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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.[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.*

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).

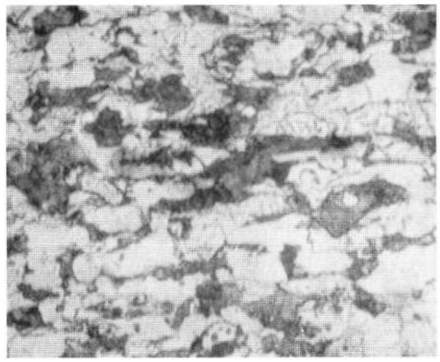


Figure 1: This is the type of microstructure top-of-the-line Ishiwata and Vitus tubings have, and is also the microstructure that plain low-carbon steels have. This microstructure consists of grains of iron (light areas), and carbide platelets embedded in iron (dark areas). Magnified 400 times.

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).

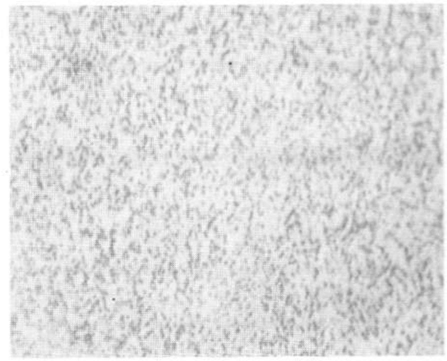


Figure 2: This is the type of microstructure top-of-the-line Tange, Columbus, and Reynolds tubings have (except Reynolds 753). It consists of small spheres of carbides (dark dots) embedded in iron (light background). Notice how fine the dispersion of carbides is. There is no significant difference in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

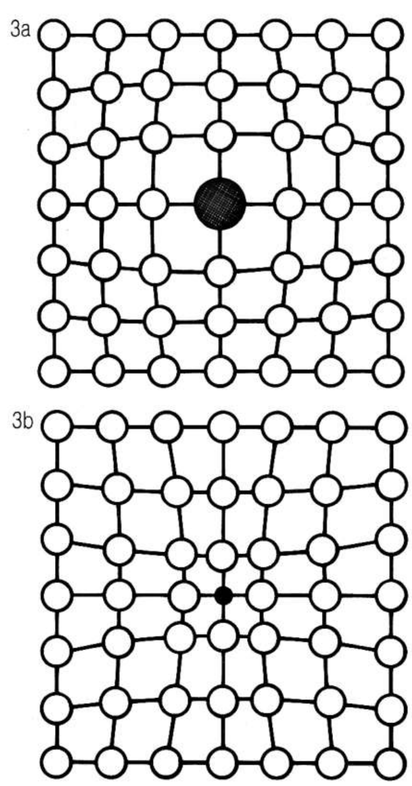


Figure 3: Adding elements which are capable of dissolving in iron at room temperature strains atomic bonds due to the difference in diameters of the atoms. This helps block slip. (From: Marc H. Richman, *An Introduction to the Science of Metals,* Ginn Custom Publishing, MA (1967), p. 303, by permission).

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 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

