show the surface finish of Vitus 181 and Reynolds 531 tubings. The Vitus 181 has a grooved surface which is probably formed during a surface finishing operation or when the tube is butted. The Reynolds 531 tube appears to be pitted, but this is merely a surface oxide layer which, if removed, would reveal a grooved surface similar to the Vitus tubing. The interior of seamless tubing is also grooved when drawn over mandrels.[1] All frame tubes have the surface features shown in Figures 1a and/or 1b.

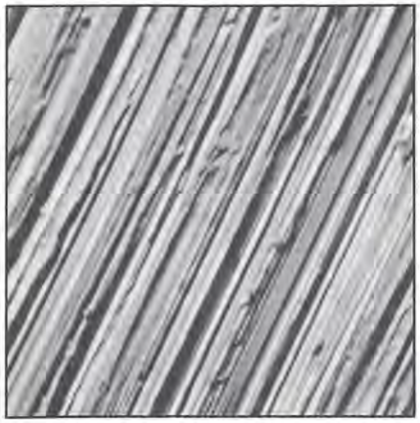


Figure 1a

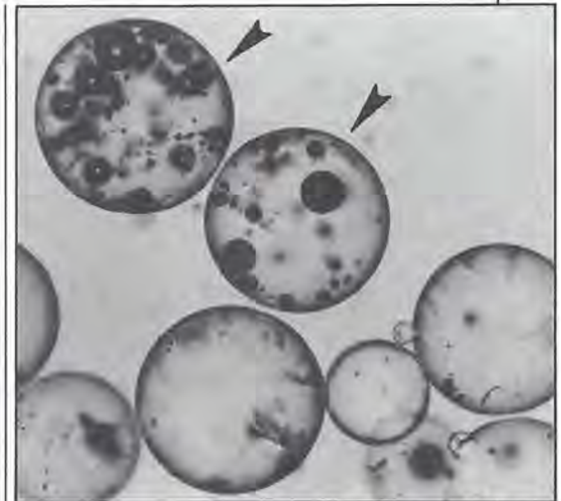
Figure 1b

Figure 1: The surface finish of Vitus 181 (top) and Reynolds 531 (bottom) tubing. 200 times magnification.

Grooves and other surface irregularities on frame tubes are a potential problem because they can create an uneven distribution of stress. To avoid this, tubing manufacturers try to control the size of these irregularities within certain tolerances. But, they are not always successful. Framebuilders occasionally receive tubes with imperfections so severe (such as deep gouges) that they can't be used.

In the past, two of the biggest names in frame tubing, T.I. Reynolds and Columbus, stamped their tubes by deforming the metal to identify the manufacturer, tube gauge, and often, the short-butted end of the tube. Stamping can produce stress raisers, and this problem magnifies as the tubes become thinner. Framebuilders knew this, and a few suspected that it caused the failure of some of their frames, but they were reluctant to switch to other brands because of their high regard for Reynolds and Columbus tubing.

Recently, Columbus has changed its marking method from stamping to the process known as electrical discharge marking. In this process, a graphite electrode similar to a rubber stamp is molded into a reverse image of the Columbus dove. A negative charge is placed on the electrode and a positive charge is placed on the tube. A high-frequency pulse of direct current arcs through the electrode and an image of the dove is burned into the tube surface. This image is confined to the surface oxide layer, so while it clearly marks the new tube for identification, it comes off when the surface is cleaned; hence, it does not deform the tube. Other manufacturers now use similar non-destructive marking methods. Ishiwata and Tange tubing, and Reynolds' ultra-thin 753, for example, are marked with paint.



100 microns

Mario Emiliani

Figure 2a: Spherical glass impact beads. Note the air entrained in some spheres (arrowed). These defects can facilitate fragmentation upon impact. 125 times magnification.

The surface finish of new tubing is an important consideration, but more for the tube's interior than its exterior, because the surface finish of frame tubing is modified during and after construction by sanding and/or particle blasting.

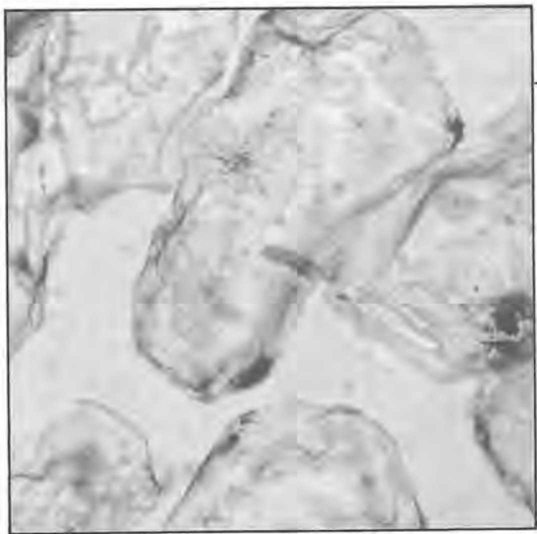
Particle Blasting

Particle blasting is a term used to describe the high velocity impact of solid particles upon solid surfaces for some beneficial effect. Particle blasting is frequently performed using sand—hence the familiar term sandblasting—but other non-metallic solid particles are also used. Glass beads, garnet crystals, and alumina are commonly used by framebuilders and professional painters.

The shapes of these particles are classified as either *spherical* or *angular*. The most common type of spherical particle is made from glass. Figure 2a shows glass impact beads 210 microns[2] in diameter. Particles

[1]*See "Straight Talk On Steel," by Mario Emiliani,* Bicycling, *July 1982, pp. 96-123.*

[2]*One micron = 10^{-6} meters = 0.00003937 inches*



Mario Emiliani

100 microns

Figure 2b: Sand, as well as most other types of particles used in sandblasting, has irregular shapes and sharp edges. 125 times magnification.

10 microns

Figure 3: Spherical particles impacting a frame produce symmetrical craters with small raised ridges along crater rims. 1000 times magnification.

such as sand, garnet, and alumina have sharp edges and are irregular or angular in shape. Figure 2b shows angular sand approximately 200 microns in diameter.

There are many situations in which particle blasting steel bicycle frames can be useful. For example, brazing flux residue, rust, and other surface debris can be easily removed to improve surface appearance and paint adhesion. Particle blasting is also a fast, inexpensive, and clean way to remove old paint. Particle blasting is so easy and effective that it is often done with little regard for overuse. There are, however, drawbacks to excessive particle blasting.

Erosion

One problem is that particle blasting removes or *erodes* metal from a frame tube. To prepare a surface for finishing, paint and rust are eroded by the impact of solid particles. Unfortunately, particle blasting removes metal in the same fashion as it does paint, although few people realize this because the metal loss is not as apparent as the paint loss. The amount of metal lost depends on the particles' shape and size, their velocity, and the length of time an area is blasted. The loss can be particularly substantial if a frame is particle blasted several times. Perhaps even worse than erosion is the cracking and pitting of the metal surface by the fast-moving particle stream. These surface irregularities, called stress raisers, will locally magnify stresses that can then initiate and propagate cracks throughout the surface and cause premature failure of the frame.

Particle Impacts

A spherical particle hitting steel produces a crater with a small raised ridge along its rim. No material is removed by a single impact, but very small subsurface voids are formed when metal is displaced to form the crater. Figure 3 shows a crater produced by a 210-micron diameter glass sphere. A few more particles striking in the vicinity of the first crater form more voids which link together to form a small crack. Subsequent impacts cause the crack to grow until a small flake, or *platelet*, of metal is removed. Thus, several impacts are needed to remove metal. Figure 4 shows two overlapping impacts which formed a platelet that is near the point of removal. The process of material loss is known as platelet formation.

Figure 5 shows an impact crater formed by a 200-micron sand particle. In contrast to impact sites produced by spherical particles, craters made by angular particles have irregular shapes and large, raised lips. If the volume of the lip in Figure 5 isn't equal to that of the crater, then metal has been removed. Nearly every impact by angular particles will remove metal; those which don't form large lips that are vulnerable to easy detachment by subsequent impacts.

Most materials used in particle blasting will fragment upon impact because they are brittle. Even spherical glass particles, particularly if they contain air pockets, can shatter into angular fragments. (See Figures 2a and 6.) If these fragments then ricochet into the frame, they can act like angular sand particles, either removing metal or becoming embedded in the surface. Subsequent impacts may remove these embedded fragments or drive them further into the metal. Your frame may be carrying thousands of glass or sand fragments that were embedded during the blasting process.

Material Loss

The removal of material by sharp-edged angular particles is called *cutting*. Platelet formation can occur simultaneously with cutting, but this depends upon the type of particles and velocity used. If the velocity is high, as in sandblasting, material loss by cutting is more likely to occur than platelet formation.

The cutting action of angular particles enables paint, flux, rust, and excess filler metal to be removed faster and more completely than if spherical particles are used. It's no wonder angular particles are the choice of framebuilders and painters. But the fact that angular particles can remove metal with nearly every impact means that the rate of material loss will be much higher than if spherical particles are used.

For a given velocity, large particles will produce greater material loss because the force upon impact is greater. Similarly, an increase in velocity (with no change in particle size) will also remove more metal, provided the particles do not fragment upon impact. But particle velocity is difficult to determine because it's a complex function of both particle size and particle-blasting equipment. For example, at a given pressure, small particles travel faster than larger particles made of the same material. Particle velocity also depends on the nozzle diameter of the particle blasting gun, the pressure used, and the distance between the nozzle and frame. Typically, framebuilders use particles ranging from 100-300 microns in size and they adjust their equipment to have particle velocities in the neighborhood of 100-300 ft/sec.

Mario Emiliani

10 microns

Figure 4: Only two overlapping impacts were needed to form a platelet (arrowed). One or two more impacts would have removed it from the surface. 1000 times magnification.

10 microns

Figure 5: Craters made by angular particles have irregular shapes and large, raised lips. Notice the crater rim opposite to the lip is hardly deformed (arrows). This illustrates the efficient cutting action of angular particles. 1000 times magnification.

100 microns

Mario Emiliani

Figure 6: Fractured glass particles. 125 times magnification.

George Retseck

Time Factor

A survey of framebuilders and painters showed that it takes one to five minutes to sandblast a top tube/head tube joint, and four to fifteen minutes to sandblast an entire (bare) frame before painting. But many frames, or portions of frames, are often sandblasted more than once. For example, some framebuilders sandblast immediately after the frame is brazed to see how well they've done. They then might file a bit, add braze-ons, re-braze gaps in the lugs, and sandblast again. If the paint job comes out badly, or if the frame owner decides to repaint it later, the frame will be sandblasted yet again. So it's possible that some frames are sandblasted for a total of 15 minutes or more. This may not seem like a long time, especially for a whole frame, but as Figures 4 and 5 show, only a few impacts are needed to remove metal. To better assess the damage caused by sandblasting, the number of particles impacting the frame must be determined.

The number of particles leaving a blasting gun will depend upon the equipment, operating pressure, and the size and type of particles used. Assuming one gram of sand particles leaves the gun each second, and after calculating the mass of a 200-micron spherical particle (I'm using spheres because it's easier to calculate their volume), roughly 100,000 particles strike the frame every second. So in 15 minutes of sandblasting, a frame can be hit by almost 90 million particles!

Because of the large number of particles involved, it's apparent that every square inch of a frame will be hit by thousands of particles. This can lead to significant metal loss. In addition to the type of particle used and operating conditions of the blasting equipment, the amount of material removed depends on the impact angle of the particles, the type of steel, and the amount of time the steel was heat treated during the brazing process. (After a steel frame is brazed, some portions will be weaker than others. "The Metallurgy of Brazing, Part 4" in the April 1983 issue of *Bike Tech* explains how the strength of steel tubing varies near a brazed joint.)

Erosion Tests

To better assess material loss rates in particle - blasted steel frames, I eroded two samples of Columbus SL tubing. The particles used in the test were 210-micron glass spheres and 200-micron sand. Both types of particles flowed at a rate of 1 g/cm²/s, and were accelerated to a velocity of 175 ft/sec. The area eroded was 0.079 cm², or about one-eighth of a square inch. These tests were performed using a sophisticated erosion rig built at the University of Rhode Island. Figure 7 is a schematic dia-

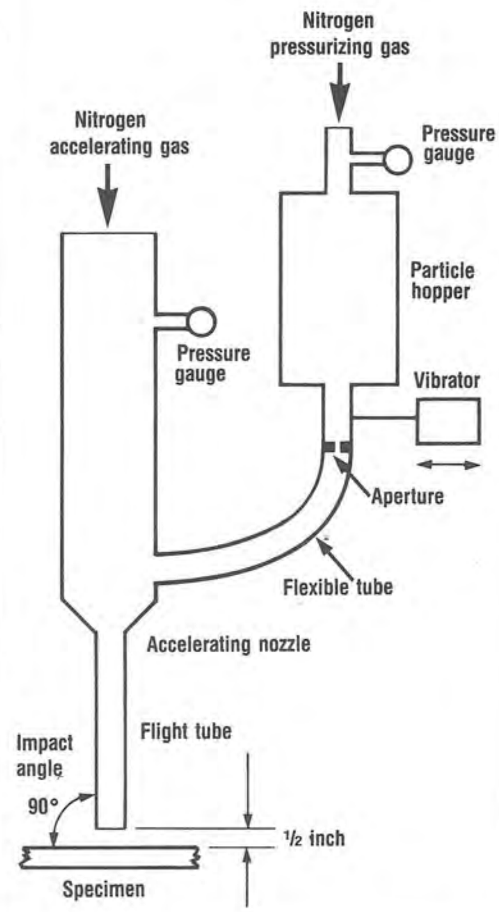


Figure 7: Erosion rig.

TABLE 1 Reduction In Wall Thickness Due To Particle Blasting

Specimen Type	Particle Type	Erosion Time, sec	Original Thickness, mm	Final Thickness, mm	% Change
Columbus SL	Sand	465	1	0.74	26
Columbus SL	Glass Spheres	465	1	0.87	13
Columbus SL	Sand	90	1	0.91	9

gram of the test equipment.

The impact angle significantly affects the erosion rate. Ductile targets, such as the steels used to make frames, exhibit the greatest material loss rates at low impact angles, about 25°. The lowest erosion rate is at 90°. But no matter what the intended impact angle is, many particles will hit at more acute angles because other particles interfere with their flight path, or because of peculiar angular rotations (especially true for non-symmetrical particles). In addition, the curvature of the tubes and the gun's angle to the tube will result in particles striking at all angles. Testing one specimen at all impact angles is impractical, so I used a microscopic impact angle of 90° to simplify testing (see Figure 7).

The Columbus SL specimens used in the tests were cut from a new fork blade. These samples were tested in the "as-received" condition, and had a yield strength of about 95,000 psi and a wall thickness of one millimeter. The strength of a steel depends upon its microstructure, which in turn determines the ease or difficulty with which metal is removed during particle blasting.

Work Hardening

It turns out that stronger steels erode faster than softer steels. This would seem to contradict logic, but can be explained as follows. Each impact causes permanent deformation which locally hardens the metal. This phenomenon is known as work hardening and can be demonstrated by simply bending a spoke, then rebending it the opposite way. You'll notice it's more difficult to bend it in the same spot again. Metals work harden because permanent deformations create atomic-sized irregularities that make it harder to further deform the metal. With this increase in strength, there is a corresponding drop in ductility. Further permanent deformation makes the metal harder and brittle, eventually causing failure. Strong steels can't work harden a lot because their structure already contains a large number of atomic-sized irregularities. Thus, only a small amount of permanent deformation (a few impacts) is needed to fully work-harden the metal. Following the first few impacts, significant material loss will occur as the hardened metal undergoes brittle fracture. Softer steels, however, are able to undergo larger amounts of permanent deformation without failure, and therefore are more resistant to material loss by particle blasting.

Each Columbus SL specimen was eroded for periods of 15 seconds, 30 seconds, one minute, two minutes, two minutes, and two minutes, for a total erosion time of seven minutes, 45 seconds (465 seconds). The specimens were accurately weighed at each of these time intervals to determine their weight change in order to chart a weight loss versus time curve. The results are given in Figure 8.

Results

It's clear that the sand-eroded target lost the most metal. The total weight loss measured 15.9 milligrams, while erosion by glass spheres resulted in a 6.8-milligram weight loss. The erosion rate using sand was 2.3 times greater than when glass spheres were used. It's important to remember that the data given in Figure 8 are merely illustrative, since actual particle blasting conditions, and hence material loss rates, can vary considerably. For example, many more particles would strike at angles less than 90°, and it's likely that different particles, higher velocities, and higher particle concentrations would be used by a framebuilder.

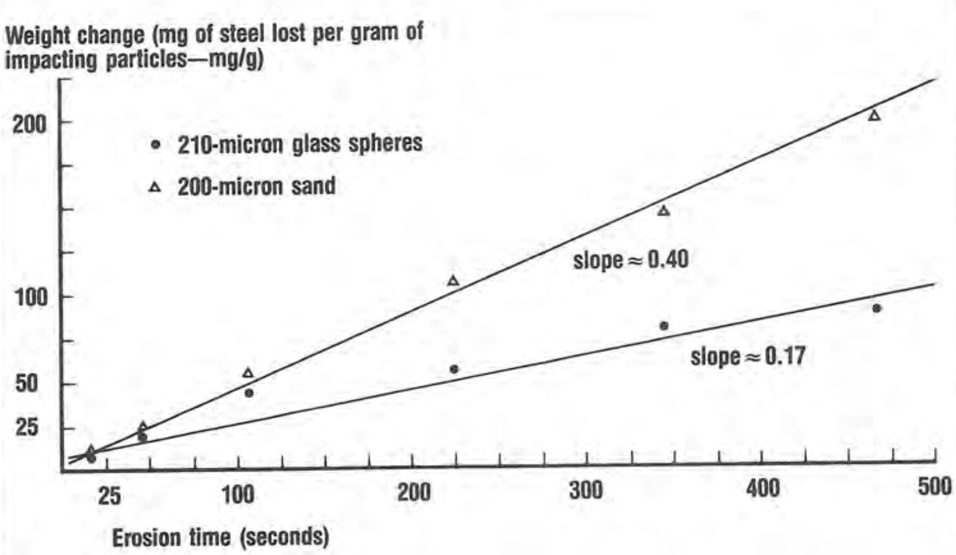
Earlier in this article, I mentioned that it's possible to significantly reduce the wall thickness of tubes by particle blasting. Measurements of the reduction in wall thickness were made by photographing cross sections of the eroded areas. The results are given in Table 1.

The specimen eroded with sand and glass spheres had a 26 percent and 13 percent reduction in wall thickness, respectively. That's quite dramatic, and here's why: the specimens were eroded for seven minutes and 45 seconds in the same spot. An entire frame can be particle blasted in that time! To get an idea of the reduction in wall thickness for more realistic particle blasting times over small areas of the frame, I eroded another Columbus SL specimen for 90 seconds. The test conditions were the same as before, but only 200-micron sand was used because angular particles are normally used on frames. As Table 1 shows, there was a nine percent reduction in wall thickness. Had the tube been 0.5 mm thick, there would have been an 18 percent reduction, obviously a significant amount.

(Quite a few frame tubes have wall thickness of only 0.5 mm. The three main tubes in a Columbus Record tube set are straight gauge 0.5 mm. Double-butted Reynolds 531SL tubing has a mid-section thickness of 0.5 mm, as do the top and down tubes of Tange's No. 1. The Ishiwata 017 tube set's three main tubes are butted 0.7/0.4/0.7, and the exotic Reynolds 753 has a 0.7/0.3/0.7-

Figure 8: Erosion rates of Columbus SL tubing ("as received" condition)

Particle velocity—175 ft/s **Target material—Columbus SL** **Impact angle—90°**



George Retseck

butted top tube. A wall thickness of 0.3 mm is 300 microns; that's not much bigger than the 200-micron sand).

Worst Case

It should be emphasized that this erosion test represents a worst-case condition. The Columbus tubing was in its strongest state and, as we saw, erosion of strong steels occurs at a high rate. Only some portions of a brazed frame will be like the test sample—the central sections of all the tubes will not have been annealed (weakened) by the heat of brazing. While all areas of a frame will be particle blasted, the time spent on the strongest (unannealed) areas will be short compared to the attention paid to the (weaker) brazed joints. And since the steel around the joints is weaker, it can endure more impacts before brittle-fracturing. Of course, if a frame is built with tubes that are ultra-thin at the joints, like Columbus Record or Reynolds 753, then great care must be taken when cleaning these areas with the blasting gun. The safest approach is to use only spherical glass particles on these delicate tubes, and blast a minimum amount of time.

Keep in mind, though, that material loss is only part of the problem. Any surface cracks, voids, or pits caused by particle impacts in areas where the frame is highly stressed can lead to frame failure. In Part 2 of this series we'll take a look at a frame that may have failed due to the effects of sandblasting. We'll also examine the theory and practice guidelines for safe particle blasting. Stay tuned.

Editor's note: Great caution must be exercised when sand blasting paper-thin tubing. Any overall reduction in wall thickness can severely compromise the tube's rigidity and strength. A rule of thumb is that any reduction in wall thickness will yield an equal reduction in both strength and rigidity. In the case of the Columbus fork blade sandblasted for 90 seconds, if we assume that the tube was blasted evenly all around, then a nine percent wall thickness reduction will result in an approximate nine percent reduction in both strength and rigidity. This estimation is approximate because the tube wall is not only getting thinner as material is removed, but the outside diameter of the tube is being reduced as well.

Reducing the diameter of a tube has drastic effects on its rigidity, with a change of a factor of k *in diameter resulting in a reduction in rigidity of about* k^3 *and a reduction in strength of about* k^2. *In this test, the effect of diameter reduction affects the strength and rigidity only a few percentage points above that wrought by reducing the thickness of the tubing wall. For a comprehensive discussion of how a tube's dimensional factors affect its strength and rigidity, see Crispin Miller's article in the August 1982 issue of* Bike Tech.

SPECIAL REPORT

On Brakes

Ed Scott

Ed Scott is the president of Scott/Mathauser Corp.

Ever since bicycles assumed their modern form at the beginning of this century, one component of the bicycle that has been considerably less than satisfactory is the brakes.

In relatively flat country and in dry weather most bicycle brakes are satisfactory. But in wet weather or down long steep hills, especially with a loaded touring bike, cyclists have been complaining for 80 years about inadequate brakes. It makes little difference whether they're centerpulls or sidepulls, and whether they cost $15 or $150. They can be beautifully polished, meticulously machined, and stamped with a near-holy name, but in practical use experienced cyclists have often admitted, "In the rain I can stop faster by dragging my feet."

Why is this so? A bike isn't a high-performance machine. Its basic purpose is to provide simple, safe, economical transportation. The bicycle was the precursor to the automobile, yet, while automobile brakes have evolved from two-wheel external band brakes, to internal shoes, servo shoes, four-wheel brakes, power brakes, disc brakes, and finally to power-boosted discs that will stop from any speed in any weather, bike brakes have only undergone a slow refinement of a basically bad design. With its slow speeds and two-foot discs (the wheel rims), a lightweight bicycle should be simple to stop.

Sidepull or Centerpull?

Even the descriptive terms for brakes are mixed-up and misleading. The key feature of a conventional caliper is not where or how the cable pull is applied, but where the arms are pivoted. This is the essential difference between side- and centerpulls. Sidepulls would be better termed "center pivots" because the cable pull can be arranged at the side, top, or in-between, by simply reorienting the primary arms. For an example of an in-between arrangement, look at the new Dia-Compe Aero brake. Likewise, the so-called centerpulls should really be called "side pivot" since this feature is what differentiates them from sidepulls.

Under normal braking conditions, the rear brake cannot be applied very hard, because a forward shift in the rider's center of mass reduces the rear tire's traction. Most of the braking must be done by the front brake, so it's important that the front brake be optimally designed. This includes choosing the correct type of brake for the front.

A centerpull is not the best brake to use on the front because the upward pull of the brake cable tends to flex the whole caliper upwards. This flexing, combined with the flexing caused by the rim dragging the caliper arms forward, upsets the firm contact of the brake pads on the rim. A sidepull is a better choice on the front because the upward cable pull is counteracted by the reaction push of the cable casing, so there's less caliper flex.

A centerpull is the better brake to use on the rear because the cable's upward pull on the caliper assembly helps counteract the downward pull on the caliper.

Design Flaws

If an engineer looked at examples of the best current sidepull and centerpull brakes, he or she would see a lot of questionable structural design. And there is an amazing similarity among almost all of the currently available caliper brakes, so they all suffer from the same design flaws.

Foremost in bad design is the choice of cross section for the caliper arms. Most arms have a cross section that is approximately a half-inch half-round. For braking duty, this is a very poor structural shape. Here's why: when a brake is applied standing still, the arms are stressed only in the plane of the cable pull. The half-round section is very rigid in this direction. But when a brake is applied on a moving bicycle, the rim tugs on the brake pads which pulls on the caliper arms. The caliper arm cross section is very weak when stressed in this direction, so the arms will flex.

To allow fender and tire clearance, the arms must sweep outward and then back in

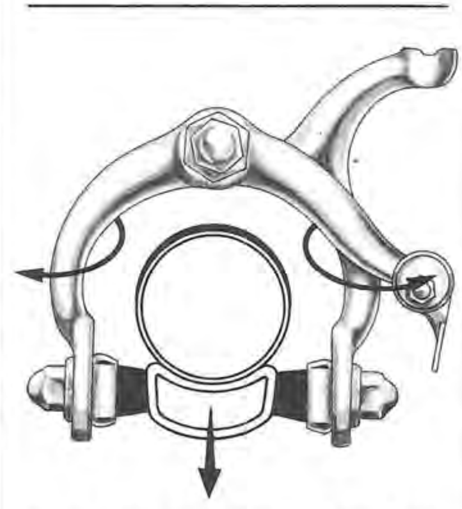


Figure 1: The caliper arms will twist when the rim tugs on the brake pads.

George Retseck

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

February 1984

Volume 3, Number 1 $2.50

MATERIALS

Can Surface Finish Affect the Strength of Your Frame? Particle Blasting, Part II

Mario Emiliani

Part I detailed the factors influencing the rate at which metal is removed from frame tubes by particle blasting. Among the most important parameters are particle size, shape, and velocity. Experiments were performed to illustrate the dependence of material removal upon the particle type. The results showed that angular particles, such as sand, removed metal 2.3 times faster than similar-sized glass spheres, and that the wall thickness of thin tubes can be reduced significantly in the time it takes to particle blast frames.

Additionally, we saw that particle blasting can put microscopic pits and cracks into the metal's surface. These surface irregularities are a potential source for stress raisers that can endanger the structural integrity of the tubing.

