Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

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IN THIS ISSUE

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.'

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.' 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 distribbition. 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.

'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.*

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

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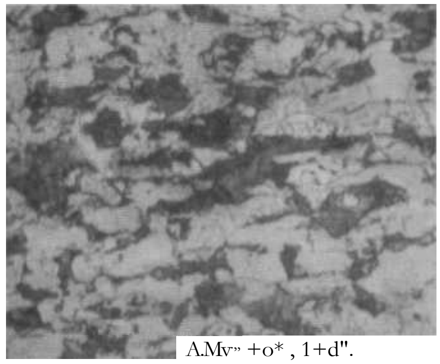
This results in a much stronger steel.

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).



A.Mv" +o* , 1+d".

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.

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).

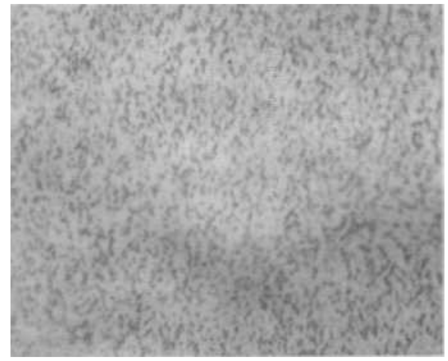


Figure 2: This is the type of microstructure top-of-the-line Tange, Columbus, and Reynolds tubings have (except Reynolds 753). It consists of small spheres of carbides (dark dots) embedded in iron (light background). Notice how fine the dispersion of carbides is. There is no significant difference in 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.

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'* 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

*"Internal energy is the sum of kinetic **and potential** energies of all the atoms **in a metal.** The strength of most metals at room ture 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.*

V

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
11111110 are mined in foreign countries, demand for them is high, and they are getting scarcer every day.

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.

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.

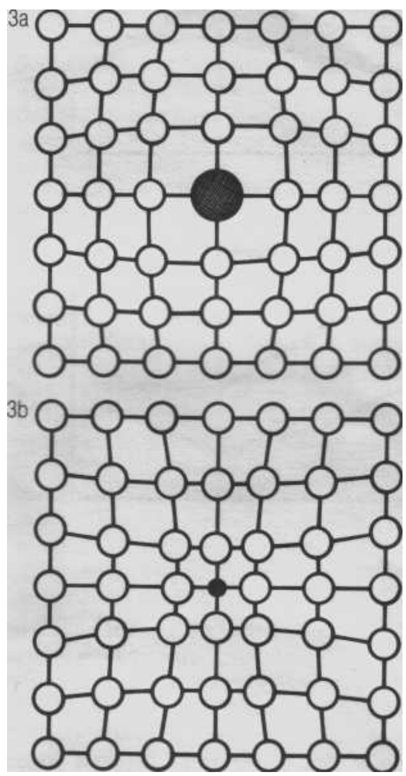


Figure 3: Adding elements which are capable of dissolving in iron at room temperature strains atomic bonds due to the difference in diameters of the atoms. This helps block slip. (From: Marc H. Richman, *An Introduction to the Science of Metals,* Ginn Custom Publishing, MA (1967), p. 303, by permission).

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.

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 ex

posed 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.