Figure 4a

Figure 4b

Figure 4c

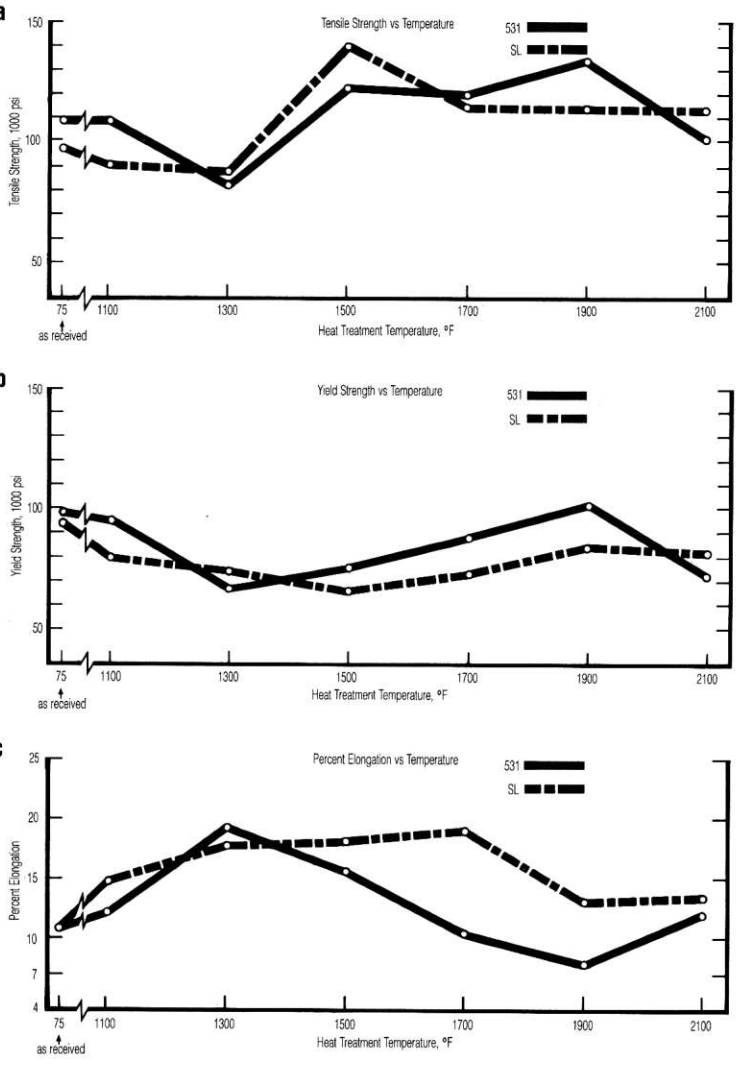


Figure 4: These curves, for a heat treatment time of five minutes, show what happens to the three basic mechanical properties of Reynolds 531 and Columbus SL tubing after tempering and normalizing heat treatments. Throughout the ranges of temperatures, the tubing remains strong and ductile.

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 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.

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/in^2	Yield Strength, lb/in^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. 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,

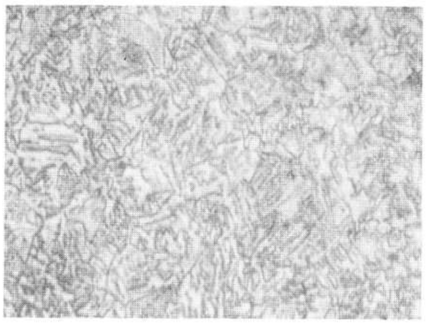


Figure 5: Reynolds 531 brazed at 1700°F for five minutes and air-cooled. This microstructure represents a slightly stronger steel than that shown in either Figure 1 or 2, since air cooling is fast enough to trap some carbon atoms in the room temperature arrangement of iron atoms. Magnified 400 times.