If an energetic engineer wired a bicycle with strain gauges and analyzed the stresses encountered while cycling, he or she would quickly find that the stresses are cyclical. For example, each revolution of the cranks places an alternating stress on the tubes connected to the bottom bracket. Other types of cyclic loading are produced by bumps, potholes and even just getting on and off the bike.

The magnitude of these stresses can vary considerably. For example, an uphill sprint

Figure 1: This fractured frame tube was weakened and may have failed from sand blasting.

IN THIS ISSUE

Mario Emiliani

7 microns —— Figure 2a Figure 2b 7 microns ——

Figure 2: Surface irregularities and embedded particles are telltale signs of particle blasting. Figure 2a shows a raised lip and an embedded sand particle. Figure 2b reveals a piece of Reynolds 531 tubing on the verge of detachment.

will put stresses into a frame far above those incurred by pedaling at a steady cadence on level ground (input torque in all-out sprinting can go as high as 150 ft-lb). Road-induced stresses can range from low magnitude thumping caused by expansion joints, to a one-time, frame-jarring stress caused by a pothole. So a typical ride will expose the frame to many different types of pedaling and road stresses that vary in quantity and magnitude.

Pedaling simultaneously produces tensile, compressive, bending, shear, and torsional (or twisting) stresses on the down tube, seat tube, and chain stays. These stresses alternate on different parts of the tubes as the cranks rotate through 360°. Road shocks will usually produce bending, compressive, and tensile stresses, mainly in the front fork, the head tube/down tube and head tube/top tube junctions, and the rear stays. When more than one type of stress acts simultaneously upon a component, the effect is called combined loading.

BIKE TECH

Executive Editor *Doug Roosa*	Chairman *Robert Rodale*
Editor *John Schubert*	President *Robert Teufel*
Editor-at-Large *John S. Allen*	Publisher *James C. McCullagh*
Contributing Editors *Fred DeLong* *Mario Emiliani* *Gary Klein* *David Gordon Wilson*	Circulation Manager *Pat Griffith* Copy Editor/ Proofreader *Patricia Peltekos*
Editor Emeritus *Crispin Mount Miller*	Art Director *John Lenaas*

BIKE TECH (ISSN 0734-5992) is published bimonthly by Rodale Press, Inc., 33 E. Minor St., Emmaus, PA 18049. *Subscription rates: United States, one year $14.97; two years $29.94; Canadian add $3.00 per year, payable in Canadian funds; other foreign add $6.00 per year for sea mail, $10 for air mail, payable in U.S. funds. Single copy price: $2.50. Inquire about bulk rates.*

Copyright 1984 by Rodale Press, Inc. All rights reserved.

POSTMASTER: Send address changes to *Bike Tech*, 33 E. Minor St., Emmaus, PA 18049. *Bike Tech* application to mail at second-class postage rates is pending at Emmaus, PA 18049. *Bike Tech* may not be reproduced in any form without the written permission of the publisher.

Tensile Stress

One of the most important types of stress to consider in materials science is tensile stress. Tensile stress is a pulling stress; strings break under tensile stress when the pulling force exceeds the strength of the molecular bonds. All materials can resist being pulled apart to some degree; how much force is required is a measure of the material's yield strength. Tensile stresses can exist by themselves, or as components of other types of stresses. For example, a component of tensile stress can be found in bending. shear, and torsion.

When any metal is subjected to cyclic stresses, it is possible that the metal will weaken, distort, or crack; in general, it can fail. This type of failure is called fatigue failure.[1] Fatigue failure will occur at a stress level below that needed to cause failure by the application of a single load (like in a tensile test). Since the stress applied to a metal that has failed by fatigue appears low, it's usually assumed that the metal's yield strength was not exceeded. This is not correct; at some point in the metal's microstructure, the yield strength was exceeded because there was a local concentration of stress sufficient to pull apart the metal's molecular bonds.

Stress concentrations are small areas on the surface or within the metal where the stress of an applied load is concentrated. This local increase in stress can be many times greater than the stress in adjacent areas and can often grow in magnitude to well beyond the yield strength of the metal. Under this condition, the concentrated stress will seek relief by breaking the metal's molecular bonds: a crack will form. If repeated tensile stresses are put into the area, the crack will continue to grow as more molecular bonds are pulled apart each cycle.

Stress Raisers

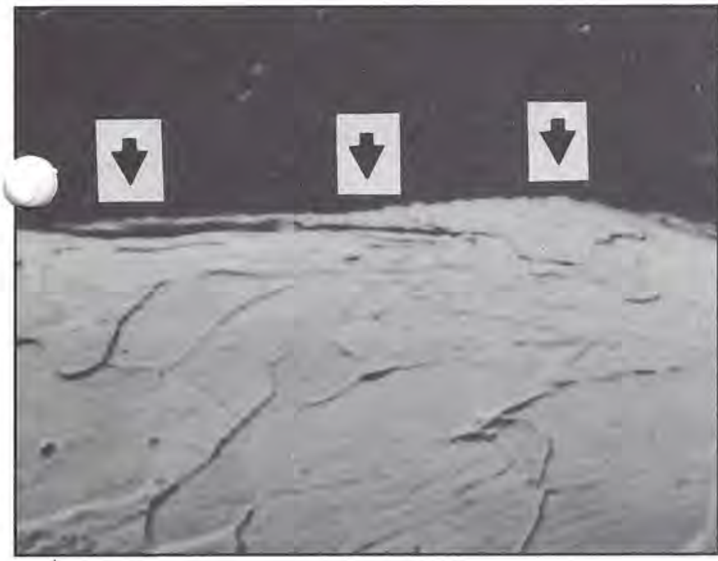
Areas that are likely to harbor stress concentrations, or stress raisers, are holes, grooves, scratches, errant file marks, and foreign substances within the metal, like oxide inclusions.[2] In general, stress raisers appear any place where there's a discontinuity, or sudden change, in either the molecular structure or the cross section of the metal. These types of stress concentrations can be found in any metal component, but on a bicycle frame, there are several particular points where they're likely to be. These include the points on lugs, fork blade and chain-stay reinforcements, and some styles of fork crowns, in addition to any sharp-angled cutouts these components may have. And, as we saw in Part I of this article, the pits and cracks placed in the frame's surface from particle blasting can act as stress raisers.

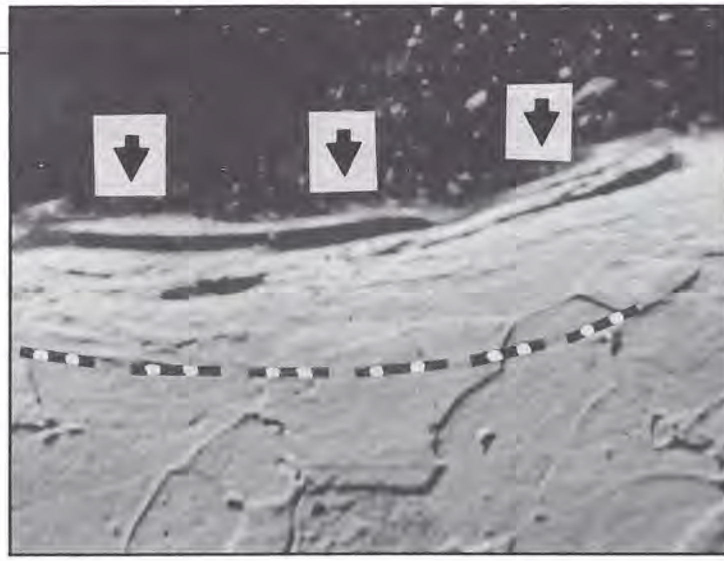
Fatigue Resistance

The magnitude of stress that is concentrated at one point is determined by the size,

1. *For a comprehensive discussion, see "What is Fatigue," by Richard Brown,* Bike Tech, *October 1982.*

[2]*Oxide inclusions are non-metallic impurities trapped within metals upon solidification.*





7 microns — Figure 2c Figure 2d 7 microns —

The thin flakes of metal and plastic deformation beneath the surface shown in Figures 2c and 2d are the result of glass bead blasting.

or radius, of the discontinuity. The smaller the radius, the greater the stress concentration. Sharp pits and cracks create the worst type of stress raiser because the radius of the crack tip is so small. Nearly every other type of defect is less severe, but they can still cause trouble, especially if the component is loaded beyond its intended use.

It is wise, then, to design and manufacture a component with a minimum amount of natural stress raisers if maximum fatigue resistance is desired.[3] With our knowledge of the perils of particle blasting, it would seem foolish to jeopardize the fatigue resistance of a component by subjecting it to the pitting action of fast-moving particles of sand or glass. But, interesting enough, some engineers believe that particle blasting can actually increase the fatigue resistance of metal by work hardening the surface of the metal (see the accompanying article, "Peening").

Surface Tension

When molten metals solidify, the atoms settle into distinct arrangements. Occasionally there are defects in the packing sequence which causes an uneven distribution of forces between atoms. But if we assume that all atoms are packed ideally so they are positioned symmetrically with respect to their nearest neighbors, then the forces acting upon atoms inside a metal will be the same from all directions. But atoms on the surface of metals aren't being pulled equally from all sides; they feel a net pull inward from the atoms below. The result is that the surface is placed in a state of tension. Since the surface of metals is normally in tension, it's no surprise that fatigue cracks tend to initiate there. Cracks can also form within metals, but this is less common.

Particle Blasted Frames

The series of Figures 2 and 3 are photomicrographs of various portions of expensive racing and touring frames that have been particle blasted. All photos are cross-sectional views of the tubing surface. Figures 2a and 2b show portions of an investment-cast lug and a Reynolds 531 tube, respectively. Notice the highly irregular surfaces. This is characteristic of metals which have been particle blasted with angular particles. Figure 2a shows a lip of steel displaced by an angular particle. The particle fractured upon impact and became embedded in the lug (arrowed). Figure 2b shows another lip of steel that is near the point of detachment.

Figures 2c and 2d show the eroded surfaces of a stamped lug. The smooth surface indicates this frame was particle blasted with small spheres. Both figures show thin flakes of metal that are at the point of detachment (arrowed). In addition, notice the small voids beneath the thin flakes in Figure 2d. Between the irregular surface and the dotted line in Figure 2d is a deformed region of metal that looks compressed. This region is marked by lines of plastic deformation, called flow lines. The depth of these lines indicates the depth of work hardening that the metal received from particle blasting. In the pictured sample, the work hardened region is about ten microns deep.

More Cracks

Figures 3a, 3b, and 3c show more cracks produced by particle blasting. Figure 3a shows an investment cast lug which has previously been particle blasted with angular particles. Note the embedded particle fragment and non-metallic inclusion to the immediate right and left of the large arrow, respectively. There is also a large crack at the base of the lip (small arrows). (Figure 3b is a higher magnification photo of this crack.) Figure 3c shows a crack in a Reynolds 531 tube; to the left of the crack is an embedded angular particle (arrowed). Note the flow lines around the crack.

Embedded particles, flow lines, thin flakes, subsurface voids, raised lips, and surface roughness are all characteristic features produced by particle blasting. The unwanted by-product of these characteristics is, of course, the microscopic regions of high tensile stress: stress raisers.

Frame Failure

In fatigue failure analysis, the role of stress raisers is central; but, in spite of the telltale characteristics imparted to a metal's surface by particle blasting, particle blasting is rarely considered as a possible cause of frame failure. I believe, however, that many frame failures can be traced back to excessive or improper particle blasting.

A well-known American frame builder I know recently had a custom touring frame fail. The frame was about two years old, and was made of Columbus SL tubing. The frame was used by a commuter and had about 10,000 miles on it. The actual riding conditions at the time of failure (i.e. rider weight, road conditions, etc.) are not known, but the bicycle wasn't in an accident and it took two years to fail, so it's likely that fatigue was the cause of failure.

The framebuilder suspected the tubing manufacturer was responsible because the failure was very close to the Columbus dove identification stamp on the tube (this was be-

[3] *See "Stress Raisers in Bicycles," in the October 1983* Bike Tech.

Mario Emiliani

Mario Emiliani

10 microns —— **Figure 3a** **Figure 3b** **7 microns** ——

Figure 3: Surface cracks and embedded particles plague a particle blasted frame. Note the crack (arrowed) forming in Figure 3a. Figure 3b gives a closer look.

fore the tubes were marked by the less destructive methods now employed. See Part I of this series in the December 1983 *Bike Tech* for more details on tube marking.). He sent the failed frame to Columbus S.r.l. for failure analysis. Columbus in turn sent the frame to the University of Milano, Department of Solid Mechanics. A short while later the framebuilder received a report from the university detailing their analysis of the cause of failure. The framebuilder then sent the report to me to see what I thought of it. Figures 1 and 4 were taken from the report.

Faulty Pickling?

Figure 1 shows the failed portion of the frame. The point of failure at the tip of the lower down tube/head tube lug (arrowed), is known to be highly stressed during cycling. It's not uncommon for frames to fail at this location.[4] Figure 4 is a cross section showing the outer surface of the down tube near the failure. Cross sections taken from other areas revealed the same type of surface features.

It's clear from Figure 4 that this frame was heavily particle blasted with large angular particles. Note the embedded particles (arrows), flow lines, and surface roughness. The report concluded that the frame failed as a result of the stress concentrations produced by these pits near the highly stressed lower lug point.

Interestingly, though, the investigators concluded that the pits were caused by "... a faulty pickling process made before varnishing the frame." "Pickling" means that the frame was placed in a corrosive liquid to clean it prior to painting. But pickling cannot deform metal, create flow lines, and embed abrasive particles such as are clearly observable in Figure 4. And, since either cleaning method works well, why would a professional painter take the time and expense to do both?

Uncertainties Remain

While both the investigators and myself acknowledge that the pits in the tubing very likely instigated frame failure, we don't agree on their origin. Nor can it be said that they were the only cause of failure. There are too many unknowns involved, including the history of stresses in the frame from the rider's weight, his baggage, and the innumerable road shocks encountered during two years of steady riding. The report from Italy did not include a stress analysis nor did it indicate if the investigators had checked for any other fatigue cracks, measured the thickness of the tubing around the break, or investigated the brazing at the joint.

Curiously, though, photos that accompanied the report showed that there were several oxide inclusions in the area of the break; one photo revealed an oxide inclusion in the fracture zone. The report judged that these inclusions were normal and did not contribute to the failure.

The failed frame is no longer available for investigation so the real cause of failure will never be known. But the evidence strongly suggests that the stress raisers put into the tubing surface by particle blasting helped to initiate the cycle of fatigue failure.

Precautionary Measures

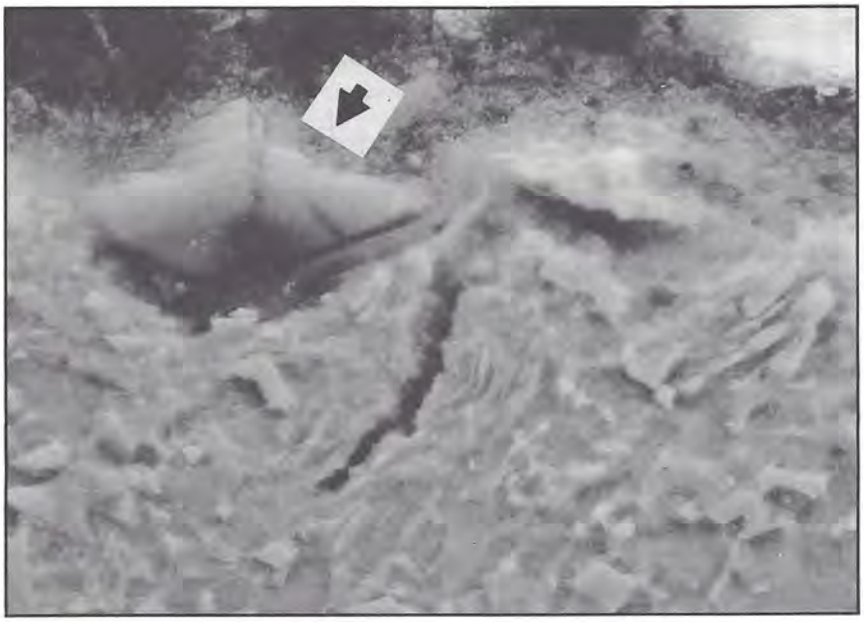
The frame failure in this story was dramatic, whatever the cause. The evidence in this two-part story suggests that more attention must be paid to the deleterious effects of particle blasting in future frame failure investigations. But of all the frames made, only a small fraction fail in normal use. This indicates that intelligent frame design and correct selection of tubing gauges gives most frames a large safety factor and, therefore, a healthy tolerance for the abuses of particle blasting.

But a frame purposely built at the limits of safe structure—one built with ultra-thin Reynolds 753 or Columbus Record tubing, for example—must be blasted with utmost care, or else cleaned by another method. Other methods include pickling, chemical stripping of old paint, wire brushing, and sanding. The first two can be economical if a large number of frames are involved, but there are problems in flushing the acids out from the tubes. The latter two are tedious and not well suited to clean hard-to-reach places.

So, the method of choice for an overwhelming number of builders and painters is particle blasting. This being the case, it's important that the safest methods for particle blasting be outlined. Here are my suggestions:

Angular particles are the worst to use because they remove metal with nearly every impact and leave sharp pits on the tube's surface. And the larger the particle, the worse the damage. Spherical particles are

[4]*Personal communications with Fabrizio Giussani, metallurgist, Columbus S.r.l.*



Mario Emiliani

7 microns ——— **Figure 3c**

Both a crack and flow lines (see text) are evident in Figure 3c.

24 microns ———

Figure 4: Deep pits like these create stress raisers that can cause fatigue failure of steel tubing.

less destructive, but are also less able to remove brazing flux, old paint, etc.; this is especially true for the smaller sized particles.

So we need to strike a compromise. If angular particles are used, they should be small—no larger than about 100 microns (140 grit). If spherical particles are used, they should be between 70-210 microns (75-160 grit) in diameter. In addition, the gas pressure (or particle velocity) should be set as low as possible to do an effective job. Above all, if a frame must be particle blasted, it should be done for the shortest amount of time.

Part III of this series will appear in the June issue.

MATERIALS

Peening

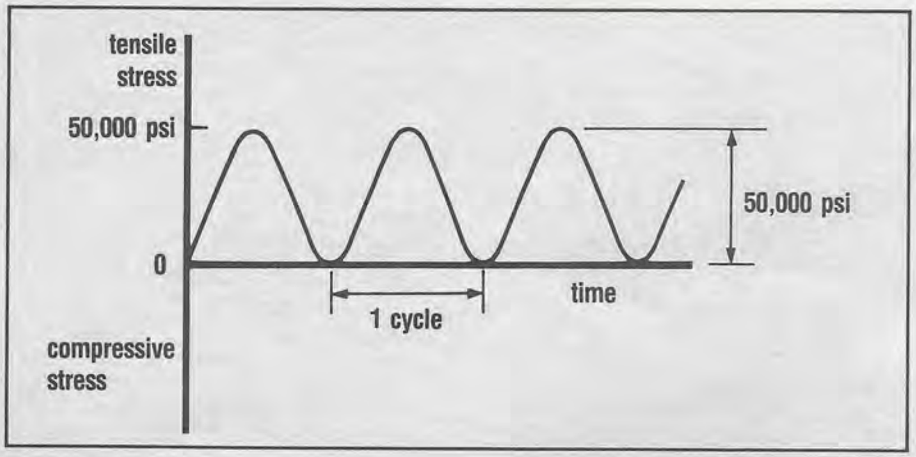
One way of improving a metal's resistance to fatigue is by altering the surface so that it is in compression instead of tension. In the old days, steels were very crude and contained many oxide inclusions. This limited the service life of cyclically stressed components. Then blacksmiths figured out that they could improve the fatigue strength of steels by hammering the surface. What they did was cold work (i.e. permanently deform) the surface by repeatedly striking it with a ball peen hammer. This placed what is called a residual compressive stress on the surface. This practice is known as peening.

Peening by hand is very labor intensive, so other means were developed to work harden the surface. Shot blasting is one such method. Hardened steel balls are propelled to high velocity using compressed air and then aimed at the surface of the metal like a thousand little hammers. Glass bead blasting, as the name implies, utilizes spherical glass beads to do the same job.

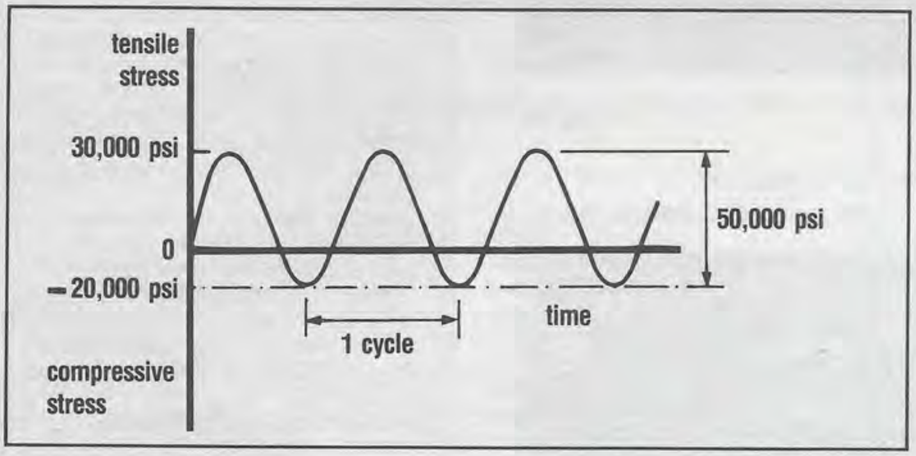
Figure 1a and 1b illustrate how peening improves fatigue resistance. Let's assume an unpeened piece of steel undergoes a simple cyclic loading sequence as shown in Figure 1a, with a maximum tensile stress of 50,000 psi and a minimum stress of zero psi. This equates to an average tensile stress of 25,000 psi. A peened specimen of the same type of steel undergoes the same cyclic loading sequence as shown in Figure 1b. However, notice the dotted horizontal line indicating zero stress. This shows that the surface of the peened specimen has a residual compressive stress. We'll assume the magnitude of the compressive stress is 20,000 psi. With this amount of compressive stress, the peened specimen can support a tensile stress of 20,000 psi and have zero net stress on its surface. Thus the net maximum tensile stress on the peened surface is 30,000 psi (i.e. 50,000 psi minus 20,000 psi), and the average tensile stress is only 15,000 psi.

It's clear that the specimen without a residual compressive stress is subjected to a greater maximum tensile stress. Also, a peened surface will be more resistant to cracking under cyclical stress and the component will have the capacity to operate under higher stresses and not fail by fatigue.

It's important to realize that a residual compressive stress can only be obtained by using spherical particles. Part 1 of "Particle Blasting" showed that one impact compressed the metal, but that after several coincident impacts, metal began to flake off. So the surface can be work hardened by glass beading, but there is only a brief "window"



Unpeened sample **Figure 1a**



Peened sample **Figure 1b**

George Retseck

Figure 1: Cyclical loading of unpeened (Figure 1a) and peened (Figure 1b) steel samples. Unpeened sample has a maximum surface tensile stress of 50,000 psi; peened sample has a surface compressive stress and "feels" a surface tensile stress of only 30,000 psi.

between work hardening and metal removal. Angular particles, on the other hand, remove metal with nearly every impact, so it is impossible to form a surface compressive stress with them.

But questions about glass beading remain. If peening imparts a residual compressive stress to the surface, then there must be a corresponding residual tensile stress somewhere within the metal. According to metallurgical theory, the residual tensile stress lies below the surface layer in compression. But if the compressive layer is not uniform, then there might be areas of tensile stress on or near the surface which can provide avenues for cracks to propagate. And if any cracks do form on the surface, is the surrounding compressive stress high enough to prevent the concentrated tensile stress from enlarging the crack or not?

These questions are not easy to answer. Successful work hardening by glass beading will occur only under carefully controlled conditions. Even then, a conscious effort may do more harm than good and, ironically, a simple clean-up job involving a quick pass over the frame with a blast of glass beads may leave a well-compressed surface.

Peening has additional limitations. It has little effect on high-strength alloys because they don't work harden as much as softer alloys. Metal will be removed before an adequate residual compressive layer can be developed. Peening also has minimal effect when the operating stresses are near the yield strength of the metal. Because of these limitations, and because of the advent of stronger alloys and improved design, production, and finishing techniques, peening metal for fatigue resistance is not used much today.

Mario Emiliani

SHOP TALK

Chain Behavior in Front Derailleurs

Crispin Miller

At first glance, the front derailleur seems like the simplest control mechanism on a bicycle—just a pair of plates to shove the chain back and forth between a set of chainwheels. But given its task and location—operating on the taut, power transmitting portion of the chain with minimal clearances between the crank and frame—it really can't be much more sophisticated than it is. Whereas the rear derailleur can control the chain in an S-curve over rollers, the front can never grip the chain, yet manages to work well, if it is properly adjusted.

In the last ten years, the front derailleur's shifting ability has improved, but because the mechanism is so minimal, the chain is free enough when being thrown from one chainwheel to the other that it can behave in ways that aren't always obvious. If you watch the chain carefully, and think about it, this behavior can suggest design features to shop for in a new derailleur and adjustments you can make on your existing one that can make a big difference in shifting performance.

(In this article I'll assume that you already know how to do the basic adjustments like setting the stop screws and adjusting the cable. For help with these adjustments, see "Front Derailleur Adjustment" in the Repair Stand column in the February 1984 issue of *Bicycling.*)

Three Problems

The challenging part of a front derailleur's job is to get the chain from a small chainwheel to a larger one. (Unless you have basic adjustment problems or improper chainwheel spacing, going the other way is easy.) Shifting up can encounter three types of problems:

—You grind along, halfway shifted, the chain unwilling to climb up onto the teeth of the larger chainwheel.

—The chain climbs up but unships.

—The chain jams between the upper chainwheel's teeth and the inner cage plate of the derailleur, carving metal off both components as you continue to pedal and fumble with the shift lever.

I'll discuss the last problem first because it involves a design feature that you can select in a new derailleur but can't change in one you already own.

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast T.M.

April 1984 Volume 3, Number 2 $2.50

DESIGN CRITERIA

The Aluminum Rim: Design and Function

Chris Juden

Editor's note: Chris Juden was, until recently, the Design Engineer for Mistral Rims, which is a division of TI Sturmey Archer Ltd. Mistral rims are fairly new in the marketplace and, unfortunately, are not readily available at the retail level in America.

Mr. Juden presents some illustrative data on the relative strength and rigidity of a handful of popular clincher rims. He subjects these rims to a radial load (in effect, squashing them) and measures deflection. But a good wheel rim must be resistant to lateral loads as well. He is preparing a test jig for lateral and torsional loading of rims and hopes to present comparative results in a future issue of Bike Tech.