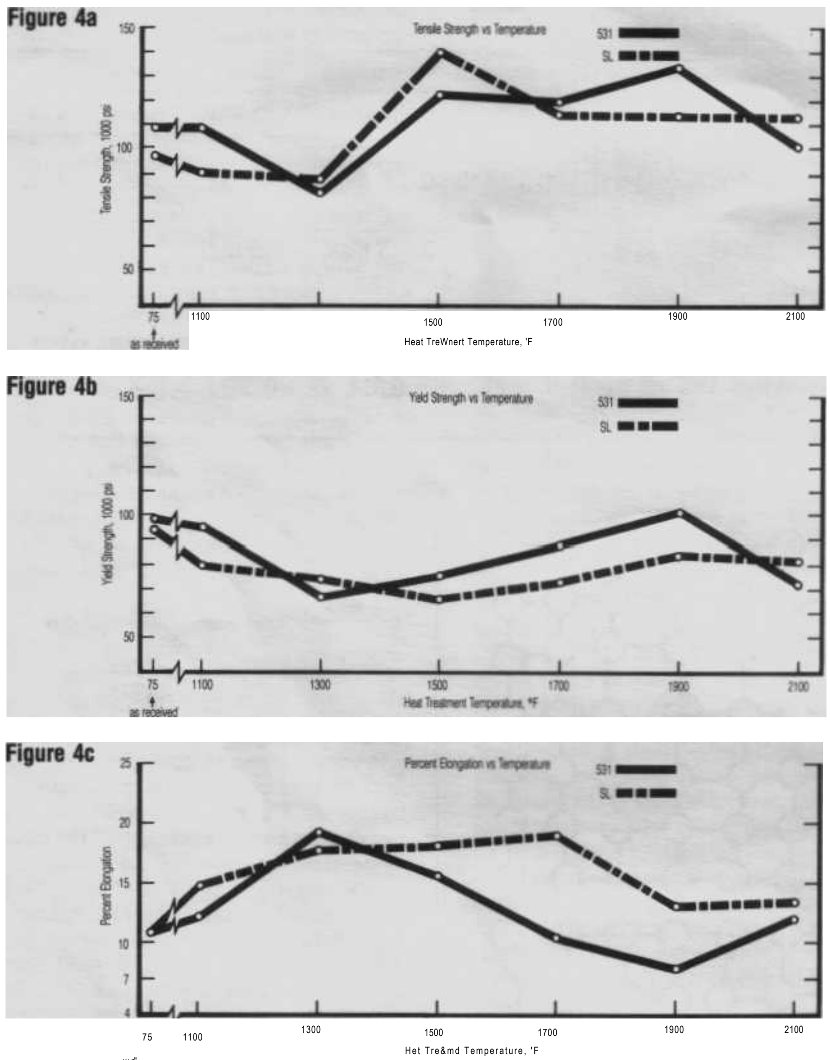


Figure 4: These curves, for a heat treatment time of five minutes, show what happens to the three basic mechanical properties of Reynolds 531 and Columbus SL tubing after tempering and normalizing heat treatments. Throughout the ranges of temperatures, the tubing remains strong and ductile.

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."

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, Iblin^{z}	Yield Strength, Win ^{2}	%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. Conse quently 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

'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,

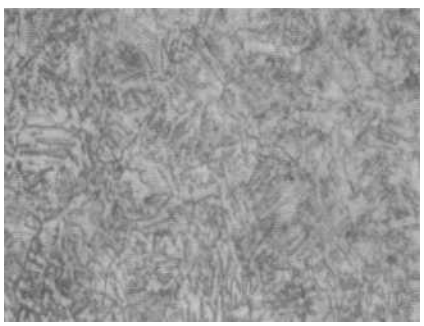


Figure 5: Reynolds 531 brazed at 1700°F for five minutes and air-cooled. This microstructure represents a slightly stronger steel than that shown in either Figure 1 or 2, since air cooling is fast enough to trap some carbon atoms in the room temperature arrangement of iron atoms. Magnified 400 times.

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[*] 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 1/16inch steel ball indenter).

"The tubes were supplied by SRC GROUP INC., Portland, Oregon.

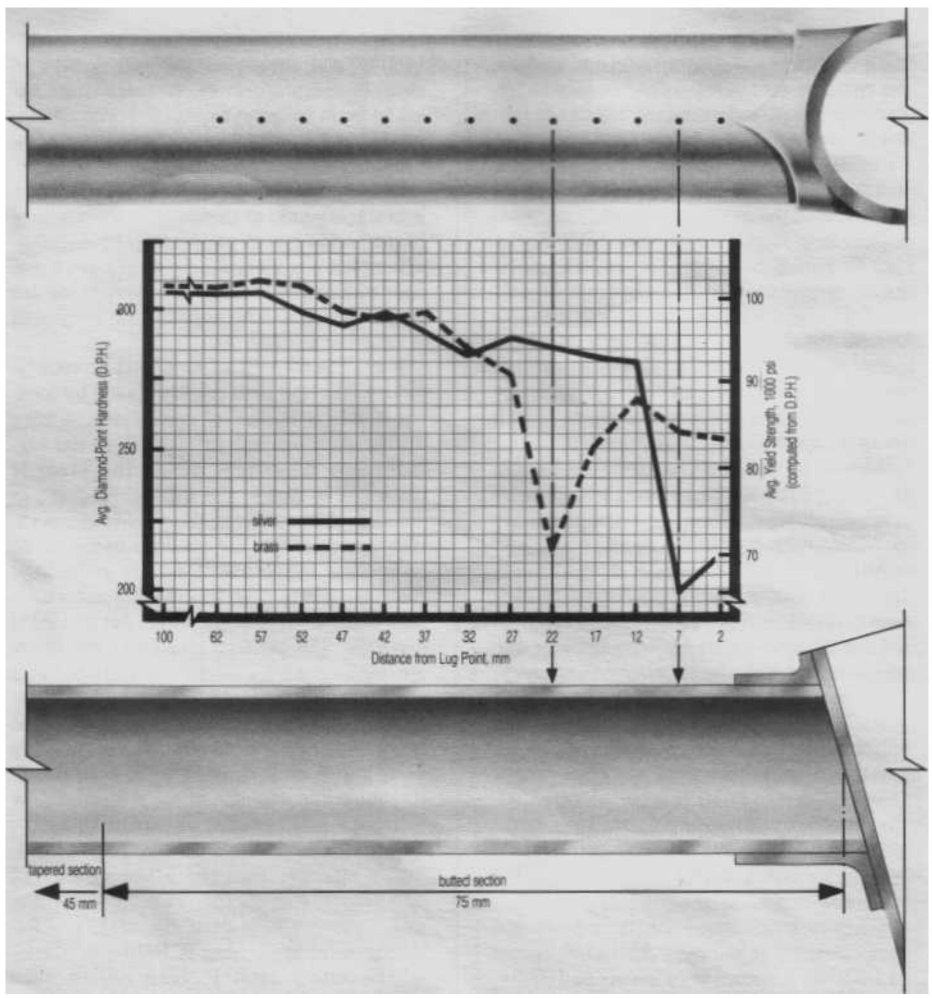


Figure 6: Test for the effect of temperature gradient on tube strength

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

yield strength in psi = 395 (D.P.H.) (B)'

where B = 0.1 and n = 0.08 for steel.' 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-la (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.

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.'	66,670	87,370	69,980	84,683

Recommended Brazing Procedures

Tubing manufacturers provide frame builders 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.

[6] *Cahoon, J.R., et al., Met. Trans., Vol. 2, July 1971, pp. 1979-1983.*