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.*

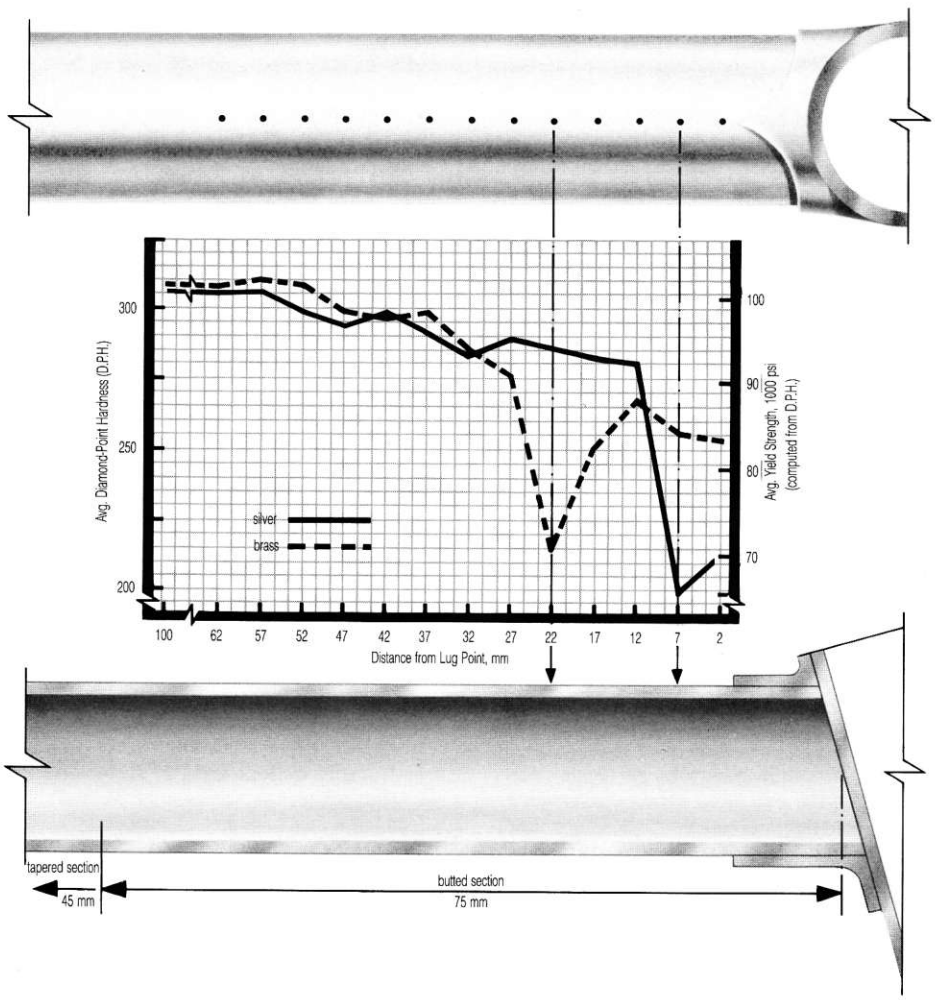


Figure 6: Test for the effect of temperature gradient on tube strength

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

yield strength in psi = 395 (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.

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

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

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.

Rolling Resistance of Bicycle Tires

Rob Van der Plas

The efficiency of the bicycle depends on two major factors — wind resistance and tire rolling resistance — but in recent years only wind resistance has been extensively investigated. After all, doesn't everybody know that significant improvements in maximum cycling speeds can be achieved only with a reduction in wind resistance?

That is fair enough as long as one considers top speeds only, but at lower speeds, much more typical of the vast majority of cycling, the effect of rolling resistance is of greater significance than is usually recognized.

Critical Factor

Rolling resistance is defined as the effect of rolling friction between the tires and the road. As with other losses (e.g., wind resistance and mechanical friction losses), the effort needed to overcome rolling resistance at a given speed may be expressed in units of power: watts (W) or horsepower (hp). Its magnitude is calculated from the following formula:

$$P = C_R \times F \times v$$

where

- P = power required to overcome rolling resistance
- C_R = coefficient of rolling resistance
- F = vertical loading of wheel
- v = riding speed

P, F, and v may be expressed in SI units (watts, newtons, and m/sec, respectively) or in English units (ft-lb/sec or hp/550, pounds force, and ft/sec, respectively), so long as the two systems of units are not mixed. C_R is dimensionless and can be used in either system.

The critical factor is C_R, the coefficient of rolling resistance. All efforts to reduce rolling resistance must concentrate on attempting to reduce this factor, which has been shown to depend on the following individual variables:

- wheel diameter
- tire pressure
- tire quality
- road surface quality
- riding speed (less significant)

Published data for tire rolling resistance are summarized extensively by Whitt and Wilson in the second edition of *Bicycling Science* (chapter 5). From this summary one may conclude that the range of rolling resistance on good road surfaces lies between approximately .002 and .01 (i.e., varying by a factor of 5). Wind resistance, on the other hand, is variable much less, within the limits of conventional (i.e., non-enclosed) bicycle design, even if recumbents are taken into consideration. The same source (chapter 7) summarizes many of the different findings to date, from which the range of frontal area can be stated to lie between $0.3m^2$ and $0.55m^2$ (i.e., varying by a factor of 1.8) and the drag coefficient between 0.8 and 1.1 (i.e., varying by a factor of 1.4); multiplying these two factors results in a total factor of 2.5 for the maximum total effect of reducing wind resistance.