Any choice to be made in the selection of high-pressure wheel rims used to be simply one of materials: steel or aluminum. Today, however, the various advantages of aluminum alloy as a structural material are widely appreciated, and a cyclist must choose among a proliferation of rim designs. Many cyclists select rims on the strength of anecdotal evidence which asserts that a certain brand is "strong" or "rigid," terms easily confused and rarely quantified. This article discusses the important and sometimes conflicting features common to all rims and considers the pros and cons of different rim designs.

Tires and Rims

A logical approach to wheel design is to start at the ground and work up. After considering the bicycle's frame size and riding conditions, such as terrain, speed, supported weight, and achievable tire pressure, the appropriate class and width of tire is chosen. This decision in turn dictates rim diameter and width. The diameter inside the tire bead must match the rim's bead seat diameter, but this is the only measurement which

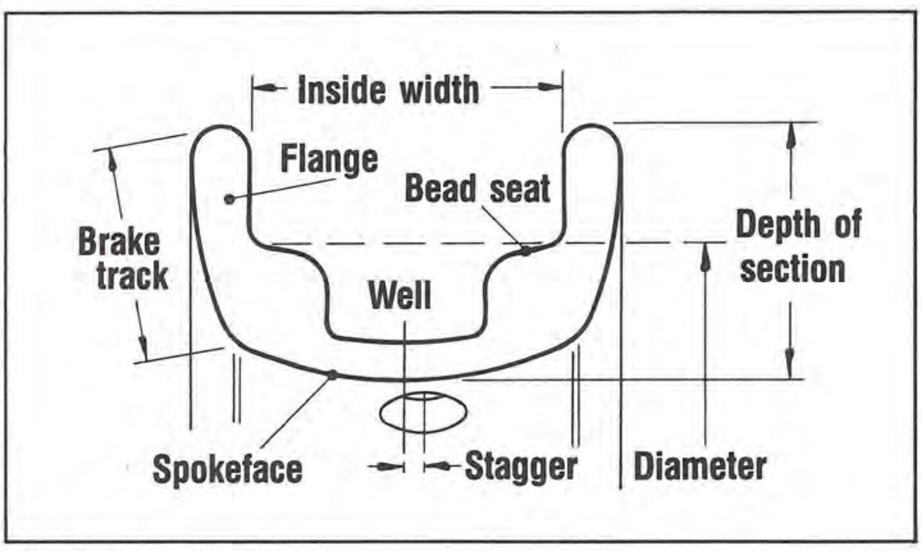


Figure 1: Rim Anatomy

IN THIS ISSUE

A simple formula involving the rim diameter D relates radial rigidity EI_R to the trace gradient, P/d:

$$EI_R = D^3 \frac{P}{d} \frac{(\pi^2-8)}{32\pi}$$

where E is the modulus of elasticity, I_R is the rim's moment of inertia, D is the rim's ETRTO diameter, P is the load, and d is the amount of rim deflection measured under the load. To avoid the weakened area around the valve hole, the rims were positioned in the Inston machine so that their valve holes were located 40 degrees from the loading point, corresponding to a position of zero bending.

A measure of the rim's strength was obtained from the same trace by calculating the bending moment M_S at the load P_S which produces a 0.5 percent reduction in diameter of the whole rim, in excess of linear elastic deflection:

$$M_S = \frac{P_S\ D}{2\pi}$$

Table 1 tabulates the values for strength and rigidity of the test rims. Figures 4 and 5 graph these values compared to the weights of the rims.

The information contained in this article appeared in an abbreviated form in the British journal Cycle Trader *in the January 1983 issue.*

DESIGN CRITERIA

Anodized Rims are More Rigid

Mario Emiliani

Chris Juden's article explains how a rim's cross-section can affect its rigidity, but there is another factor to consider. Many of the clincher rims made today are available with hard anodized surface finishes. These rims are different from ordinary rims in that a thick layer of aluminum oxide covers all surfaces of the rim. Since the modulus of elasticity (or stiffness, as it is sometimes called) of this oxide is about five times greater than the aluminum to which it is attached, the overall stiffness of the rim is increased. The precise amount can be calculated as follows.

We'll assume the wall thickness of the rim is a constant 0.0394 inches (1 millimeter), and that the thickness of the oxide layer is 1.023×10^{-3} inches (0.026 millimeters). (These dimensions were taken from one of the anodized rims in my article on rims in the October 1983 issue of *Bike Tech*.) This situation is shown in Figure 1.

The equation to calculate the increased stiffness is:

$$\delta = \frac{PL}{AE}$$

where δ = elongation, P = load, L = length, A = cross-sectional area, and E = modulus of elasticity.

The cross-sectional area of the aluminum (cross-hatched) and oxide (shaded) is 0.0372 inches^2 and 2.12×10^{-3} inches^2, respectively. The modulus of elasticity of the aluminum and oxide are 10 million lb/in^2 and 50 million lb/in^2, respectively. Assuming a strip of aluminum 2 inches long and a load of 1000 pounds, the aluminum elongates

$$\delta_{Al} = \frac{P_{Al}\ L}{A_{Al}\ E_{Al}}$$

$$= \frac{(1000\ \text{lb})\ (2\ \text{inches})}{(0.0372\ \text{in}^2)\ (10 \times 10^6\ \text{lb/in}^2)}$$

$$= 5.37 \times 10^{-3}\ \text{inches.}$$

The amount the oxide elongates must be equal to the amount the aluminum elongates because they are bonded together. Thus,

$$\delta_{oxide} = \delta_{Al} = 5.37 \times 10^{-3}\ \text{inches.}$$

Solving for the load needed to produce the same amount of elongation in the oxide layer gives,

$$P_{oxide} = \frac{\delta_{oxide}\ A_{oxide}\ E_{oxide}}{L}$$

$$= \frac{(5.37 \times 10^{-3}\ \text{in})(2.12 \times 10^{-3}\ \text{in}^2)(50 \times 10^6\ \text{lb/in}^2)}{2\ \text{inches}}$$

or $P_{oxide} = 285$ lb.

The total load needed to produce 5.37×10^{-3} inches of elongation when the aluminum and oxide are bonded together is,

$$P_{Total} = P_{Al} + P_{oxide}$$

$$= 1000\ \text{lb} + 285\ \text{lb} = 1285\ \text{lb.}$$

Solving for the modulus of elasticity needed to produce 5.37×10^{-3} inches of elongation when the aluminum and oxide are bonded together as a composite gives

$$\delta_{composite} = \frac{P_{Total}\ L}{A_{Total}\ E_{composite}}$$

where $A_{Total} = A_{Al} + A_{oxide} = 0.0393$ in^2, and $\delta_{composite} = \delta_{Al} = \delta_{oxide} = 5.37 \times 10^{-3}$ inches.

or

$$E_{composite} = \frac{(1285\ \text{lb})\ (2\ \text{in})}{(0.0393\ \text{in}^2)\ (5.37 \times 10^{-3}\ \text{inches})}$$

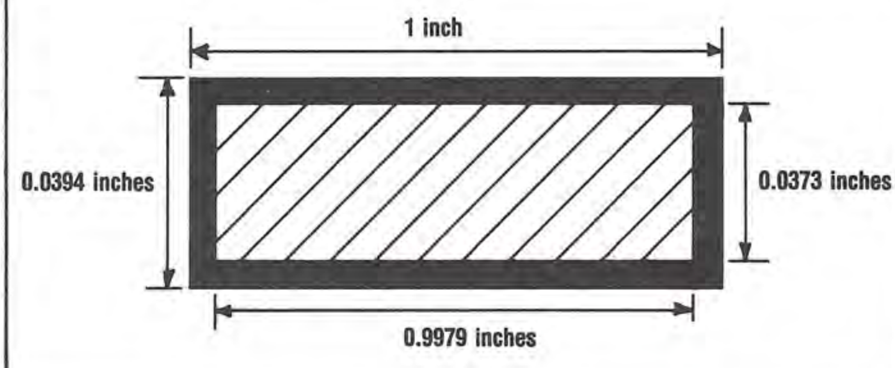
$$E_{composite} = 12.18\ \text{million psi.}$$

Thus the oxide layer increases the stiffness of the rim by over 21%. The rigidity of a rim is directly related to its cross-sectional shape (as you have seen), cross-sectional area, and modulus of elasticity. The equation governing this relationship is:

$$R = EI,$$

where R is the rigidity, E is the modulus of elasticity, and I is the moment of inertia, which incorporates both cross-sectional shape and area. So for the rim used in these calculations, its rigidity is 21 percent greater than it was if not hard anodized.

Figure 1: Cross section of a hard anodized piece of aluminum. Thickness of the oxide layer is exaggerated for clarity.



Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

June 1984

Volume 3, Number 3 $2.50

MATHEMATICAL ANALYSIS

The Effect of Winds on a Bicyclist's Speed

Osman Isvan

A cyclist's sense of wind can be very different from the actual wind conditions. The perceived or apparent wind is a combination of the relative air velocity felt by the moving cyclist and the additional air movement—the wind—that is sensed even when standing still. Air drag is determined by this combined wind.

The combination plays tricks with your perception, so that the true effect of wind—especially wind from the rear quarter direction—can come as a surprise. This article is a mathematical exploration of how wind affects the ground speed of the cyclist, and of how the cyclist will perceive the wind speed and direction from his moving vantage point.

We will assume in this article that the terrain is flat, the cyclist's power output is constant, and that all the cyclist's power is expended to overcome air drag. This constant power assumption introduces a unique feedback loop that affects the cyclist's final speed into the wind: a change in the wind speed and/or direction results in a change in the bike speed which, in turn, results in a change in the apparent wind, the actual input.[1]

Head Wind

Let's consider a specific case of a cyclist that generates a power P, and rides at a speed c, in still air. When riding into a

[1] *Tire rolling resistance and mechanical losses are assumed small and are not included in this discussion. This assumption lessens the accuracy of this discussion at low power outputs. However, as you'll see, final bike speed is normalized with respect to no-wind bike speed, so only the change with speed of these two drag factors is ignored at higher power outputs. Therefore, the results of this discussion become more accurate as power output increases.*

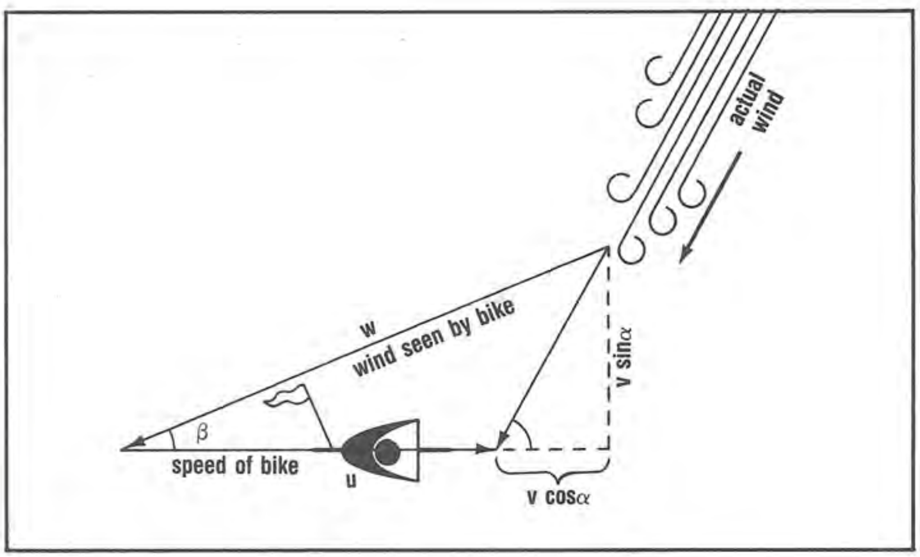


Figure 1: The velocity vector triangle.

IN THIS ISSUE

on areas of the paint that have been chipped or scratched. If the steel was not phosphate treated, a blister of paint will form around the scratch as the corrosion proceeds to eat the metal underneath the paint (see Figure 5).

Phosphating provides temporary protection between the time a frame is brazed and cleaned and when it is painted. The phosphate crystals also provide a good surface for paint to adhere to.

When painting steel for maximum corrosion protection, it must first be thoroughly cleaned of all surface rust and grease. Next, a phosphate coating is applied, followed by a coat of primer paint. The top coat is the final moisture barrier and, as we'll see in Part II of this article, is also the primary defense against bangs and scrapes that could put chips or scratches into this multi-layered protection.

Bibliography

Brubaker, G. R. and P. B. P. Phipps, eds. *Corrosion Chemistry.* Washington, D.C.: American Chemical Society, 1979.

Evans, U. R. *Corrosion and Oxidation of Metals: Scientific Principles and Applications.* London: Edward Arnold, Ltd., 1960.

Fraunhofer, J. A. and J. Boxall. *Protective Paint Coatings for Metals.* Redhill, England: Portcullis Press, 1976.

Hare, C. H. *Corrosion and the Preparation of Metallic Surfaces for Painting.* Federation Series on Coatings Technology, Unit 26. Philadelphia: Federation of Societies for Coatings Technology, 1978.

_____. *Anti-Corrosive Barrier and Inhibitive Primers.* Federation Series on Coatings Technology, Unit 27. Philadelphia: Federation of Societies for Coatings Technology, 1979.

The Chemistry of Steel Corrosion

The corrosion cell modeled in the main article is called a differential-aeration cell because there are different concentrations of dissolved gas at the two electrodes. This difference in oxygen concentration provides the impetus for electrons to migrate from the oxygen-poor anode under the water to the oxygen-rich cathode at the edges.

The rate of the redox reaction is influenced by the amount of dissolved salts in the water, its acidity, and by other impurities in the water. Dissolved salts aid the movement of ions by lowering the resistance of the electrolyte; acid in the water contributes H^+ ions which accelerate the reduction reaction at the cathode.

Let's consider some simplified chemistry of the corrosion process as two half-cell reactions:

The dissolution of iron in the water at the anode is,

$Fe \rightarrow Fe^{2+} + 2e^-$,

standard reduction potential, $\epsilon° = +0.41$ volts.

The reduction of oxygen (and some hydrogen in an acidic solution), is either,

$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$ (basic solution; $pH > 7$), $\epsilon° = +0.41$ volts

or,

$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (acidic solution; $pH < 7$), $\epsilon° = +1.23$ volts.

The full-cell reactions will be either,

$Fe + H_2O \rightarrow Fe^{2+} + 2OH^- + \frac{1}{2}O_2$,
$\epsilon° = +0.81$ volts

or,

$Fe + 2H^+ + \frac{1}{2}O_2 \rightarrow Fe^{2+} + H_2O$,
$\epsilon° = +1.64$ volts.

Since the reduction potentials are positive, these reactions will occur spontaneously. The higher potential in an acid solution drives the reaction more vigorously. But it is important to realize that the potential values are correct only for specific concentrations[2] of dissolved gases in the cells. At lesser concentrations, for instance, the corrosion reaction "runs" at a slower rate because the cell voltages are less. This means, then, that the pH of the electrolyte will have an effect on the cell potential value.

Once in solution, the Fe^{2+} ions will lose another electron,

$4Fe^{2+} + 4H^+ \rightarrow 3Fe^{3+} + 2H_2\uparrow$, (acidic solution)

$4Fe^{2+} + O_2 + 2H^+ \rightarrow 4Fe^{3+} + 2OH^-$, (basic solution).

The corrosion reaction end-product, rust, is formed by,

$4Fe^{3+} + 6O^{2-} + xH_2O \rightarrow 2Fe_2O_3 \cdot xH_2O$.

Other products form in lesser amounts, primarily FeO, Fe_3O_4, and FeO(OH).

The beginning and end products of this reaction are identifiable, but there are many intermediate compounds that form temporarily in the solution as the cell "runs," that have not yet been identified.

Other than the iron oxides, water, and various hydroxyls, heat and an increase in entropy are by-products of corrosion, the inevitable adjuncts of a system reverting to a more stable state.

[2]These conditions are specified in any introductory chemistry text in a Standard Reduction Potentials table.

MATERIALS

Can Surface Finish Affect the Strength of Your Frame? Part III: Chrome Plating

Mario Emiliani

There are numerous ways to protect steels from rusting. The easiest and most widely used method is painting. Paint acts as a barrier to oxygen and moisture, two of the necessary ingredients for corrosion. But paints can chip off easily, exposing steel to the atmosphere. Steel bicycle frames must live in a tough environment; inept mechanics (and even good ones!) can ruin hundred-dollar paint jobs with a slip of a tool, chains inevitably slap chainstays when riding over bumps, and dropouts can't retain paint. There isn't much that can be done to prevent marring the paint job with a tool, but the latter two problems can be prevented by coating these vulnerable areas of the frame with a harder and more chip-resistant substance, such as metal plating.

The application of a thin coat of another metal onto a steel frame is accomplished by a process called *electroplating.* Metals are hard, and electroplated metals adhere strongly to the base metal, since metal-to-metal bonds are formed. But the choice of metals is important. For example, it wouldn't make sense to plate dropouts with copper because it's too soft and would quickly wear off. In addition, copper tarnishes. Chromium, however, is a much harder metal and is therefore well suited for wear resistance. Chrome plate also remains bright and is easy to care for. Because of these advantages, chrome plating can be used as an alternative to paint on some areas of the frame.

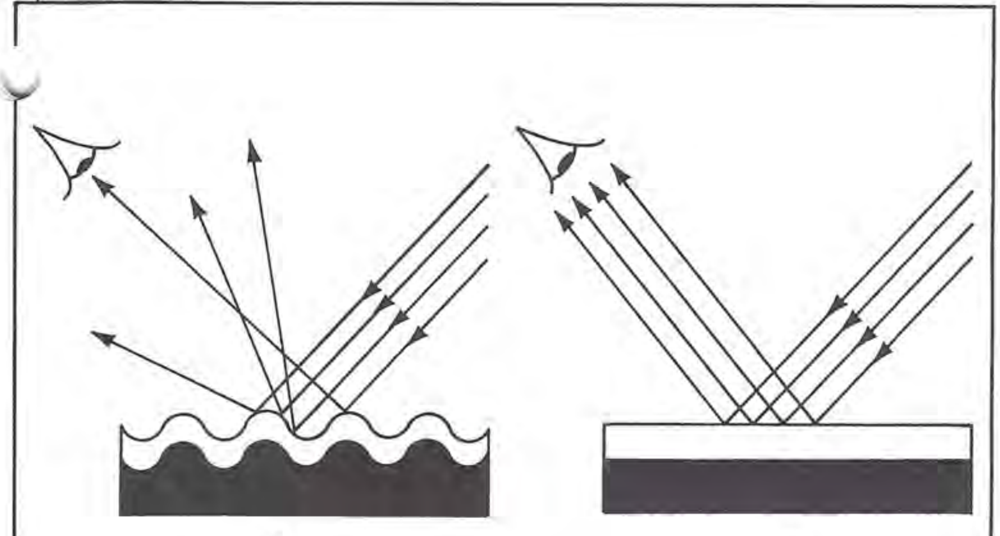


Figure 1: Chrome plate tends to reproduce the surface texture of the substrate. An irregular substrate results in a dull looking plate because some of the light rays aren't reflected back into your eyes (Figure 1a). Chrome plated onto a smooth substrate appears much brighter (Figure 1b).

George Retseck

Surface Preparation

Before a frame can be chrome plated, its surface must be thoroughly cleaned to provide a suitable substrate to which chromium ions can easily attach themselves. Thus the frame, or portions of the frame to be plated, must be free of rust, grease, and brazing flux for maximum adhesion. If this isn't done, the chrome plate will blister and/or peel off.

For cosmetic reasons, the surfaces to be plated must also be relatively smooth. Chrome tends to follow the contours of the surface to which it's plated. Figure 1a shows an irregular substrate that has been chrome plated. Notice how the surface of the plate matches the contours of the substrate. This can be a problem because a rough plated surface appears dull since some of the light hitting it isn't reflected.

But there is no need to have extremely smooth substrates, because very small surface irregularities actually improve adhesion by mechanically locking the metal plating onto the substrate and providing more surface area. Certain chemicals added to the plating bath can make the chrome plate smoothly over small surface irregularities by inhibiting plating on hilltops but allowing valleys to become filled. Bicycle tubes, if they haven't been particle blasted, gouged with files, or roughened by wire brushing, are normally quite smooth. So surfaces to be chrome plated need only be fine sanded and lightly buffed in preparation for plating.

The next step is to remove residual buffing compounds and other oils and greases. This is usually done by placing the surfaces to be plated in an agitated alkaline solution[1] which is maintained at about 60° C (140° F). The frame is left in the tank for about three minutes, then placed in an acid bath to remove oxides (rust, etc.). Typically, platers use dilute (~10 percent) sulfuric or hydrochloric acid at about 55° C (130° F). The immersion or tank time varies depending on the amount of cleaning needed, but usually runs between three to ten minutes. This process is known as *acid pickling*, and is widely used because it is cheap and effective. Between the alkaline and acid cleaning steps, there is usually a series of rinses to avoid contaminating the solutions.

Once the surface has been cleaned of oils and oxides, one or more metallic undercoatings can be applied before the chrome plating. Frames may be plated first with copper or nickel, or both, because these surfaces provide good adhesion and a smooth substrate for the chromium atoms to plate to, and they provide an extra measure of corrosion protection.

Electroplating

To enhance our understanding of the electroplating process, which is electrochemical in nature, let's take a quick look at the general nature of the electrochemical reaction. An ordinary dry cell battery (e.g., a flashlight battery) is a classic example of an electrochemical cell. The cell consists of an anode, a cathode, an electrolyte, and an electrical connection between the anode and cathode. If any one of these four ingredients is missing, electrochemical reactions won't occur.

The anode is simply the portion of the cell that dissolves (corrodes) under some action of the electrolyte. When this happens, each metal atom loses a few electrons[2] which are conducted to the cathode because the anode and cathode are in electrical contact. The result is a flow of electrons from the anode (or positive electrode) to the cathode (or negative electrode). A battery continuously produces a flow of electrons when electrical contact is made between the anode and cathode. When all of the anode has dissolved away, the battery is dead. This illustrates how electricity (or flow of electrons) is created by chemical reactions.

As more and more electrons flow to the cathode, an electrical charge imbalance develops in the electrochemical cell. That is, the cathode has an excess number of negatively charged electrons, while the electrolyte contains a large number of positively charged ions. Since oppositely charged particles attract each other, ions move toward the cathode and attach themselves to it in order to regain the electrons they lost at the anode. Thus, ions from the anode plate onto the surface of the cathode and remain there because they are now stable (i.e., they have equal numbers of protons and electrons).

Figure 2a shows a cross-sectional view of a dry cell battery. The cathode is the carbon core, the zinc case is the anode, and the electrolyte is a moist chemical paste (usually ammonium chloride). When contact is made between the anode and cathode, the zinc case begins to dissolve into zinc ions and two electrons (Fig. 2b). The electrons flow to the cathode, lighting up the bulb along the way. At the same rate the anode is dissolved, zinc ions plate onto the cathode (Figures 2c and 2d). This portion of the electrochemical reaction is called electroplating.

The reason why electrons must flow from the anode to the cathode is that the carbon rod is more *noble*, that is, it has a much lower tendency to dissolve into carbon ions compared to zinc. Stated another way, electrons flow from the anode to the cathode as water flows from high ground to low ground. It's not possible for the opposite to happen unless energy is added (i.e., water will go uphill only when pumped).

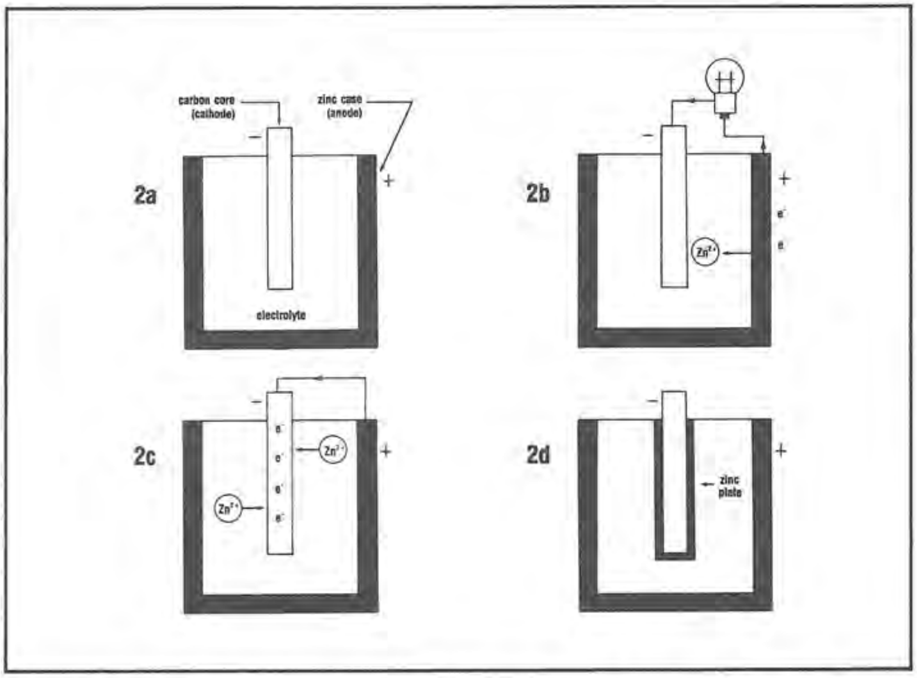
Electroplating occurs by the same principle as in the dry cell battery: metal ions form at the anode and migrate to the cathode where they plate. However, steel has a

[1] *Alkalines are the chemical opposites of acids.*

[2] *Atoms are made up of particles called neutrons, protons and electrons. Neutrons have no electrical charge, but protons have a positive charge and electrons have a negative charge. Stable atoms have equal numbers of protons and electrons to maintain electrical neutrality. Ions are atoms that have either extra or too few electrons, so they can have either a net negative or positive charge.*

greater tendency to dissolve (i.e., it's more anodic) than many of the metals that are commonly plated on it. For example, imagine we wanted to plate copper onto steel. If steel were the anode and copper the cathode, as in Figure 2a, steel (actually iron) would plate onto copper. But this is the reverse of what we want! To remedy this, copper is made the anode and the steel frame is made the cathode. This is done by reversing the direction of electron flow with the help of an external source of electricity. In other words, the steel frame is made more noble relative to the copper by adding energy to the electrochemical cell. This is what happens in principle.

In practice, anodes are sometimes used which don't dissolve to supply the cathode with metal ions. Instead, the metal to be plated on is contained in the liquid electrolyte in small concentrations. The anode, which can be a completely dissimilar metal (for example, lead), simply provides a surface whose energy is high enough to transform metal atoms in solution into metal ions (a process known as ionization). These ions then plate onto the steel cathode. The electrolyte must be replenished periodically with metal atoms. This is the case in copper, nickel, and chrome electroplating.



George Retseck

Figure 2: A simple dry cell battery. Electrons are represented by e^- and zinc ions by Zn^{2+}. When electrical contact is made between the anode and cathode, each zinc atom dissolves into a zinc ion and two electrons (Figure 2b). The electrons flow from the anode to the cathode and attract zinc ions to the cathode (Figure 2c). The zinc ions then plate onto the cathode to regain the electrons they lost at the anode (Figure 2d).

Copper Plate

Standard copper electroplating solutions tend to deposit copper at such a rapid rate that the plate is rough and likely to crack and peel. To obtain a smooth coating, copper is electroplated in two steps: first, a copper strike is applied; then an acid copper plate. The copper strike bath consists of a low concentration of copper ions in a cyanide-based electrolyte. This, coupled with low current densities[3] and short plating times, produces a controlled rate of metal deposition. The resulting plate of copper is about five microns thick and adheres well to steel. Now a thicker layer of copper can be plated on without cracking.

Acid copper plating baths consist of a copper sulfate electrolyte which contains a higher concentration of copper atoms than copper strike baths. Higher current densities and longer plating times produce a copper plate about four times thicker than the copper strike. After these steps, nickel or chromium can be plated on.

Nickel Plate

Nickel easily plates onto bare steel or copper-plated steel in a single step using a nickel sulphate solution. The current density is about the same as that used in acid copper plating, but the plating times usually are longer. Very high plate hardnesses can be obtained with nickel depending on how variables such as plating time, electrolyte temperature, and current density are controlled. Nickel plate is hard and durable, but it tarnishes easily and must be polished frequently to maintain brightness. For this reason, chrome is usually plated on top of nickel. When used as an undercoat for chrome plate, nickel plate is usually applied about 30 microns thick.

Chrome Plate

There are two varieties of chrome plating: hard chrome and decorative chrome. Hard chrome plates are very thick (from about 2.5 microns to 500 microns or more), very hard, and corrosion resistant. They have a low coefficient of friction and adhere strongly to the base metal so no metal undercoating is needed. These properties make hard chrome plate a great surface coating to use where sliding wear is a problem. For example, piston rings in automobile engines can last five times longer when hard chrome plated.

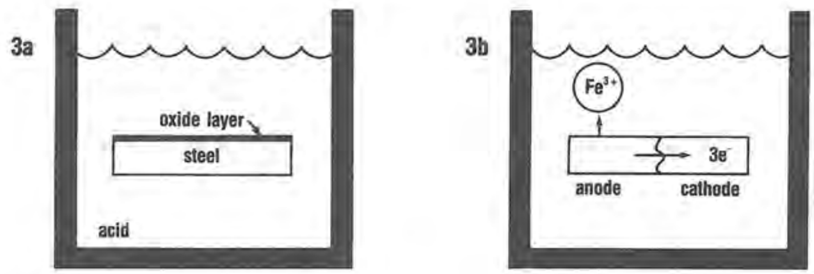
Decorative chrome is very similar to hard chrome plate except that it is much thinner (from about 0.13 to 1.3 microns) and, due to a slightly different plating procedure, is not quite as hard. For best results, decorative chrome should be applied over metal undercoating(s). This is the type of chrome plating found on bicycle frames. Decorative chrome plating requires an electrolyte (usually chromic acid) that contains a high concentration of chromium atoms and liquid catalyst to make the plating reaction occur. The anodes, usually made of an insoluble lead alloy, provide the surface upon which chromium atoms are ionized. Current densities are about three times higher than for nickel plating, and plating times are very short.

Table 1 shows cleaning and plating sequences which may be performed on bicycle frames. Please keep in mind that this information doesn't reflect the exact procedures used on bicycle frames. Actual cleaning and plating operations can be much more complicated.[4] For example, the rinses between cleaning and plating can require several steps. Also, there are many plating solutions to choose from, as well as literally hundreds of chemical additives to slow the rate of metal deposition, enhance brightness, and level small surface irregularities. These variables, in addition to current density, plating time, and bath temperature make electroplating more of an art than science.

Incidentally, by altering the chemical conditions of the plating process, it is possible to obtain chrome plate of different colors. The most familiar non-silver chrome plate is black chrome.

[3] *Current density is the amount of electricity per unit area placed on the cathode to ensure a good deposition of metal ions.*

[4] *For a lengthy discussion of metal cleaning and electroplating procedures, see the* Metals Handbook, *9 th edition, volume 5 (The American Society of Metals, 1982).*



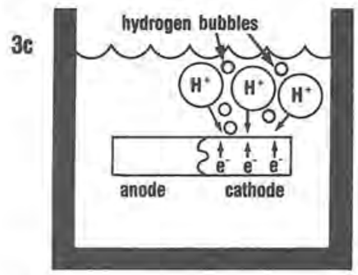


Figure 3: When a piece of steel is placed in acid, the oxide layer dissolves away, exposing small anodic and cathodic areas (Figure 3b). Iron atoms are dissolved into iron ions (Fe^{3+}), and three electrons per atom move to the cathode. Hydrogen ions in the acid plate onto the cathode and combine to form hydrogen gas (Figure 3c).

Table 1 Steps Involved in Chrome Plating (Copper, Nickel, Chrome Plate)

buff	copper plate
degrease	rinse
rinse	nickel plate
pickle	rinse
rinse	chrome plate
copper strike	rinse
rinse	buff (if necessary)

Problems with Electroplating

Unlike painting, electroplating and associated cleaning methods can actually detract from the strength of a frame.[5] Several problems can crop up if the plating process is done carelessly. One of the worst problems occurs at the start of the plating process: cleaning the frame in the acid pickling tank.

Why are acids used to clean frames? Acids contain certain chemical species that aggressively attack and dissolve iron oxides, which is good. But after the oxides are removed, the acid proceeds to corrode the bare steel. This occurs because steel (like all other metals) has microscopic portions of its structure that have a greater tendency to dissolve than others. These anodic areas are bonded to cathodes, so they are in electrical contact. The dilute acid solution used in the pickling process is a great electrolyte; dipping a frame into the pickling tank completes the formation of thousands of electrochemical cells, so corrosive attack begins over the entire surface of the frame.

As the corrosion action begins, iron atoms begin ionizing at the anodes, so there has to be some sort of plating action at the cathodes (see Figure 3). Certain constituents of the acid and the water used to dilute the acid begin plating onto the cathode surface. These constituents combine, with the help of excess electrons at the cathodes, to form gases, water molecules, and different types of ions. The concentration of gas at the cathodes increases with time, and eventually forms gas bubbles. These bubbles rise and new ones begin forming at the cathodes. We'll discuss the significance of this gas a little later.

As the anodic areas continue to corrode, the acid becomes progressively richer in iron and other metal ions and atoms (some alloying elements in the steel are ionized, some aren't). The acid prevents any of these iron or metallic ions from plating onto the cathodic surfaces, so they remain in the electrolyte. It's apparent, then, that the pickling process literally eats away the steel surface, thinning the tubes. The amount of thinning varies considerably depending on the condition of the steel and the strength and exposure of the pickling bath, but losses in wall thickness of up to three percent[6] are not uncommon. And if the pickling solution is allowed to get inside the tube, then wall-thickness reduction could easily be six percent.

Whatever the percent reduction in tube thickness, there will be a corresponding increase in stress on that part of the frame. And as Part I of this series showed, small reductions in wall thickness become increasingly significant as the thickness of the tube decreases. So it's important to minimize reductions in wall thickness to acceptable values (probably fractions of one percent) by cleaning the frame prior to pickling so the frame spends minimum time in the pickling tank, and making sure that the insides of the tubes aren't pickled. A sure sign that a frame stayed too long in the pickling tank is a roughened surface on it caused by preferential corrosion (i.e., some areas are more anodic than others).

A related problem is *pitting*. Pitting usually occurs during *electrolytic pickling*. In this process an electrical current is passed through the component (or anode) to accelerate pickling. When small pieces of oxide break off, exposing bare metal to the acid, the metal dissolves at a rate faster than normal and a pit is produced.

Hydrogen Embrittlement

As I said earlier, one of the reactions that takes place at the cathode during pickling is the formation of gases. Usually, hydrogen is the gas evolved at these sites. Single hydrogen atoms[7] are very small and can easily be absorbed by steels. If enough hydrogen is absorbed, the steel can suffer a drop in mechanical properties[8] because the steel becomes embrittled.

Nobody knows exactly how hydrogen embrittles steel, but here are two theories. Since hydrogen is such a small atom, one theory says that it can take up positions between iron atoms; the iron atoms become bonded to hydrogen atoms instead of neighboring iron atoms (see Figure 4). The bond strength between iron and hydrogen atoms is assumed to be less than that between just iron atoms, so cracks can form more easily in the steel at low stresses.

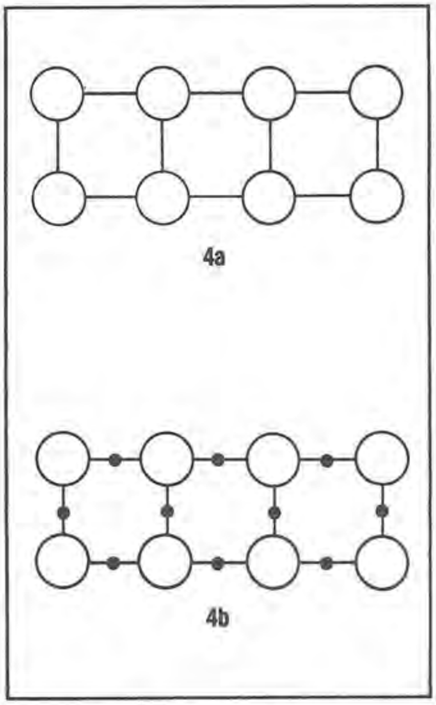
The actual strength of metals (and most other crystals) is only a fraction of what it theoretically should be. This phenomenon puzzled metallurgists for a long time until it was theorized (and later proved) that atom-sized defects are present in crystals (these defects make metals malleable). Hydrogen atoms absorbed by steel diffuse and eventually come to rest at places where they fit in well; a second theory suggests that they collect at crystal defects (see Figure 5). Hydrogen atoms residing at these defects combine to form hydrogen gas. This gas can't move around as easily as single atoms can, so a pressure is exerted on the surrounding iron atoms. This local pressure pries the steel apart, so only small external stresses are needed to form cracks. Whatever the actual mechanism, hydrogen embrittlement begins in the pickling tank.

[5] Paint itself is harmless, but some chemicals and procedures used to prepare and clean steel for painting, like phosphating, baking, and chemical stripping can, in theory, affect the strength of frames.

[6] Reference 4, p. 13.

[7] This is in contrast to hydrogen gas, which has two hydrogen atoms bonded together.

[8] Mechanical properties include tensile strength, yield strength and ductility.



George Retseck

Figure 4: Iron atoms in steel. When hydrogen enters steel, they may take up positions between the iron atoms as depicted by the dark circles in Figure 4b. The bond strength between iron atoms will be reduced, increasing the likelihood that low level stresses will crack the steel.

The threat of hydrogen embrittlement is also present during electroplating. If the plating process is less than 100 percent efficient (i.e., all the electrical energy does not go into plating metal ions onto the cathode), some fraction of electrical energy is used to create unwanted chemical species, like hydrogen. Chrome plating has a very low plating efficiency (about 20 percent; this is why the current density is so high in chrome plating), so a lot of hydrogen will be produced. Copper and nickel can be electroplated with much higher efficiencies, but small amounts of hydrogen will still be formed. Hydrogen formed during electroplating can then diffuse either directly into the base metal, or through the undercoatings to the base metal. And if pickling and electroplating solutions enter tubes, hydrogen will be formed on two surfaces instead of one. It is these multiple exposures to hydrogen (similar to multiple particle blastings) which can compromise the mechanical properties of steel tubing.

The presence of hydrogen bubbles at the cathode can also compromise the aesthetics of chrome plate. These bubbles prevent the chromium ions from plating smoothly and securely onto the cathode. This results in small pits in the plate which can be removed only by stripping the old plate and starting over. To avoid this, wetting agents are added to the electrolyte to promote detachment of bubbles from the cathode.

Corrective Measures

The entire electroplating process, from acid pickling to chrome plating, takes approximately one hour. In this time span, a great deal of hydrogen can be absorbed. The steels most susceptible to hydrogen embrittlement have yield strengths of about 200,000 psi or more. Since the steels used to make bicycle frames have yield strengths of about 100,000 psi or less, hydrogen embrittlement should be less of a problem. However, the amount of time a component is exposed to hydrogen isn't the only factor in determining how much hydrogen is absorbed; surface finish, microstructure, and residual stresses caused by brazing also play a role.

Tests have shown that the more crystal defects in the steel there are, the more hydrogen is absorbed. So there appears to be a relationship between the two, even though this mechanism of embrittlement stated earlier is conjecture. Frames that have been particle blasted prior to plating are likely to pick up more hydrogen than those that weren't because sandblasted steel exhibits more crystal defects.

Similarly, hydrogen may tend to segregate to areas of the frame that have been distorted by brazing. So it's possible that frames can absorb too much hydrogen, especially since thin tubes are more quickly saturated with hydrogen than thick tubes. If it can be determined that frame tubes absorbed a lot of hydrogen (an analysis that can be done, but that is extremely expensive), corrective measures can be taken.

A low temperature heat treatment will reduce hydrogen's embrittling effect. Low temperature baking is sufficient to remobilize hydrogen atoms, which can then diffuse out of the steel. Since temperatures are low, the structure of the steel isn't changed appreciably from its original (before plating) properties. Although there are no established standards for heat treating hydrogen-embrittled bicycle frames, baking in the range of 200° C - 240° C (390° F - 465° F) for three to four hours is suitable.[9] Electroplaters I've talked to who plate bicycle frames are aware of hydrogen embrittlement but don't perceive it as a problem. As a result, they don't bake the frames after plating.

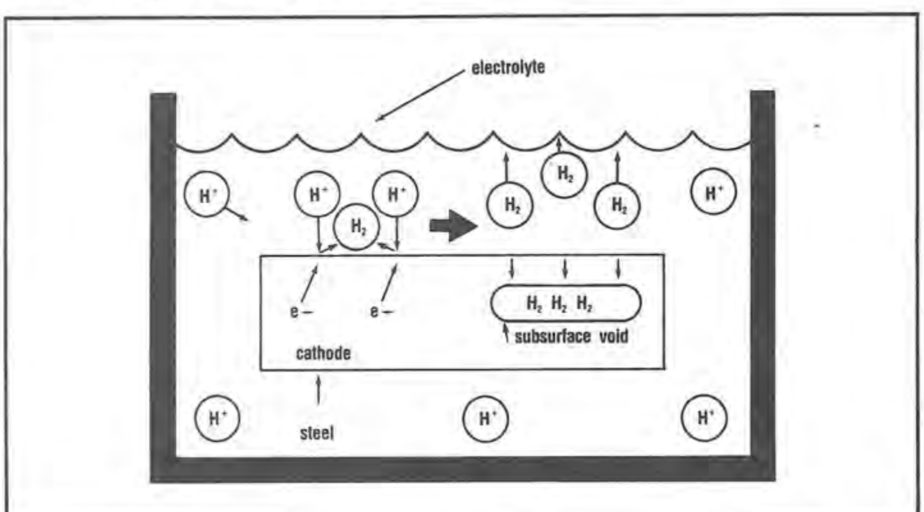
Stripping

If a poor job was done electroplating copper, nickel, or chrome, the plate can be stripped off by immersing the plated areas in acid. And like pickling, stripping can be done electrolytically to save time. But acids must again be used; their concentration and type vary, depending on the metal which must be removed. Suppose, for example, a frame were nickel plated. Concentrated nitric acid can be used to strip it, but this will also attack the steel tubes. If chrome must be removed, the metal undercoat may be attacked. The frame may then have to be treated with yet another acid to prepare it for new chrome plating.

Redoing a bad plating job or refinishing a frame can result in further reductions of wall thickness if the plate closest to the steel is removed, and/or if stripping acids enter the tubes. In addition, more hydrogen can be picked up by the steel during stripping and subsequent recleaning and replating. This might lead to dangerously high levels of hydrogen in the steel.

[9] *Reference 4, p. 81.*

Figure 5: Hydrogen ions in the electrolyte pick up electrons at the cathode and form hydrogen atoms. These atoms can either combine to form a gas bubble on the surface of the cathode, or diffuse into the steel.



George Retseck

Corrosion

Some framebuilders go to great pains to make sure that pickling and plating acids don't enter the tubes. If chainstays are being chromed, they ask the electroplater not to immerse the bottom bracket area. When forks are plated, air holes are brazed shut. But if the entire frame is chrome plated, or if the framebuilder doesn't explicitly instruct the electroplater, it's likely that pickling and plating acids will enter the tubes. Once these acids are in the tubes they're difficult to get out. Rinses between pickling and plating must be done carefully to ensure that the insides are thoroughly cleaned. The problem here is that the rinses may not get inside the tubes as far as the electrolyte did because thin tubes are hard to flush out unless there are bleed holes. Any acid residues left inside the tubes eventually dry out and leave behind small crystals of acid salts.

If water then enters the tubes (either as rain or humid air), the acid salts left in the tubes will redissolve to form a new liquid or paste electrolyte. The concentration of this acid will be higher than that used in electroplating because the ratio of acid salt to water is higher. The stage is set for tubes to corrode from the inside out. This can be a particularly dangerous situation since it's not apparent when areas of a tube have thinned to unsafe dimensions. Figure 6 shows what can happen to the inside of a chrome plated tube.

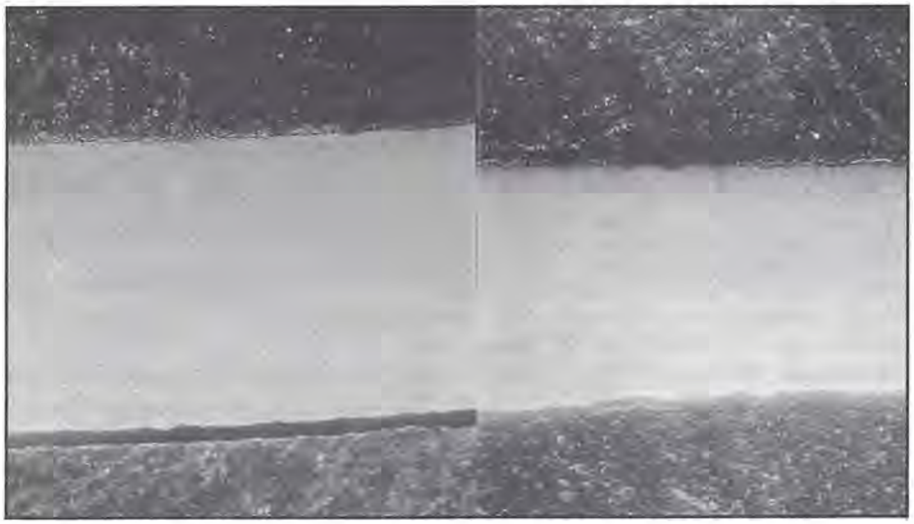


Figure 6: These photos were taken from two locations inside the head tube/down tube joint of a high-quality frame several years old. They are cropped together to show the differences in tubing thickness at each location. Plating solutions entered the tubes when the lug was chromed and were not completely flushed out. As a result, severe corrosion occurred, causing an estimated 20 percent difference in wall thickness between the two locations pictured. 40 times magnification.

Microcracks

Chromium is a more reactive metal than iron, but exposure to oxygen in air forms a very thin but tough oxide layer on its surface, which protects the remainder of the chrome from corroding. However, you may have noticed chrome plating that appears to be rusting. This isn't because the chrome layer has corroded. Rather, moisture has passed through the chrome plate and has rusted the steel beneath.

Chrome plate can have a porous or *microcracked* structure during application depending on the plating process used. The reason why the plate becomes cracked during application isn't known. Perhaps it is due to the way the plate grows, or maybe the crystal structure of the chrome changes during plating, causing it to contract. Perhaps plating cracks in an effort to relieve its surface tensile stresses. Cracks in thick plates are usually restricted to the surface because cracks that form closer to the substrate are filled by plating on top. But thin, decorative plating is usually cracked all the way through and it allows oxygen and water to reach the base metal, causing it to corrode.

This is one reason why metal undercoatings are used. But the choice of undercoatings is not accidental. Nickel is used because it is anodic to chromium and thus corrodes instead of the chrome. Since iron is anodic to nickel, corrosion that makes it past the nickel plate means the steel will corrode. Corrosion that has reached the steel causes the chrome to blister. Copper plate beneath nickel helps improve nickel's corrosion resistance and thus protects the steel better.

For maximum corrosion resistance then, steel frames should be copper, nickel, then chrome plated. However, bicycle frames are frequently only nickel and chrome plated or just chromed with no undercoats at all. This eliminates the two-step copper plating process, perhaps to save money, or maybe because manufacturers and builders feel that frames don't need the extra corrosion protection. Just chrome plate may be acceptable, as long as the plate is thick and isn't cracked all the way through. Figure 7 shows a thick, crack-free plate with no undercoat.

Fatigue

Fatigue is a process whereby metals fail due to repeated application of stresses. Sometimes the stresses are well below the yield strength of the metal, but stresses near surface or structural discontinuities can be very high. This may produce a crack which can grow and cause eventual failure. Bicycle frames, as noted in other *Bike Tech* articles,[10] are subjected to repeated stresses, so nothing should be done to frames to decrease their fatigue resistance.

However, it's been shown that chrome plated surfaces decrease the fatigue strength of steel.[11] This happens because the plating contains residual tensile stresses which stretch the surface of the base metal. When this happens, the base metal develops its own surface tensile stresses, so chrome plating can have the opposite effect of peening by locking in rather than relieving these stresses. As stated earlier, these residual stresses may work themselves out by cracking the chrome plate.

In addition, cracks in the chrome plate can act as stress raisers which may grow into the base metal. However, fatigue tests that I'm aware of have not utilized samples with copper and/or nickel undercoatings,[12] so test results can be applied only to those frames with no undercoatings, such as in Figure 7.

Summing Up

The most important concern in the plating process is to keep the pickling and plating acids from getting inside the frame tubes. If those acids get in, the tubing will be thinned twice as much, hydrogen will be absorbed on both surfaces, and, unless these harsh chemicals are completely rinsed out, they can lead to severe corrosion problems later on. These problems can be avoided if only the front fork or the chainstays are chromed — the air holes can be brazed shut and it's not too difficult to keep the bottom bracket shell out of the pickling and plating tanks. But if the entire frame is chrome plated, it is

---

[10] *See "Can Surface Finish Affect the Strength of Your Frame? Particle Blasting, Part II,"* Bike Tech, *February 1984, and "What Is Fatigue?"* Bike Tech, *October 1982.*

[11] Modern Electroplating, *F. Lowenstein, Ed. (New York: John Wiley and Sons, Inc.) p. 128.*

[12] *Reference 11, p. 128.*

Figure 7: This is a cross section of a seat stay from a Japanese frame. The chrome is plated directly on top of the steel. The plate is about 16 microns thick, and is not cracked. 1435 times magnification.

inevitable that these acids will seep in unless special care is taken to seal the head tube, seat tube, bottom bracket, and all the brazing air holes.

It may seem excessive to bother plating copper and/or nickel on frames if a crack-free chrome plate can be put on. This may have been the reason why the frame in Figure 7 was not undercoated. However, a slapping chain can put nicks in the thin chrome plate on the chainstay and expose the steel below. The same is true if chrome is worn off the dropouts. Thus it would be worthwhile to have a thick, hard nickel plate beneath the chrome to help resist wear and corrosion.

If frames are chrome plated with no undercoating, their fatigue resistance will be lowered. But is this drop in fatigue strength enough to cause concern? Maybe, maybe not; but to be on the safe side, I don't recommend chroming high stress areas of the frame like the front fork. I also suggest for better fatigue resistance and corrosion protection that chrome be done on top of a copper and nickel undercoat. The chrome plating on the frame in Figure 7 may not be indicative of all bicycle chrome work, but I suspect that it is common practice, especially in Europe, to plate only with chrome.

Interestingly, the latest (1984) Columbus tubing catalogue lists some guidelines for chrome plating and pickling their tubing. This is the first time, to my knowledge, that any of the bicycle tubing manufacturers has offered any such information. Columbus does "not recommend" that their tubes be chrome plated. They also recommend that their tubes be pickled in a mild three to four percent solution of sulfuric acid at a temperature of 40° C (104° F). This is a much less aggressive solution than that recommended by other sources.[13] These recommendations indicate to me that Columbus is concerned about the dangers of thinning and pitting their tubing in a strong pickling bath.

Columbus doesn't indicate whether chrome plating voids the warranty on their tubing, but you can be sure that they'll not warrant any tube that fails from the effects of pickling and/or plating. Thus it is important to be aware of the problems inherent in the electroplating process so that the already thin tubing used in bicycle frames will not be thinned, corroded, or embrittled with hydrogen any more than the process requires.

Acknowledgement

I'd like to acknowledge the following people for their assistance with this article: Bob Beecroft, Beecroft Cycle Works; Antonio Colombo, Columbus SpA; Eric Hjertberg, Wheelsmith Fabricators, Inc.; and Angel Rodriguez, R + E Cycles.

Postscript

Steel tubing undergoes a reduction in wall thickness at each step of the frame building process. The high temperatures of brazing cause oxidation of the tube's surface. Particle blasting and pickling both take their toll on tubing wall thickness. Chrome plating can create surface tensile stresses and, if the plating bath electrolyte gets inside tubes and isn't thoroughly rinsed out, the residual acids will certainly cause the tube to rust on the inside.

Any additional particle blasting or pickling of the frame, to remove a defective finish or as the first step in refinishing, removes still more metal. All three procedures, even when done with great skill, will reduce tubing wall thickness, leave residual stresses and corrosive acids in the tubing, pit the tubes, and/or embrittle the tubes with hydrogen.

I believe the major question that has arisen from this series of three articles on the effects of surface finish on frames is whether or not frame tubing was ever designed to be subjected to particle blasting, pickling, and chrome plating. Most frame tubing is quite thin to begin with; how much thinner can it get before its structural integrity is compromised? And when do the stress raisers put into tubing become too large or too numerous?

Most frame tubes appear thick enough to withstand some abuse they might not have been designed to take. This is fortunate because particle blasting, pickling, and chrome plating are cost-effective, time-saving, and aesthetically pleasing steps in frame building that few builders can do without. I would caution against the use of these procedures when working with ultra-thin tubing like Reynolds 753 and Columbus Record and KL, but even then, if these procedures are done properly, few problems should arise. But disregard or ignorance of the potentially damaging effects of particle blasting, pickling, and chrome plating could set a frame up for early and possibly dangerous failure.

[13] *Reference 4, p. 69.*

Subscribe Now to BIKE TECH...

Bicycling Magazine's Newsletter for the Technical Enthusiast

#61064

YES!

NAME ______

ADDRESS ______

Send me one year (6 issues) of BIKE TECH, and bill me for just $14.97.

CITY ______

BIKE TECH™
Emmaus, PA 18049

STATE ______ ZIP ______

Canadian orders add $3.00. Other foreign add $6.00 for sea mail, $10.00 for air mail.


BICYCLE
guide
AUTUMN 1984•$2.50
EXCLUSIVE
OLYMPIC
COVERAGE!
Carpenter & Twigg
One-Two
Mark Gorski's
Olympic Diary
TOURING
Almost Paradise
ROAD TESTS
Schwinn
Trek
Lotus
Cannondale
FIRST LOOK:
CAMPAGNOLO'S
New Components
SPECIAL PREMIER ISSUE
RACING USA

BICYCLE guide

Volume 1, Number 1

AUTUMN 1984

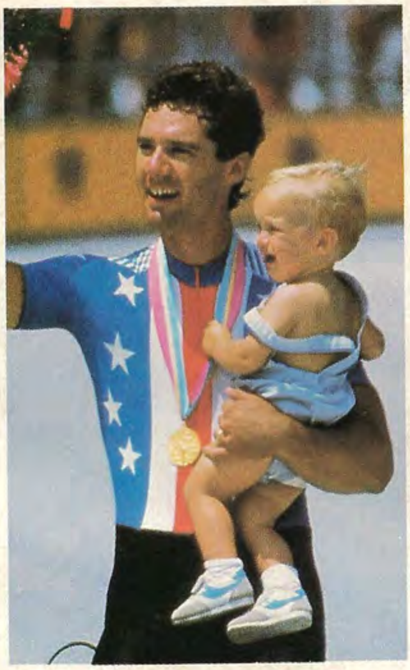
SPECIAL OLYMPIC SECTION

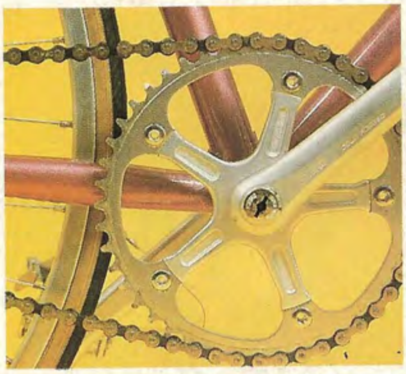
ROAD TESTS

OUT AND BACK

TRAINING

TECHNICAL PAGES





THIS MONTH

COVER Connie Carpenter. Photography ©1984 Annie Leibovitz/Contact

STEEL FRAME TUBING

By Mario Emiliani

What Are the Differences?

Wood, plastic, aluminum, titanium, carbon fiber/epoxy composites, and steel have all been used to make bicycle frames, but with the exception of aluminum, only steel has had great commercial success. Gary Klein and Cannondale have given credibility to aluminum as a frame material by building fine frames at a reasonable price. The Teledyne Titan titanium frameset had brief success, but titanium is expensive and requires special handling and equipment, including a vacuum welding chamber, to join. At various times, O. F. Mossberg, Composite Sport, and Exxon made frames with carbon fiber/epoxy composites, but these space-age materials require special joining methods and have design limitations (you can't make a fork out of the stuff) and are, at this time, impractical.

But steel is, by far, the most common frame material. Steel is inexpensive and it makes a frame that is strong, rigid, and light enough to suit most riders. Perhaps most importantly, it is easy to work with. Steel is easy to machine, and it can be joined by methods learned in shop class with equipment that is affordable.

However, not just any steel is used; there are only a few varieties which are suitable. But you wouldn't get this impression by looking at all the tube decals on bikes at the local bike shop. Nearly every tubing manufacturer has its own code or buzz-word to make its product appear different and more worth your money.

Decals you're likely to spot on popular brands of bicycles will say cryptic things like "Mangaloy 2001," "Columbus SLX," "Reynolds 531ST," "High Tensile," and "Prestige Cr-Mo." These codes can indicate the manufacturer, the type of steel, and the weight or intended purpose of the tubing. For example, Reynolds is a tubing manufacturer; 5-3-1 is, according to Reynolds, the approximate ratio of certain alloying elements added to the steel (I've never been able to determine the elements in question, however); and ST means that the tubeset is intended for a touring bicycle.

Sometimes the decals are designed to look nice and sound catchy without conveying much information. For instance, the Tange "Mangaloy 2001" decal sounds pretty futuristic, but it's derived from the words manganese alloy. As far as I know, "2001" means nothing.

Actually, the differences between the steel in the highest quality hand-built frameset and the discount store special are not that great; it is the addition of small amounts of other elements to the "base" steel that makes one steel stronger and more expensive than the next. It's also a matter of how the tubes are made; there are cheap ways and expensive ways to make tubing. It's a safe bet, though, that in the same price range, the steel tubing from which various bicycles are made will be of comparable quality.

Table 1 lists the codes and generic names of common bicycle steels. These codes are a numbering system devised by the American Iron and Steel Institute (AISI) consisting of four numbers to identify steels. These numbers are broken into two pairs. The first pair indicates the principal alloying element(s). For example, Tange Champion No. 2 is an AISI 4130 steel with the 4 indicating it's a chromium-molybdenum steel and the 1 indicating it contains a total of about one percent chromium and molybdenum.

The second pair gives the average carbon content in hundredths of one percent. So the "30" in 4130 means that it contains an average of 0.30 percent carbon. With this chemistry, a steel is given the catchy phrase "Cr-Mo," or "Chrome Moly."

The first two AISI steels listed in Table 1 are called plain carbon steels because they contain only carbon and manganese as intentional alloying elements. Steels that contain a total of about one to 4.5 percent chromium, molybdenum, nickel, and other elements (in addition to carbon and manganese), are termed "alloy steels." Both 31XX and 41XX are alloy steels.

Table 2 lists the specific elements that are added to steels. The main function of these alloying elements is to increase strength. In addition, they control the strengthening process when steel is heat treated. A stronger steel can withstand a higher level of stress so less of it is needed in a frame. This means that the wall thickness of the tubes can be decreased, which results not only in a lighter frame, but also enhanced ride comfort because thinner tubes make a bicycle feel more lively and responsive.

Alloying elements also help maintain the steel's strength during brazing. Joining steel tubes requires heating the tubes to between 1200-2100 degrees F, depending on the brazing process. Such temperatures will alter the steel's internal microstructure and weaken it in certain areas, but alloying elements such as chromium, vanadium, nickel, niobium, and molybdenum reduce steel's sensitivity to heat and retard this tendency.

One alloying element that is always present in steel is carbon, because it's the mixture of iron and carbon that makes steel. Small amounts of carbon add a lot of strength to iron. But too much carbon makes steel brittle and less ductile (i.e. likely to deform before breaking). Ductility is important because you don't want your frame tubes to break suddenly in an accident. Rather you want

Table 1 ***AISI STEELS USED FOR FRAME TUBING***

STEEL	TYPE	MAJOR ALLOYING ELEMENTS
10XX	plain carbon	up to 1% manganese
15XX	plain carbon	1.00–1.65% manganese
31XX	nickel-chromium	1.10–1.40% nickel, 0.55–0.90% chromium
41XX	chromium-molybdenum	0.80–1.10% chromium, 0.15–0.25% molybdenum

XX represents the carbon content in hundredths of one percent.

Table 2 ***AVERAGE COMPOSITIONS OF SELECTED FRAME TUBING***

BRAND	%CARBON	%SILICON	%MANGANESE	%CHROMIUM	%MOLYBDENUM	%OTHER	AISI NUMBER
Columbus SLX, SL, SP, PL, PS, Record, KL, GT, OR (off-road)	0.22–0.28	0.35 Max.	0.50–0.80	0.80–1.10	0.15–0.25	—	4130
Ishiwata 015, 017, 019, 022, 024, EXO-L, EXO-M, EXO-H, EX-F, EX-T, MTB-D	0.28–0.33	0.20–0.35	0.40–0.60	0.80–1.10	0.15–0.25	—	4130
Ishiwata MAGNY-V, MAGNY-X, EXO-V, EX-V	0.10	0.29	1.40	—	—	0.050 vanadium 0.042 nobium 0.022 aluminum	—
Reynolds 753T, 753R, 531PRO, 531C, 531ST, 531BMX	0.23–0.29	0.15–0.35	1.25–1.45	—	0.15–0.25	—	—
Super Vitus 980, Vitus 181	0.22 max.	0.5 max.	1.5 max.	0.15 max.	0.10 max.	0.15% nickel, max.	—
Tange Prestige, #1, #2, #3, #4, #5, MTB (Mountain Bike)	0.33	0.35	0.85	1.2	0.25	—	4130
Tange Mangaloy 2001	0.08	0.03	2.23	—	—	—	—

This information was compiled from sales catalogues and correspondences with manufacturers and importers. All of the steels listed contain impurity levels of both phosphorus and sulfur.

Table 3 ***AVERAGE MECHANICAL PROPERTIES OF SELECTED FRAME TUBING***

BRAND	BEFORE BRAZING			AFTER BRAZING (at recommended temp.)			RECOMMENDED BRAZING TEMPERATURE, °F
	TS, psi	YS, psi	%E	TS, psi	YS, psi	%E	
Columbus SLX, SL, SP, PL, PS, Record, KL, GT, OR (Off-Road)	128,000	107,000	10	—	—	—	1290, max.
Ishiwata 015, 017, 019, 022, 024, EXO-L, EXO-M, EXO-H, EX-F, EX-T, MTB-D (Mountain Bike)	113,790	106,675	5	109,200	—	6	about 1562
Ishiwata MAGNY-V, MAGNY-X, EXO-V, EX-V	106,675	99,560	—	93,750	—	—	2012, max.
Reynolds 753T, 753R	168,000	134,000	8	145,600	—	—	1202, max.
Reynolds 531PRO, 531C, 531ST, 531BMX	116,500	100,800	10	108,000	89,600	—	1562–1742
Super Vitus 980, Vitus 181	120,890	103,120	10	—	—	—	1562, max.
Tange Prestige	175,660	—	10	—	—	—	1382, max.
Tange #1, #2, #3, #4, #5, MTB (Mountain Bike)	129,570	—	10	98,430	—	12	about 1562
Tange Mangaloy 2001	112,650	—	6	94,090	—	18	about 1967

This information was compiled from sales catalogues and correspondences with tube manufacturers and importers. TS = tensile strength; YS = yield strength; E = elongation.

the frame damage to occur as cracking or buckling which can be easily spotted before catastrophic failure occurs. So to ensure adequate ductility, the carbon content is kept below 0.4 percent.

Table 3 lists the mechanical properties of the steels in Table 2 before and after brazing at the manufacturers' recommended brazing temperature. But there is one problem with this data—it is not always reliable. I have tested different brands of bicycle tubing over the years, and found that the data is usually exaggerated, so take it with a grain of salt. It's clear, however, that the strength of tubing both before and after brazing varies widely, depending on the type of steel. Confusing the situation further, test methods are not always realistic. However, don't be too concerned about small discrepancies; the tubes are strong enough in normal use.

I've also determined that it is not easy to pinpoint where in a tube this strength reduction occurs; its location depends on how hot the tube got when it was welded or brazed. Knowing the magnitude and location of the strength reduction is important, because if it drops too far in the wrong part of the tube, then the frame may not hold up to the normal forces of cycling.

For those readers unfamiliar with the strength terms given in Table 3, here is a quick summary: tensile strength is a measure of how much force per unit of area, or the stress, it takes to break the tube; yield strength is the stress needed to permanently deform the tube a specific amount; and percent elongation, a measure of the tube's ductility, is the amount the tube stretches relative to a portion of its original length.

Frames are made from either seamed or seamless tubing. Generally, inexpensive discount store bikes are made from seamed tubing because it's cheap to make. Most seamed tubes are made of low-strength plain carbon steel; these tubes must be thick walled to compensate for their low strength, but they are adequate for a bicycle that features a bargain-basement price rather than quality.

A seamed tube begins life as a flat strip of sheet steel which is rolled into the shape of a cylinder and then welded along its length. The steel always suffers a drop in strength in the vicinity of the welded seam that only additional processing can correct. This seam is easy to spot and is the best way to identify this type of tubing. Figure 1 shows how seamed tubes are made, and the resultant seam.

Most bicycles that you'll see within the covers of this magazine will be made from seamless tubes. In fact, all tubesets listed in Table 4 are seamless. Seamless tubes are more expensive than seamed tubes because they are made from better quality steel and they are manufactured by costlier methods. Seamless tubes are made either from solid bars of steel or else fabricated like seamed tubes with additional processing.

A seamless tube made from bar stock starts out red hot (between 1700-1800 degrees F). It is first pierced and drawn over a pointed steel bar called a mandrel. The tube is kept hot as it's next drawn between a series of dies until its dimensions are close to that of the finished tube. The tube is then softened by heat treating, cooled, cleaned to remove surface oxides, and then cold drawn to its final dimension. Figure 2 illustrates the drawing process.

Cold drawing also involves placing different sized mandrels inside the tube and drawing it between dies. But cold drawing is done at a temperature below 1300 degrees F. As the final drawing operations take place, the tube is given a series of low temperature heat treatments to refine its microstructure. Lastly, the tube is cleaned and polished.

The second way to make a seamless tube is a hybrid of the seamed and seamless methods. Sheet metal is rolled and welded into a seamed tube, and then cold drawn to flatten out the seam. A final heat treatment refines the entire tube's microstructure so that it's impossible to distinguish from genuine seamless tubing.

Tubing made from strip costs less than tubing made from bar stock because the machinery, mandrels, and dies needed to hot-pierce and draw solid bars of steel are very expensive. Several good quality tubesets are made from strip, including the Magny-X and Magny-V tubesets from Ishiwata. Also, a domestic company, True Temper, located in Memphis, Tennessee, has recently begun supplying Schwinn and Trek with tubes for use in some of their production bicycles. The seamed and heat treated True Temper tubes are every bit as good as the seamless tubes from Europe; True Temper makes its tubes from strip simply to be price competitive.

Most high-quality seamless tubes go through one final manufacturing step that has evolved just for bicycles. They are internally "butted"— made thicker at the ends than in the middle— while their outside diameters remain constant. Butting is done for two reasons: it puts metal where it is needed the most—at the joints where stresses are highest—and it saves weight. Butting is accomplished by placing a mandrel shaped like the desired inside dimensions into the tube. Both tube and mandrel are then drawn through a series of dies so that the inside of the tube molds to the shape of the mandrel.

Once butting is completed, the mandrel must be removed. According to TI Reynolds Limited, the standard industry practice is to put the tube into a machine called a reeler. This device spins the tube between inclined rollers which increase the tube's diameter just enough to allow removal of the mandrel.

The high-quality butted tubeset of a few years ago had only double butted, single butted, and straight gauge tubes. But some tubing manufacturers now feel that a frame needs different amounts of reinforcement in different areas. So to optimize frame design, tubing now comes in five different butting arrangements: none, single, double, triple, and quadruple. A tube without a butt has constant wall thickness; it is called a straight gauge tube. A single butted tube is thicker at one end; double butted tubes are thicker at both ends (each end of the same thickness); triple butted tubes have ends of unequal thickness; and quadruple butted tubes have ends and midsections of varying thickness. Figure 3 shows each of these butting configurations.

Figure 1:
Seamed tubes are made by rolling a flat strip of steel into the shape of a tube and then butt welding the joint. The finished tube has a noticeable seam, characteristic of inexpensive tubing.

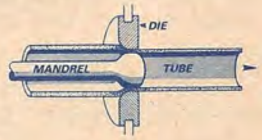


Figure 2:
Wall thicknesses and outside diameters are reduced by drawing tubes through a series of dies and mandrels.

Table 4 lists the wall thicknesses and weights of many popular brands of tubing. I've also included approximate guidelines for the type of cycling each tubeset is best suited and the limitations on rider weight. The tube thicknesses given in Table 4 correspond (from left to right) to the dimensions of the tubes shown in Figure 3.

Bicycle manufacturers take pride in displaying tubing manufacturers' decals on their bicycles that say the frame tubes are butted. But sometimes the decals aren't entirely accurate. Take, for example, the decal found on a frame built with an Ishiwata EX tubeset. It says, "Guaranteed built with EX Cr Mo Triple Butted Tubes." This statement implies that all the tubes are butted, and triple butted at that. In reality, only the top and down tubes are triple butted. The seat tube and steering tube are single butted, and the fork blades, chainstays, seatstays, and head tube are straight gauge. This mix of butted tubes is standard for most high quality tubesets, but check Table 4 for variations.

"Taper Gauge" is another buzz-word bantered about in conversations about frame tubing. This term, used by TI Reynolds to describe the cross-sectional dimensions of their fork blades, implies that the wall thickness of the blades tapers. But it doesn't; the wall thickness of a Reynolds fork blade is constant. Rather, the tubes are tapered prior to becoming fork blades.

The tapering is done to assure that the wall thickness of the fork blade is constant after one end is reduced in diameter. Otherwise, a tube of constant wall thickness would be made into a blade with a wall thicker at the narrow end. So to make fork blades with a constant wall thickness, you must start out with a tube which has a gradual decrease in wall thickness over the length of the tube. Hence, a

Table 4 ***WALL THICKNESSES AND TUBESET WEIGHTS OF SELECTED FRAME TUBING***

BRAND	Thickness, in millimeters								TUBESET WEIGHT, in grams	TYPE(s) OF CYCLING[2]	MAXIMUM RIDER WEIGHT[2] in pounds
	TOP TUBE	DOWN TUBE	SEAT TUBE	HEAD TUBE	FORK BLADES	CHAIN STAYS	SEAT STAYS	STEERING COLUMN[1]			
Columbus Record	0.5	0.5	0.5	0.8	0.9	0.5	0.5	2.5/1.65	1610	track record attempts	125
Columbus KL	0.7/0.5/0.7	0.7/0.5/0.7	0.5/0.7	0.8	0.9	0.5	0.5	2.5/1.65	1670	road racing and time trials	125
Columbus SLX	0.9/0.6/0.9	0.9/0.6/0.9	0.6/0.9	1.0	0.9	0.7	0.7	2.5/1.65	1959	road racing	150
Columbus SL	0.9/0.6/0.9	0.9/0.6/0.9	0.6/0.9	1.0	0.9	0.7	0.7	2.5/1.65	1925	road racing	150
Columbus SP	1.0/0.7/1.0	1.0/0.7/1.0	0.7/1.0	1.0	1.05	1.0	1.0	2.5/1.65	2295	racing/ touring	200
Columbus OR	1.0/0.7/1.0	1.1/0.8/0.9/ 1.2	0.7/1.0	1.0	1.10	1.0	1.0	2.7/1.65	2580	off-road	all weights
Ishiwata 015	0.6/0.4/0.6	0.6/0.35/0.6	0.7/0.4	1.0	1.0	0.8	0.6	2.2/1.60	1595	record attempts	125
Ishiwata 017	0.7/0.4/0.7	0.7/0.4/0.7	0.7/0.4/0.7	1.0	1.0	0.8	0.6	2.2/1.60	1855	record attempts	150
Ishiwata 019	0.8/0.5/0.8	0.8/0.5/0.8	0.8/0.5	1.0	1.0	0.8	0.6	2.2/1.60	2015	road racing	150
Ishiwata 022	0.9/0.6/0.9	0.9/0.6/0.9	0.9/0.6	1.0	1.0	0.8	0.8	2.2/1.60	2185	racing/ touring	175
Ishiwata EXO-L	0.8/0.5/0.4/ 0.7	0.8/0.5/0.4/ 0.8	0.8/0.5/0.4/ 0.7	1.0	1.0	0.8	0.8	2.2/1.60	1950	road racing	150
Ishiwata EXO-M	0.9/0.6/0.5/ 0.8	0.9/0.6/0.5/ 0.9	0.9/0.6/0.5/ 0.8	1.0	1.0	0.8	0.8	2.2/1.60	2125	racing/ touring	175
Ishiwata EX-F	0.9/0.6/0.7	0.9/0.6/0.7	0.9/0.6	1.0	1.0	0.8	0.8	2.2/1.60	—	road racing	175
Ishiwata EX-T	1.0/0.7/0.8	1.0/0.7/0.8	1.0/0.7	1.0	1.0	0.8	0.8	2.2/1.60	—	racing/ touring	200
Ishiwata MAGNY-V	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7	1.0	1.0	0.8	0.8	2.5/1.60	2235	racing/ touring	200
Ishiwata MAGNY-X	0.9/0.6/0.9	0.9/0.6/0.9	0.9/0.6	1.0	1.0	0.8	0.8	2.5/1.60	2420	touring	200
Ishiwata MTB-D	1.2/0.9/1.2	1.2/0.9/1.2	1.2/0.9	1.5	1.2	1.2	1.0	2.7/1.60	—	off-road	all weights
Reynolds 753T	0.7/0.3/0.7	0.8/0.5/0.8	0.7/0.3	1.0	1.0/0.5	0.6	0.5	1.55	1750	pursuit/time trials	150
Reynolds 753R	0.7/0.5/0.7	0.8/0.5/0.8	0.7/0.5	1.0	1.0/0.5	0.6	0.5	1.55	1800	road racing/ cyclo cross	150
Reynolds 531PRO	0.7/0.5/0.7	0.8/0.5/0.8	0.7/0.5	1.0	1.0/0.5	0.6	0.5	1.55	1900	road racing/ time trials	150
Reynolds 531C	0.8/0.5/0.8	0.9/0.6/0.9	0.8/0.5	1.0	1.0/0.5	0.8	0.5	2.3/1.60	2050	road racing/ track/cyclo cross	150
Reynolds 531ST	0.8/0.5/0.8	1.0/0.7/1.0	0.8/0.5	1.0	1.2/0.8	0.8	0.9	2.3/1.60	2200	touring	175
Reynolds 501	0.9/0.6/0.9	0.9/0.6/0.9	0.9/0.6	0.9	0.9	0.9	0.9	2.3/1.60	2300	general purpose	200
Reynolds 501 All-Terrain	1.0/0.7/1.0	1.2	1.0/0.7	0.9	1.4/0.9	1.2	0.9	2.3/1.60	2900	off-road	all weights
Super Vitus 980	0.8/0.5/0.8	0.9/0.5/0.8	0.8/0.5	1.0	1.0	0.8	0.6	2.5/1.60	1805	road racing	150
Vitus 181	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7	1.0	1.2	0.9	0.8	2.5/1.60	2241	road racing/ touring	175
Tange Prestige	0.7/0.4/0.7	0.7/0.4/0.7	1.2/0.9/0.6	1.0	0.9	0.6	0.6	2.5/1.60	1987	road racing/ track	150
Tange Champion #1	0.8/0.5/0.8	0.8/0.5/0.8	0.9/0.6/0.9	1.0	1.0	0.8	0.8	2.5/1.60	2220	road racing/ track	175
Tange Champion #2	0.9/0..6/0.9	0.9/0.6/0.9	0.9/0.6/0.9	1.0	1.0	0.8	0.8	2.5/1.60	2290	road racing/ track/touring	200
Tange Champion #3	1.0/0.7/1.0	1.0/0.7/1.0	0.9/0.6/0.9	1.0	1.0	0.8	0.8	2.5/1.60	2360	touring	200
Tange Champion #4	0.9/0.7	0.9/0.7	0.9/0.7	1.0	1.0	0.8	0.8	2.5/1.60	2270	touring	175
Tange Mangaloy 2001	1.0/0.7/1.0	1.0/0.7/1.0	1.0/0.7/0.85	1.0	1.0	0.9	0.9	2.7/1.60	2415	road racing/ touring	200
Tange MTB	1.0/0.7/1.0	1.2/0.9/1.2	1.0/0.7	1.0	1.1	1.0	1.0	2.6/1..60	3207	off-road	all weights

This information, except for the column on the far right, was compiled from sales catalogues and correspondences with tube manufacturers and importers. It's possible to special order some tubes in different thicknesses and tapers for almost every tubeset listed in this table. The tubes listed here are the ones you're most likely to encounter.

Butting configurations are read as follows:

plain gauge	*0.9*
single butted	*0.9/0.6*
double butted	*0.9/0.6/0.9*
triple butted	*0.9/0.6/0.8*
quadruple butted	*0.9/0.6/0.7/0.8*

1. *In addition to being single butted, the steering columns for each of the following tubesets contain straight or helical reinforcing ribs to better resist torsional (twisting) stresses: COLUMBUS RECORD, KL, SLX, SL, SP, OR; ISHIWATA 015, 017, 019, EXO-L, EXO-M, MTB; SUPER VITUS 980, VITUS 181; TANGE PRESTIGE, TANGE CHAMPION #1–4, TANGE MTB.*

2. *The "TYPE(s) OF CYCLING" and "MAXIMUM RIDER WEIGHT" columns are intended to be only rough guidelines. Each of these can vary depending upon frame size, expected frame life, desired performance characteristics, weight, etc.*

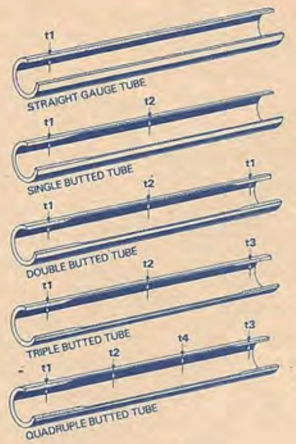


Figure 3:
Butted tube cross sections.

"taper gauge" tube.

Some fork blades listed in Table 4 appear to be single butted, but those numbers represent their dimensions prior to tapering. As supplied to a bicycle manufacturer, they are straight gauge.

Bicycle frame tubes are joined by welding, brazing, or braze welding (also known as fillet brazing). Most BMX framesets are welded, as are several brands of off-road klunkers. But most good road bicycle frames are joined by brazing. And most tandem frames are joined by the braze welding technique. I'll leave the discussion of welding for another article.

Brazing bonds tubes together by heating the joint to a suitable temperature, then introducing a non-ferrous filler metal. The filler metal, usually copper- or silver-based, must melt at a temperature above 840 degrees F, but below the melting point of the base metal (i.e., the tubes). Molten brazing alloy is sucked into and distributed throughout the joint by forces developed by close-fitting surfaces, called capillary forces. Only lugged frames can be joined together by brazing since only they have the required close-fitting surfaces.

Braze welding is similar to both brazing and welding. Like brazing, braze welding uses filler metal to bond the tubes together, but the filler metal is built up around the joint like a weld bead rather than being distributed into it by capillary forces. Braze welding simply involves getting the joint hot enough so that the filler metal will stick to the tubes and hold them together. Unlike welding, the base metal is not melted. Copper-based filler metals are preferred over silver-based alloys because they are easier to build up into a bead.

Each tubing manufacturer recommends a maximum brazing temperature, as shown in Table 3. They feel that higher temperatures will jeopardize the strength of the steel tube. If this and a few other recommendations are followed, the manufacturers guarantee their tubes against failure. But many, if not most, experienced bicycle manufacturers and framebuilders neglect recommended brazing temperatures. They've discovered that tubing failures are uncommon, even when they braze at temperatures well above the recommended limit. Another reason manufacturers exceed the recommended limits is to make production more flexible and economical. If they were to conform to the recommended temperatures, they would have to use a silver brazing alloy which contains 45 - 50 percent silver and is just too expensive. It's really the skill and technique employed in the framebuilding process that determine the integrity of the brazed joint.

However, TI Reynolds won't distribute their ultra-thin 753 tubing to any frame manufacturer that won't follow recommended brazing techniques. Reynolds specifies a brazing temperature of 1200 degrees F or below for this tubing. They're concerned that higher temperatures will create a weakened area in the tube.

Figure 4 shows the results of some work that I did a few years ago comparing the location of the softened zones produced by brazing at about 1200 and 1700 degrees. Notice that when brazing at 1200 degrees, the tube is softened up to about 7 mm behind the lug, while the higher temperature softens the tube at a point about 22 mm behind the lug. In each case the softened zone is normally well within the butted section of the tube.

But it's possible that when sizing tubes, some framebuilders may have to cut off a good portion of the butted section. If they then use a high brazing temperature, the softened area may form past the butted section in the tapered section or even thinner straight gauge section of the tube. This puts a weak spot in the tube in an area of the frame that may not be able to take the stress.

Conforming to Reynolds' temperature restrictions requires brazing 753 with low-temperature, high-priced silver brazing alloys. But some framebuilders prefer to use these alloys on all frames they build, even when they don't have to. There are several reasons why they choose to do so, although there is less validity in some than others:

—Lower temperatures cause less distortion of the tubes, so less post-brazing frame alignment is required. This is true, but a competent framebuilder knows how to minimize joint distortion at his or her preferred brazing temperature by deft use of the brazing torch or else compensate for it either by pre-brazing misalignment or by periodic alignment during construction. Even so, most frames need a small amount of cold-setting to be in proper alignment.

—It's easier to braze with silver brazing alloys. This is true; silver brazing alloys flow better into a joint and there are fewer problems during brazing and with post-brazing cleanup.

—Silver brazed joints are stronger. This is not true; joint strength depends on factors other than just the type of filler metal. The main factor is where the tubes soften, which is temperature dependent. Silver brazing places the soft spot closer to the joint.

—Frame repairs are easier to make on frames that have been silver brazed. This is true; less heat is needed to remove damaged tubes.

—Low-temperature silver brazing is a sales feature. No doubt about this. Many hand-built frames are regarded as jewelry by their owners. To say that the frame is silver-brazed adds to the mystique. It is also easy to strike fear into a customer with talk of the dire effects of heating steel tubes to orange-hot when brazing with brass filler. But Figure 4 clearly shows that higher temperatures only push the softened zone farther back from the joint and actually detract less from the yield strength of the tube ahead of the softened zone. This is not a problem if the right tubeset is selected.

Most frame tubing is not nearly as finicky as Reynolds 753. In fact, the only reason that 753 needs special care is that it is so thin, not because it is any special sort of steel. (Table 2 shows that 753 is the same alloy as 531; 753 just has a different heat treatment.) Columbus Record tubing, for example, is just as hard to work with because its walls are also very thin.

All tubing listed in Table 3 is plenty strong if the tubing gauges are sized correctly for the intended rider. This is why I included the tubeset weights and maximum rider weights in Table 4. A frame built from Tange Prestige tubing will give a great ride to a sub-150-pound rider, but the same frame in the hands of a 200 pounder will be too flexible and may actually fail in use. Heavy riders need heavy gauge tubing.

Since all the steels are very similar to each other, it is hard to pick favorites. Yet people who have ridden a number of bicycles made from different brands of tubing often claim that one brand of tubing is more rigid than another. This is not true; rigidity of steel tubing is a function of its outside diameter, wall thickness, and length. And since the outside diameter of tubing is fairly standard, a frame's rigidity will depend only on the thickness of the tubing and frame geometry.

Thicker tubes resist bending simply because there's more metal there; short tubes bend less because forces act over shorter distances. So for equal lengths, gauges, tapers, and frame geometries, a frame made of Columbus SL tubing will be as rigid and ride identically to the same frame made from Ishiwata 022.

Even though many new types of tubing have been introduced in recent years, the steels used to make them are nearly the same as those used for the last 40 years. I think that is surprising, considering how much more we know about steels today. What has changed over the years are the types of heat treatment and the manufacturing processes used to impart impressive before-brazing strengths.

Reynolds 753 and Tange Prestige tubesets are examples of tubes whose chemical compositions are the same as sister tubesets (Reynolds 531 and Tange Champion, respectively), but have different microstructures because of different heat treatments. Their increased strength allows them to have very thin walls. However, you may notice that Tables 3 and 4 list other tubesets with walls as thin or thinner than these (Columbus Record and Ishiwata 015, for example), which aren't any stronger than thicker grades in the same quality product line. These tubes have proven themselves to be reliable performers (within the limits of their intended use), so the justification for producing exotic tubing like Reynolds 753 and Tange Prestige out of standard alloys with current manufacturing techniques can be called into question.

The main drawback with the current crop of high quality frame tubing is that they get soft in certain areas after brazing.

I propose a solution to this situation. It's not possible to eliminate the problem, but the loss in strength of a brazed frame tube can be minimized by simply switching to a new alloy. The alloy could be developed from scratch and designed specifically to have high strength and maximum resistance to softening. The next best thing would be to pick an alloy off the shelf, so to speak, which has properties as close to the desired ones as possible. Either way, whichever tube company first takes the plunge and markets such new tubing will truly have something to advertise and a valid reason for designing a whole new set of decals.

Naturally, I have an idea about which alloy I think will work best, and since I can't keep it a secret, I'll go ahead and spill the beans. The alloy is AISI 4335 (or Mario's tubing, if you prefer). It's not quite off-the-shelf (AISI 4340 is), but it's close enough that an existing alloy could be modified if the demand were sufficient. My hypothetical 4335 is a notch up from 4130 in that it contains another alloying element, nickel. Its average chemical composition would be: 0.35 percent carbon, 0.55 percent manganese, 1.80 percent nickel, 0.80 percent chromium, and 0.25 percent molybdenum. And if I had the liberty to design an alloy from scratch, I'd also throw in small amounts of titanium, vanadium, and niobium.

How strong would this steel be? Well, it's stronger than 4130 for all heat treatment conditions. In addition, such a steel could be produced with a ductility of over ten percent. Remember that softening can't be eliminated completely; rather, the object of the game is to raise the strength of the tubing and lower the percent decrease in strength caused by brazing. Thin tubes made from such an alloy could be joined with inexpensive, higher melting temperature brass alloys and still retain excellent strength throughout the joint.

Of course, this idea will go for naught if the tubing companies don't produce this new tubing in desirable wall thicknesses and tapers. This is an important concern of many framebuilders, and is why they prefer some brands of tubing.

Aside from new alloys, heat treatments, and a greater selection of tapers and gauges, it's hard to improve upon steel frame tubing. What else can be done? Well, Columbus recently introduced a new type of tubing that they claim has an advantage. SLX is their latest line of tubing; they call it a "super-butted" tubeset. What Columbus did was put in five helical reinforcing ribs along the entire length of the butt inside four SL tubes: the down tube, seat tube, and chainstays (actually the chainstays aren't butted, but the ribs are supposed to be long enough so that they're still there after the tubes are cut to length).

Columbus says that the ribs reinforce one of the most stressed regions of the frame—the bottom bracket—and reinforce the area where the brazed-on front derailleur attaches. This seems reasonable, but the helical ribs stand out only 0.35 mm (0.0138 inches) from the inside of the tube. That's not much, so whether they really do what they're advertised to do remains to be seen. Time will tell if it was a good idea; it's certainly an expensive idea. An SLX tubeset costs almost twice as much as an SL tubeset.

So there you have it; the latest in tube technology, and my suggestions on where the future of steel tubing should be headed. I wouldn't be at all surprised if new tubesets are available by the time you read this; if they offer any significant differences over the current lot of tubing, I'll be sure to give you an update. □

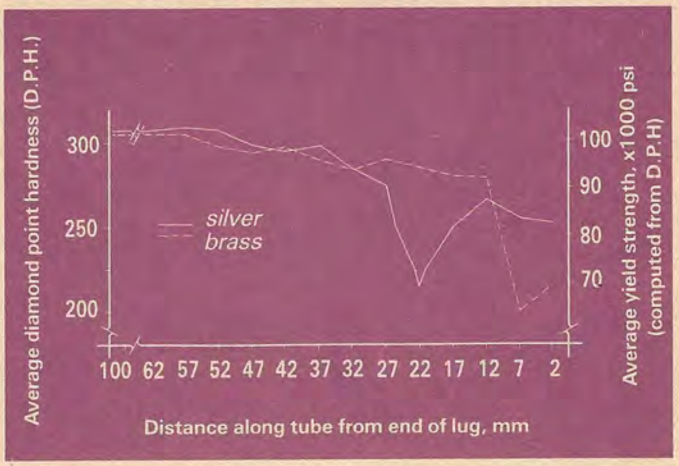


Figure 4:
Samples of Reynolds 531 tubes were brazed with brass and low-temperature silver brazing alloys. Each brazing method produced a temperature gradient in the tube, with the higher heat needed to braze with brass producing a temperature gradient farther down the tube. The critical temperature range for steel to soften and lose strength is between 1100-1300 degrees F, so the softened zone produced by brass brazing is well behind that produced by silver brazing. Hardness tests were conducted to determine the loss in strength along the tubes. The results are graphed.

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

Fall 1985 Volume 4, Number 4 $3.00

COMPONENTS

The Next Unfair Advantage

The Browning Bicycle Transmission

Angel Rodriguez

I remember the first lesson I learned with my new ten-speed many years ago. "You have to ease up on the power to make the shift," the shop man kept saying. But I couldn't. I was shifting because I was slowing down to go uphill, and if I slowed down any more I wouldn't be going forward, and then shifting would be impossible. I finally mastered that paradox, but it took some mental anticipation and physical coordination. The shifting usually took only a fraction of a second, and if I made the shift in time, everything was fine. But heaven help me if I missed the shift.

Eventually I tried racing. And I quickly discovered the difficulty of shifting while riding uphill in a pack. I didn't have even a fraction of a second for a shift. If I sat down to let off the power, it was all over, and if I didn't shift it was all over too. What a deal. I often wished for something that would allow me to shift whenever I wanted, under full power, and with no possibility of missing a shift. What a dream.

The derailleur system, the most widely used transmission on today's bikes, is the source of these shifting problems. After all, pushing the chain off one chainwheel, in hopes that it lands on another, is a primitive, brute-force approach. Derailleurs were first conceived in France around 1934, and have remained virtually unchanged ever since. Their disadvantages are well known. A recent *Bike Tech* article stated: "conventional

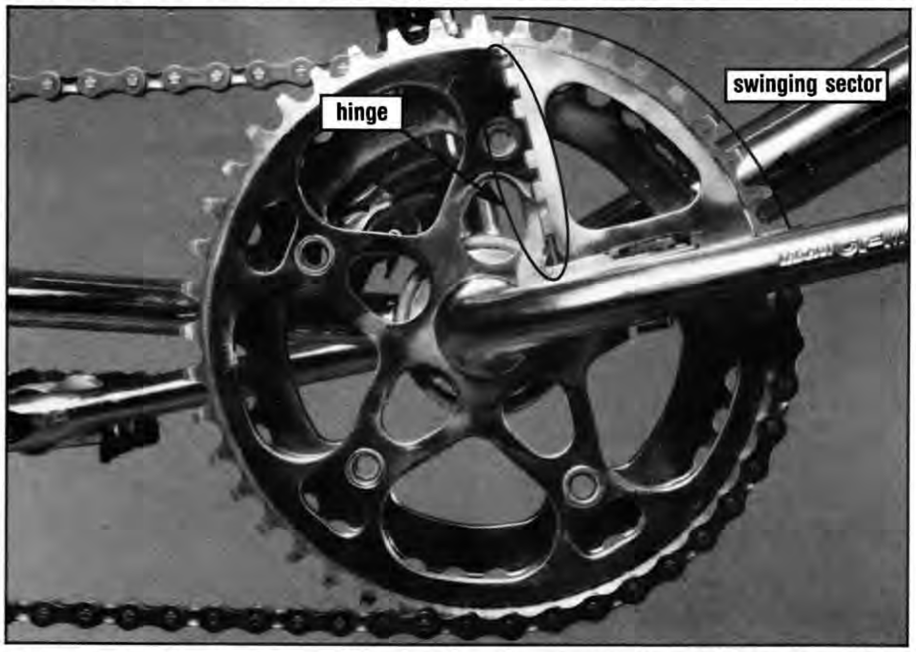


Figure 1: The Browning two-speed transmission, shown here in the middle of a downshift. Note chain engaged on both large and small rings simultaneously. The "ring cassette" assembly is comprised of two chainrings, hinge, and swinging sector.

IN THIS ISSUE

Note: Due to space limitations, the test report on bicycle headlights, originally scheduled for this issue, has been postponed to the next issue.

Figure 9: Two views of the main test machine at Octo Company. The fixture holds the bike upright and applies a load at the seat. A hydraulic motor drives the crank axle from the left side through universal joints. A friction brake attached to one of the rear rollers applies resistance. By measuring rotational speed and torque at the friction brake, power through the transmission is calculated.

Figure 10: Bowed teeth on the swing sector for the ATB/touring model are needed to accomodate wide chain angles due to shifting on the multi-gear freewheel.

SPECIAL REPORT

American Frame builders: A Status Report

An In-Depth Survey of Twenty-Four Craftsmen

Mario Emiliani

A mention of the occupation "frame builder" evokes a host of visions: beautiful hand-craftsmanship, smooth-riding bicycles, custom fit, status. Frame builders receive their share of both admiration and envy; after all, they make something which is truly beautiful and yet very functional. Too bad we're not all so talented!

Except for those folks who are personal friends with a frame builder, most people's knowledge about frames and frame building is gleaned from magazines and books. Unfortunately, some of these sources have been inaccurate, misleading, or even highly biased.

For example, there has long been a myth that one has to have gray hair and speak Italian in order to produce a good frame. For that reason, many people have discounted as inferior the brilliant, young new breed of American frame builders.

Contributing to the problem is that American frame builders have never had much of a forum for informing the public about their craft, or to toot their own horn—as well they might. Fact is, American builders have made an immense contribution to the art of frame building. To be competitive with today's American-made frames, imported frames must now exhibit consistently excellent alignment, craftsmanship, and paint and chrome finishes. Most imported frames can't compete.

In an attempt to provide the sort of forum American frame builders deserve, I sent a long questionnaire last year to many leading American frame builders. Their responses, both facts and opinions, are summarized below with a minimum of editing. In a few places, I have added my own comments (clearly identified as such) to help put matters into perspective. The resulting status report is surely the most comprehensive view yet presented, regarding the American frame builders, their techniques, and their practices.

Anyone considering the purchase of a high-quality frameset or bike should find in our survey many good reasons to "buy American." The survey results should help you understand how American frame builders work, and may help you decide which frame builder is best suited to satisfy your riding needs.

Finally, those of you who have been tempted by visions of jigs, brazing rod and torches should find much valuable information about the frame building business in these pages. Good luck!

The Frame builders

The questionnaire was divided into four sections: 1) The Frame builder and His Business; 2) Frame Tubing, Frame Components, and Brazing; 3) Frame Failures and Product Liability; and 4) Miscellaneous Questions.

I sent the questionnaire to 32 American frame builders chosen on the basis of geographic diversity, range of experience, and production volume. Prior to sending the survey, I asked each frame builder if he would answer the questions, some very personal. To my surprise, nearly every frame builder was eager to respond to even the most sensitive questions. I received back 24 questionnaires, a 75 percent return rate. These builders are listed in the accompanying box.

I do not list individual names along with specific responses since I promised anonymity in order to obtain more candid and complete responses.

Two notes: Although Albert Eisentraut is making very few frames these days, he will be gearing up for increased production soon. Albert has a lot of experience, and I have high regard for his opinions. Also, Dave Moulton is still a British citizen but can be considered an "American" frame builder since he is working in this country.

On some questions, I sensed a general consensus of opinion, and tried to group the responses to reflect this. On other questions, there was a wide diversity of opinions, and I have tried to represent them all fairly.

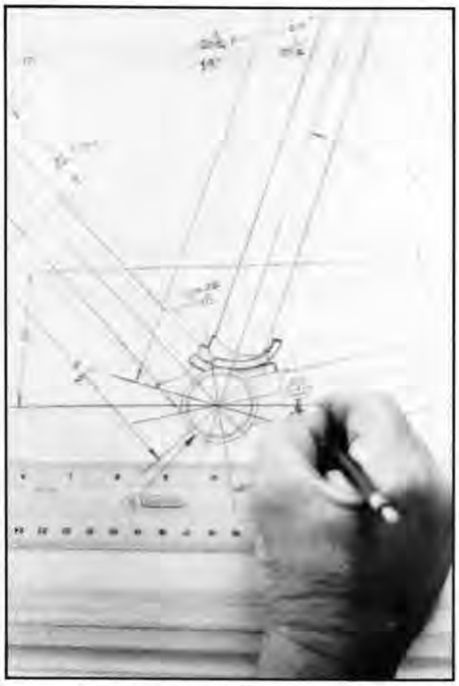
The Frame Building Business

Q: *How long have you been building frames? How long have you been selling frames?*

A: The 24 frame builders have been building frames for 3.5 to 27 years, with an average of 10.95 years. The person with 3.5 years experience had worked with a torch for 21 years as a designer and sculptor. The frame builders have been selling frames (mostly under their own names) for 3 to 22 years, with an average of 9.31 years.

Q: *Are you a full-time builder? If so, how long? If you're a part-time frame builder, what do you do for a living?*

A: Sixteen frame builders make frames full-time and have an average of 8.59 years of experience. Four builders work part-time



and hold such diverse jobs as hairstylist, machinist, railroad brakeman, and manager for the phone company. The rest divide their time between frame building and running their bike shop and/or import business.

Q: *Do you repair frames? Do you paint frames? Do you import cycling goods or engage in other types of business directly related to bicycles? How much of your business does each of these activities account for?*

A: All 24 frame builders repair frames to various extents. Some specialize in repairs, and a few do it as a service only to buyers of their frames. Twenty-one paint frames, and many refinish frames. Fifteen builders are involved in related activities such as importing, retail sales, wheel building, manufacturing custom touring racks and other components, research and development, and computer software for frame design. Only three builders derive over half of their business from selling or importing general "bike shop" merchandise; the remainder have very small retail or import businesses. So 85 percent of the typical frame builder's business is derived strictly from frame building, frame repair, and frame painting.

Q: *Are you the only frame builder in your shop? If not, how many people build entire frames? How many build just portions?*

A: Thirteen frame builders work alone, four builders employ others (two to six people) to build entire frames, and three frame builders employ one to three people to build portions of frames. One builder employs an apprentice, and the rest have up to three persons who do finishing work, i.e., filing lugs, sanding, painting, etc.

Q: *How many hours does it take you to build an average frame? How many frames do you build each year? How many frames have you built in your career?*

A: To build a standard ten-speed frame (minus the paint job) takes from 9 to 47.5 hours, with an average of 25.10 hours. Five frame builders make basic no-frills production framesets, which in one case takes as little as 6 hours.

The frame builders make from 5 to 400 frames a year, with an average of 118 frames a year. If the five builders who make over 100 frames are removed from the analysis, the average number of frames built is 53.

Over their careers the frame builders have made from 36 to 3500 frames, with an average of 843 frames. Clearly, some builders have made a *lot* of frames. If the eight frame builders who have made over 500 frames are omitted, the average number of frames built is 219.

Q: *What types of frames do you make? What is the average retail price of an average frame? Do you sell complete bicycles? If so, what percentage of your sales is made this way?*

A: Forty-two percent of the builders make frames for sport cycling, 40 percent make road-racing frames, 33 percent make touring frames, 10 percent tandem frames, 6 percent off-road frames, 5 percent track, and 6 percent other (i.e., recumbent, wheelchair, tricycle, mixte, etc.).

The average retail price of a custom-built frame is $728. However, the price can exceed $1,500 for special custom frames, or can be as low as $475 for non-custom-fit production frames. Twenty of the frame builders sell complete bicycles, which account for an average of 44 percent of their sales as a group. The percentage of complete bikes sold ranges from 8 percent to 95 percent.

Q: *What guarantee do you give with new frames? Is it in writing? If you had your way, would your guarantee be any different than it is today?*

A: The frame builders give three types of guarantees: lifetime, limited-time warranty, and "case by case"; and these guarantees generally cover alignment, performance, and defect-free materials and workmanship. Thirteen builders give lifetime guarantees on their product, usually only to the original owner. Only two give warranties covering a fixed-year time period; one covers five years and the other covers one year. One frame builder gives a five-year warranty on racing frames, and lifetime on touring frames. The rest have no fixed policy, but make a sincere effort to do what they can to please the customer.

Eight builders put their guarantee in writing. The remainder don't because customers don't ask for it, or because they feel it's a worthless document. The frame builders are very concerned about preserving their good reputation, and they believe this is best done by giving their word that they will satisfy the customer completely.

Only two builders said they would like to change their guarantee. One would like to make it 15 years instead of the five years his lawyer recommended. He feels that this is a realistic warranty period, unlike lifetime warranties. The other frame builder who now gives a lifetime warranty would like to give a limited-time warranty. He believes that a frame can't be expected to last forever; frames are subject to rusting, wearing out, and simply deteriorating, just like other components on the bike, he says.

The warranty questions stirred up a lot of emotion. One frame builder said that lifetime warranties are ridiculous since so many builders have gone out of business and are no longer around to back their guarantee. But all frame builders felt that they would do whatever it takes to please the customer. One builder gave a free new frame to a customer whose old frame failed as a result of a mild crash. (I know that many frame builders will gladly repair the frames they build, at their own expense, even when the damage is not their fault. You won't find this kind of commitment with imported frames.)

Q: *Do you guarantee repairs made on your frames? On other brands of frames?*

A: Eighty-seven percent guarantee repairs made on their own frames, and 70 percent guarantee repairs made on other brands of frames. Most frame builders limit coverage to what was actually fixed—a tube that breaks next to a repaired joint wouldn't be covered, for example. Five builders said they would continue to warranty their own frame even after they had made repairs as the result of a crash. Some builders were not willing to guarantee even repairs they made on their frames if they'd been crashed because hidden defects could cause failure. Others refuse to guarantee temporary or "quick and dirty" repairs requested by the customer. Those who don't guarantee repairs on other brands of frames said they don't want to take responsibility for another person's work.

Q: *How do you fit frames to customers?*

A: All respondents employ a combination of methods to determine frame size. The most popular technique combines tape-measured body measurements, the customer's old frame size, the frame builder's catalogue of geometries he can build, and experience. Five builders also use the FIT-KIT, a system devised by Bill Farrell of New England Cycling Academy, Lebanon, N.H. Two frame builders also use their own measuring jig, and one also uses a computer program for frame design.

Q: *How do customers find out about you?*

A: While almost everyone agreed that word-of-mouth is the best way to attract customers, all but eight builders supplement this method with advertising in print, articles in cycling magazines, references in books, and appearances at trade shows, races, and tours.

Q: *What percentage of your sales are through bike shops?*

A: Five of the builders sell over half of their frames through bike shops, eight builders sell less than half through bike shops, and eleven sell all their frames directly to customers.

Q: *What are the main selling points of your frames?*

A: Nearly everyone mentioned quality control, fit (of rider to frame, and suitability for intended cycling use), workmanship, finish, ride, and the availability of custom features. Six builders, who had the capability to fill orders with little or no wait, said availability was also a sales feature.

Frame Tubing, Frame Components, and Brazing

Q: *What brands of tubing do you use? Why?*

A: All but one builder listed Reynolds and Columbus as their brands of choice. Seven also use Tange, Ishiwata, and generic AISI 4130 tubing for certain applications. Nobody uses Vitus tubing on a regular basis. Four frame builders use *only* Columbus tubing, while two use *only* Reynolds tubing. One builder says his choice of tubing is a "secret" and sells his frames without a tube identification decal.

Most frame builders explain their choice of a specific brand of tubing by citing "consumer demand" and "good availability." Other reasons were low price and high quality. One builder said he uses Columbus tubing because of the variety of gauges and tapers available.

Q: *How do you decide which gauges of tubing to use? Do you use ultra-thin tubing?*

A: All said they choose the tubeset according to height and weight of the rider, as well as the type of frame and riding conditions. Twelve builders said they're willing to follow customers' preferences for tube gauges, and three are concerned with the riding style of the cyclist.

Eleven of the frame builders prefer to avoid ultra-thin tubes, believing that weight savings are negligible and that such frames don't last long. Thirteen builders said they don't mind using thin tubes, but generally with the qualification that they use them only if the situation calls for it (e.g., time trial bikes). Many would warn their customers of the limitations of thin tubing.

Comment: Years ago, some American builders were willing to try anything—some of their frames were quite far from the norm. Thus they gained a reputation as either iconoclasts or frivolous amateurs. But these responses seem to indicate a reversal: American frame builders showing truly professional concern that customers get the proper size and weight tubeset—while many foreign manufacturers will mass produce ultra-light frames and sell them to all comers.

Q: *Do you use different filler metals on different areas of the frame?*

A: All use at least 2 or 3 different brazing alloys in different areas of the frame. Their choices depend partly upon the type of joint, i.e., lugged or lugless. There are two classes of filler metals: silver and brass brazing alloys. Most users of silver brazing alloys use them for lugged joints - that is, top tube/head tube joints, bottom bracket joints, fork blade-to-crown joints, etc. The silver alloys characteristically melt between about 1145-1350 degrees F and are favored because silver-brazing is quick, clean up is easy, tubes can be readily replaced, and tubes are distorted less by the heat.

Brass-brazing alloys melt between about 1630-1720 degrees F, and are preferred for joints with large gaps, such as dropouts. That's because these alloys have a wide melting range (i.e., the difference in temperatures at which the alloy is completely solid and completely liquid), and are thus easy to build up or fillet. Brass filler metals are also used to avoid remelting on certain joints that will be reheated to the silver-alloy range. For example, seat stays are often "capped" by brass-brazing and then the seat cluster is joined by (cooler) silver-brazing. Finally, brass is widely used because it is economical.

Q: *Do silver-brazed frames have greater sales appeal?*

A: Sixteen builders thought so, but their reasons varied widely. Five builders feel that silver-brazing really does produce a mechanically better joint, and thus its sales appeal is justified. They cited mostly correct reasons, including: easier clean-up and repair methods with silver-brazed frames, and less tube distortion due to lower silver-brazing temperatures.

One frame builder called silver-brazing a "sales gimmick," another thought it cost prohibitive, and another said consumers incorrectly assume price is synonymous with quality. Five builders who acknowledged silver's sales appeal said a skilled builder can make a good frame no matter what brazing alloy is used; I'm sure many others feel the same way.

Q: *What defects do you find in frame tubing? Which brands of tubing have the most defects? Which brands have the best quality control?*

A: The answers here depended on how many frames the builder had made; small builders see few defects, and long-time builders aren't likely to be bothered by a few defects because tubing quality is much better now than in the past. Also, users of only one brand of tubing will never encounter defects in other brands.

Overall, the frame builders didn't feel that tubing defects are a big problem, since the frequency of defects was very low (on the order of about 3 percent). As for quality control, the consensus was that Columbus, Reynolds, and Tange, in that order, were the best. But at least three builders felt that all the manufacturers have about the same level of quality control.

The most common defects mentioned were: out-of-round tubes, oversized tubes, slightly bent or bowed tubes, drawing tears (i.e., gouges along the length of the tubes), dents, rough surface finishes, spiral bulges caused by not pulling the mandrel out straight, and pits.

Because Reynolds and Columbus are the most popular brands, it's no surprise that frame builders would single them out when listing defects. The major defects are drawing tears in Reynolds 531, and bowed tubes in both Reynolds and Columbus. When asked whether they reject tubes at an "uncomfortably high rate," 79 percent said no. One person said the quality of all tubes except Reynolds 753 satisfied him. One small builder noted that all tube rejects hurt because he cannot absorb the cost. Another said rejects are part of the cost of doing business since it's too much effort to return a few tubes.

Q: *Do you find defects in frame components (i.e., lugs, bottom brackets, dropouts, fork crowns, braze-ons, etc.)? Are they associated with any particular manufacturer?*

A: Nineteen builders said the rejection rate for frame components isn't high enough to be a problem.

Common defects in frame components were: undersized outside diameters of lug sleeves (or oversized tubes!), pits in investment cast components, angles of the chainstay sockets in bottom brackets are off, and cable guide holes are off-center. Campagnolo dropouts were listed specifically by seven builders as having poor forging quality. Eight frame builders said defects weren't a problem (some fix minor irregularities), and nine said that defects weren't associated with any particular manufacturer. Those who did list manufacturers spread it out evenly over those producing frame components.

Q: *What guarantees would you like to have from manufacturers of tubing and components?*

A: Eight builders thought the existing warranties good enough, while six said that manufacturers should assume complete liability for defective products. Four builders thought that manufacturers should simply inspect their products better, three said no warranty is needed, one thought replacement of defective parts would be sufficient, and the rest didn't answer the question thoroughly.

Q: *Do you normally cold set frames and forks?*

A: Cold setting is a process used to align and straighten frames, forks, and dropouts by bending them to their proper position after joining (and sometimes at periodic intervals during joining). Also, forks and rear triangles are often spread apart a small amount after joining to compensate for thermal stresses which draw the dropouts together.

Consumers think that competent frame builders shouldn't "resort to" cold setting; they imagine that frames and forks come out of the jig straight as an arrow. However, frames rarely come out straight enough for no-hands riding because jigs aren't perfect, thermal stresses alter alignment, and tubes aren't straight to begin with. These all contribute to small amounts of misalignment, so cold setting must be done to ensure a proper ride. It's as much a part of the manufacturing process as is filing lugs.

Twenty-two builders said they cold set their frames and forks by "small amounts," typically less than 2 millimeters. Only two said cold setting a correctly brazed frame is unnecessary. One frame builder who said this noted that he cold sets his dropouts "occasionally" to make them parallel to each other, and the other aligns the rear triangle with his torch. (This torch method works - I've done it - but it is inexact and may cause the stays to spread farther than is needed.)

Two frame builders objected strongly to those who say they don't cold set their frames: They said that a frame builder who doesn't cold set is "either lying or kidding himself that his frames are straight." One noted that "all fork blades are ovalled and bent cold, so why are consumers so concerned about cold setting?"

The most prevalent reason given for the need to cold set is that it's the only way to obtain a near perfect alignment. Some frame builders said that even though they make very straight frames, their own standards for alignment dictated small corrections after joining. One builder expressed concern over frame builders who, by making large cold-set adjustments, can put bulges in tubes or cracks into brazed joints. In summary, builders would like to end the controversies about cold setting. They would tell you that, used intelligently, it's nothing to be concerned about.

What If . . . the Frame Fails

Q: *How many of your frames have failed? Did they fail consistently in any particular place? Was anyone injured?*

A: I was surprised that all but two of the frame builders answered this question. Five said they'd had no failures. The seventeen others averaged 4.5 frame failures, with four of the seventeen having only one failure. The greatest number of failures was 15 to 20 by one highly respected long-time builder who's made over 2000 frames.

Many pointed out that most failures occurred early in their careers and that they have long since corrected the way they make frames. In addition, many failures were attributed to defective components which frame builders couldn't have known about beforehand. I found no correlation between the number of frame failures and the number of frames built.

Only one builder had a failure which resulted in (minor) injury. Apparently the steering column separated from the fork crown. Ten builders said they'd experienced a similar type of failure in their frames, but all have made corrections in their fabrication process to prevent a recurrence.

Q: *If you had a frame failure caused by defective components, did the manufacturer of the components pay for repairs?*

A: Only thirteen frame builders answered this question, all saying no manufacturer has ever covered the cost of labor, repainting, or frame replacement due to a component failure. A few were able to obtain new parts free from the importer or manufacturer, but felt it wasn't worth the effort of proving who was at fault.

Some builders noted that importers don't handle claims for defects, and distance makes it impractical to seek restitution from foreign manufacturers. One frame builder said "most manufacturers will never accept responsibility, so there's no point in asking." He stated further that he repairs "about 10 cracked Campy 1010B right rear dropouts each year (on all makes of frames)," and believes those dropouts have a "design defect." Another builder said that "every self-employed person has to do some work for nothing for the sake of good customer relations."

Comment: Even though failures are rare, frame builders spend more time and money than they'd like fixing frames which failed as a result of defective components. Many would like to see manufacturers assume responsibility for the components they make. But nobody thinks manufacturers will willingly change their "you-bought-it, you-own-it" method of doing business.

Q: *Are you incorporated? Do you carry product liability insurance?*

A: Only seven of the builders, most of whom also have retail or import businesses, are incorporated. They did so for financial and tax purposes, and to separate themselves from business liabilities. The rest, who aren't incorporated, either haven't looked into it or were advised by lawyers or accountants that their business is too small.

Fifteen frame builders have product liability insurance, with coverage ranging from $25,000 to $3,000,000 per accident. Most of those without coverage said that its cost was too high. But the costs mentioned by those with coverage were $0.69 to $10 per frame. To my mind, that's very little money for peace of mind in today's litigious society.

Customer Relations

Q: *Do consumers have realistic expectations when they want to buy a frame?*

A: Eleven frame builders said consumers' expectations were about right. They said today's customers are "well-informed," and that the builder's own standards are usually higher than the consumers' anyway. To my surprise, only four builders thought expectations were too high. One reason is that "customers aren't aware of the limitations of hand craftsmanship and the materials used." And problems with handmade frames do occur. The most common are minor cosmetic blemishes in brazing or paint.

Believe it or not, five frame builders thought consumers' expectations weren't high enough. The most sensible reason is that consumers "don't fully appreciate the effect of the time and effort put into custom frames." One frame builder said this is the fault of "magazines, books, and bike shops, which glorify inferior products."

Q: *Do you think frame building quality standards should be adopted?*

A: I asked this question because some frame builders feel that inexperienced part-time builders reflect badly upon their business. However, only four builders said they favor frame building standards, while two said "maybe," noting that minimum safety standards and assumption of liability by the builder would be desirable. The remainder said no standards should be set. Most felt that "hobbyists" don't affect their business much, and those who can make good frames deserve the business.

Q: *Would you support a frame builder's craft guild?*

A: Several years ago, an attempt to form a guild failed, partly because some builders suspected, rightly or wrongly, that the organizer (a frame builder and importer) was trying to monopolize the market for frame building supplies.

Fifteen builders thought a craft guild a good idea; most said it could increase their buying power for materials, advertising, and liability insurance. Two builders had no opinion, and the remainder were opposed.

The comments I received indicate that organizing a guild would be difficult, no matter how desirable. For example, one frame builder said he would join only if "four or five others whose work I respected would be the (other) members."

Q: *How many frames must a person make to become a competent builder?*

A: Many builders said that an exact number could not be specified, since differences in learning ability and investment in fixtures and equipment were also important. Others said that about 50 frames was the minimum, but noted that some builders have been working for years and still can't get it right.

Q: *Do you notice problems with imported frames?*

A: The frame builders felt, in general, that imported frames suffer from inconsistent quality and poor mitering, brazing, alignment, and finish. One builder said imported frames are "all hype, decals, and chrome; they may look as good as hand-crafted frames, but they are just cheaply built frames made from high quality materials." He also said "the public is led to believe these imports are the same quality" by extensive advertising.

Another comment on imported frames: "They all come from much larger shops than mine, and as such cannot give as much attention to details. The paint jobs on some of them are pathetic . . . alignment can also be a problem. I loved the ad a few years ago for a leading Italian frame that was designed to take either five- *or* six- speed rear hubs! I guess they put those dropouts somewhere in the middle and you just made up the difference with a little push and shove."

Another builder noted, "There are foreign builders doing beautiful work, but importers bring in the shoddy, fast-buck frames. These bikes have problems, all (of) which indicate a hurried building process." Another said he is impressed by the mid-priced ($500-$800) Japanese production frames, and noted that "their alignment, brazing, and quality control are far better than the European bikes in that (price) range."

Finally, one builder said that imported frames "sell because they are available." (A good point, I think; many customers are not willing to wait 2-6 months for a frame.)

Q: *How do you justify the higher price of your frames, compared to imports?*

A: Most said they don't justify it; one look is enough to convince people that their product is superior. But some builders said their "overall quality is better" because they spend more time on each frame and pay closer attention to details.

Some builders pointed out that they make production frames or relatively inexpensive custom frames that are competitively priced and higher in quality than mass-built imports.

Q: *Do you lose much business to the imported frame market?*

A: Ten frame builders said no, citing such reasons as: "I have all the business I can possibly handle," and "Our market is with people who want a finely finished frame. The import customer wants lots of chrome, stickers, and pizza sauce."

One builder said that "American builders must become automated if they are to compete with imported frames in the years ahead. They must use automation to decrease the time spent on machining, alignment, etc., thereby allowing an increase in time spent on the real craft of frame building; . . . hand shaping of lugs, finish, and customer interaction."

Eleven frame builders said they lose *some* business to imported frames. (One added ". . . but *they* are also losing some business to me.")

Conclusion

Conducting this survey was quite an adventure. Some frame builders who did not participate were nothing short of rude at my attempts to enlist their help. One builder said he couldn't fill out the questionnaire because it was suited only for "garage-shop amateurs." (He considers anyone building less than several hundred frames a year an amateur.) I asked him to change the questions to suit himself, but I never heard from him again.

Another frame builder declined to participate because he felt that "customers knew too much already." He said past technical articles told customers more than they need to know, and they ask a lot of questions he doesn't have time to or want to answer.

Aside from these few, all the other responses I received were sincere and helpful. American frame builders are definitely committed to the highest degree of technical excellence in their craft. In my opinion, no one can seriously claim that American-made frames are inferior to those of the European "master" builders. In fact, American frames as a group have the highest, most consistent, quality of any frames in the world.

Thanks to the frame builders whose responses to the survey made this article possible: **Matt Assenmacher,** Assenmacher Lightweight Cycles; **Bob Beecroft,** Bob Beecroft Cycles; **Ron Boi,** RRB Cycles, Ltd.; **Bill Boston,** Bill Boston Cycles; **Sam Braxton,** Braxton Bike Shop; **Bill Davidson,** Davidson Cycles; **Albert Eisentraut;** Glenn Erickson, **R + E Cycles; Bruce Gordon,** Bruce Gordon Cycles; **Jim Holly,** Cycles Griffon; **Skip Hujsak,** Hujsak Bicycles; **Tom Kellogg,** Spectrum Cycles, Inc.; **Chris Kvale,** Chris Kvale Cycles; **Boone McReynolds,** Doablo Cycles; **David Moulton,** David Moulton Bicycles; **Andy Newlands and Damian Bollermann,** Strawberry Cyclesport, Inc.; **Mark Nobilette,** Nobilette Cycles; **Peter Quellette,** Quellette Cycles; **Jim Oxford,** Oxford Design; **Chris Pauley,** Chris Pauley Frame Design; **Dave Plantenga,** Plantenga Framesets; **Angel Rodreguez,** R + E Cycles; **Richard Sachs,** Richard Sachs Cycles; **Peter Weigle,** J.P. Weigle Cycles.

Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

Bicycling Magazine's Newsletter for the Technical Enthusiast

Spring 1986 | Volume 5, Number 1 | Single Copy $3.

PROTOTYPES

Molded Composites: The Next Step in Frame Design?

Getting Ready for the '88 Olympics

The *Bike Tech* Editors

In the aftermath of the 1984 Olympics, Mike Melton, builder of Raleigh's glued aluminum "funny bikes," predicted that the next wave of Olympic machines will make extensive use of graphite and composite fibers in the frame[1]. He didn't say exactly *how* these frames will be made, but we are now beginning to see a few clues as to what he might have meant.

Frames built of composite tubes are not big news anymore, of course. The Alan "Record Carbonio", the Vitus "Carbone" series[2], and the Peugeot PY 10 FC (assembled by Bador)[3] are three examples of the composite-tube design that have been mass-produced for several years. The tubes of these frames are made of carbon-fibers or a woven mix of carbon and Kevlar fibers; the fibers are bonded together by a "resin matrix", usually a two-part (chemically-curing) epoxy. The frame is then assembled by gluing the tubes into cast lugs, usually using a one-part (heat-activated) epoxy adhesive. From a distance, these frames all look like the conventional 7-tube steel or aluminum variety.

But there's another way to get the lightweight strength of carbon and Kevlar fibers into a bike frame: *molded composite* construction. With this method, there are no tubes; the frame is "all one piece." And, as you can see from the photos in this article, you'll never mistake such a frame for anything else.

---

[1]Bicycling, *March 1985, pp. 104-112.*
[2]Bicycling, *December 1985, pp. 75-77.*
[3]Bicycling, *March 1985, pp. 96-102.*

Dan Darancou's prototype: a Kevlar mat lay-up construction with a flat carbon fiber layer in the center plane.

IN THIS ISSUE

cross sections, for example, are derived from low-drag airfoil profiles. And his lay-up process uses "pre-pregs" (fabric sections pre-saturated with a controlled weight of resin at the factory), a standard aircraft building procedure. But Trimble is reluctant to discuss further details until his patent application, now pending, is granted. In any case, it's clear that the small-scale aircraft industry has already developed the materials and methods that bicycle framebuilders can use.

We rode the Trimble time-trial bike pictured here, serial #1 out of Trimble's mold, and found it acceptably stiff and comfortable. It is a bit heavy for its class (20.55 lb. with two disk wheels), but a few pounds could easily be shed by switching the steel fork to aluminum, and using a spoked front wheel. The real low-weight story is the pursuit bike: it weighs the same as the 12-pound Olympic aluminum funny bikes. The next batch of frames will weigh even less, Trimble says, thanks to a narrower cross section.

Trimble is also working on an all-composite all-terrain bike, and an all-composite front fork. He says he has "barely scratched the surface" in applying composite technology to bike design, and we're inclined to agree. Composite construction, whether molded, tubular, or a hybrid, might be just what's needed to make Mike Melton's prediction of a nine-pound track bike come true.

The View from Colorado Springs

Steve Bishop, Head Mechanic for the US National Cycling Team at the USCF training camp in Colorado Springs, made these comments to Bike Tech *about the Trimble bikes.*

BT: *What were your experiences with the Trimble bikes?*

SB: We had three different bikes out here this past summer, and they were all carbon fiber and Kevlar composite work. One of them had fully enclosed front and rear triangles, and one of them had just a closed rear triangle. One of these bikes was used down in the sports festival in a kilo and also in a pursuit event. Heidi Hegg has one and Kit Kyle, who's about the same size, rode her bike and liked it a lot.

We had a road bike here too, and everybody was surprised how well it runs. It had a Vitus fork, and was a really fun to ride. It is a different shape than the pursuit bikes that we got later in the summer though.

BT: *How do the composite bikes ride, compared to your standard lightweights?*

SB: There were interesting parts on each one of these bikes, and each one rode differently. But I have to say that they were all on the flexible side. I don't mean to be negative about them, because I think they were a really good effort for the first batch of all-composite bikes. I'd even say the road bike rode better because it was on the flexible side. But in the pursuit bike, it seems that the front triangle could be beefed up a bit.

BT: *Could they add more material and still keep the weight down?*

SB: Probably. One of designs was incredibly light, and we all definitely feel like going with the lightest possible equipment. It's to our advantage because of being able to accelerate the bike faster. But the lightest bike didn't seem to have enough material to be really rigid, so it may have to be beefed up. Maybe internally, or by adding different materials. It's all new technology, and these are just the very first efforts. The people seem to know their materials and processing and do a fine job of construction. All the bikes had an excellent finish and surface.

BT: *How important are the enclosed triangles?*

SB: There seems to be a big improvement in the aerodynamic characteristics. This still has to be measured with lab tests and wind tunnel information. But I'm sure you'll see a lot of designs in the future with the rear triangle enclosed from the seat tube. The seat tube, the seat stay, and the chain stay are all enclosed and the wheel fits inside. You get a lot more strength in the rear triangle. I think they are on the right track with the basic enclosed design.

BT: *Are molded composites really going to challenge the place of aluminum and steel in bike frames?*

SB: I'm sure of it. Look at the aircraft industry and motor racing industry. They are all racing with the composite materials. All the Indy cars have composites in the chassis. That really changed the way those cars worked. They got much faster cars immediately just because of the extra rigidity and weight savings.

BT: *How much difference will a composite frame make?*

SB: It depends mainly on the weight savings. The more weight you save, the more advantages there are. There's so little weight to a bike frame to begin with, it's hard to reduce the weight much more. A half pound [savings] is significant and a couple of pounds is pretty extraordinary. But now the weight of aluminum bikes is the standard. Still, I think we can push the envelope a bit more and squeeze something out of the new fiber materials. It's not going to drop a couple more pounds again, maybe just a pound or a half-pound. A lot of people will choose the [enclosed triangle] aerodynamic design and live with more weight, thinking that the bike moves through the air faster. I think there will be significant advantages to these enclosures.

DESIGN

Bicycle Chains

Materials, Chain Wear, and Lubrication

Mario Emiliani

Bicycle roller chains must be strong, durable, reliable, easy to maintain, and inexpensive. These requirements might seem easy to satisfy, but they're not. This is why modern roller chains are made from steel, and why their design differs little from that developed some 450 years ago by Leonardo da Vinci. And while today's roller chains work well in many applications, they seem heavy and even antiquated for modern lightweight bicycles.

Other materials could be used to make bicycle chains. A titanium or aluminum alloy chain, for instance, could be several ounces lighter than the typical 380 gram (13 oz) steel chain. Even composite plastic/metal chains, or all-plastic chains, could someday see widespread use. But before any of these become practical, some major advances in design and manufacturing technique will be needed. In any case, the final test for a new chain design will be whether it works as well as existing steel chains do.

In this article, we will look at steel bicycle chains, their performance and limitations, and the opportunities for using new materials in the future.

Steel

Most bicycle chains sold today are made entirely of steel, since few other materials are as strong, resistant to wear, easy to fabricate, and inexpensive, as steel. A wide selection of steel alloys, with a variety of heat treatments, is available to manufacturers of bicycle chains. Practical constraints, however, limit their choice to a few specific materials.

Low cost is a prime requirement for a bike chain, since it must be replaced often. Thus, stainless steels and other so-called "high alloy" steels are not used, since they contain large amounts (i.e., more than 5% to 10%) of expensive alloying elements like chromium, nickel, and molybdenum.

Two other prime requirements for chains are strength, to resist high operating stresses, and hardness, to resist wear. For-

Text and photographs of this article, except Figures 1 and 2, and Editor's Note, are Copyright C 1985 by Mario Emiliani.

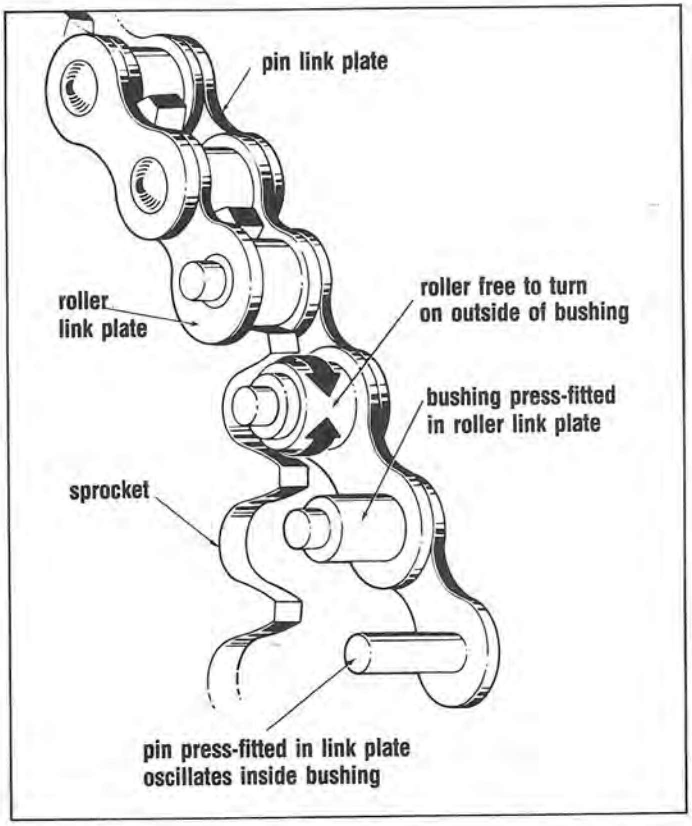


Figure 1: A standard roller chain. (Adapted with permission from Ref. 1)

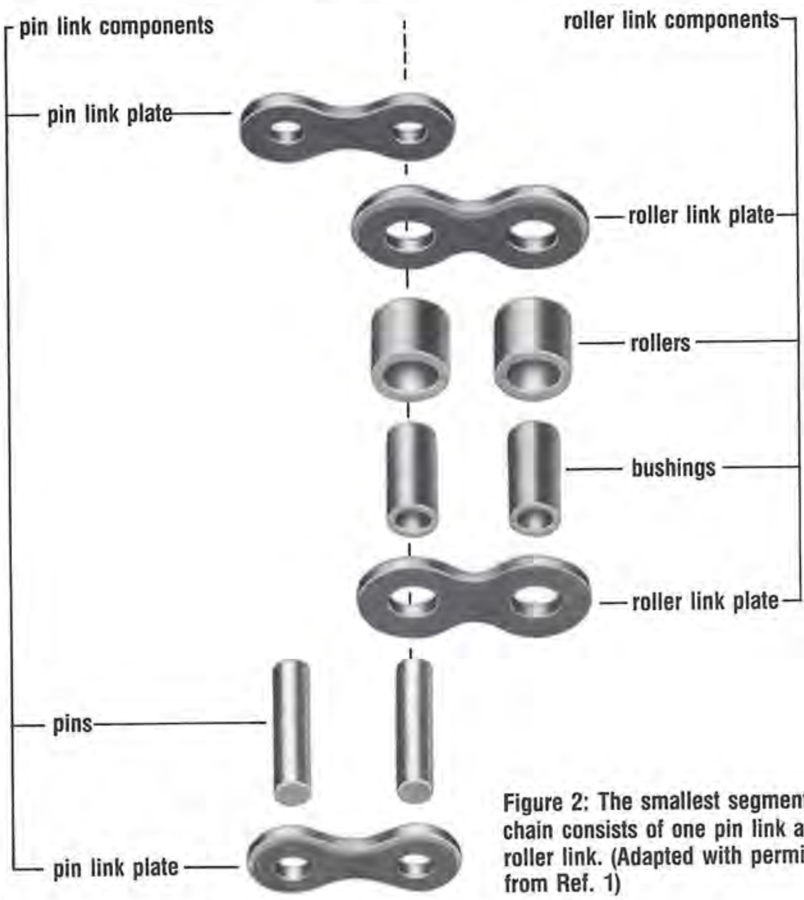


Figure 2: The smallest segment of a roller chain consists of one pin link and one roller link. (Adapted with permission from Ref. 1)

tunately, these properties are inseparable: the stronger the material, the better it's wear-resistance.

An outstanding combination of strength and moderate cost is found in the so-called "low alloy" steels (they contain less than about 2% of the expensive alloying constituents). This class includes the AISI 4140 and 4130 steels (the material commonly used in bicycle frame tubing).

Fortunately, some of the least expensive varieties of steel, namely the "plain carbon" steels such as AISI 1040 and 1060, work well in a bicycle chain. These steels contain about 0.6% to 1% carbon, and are in the same class as AISI 1010 and 1020, which are often used for frame tubing in inexpensive bicycles.

Most bicycle chains currently on the market are made from plain carbon steel because, besides its low cost, its strength and hardness are adequate. It is true that a low-alloy steel would be stronger and harder than plain carbon steel, *provided* that both received the same heat treatment. Its also true that a plain carbon steel, *if properly heat-treated*, could almost equal the properties of some low-alloy steels. For this reason, in trying to compare the various brands of bike chain, it is not sufficient merely to know the chemical composition; the complete history of processing and fabrication must be known.

It is not practical, in this article, to analyze every make of bicycle chain in such detail. After all, there are many brands worth mentioning (including the new ATB chains), and a minimum of four non-redundant parts per link would require testing. Instead I'll use the popular Sedisport as an example when I talk about how chains withstand wear.

Roller Chain Design

Chain drives of various forms were known for at least 2000 years, but da Vinci's designs were the first ones put to practical use. Even then, chains were expensive and difficult to make. And because the quality of steel available at that time was poor, early chains often wore out after a short period of use. It wasn't until 1895 that roller chains came became truly practical, when they were first introduced on the rear-wheel drive "safety" bicycle. Better quality steel and this new application brought a renewed interest in roller chain design and its other potential uses.[1]

The chains we use today are remarkably similar to those on the early bicycles. The

[1] ***Design Manual: Roller And Silent Chain Drives*** *(3rd ed.), by Jackson and Moreland; Washington, DC: Association of Roller and Silent Chain Manufacturers; 1958. The current version of this manual is* ***Chains for Power Transmission and Material Handling*** *(1982), available for $20. from: American Chain Association, 152 Rollins Ave., Suite 208, Rockville, MD 20852 (301-984-9080).*

standard roller chain is made from two basic sub-units: a **roller link** and a **pin link**, which are spaced alternately along the length of the chain (see Figure 1). When adjusting a chain's length, both a roller link and a pin link must be added (or removed). Since the pitch (pin-to-pin distance) of bike chains is a standard 1/2 inch (12.7 mm), length adjustments must be made in discrete 1-inch steps.

Figure 2 shows the smallest segment of chain (one roller link and one pin link) in detail. Note that this segment consists of *ten parts*. Thus, the typical 56-inch bike chain contains some 560 individual pieces: perhaps more than all the rest of the parts of the bike put together! A medium-priced chain today costs about $8., so you're paying less than 2 cents per piece; a tribute to the economies of mass production.

The plates are stamped from sheet metal, the bushings and rollers are made by rolling up small sections of sheet metal, and the pins are simply small rods. Each link is held together by press-fitting the bushings and pins into the roller and pin link plates, respectively. Each roller link and roller is sized so that it will move easily between each fixed pin link. This gives the roller chain the flexibility it needs to freely engage with the sprocket.

So-called "narrow" chains like the Sedisport are different in three major ways from the "standard" roller chain just described. First, the Sedis chains have no separate bushings at all. Instead, the rollers roll directly on integral "bushings" that are stamped directly into the roller link plates. Thus, the smallest segment (i.e. two links) of a Sedis chain contains only eight parts.

The second difference is that the chain width (i.e. length of the pin) and height of the Sedis chain are less than in regular roller chains. These smaller dimensions, coupled with close tolerances, allow 6-speed freewheels to be used on standard 120 mm wide rear chainstays. The table (Figure 3) shows some dimensions of the narrow Sedisport compared to two regular width chains.

The third difference is that the narrow chain has more side-to-side play compared to regular bike chains. For example, I measured 4.1 cm side-play over 15 links in a new Sedisport chain, compared to only 2.6 cm in a new Regina Oro. The Sedis has greater side-play because the roller link plates overlap each other less than on the Regina Oro. This is the reason for the Sedisport's much talked-about "smooth shifting" characteristic over narrow gear ranges, and its poor shifting over wide gear ranges. Finally, the Sedisport's roller link plates are flared at the edges, to improve the chain's ability to engage with sprocket teeth during shifting.

The design of Sedisport chains seemed quite novel when it was first introduced several years ago, but it isn't really new at all. The same general design (except for the flared roller links) is at least 89 years old, and can be seen on page 400 of Archibald Sharp's book, **Bicycles & Tricycles**[2].

Figure 3: Selected dimensions of popular derailleur chains.

Dimension	SEDISPORT	REGINA ORO	REGINA TITANIO
nominal chain pitch	12.7 mm	12.7 mm	12.7 mm
pin length (chain width)	7.3 mm	8.1 mm	7.9 mm
roller plate: width	4.4 mm	4.5 mm	4.3 mm
thickness	1.1 mm	1.0 mm	1.0 mm
length	20.9 mm	23.1 mm	23.3 mm
pin plate: width	6.7 mm	6.7 mm	6.9 mm
thickness	1.0 mm	0.95 mm	1.0 mm
length	20.8 mm	20.1 mm	20.0 mm

Chain Wear

Of the many wear processes which conspire together to remove metal from your chain, the major malefactor is *abrasive wear*. This type of wear occurs when "hard" particles (typically sand) become trapped between two sliding surfaces (see Figure 4). The small size of these particles (typically 0.0002 to 0.010 inch) makes them virtually invisible, but allows them to easily settle into even tight-fitting joints. The particles then gouge metal out as the parts slide past each other.

To make matters worse, the products of abrasive wear cause further abrasion. In time, the gouged-out metal fragments accumulate and do their own share of gouging, while the larger sand particles are crushed into smaller pieces, each with fresh, sharp cutting edges. Clearly, the best way to minimize abrasive wear is to keep the "invisible" sand out in the first place.

Bicycle chains are also subject to *adhesive wear*, but this is much less of a problem than abrasive wear. Adhesive wear occurs when the layer of lubricant on the surfaces is either too thin or is absent altogether. When the two surfaces were pressed together, the high points come into direct contact and become, in effect, welded together. When the surfaces are later moved apart, the high points remain welded together, and small pieces of metal are torn away from the adjacent surface in the process. In bike chains, adhesive wear removes much less metal than abrasive wear, because there usually is enough lubricant to prevent it.

[2]***Bicycles & Tricycles,*** *by Archibald Sharp; Cambridge, MA: The MIT Press; 1977. Reprint of the 1896 edition published by Longmans, Green; London.*

A Closer Look

Figures 5 to 9 are scanning electron photomicrographs showing parts of my own Sedisport derailleur chain. Chemical analysis showed that all parts of the chain were made from a plain carbon steel, perhaps AISI 1050. I was surprised at how little wear I found on the chain. It had about 3000 miles on it, and I hadn't given it particularly good care. It's true that I rode it mainly in dry weather, but the only cleaning I gave it was an occasional wipe and a relubrication when it seemed necessary.

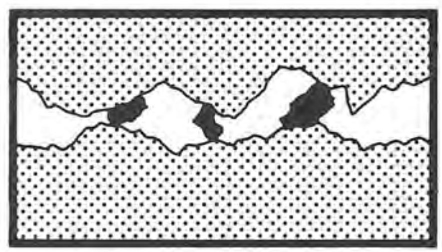


Figure 4: Abrasive wear starts when hard, sharp particles are trapped between sliding surfaces. These particles cut metal from both surfaces, and the metal fragments contribute to further abrasive wear.

**Editor's Note: Stresses on the chain can be estimated using the following formulas:*

1. *radius of front chainwheel = chain pitch x gear teeth / (2 Π)*
   Example: radius of 52T chainwheel = 12.7 mm x 52T / 6.28 = 105.1 mm
2. *Mechanical Advantage of front chainwheel = crank radius / chainwheel radius*
   = 170 mm / 105.1 mm = 1.62
3. *chain tension = pedal force x M.A. of front chainwheel = 250 lb x 1.62 = 400 lb.*
4. *shear stress across each pin (approx. 0.15" dia.)*
   = chain tension / (2 x pin cross-section area)
   = 400 lb / (2 x Π x $diameter^2/4$
   = 400 lb / 0.035 sq in
   = 11,300 psi
5. *compressive stress on pin's surface*
   = chain tension / 60% of pin's width x 20% of pin's diameter
   = 400 lb / 60% x 7.3 mm x 20% x 0.15"
   = 400 lb / 0.0052 sq in
   = 77,300 psi

(The factors 60% and 20% are approximations intended to represent the pin's "effective" area in carrying the chain-tension load.)

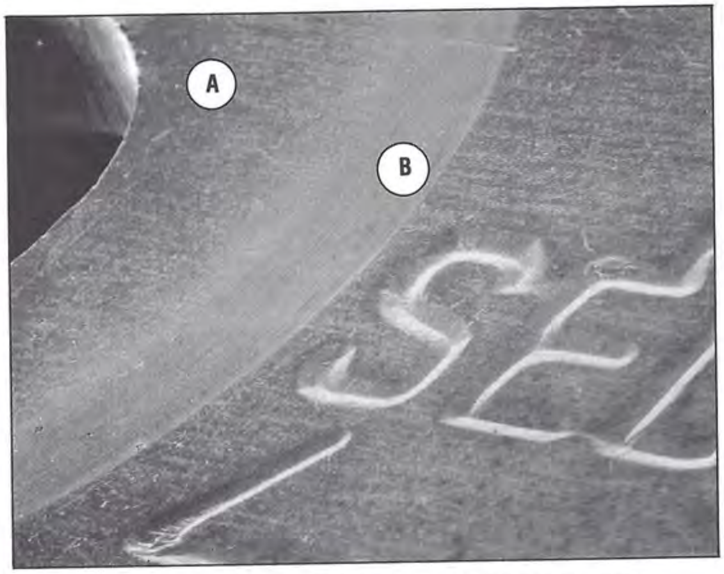


Figure 5: Chain misalignment is the cause of this uneven wear pattern on the pin link plate, where the roller link plate rubs against it. Note that area close to hole (A) is not worn, but the outer area (B) is. 40X.

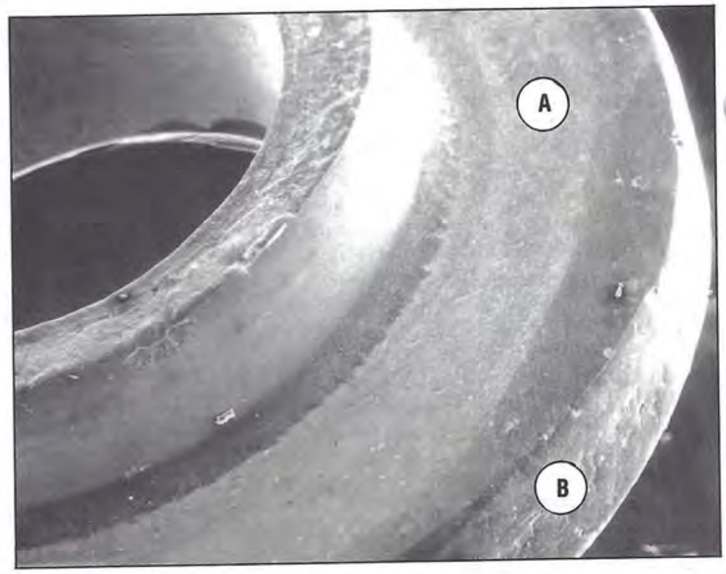


Figure 7: On this roller link plate, the worn region at A is expected, since this is where the side of the roller contacts the plate. The plate's edge (B) is noticeably fractured, indicating that it was stamped from sheet metal prior to heat treatment (when the metal was more formable). 38X.

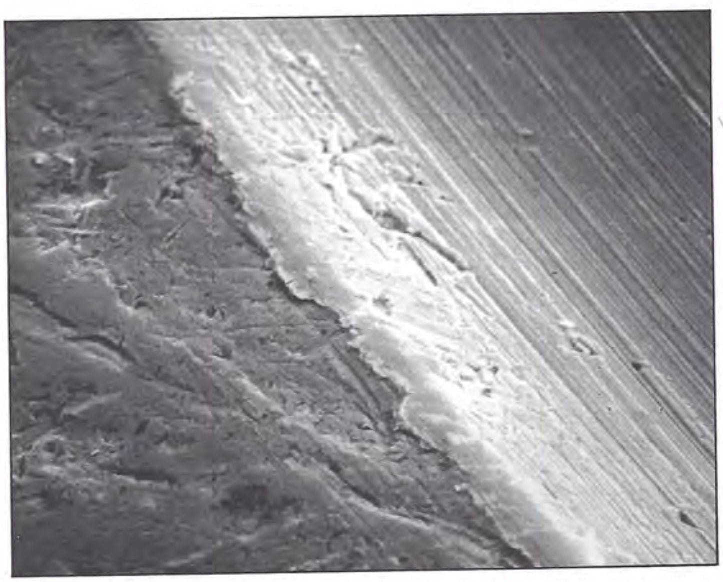


Figure 6: A closer look at the scoured area (B) shown in Figure 5. The deep gouges (upper right) are typical symptoms of abrasive wear. Note that the gouges are all approximately the same size and depth, an indication that the sand which caused the wear was crushed into small particles which did not decrease further in size. Note also the lip curling onto unworn metal (near center). 970X.

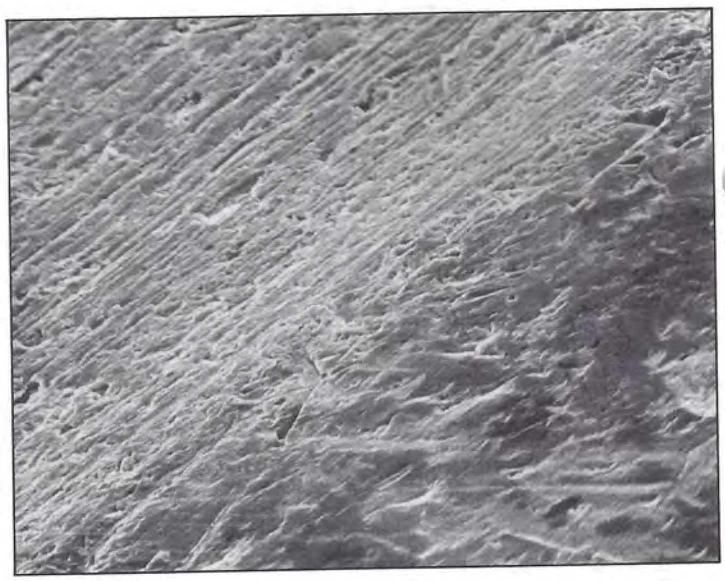


Figure 8: Close-up of the roller link plate shown in Figure 7. The scoured region (upper left) shows slight, uniform wear, an indication that the forces between roller link plate and roller are fairly low. The original surface finish of the chain, with no wear, is seen at lower right. 1000X.

Figure 5 shows the inner surface of a pin link plate. It is apparent that the outer third of the plate wore the most, and that this was due to chain misalignment (rubbing between the inner surface of the pin link plate and the outer surface of the roller like plate). A closer look at the worn region is seen in Figure 6.

Figure 7 shows the roller link plate and its integral bushing. The sides of roller link plate are worn over most of the surface where it contacts the sides of the roller. Figure 8 is a closer look, showing a scoured region with slight, uniform wear.

A polished cross-section of the pin (Figure 9) revealed that it had been electroplated. Chemical analysis of the surface of the pin showed a high chromium content. Chrome plating, as found on Sedisport and some other high quality chains, produces a very hard surface. This hard surface inhibits abrasive wear and, as a result, decreases friction between the pins and bushings. The chrome plate really seems to help; my pins had so little wear that the photomicrographs showed nothing of interest.

Pins are usually the most highly stressed part of the chain.* (However, if the centers of the pin link plates have holes drilled in them, *they* could be the highest-stress region.) In any case, chrome plating on the pins can prevent that incurable malady: "chain stretch."

Actually, "stretch" is a misnomer, since it implies that the chain stretches elastically like a rubber band. In fact, the chain elongates *permanently*, and the chain pitch (distance between pins) increases. The elongation is caused by wear: the outside diameter of the pins decreases and/or the inside diameter of the bushings and rollers increases. As little as 1/1000th inch change at each of these surfaces can make the chain almost 1/4 inch longer. Excessive chain stretch causes poor shifting: the chain no longer engages properly with teeth on the freewheel or chainring because each link is longer than the sprocket tooth spacings. In extreme cases, the stretched chain hops over small diameter freewheel cogs like a toad hops over a hot rock.

Coatings other than chrome plate are sometimes used on chains. For instance, I found by chemical analysis that the gold-colored Regina Oro chains are brass plated, while Shimano's silver-colored Dura-Ace UniGlide chains are nickel plated. In both cases, the electroplatings probably have some beneficial effects in reducing wear. Electroplated brass coatings are soft, so they serve as a solid lubricant. On the other hand, nickel plating is hard and, like chrome, reduces wear by virtue of this hardness. As the coatings wear off, of course, the wear resistance is lost.

Other Metals

What are the prospects for metals other than steels? To my knowledge, no major chain manufacturer currently sells anything besides steel chains. Nevertheless, titanium and possibly aluminum could be used in chains in certain circumstances and sold, I believe, at reasonable prices ($25-$50).

Aluminum is an obvious choice because it is only one-third the weight of steel, and certain alloys could be made strong enough, by proper processing, for sideplates. But few aluminum alloys are hard enough to take the abrasion that pins, rollers, and bushings receive. A workable design might use aluminum side plates with integral bushings (a la Sedis), plus steel rollers and pins.

Another factor to consider is sideplate rubbing due to chain misalignment. This might be reduced by hard anodizing the roller and pin link plates. (Anodizing produces a hard surface layer of aluminum oxide, about 0.02 mm thick, which helps resist wear.)

Such a chain should be used only with an aluminum freewheel (and aluminum chainrings, or course), since hard steel sprockets would quickly wear through the chain's oxide layer. If the chain was cleaned and lubricated regularly, it would probably work very well. The most suitable application for aluminum/steel chains would probably be pursuit bikes, where extreme light weight is a virtue, and road grit is not a problem.

Figure 9: Cross-section of a pin from a Sedis chain, showing chrome plating on the surface. The plating is about 1/40th mm thick. Note how the chrome plating appears to have penetrated into the steel (i.e. the silvery whiskers). Apparently, the pin developed surface cracks due to high thermal stresses during heat treatment or quenching (fast cooling) when the pin was hardened. The pin was then plated, and the chrome filled into the cracks, producing whiskers below the surface. The surface cracks caused no problems during the lifetime of my chain, but they may be the cause of some otherwise mysterious chain failures. 270X.

Titanium, which is also strong and light (almost one-half the weight of steel) could also work well, especially in the sideplates. The main drawback to titanium is that it costs about 10 times more than steel, partly due to the special requirements for processing it. As with aluminum chains, the pins, bushings, and rollers would probably have to be made of steel. Unfortunately, this necessary use of steel parts in an aluminum or titanium chain puts a severe limit on the overall potential for weight savings.

Regina apparently discovered this when they made the "Titanio" titanium chain. This little gem, with a retail price of about $200 (before it disappeared from the market several years ago), had the same dimensions as the Regina Oro (Figure 3).

I recently examined a few links from a used Regina Titanio. The side plates are made of a heavily cold-rolled titanium alloy containing small amounts of aluminum and vanadium, probably less than 10% total. (Cold rolling, one of several methods used to strengthen metals, is accomplished by deforming the metal below about 1/3 its melting temperature.) The titanium sideplates do not have any special surface finish, and steel is used for the rollers, pins, and bushings. None of the components were excessively worn, but I don't know how severely it was used. I have been told that the Titanio chains wore out rapidly, but I'm more inclined to believe that their high price was the cause of their demise.

Reinforced Plastic Chains

An essential ingredient of Brian Allen's 22-mile flight across the English Channel in 1979 was a reinforced plastic chain. Allen's aircraft, the Gossamer Albatross, needed an 18-foot long chain to connect the pedals to the propeller. A steel chain was unthinkable because it would have weighed about 6 pounds—nearly 10% of the weight of the entire aircraft. The solution was a light polyurethane chain reinforced with 1/16 inch stainless steel cables. Eighteen feet of this chain weighed only 20 ounces.

This and other types of reinforced plastic chains have undeniable advantages. They are light, cheap (a few dollars per foot), have no moving parts, require no lubrication, and do not wear (if kept clean), stretch, backlash, make noise, or corrode. Even so, there are at least five reasons why reinforced plastic chains aren't yet on bicycles:

1. The Consumer Product Safety Commission requires that bicycle chains be able to support at least 1800 pounds of tension[3]. The best plastic chains with 1/16" stainless steel cables, can support a maximum of only about 400 pounds when sprinting or hill climbing.

2. Stainless steel cables in plastic chains are prone to fail prematurely by fatigue. The severe flexing, as the cables in a bicycle application passed over small diameter free-

[3]***Code of Federal Regulations,*** *Commercial Practices, #16, published by United States Government Printing Office.*

wheel cogs and derailleur pulleys, would pose fatigue problems.

3. Dimensions of the reinforced plastic chains that are currently available are wholly incompatible with the sprockets used on bicycles. I don't expect the derailleur/crankset/freewheel manufacturers to re-tool just to use plastic chains.

4. The splice design currently used on plastic chains is neither narrow nor flexible enough to go through the twists and turns imposed by derailleur gearing.

5. While plastic chains won't rust, they could suffer other types of environmental degradation, including attack by sunlight, ozone, water, road oil, road salts, and temperature extremes.

Clearly, it's no simple task to develop a reinforced plastic bicycle chain that could be sold to the general public. Still, it's not impossible. As a starting point, the loads on chains must be better defined. Then, a new splicing method would have to be developed. Most important, new materials would be needed to meet the extreme requirements listed above. I expect that the reinforced composites used in the aerospace industry (Kevlar, graphite fiber, and silicones, for example) will be the way to go.

I am convinced that practical reinforced composite chains will be with us in the near future, and could even replace steel entirely. Light metal chains (titanium, aluminum) will most likely remain a novelty, like the Regina Titanio. And meanwhile, when your steel chain develops that distinctive rasping sound that says "clean me" . . . , grit your teeth and do it.

I'd like to thank the following for their assistance with this article: Chris Allen (SunTour); Cec Behringer (Behringer Company, Inc.); Bill Fiss (W.M. Berg Co., Inc.); Angel Rodrigues (R+E Cycles); Peter Weigle (J.P. Weigle Cycles); Shimano Sales Corp.

Mario Emiliani, a practicing material engineer in Providence, RI, has built a variety of bicycle frames over the past ten years. He has degrees in Mechanical and Chemical Engineering, and is now completing his Ph.D. in Materials Engineering at Brown University.

The Black Art of Chain Lubrication

Regardless of the alloy or surface plating that is used on a chain, friction between moving parts would ruin it in short order were it not for the *lubricant* on (we hope) all the surfaces.

Lubricants come in many varieties: solid (such as graphite), liquid (WD-40, LPS-1, and LPS-3), and liquids containing suspended solids (Teflon or molybdenum disulfide in TRI-FLOW, Super Lube, and Chain Life). Besides inhibiting wear, lubricants may protect against corrosion, form seals against the intrusion of contaminants, and dissipate heat. In addition, some lubricants penetrate into close-fitting surfaces better than others. Different areas of the bicycle operate under different conditions, and so the choice of lubricant varies with application.

The single most important property of a lubricant is its *viscosity*. This is a measure of its ability to resist flow when a pressure is applied; greater viscosity means that the lubricant is "thicker" and resists deformations better.

Placed between bearing surfaces, a lubricant forms a thin film which holds the surfaces a (small) distance apart. The layer of lubricant can carry large loads in compression, but can also be easily sheared by a relative sliding motion between the parts, thus minimizing friction. The more viscous the lubricant, the greater the compressive load it can sustain before "bottoming out" (when the metals parts come in contact), but the more friction it causes under sliding motion. The ideal then, is to choose a lubricant that is no more viscous than is needed to support the compressive load between adjacent moving parts.

By this criterion, many bicycle manufacturers could be guilty of lube overkill; their chains, when shipped from the factory, are coated with some of the highest-viscosity lubricants imaginable. The heavy lubricant is surely effective at preventing chain wear, but it is far from the minimum-friction solution. In addition, this may mislead some riders into thinking that their chain never needs cleaning and relubrication.

Those who *do* clean their chains are usually motivated into action by the sight of grimy sludge building up after a few hundred miles of riding. Some wait until rasping noises from the chain become unbearable. A small virtuous minority, including chain manufacturers, insist on cleaning the chain at *fixed intervals*. For instance, the small print on the Sedis package suggests a cleaning every 300 miles, but gives not a hint as to *how*. What, then, is the best way to clean and relube a chain?

Choosing Your Poison

Soaking the dirty chain in Kerosene (or parts-degreaser solvent) is common. If done improperly, however, this may be worse than no cleaning at all. Kerosene provides a satisfying cosmetic removal of visible road grit, but also strips the heavy factory grease from the chain, including that inside the pins and rollers, where the stresses are highest. When you re-lube the chain, the lubricant may not totally penetrate into these crevices. And even if the new lube makes it into every crack, residual solvent may thin it (reduce its viscosity) excessively. At every hand, you are faced with the potential of a new wear problem in just a few miles of riding.

What to do in this grim situation? If you are not concerned with grease accumulations on your chain, the just wipe it down with a clean rag and lubricate it after every couple of rides. After a season or so or riding, throw the chain away and buy a new one.

The other approach is to soak the chain first in kerosene, then in a more volatile solvent like naptha (white gas). The latter solvent will remove kerosene residue, and will quickly evaporate from even the tightest cracks, thanks to its volatility. At all costs, avoid setting yourself on fire, since naptha is highly flammable. You might want to repeat both soaking steps to ensure that all dirt and grease is removed. Then the chain can be relubricated as usual.

Here are some additional points to consider. In the no-soak wipe-down approach, relubrication may be ineffective because small passages are likely to be clogged with old grease and road grit. Your lubricant of choice, then, should be one with *low viscosity*, such as WD-40 or LPS-1. This will act as a solvent, soften the heavy grease deposits, and maybe even reach those close-fitting, high-stress areas.

In the Kero/naptha double-soak approach, you should use a moderate to high viscosity lubricant. Heavy gear oil (about SAE 80 viscosity) or paraffin are ideal, provided they are heated first to reduce the viscosity. (Caution and good ventilation are appropriate when working with hot oil.) An alternative is to use LPS-3 or TRI-FLOW, which both become quite viscous once their volatile constituents have evaporated. Using the high viscous oil, and making sure it reaches every surface, will give you the longest-lasting lube job possible.

Which approach is best? I used to be a fan of fixed-interval cleaning. For several years I cleaned my chain regularly in kerosene and naptha, and relubricated it with excessive amounts of LPS-3—even when it (probably) didn't need it. I now perform the ritual only if I get stuck riding in the rain, or ride on unpaved roads, or find a really objectionable amount of grime on the chain. Otherwise, I just wipe it down every couple of rides, and give it a light lube.

To those who've put off cleaning the chain for too long, remember: your chain is not the only potential victim of grime. Aluminum chainrings and freewheels, rear derailleur pulleys, and both derailleur cages are made of far softer materials than your chain. Wouldn't it be an outrage if these expensive components were destroyed by a dirty $10 chain!

—Mario Emiliani