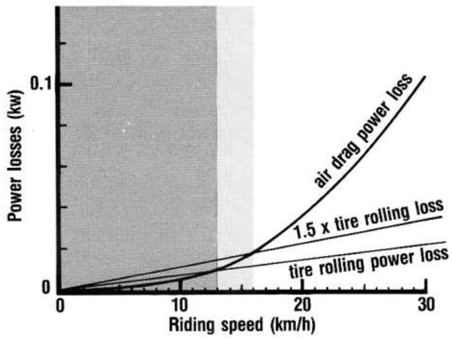


Figure 1: Data for rolling resistance and wind resistance power losses given by Whitt and Wilson in *Bicycling Science*, plotted in S.I. units, with speed in km/h. The additional line marked "1.5 x tire rolling losses" is the basis for the contention that rolling resistance is a more significant factor than air drag losses at speeds up to 16 km/h (10 mph). See text for explanation. Within the dark shaded area rolling resistance exceeds wind resistance.

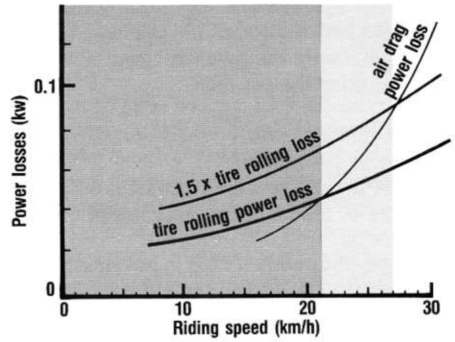


Figure 2: Similar data with different results, based on Shimano's published figures (Shimano's figures are given in resistance force in newtons — they have been multiplied by the speed in m/sec to arrive at power losses in watts, to allow comparison with Figure 1). Here rolling resistance is important up to 27 km/h.

More from Less

The wider range of variation in rolling resistance offers the possibility that for a given bike, better tires can make more difference than air drag reduction (short of using fairings), even at speeds for which air drag is somewhat greater than rolling resistance. While the exact result will depend on how draggy (in both respects) the bike is to begin with, a plausible example is that for a bike which is about mid-range in both air drag and rolling drag, optimizing the tire drag will make more difference than optimizing the air drag for all speeds whose initial air drag is less than $1^1/_2$ times the initial rolling drag.

(To illustrate: At $1^1/_2$ times rolling drag, the air drag would be $^3/_5$ the total drag — ignoring bearing friction, which is very small. If the air drag were at the middle of the range just mentioned, it would be about 1.75 times the minimum value in the range, and so could be reduced by 43 percent, which would reduce the total drag by $^3/_5 \times 43$, or 26 percent. Meanwhile if rolling drag were at the middle of its range, it would be three times its minimum possible value and so could be reduced by 67 percent. Although rolling drag would be only $^2/_5$ of the total, then, this larger change would reduce the total drag by $^2/_5 \times 67$, or 27 percent.)

This example doesn't make $1^1/_2$ a magic number, of course; it simply illustrates a general magnitude to bear in mind. With different numbers, rolling resistance will have somewhat different importance.

With rising speed the relative importance of rolling drag will decline, but not as suddenly as might be expected — the actual power it consumes will increase, and in the range of speed to which the example applies, the percentage of total drag due to rolling drag will decrease by a ratio only slightly greater than the ratio of increase in the speed itself. Though overshadowed, it doesn't suddenly vanish.

The speed at which the 3:2 ratio applies will depend on the initial values of all the variables already mentioned, and estimates vary on the values for a "typical" bicycle and rider. If we use data given by Whitt and Wilson (*Bicycling Science*, pp. 158, 159) wind resistance reaches $1^1/_2$ times rolling resistance at 16 km/h (10 mph). Another set of data — from Shimano (Shimano Aerodynamics catalog, 1980) — places the critical speed significantly higher: about 27 km/h (17 mph). So it seems realistic to consider rolling resistance of dominant importance for all cycling at speeds below 16 km/h (10 mph), and per-

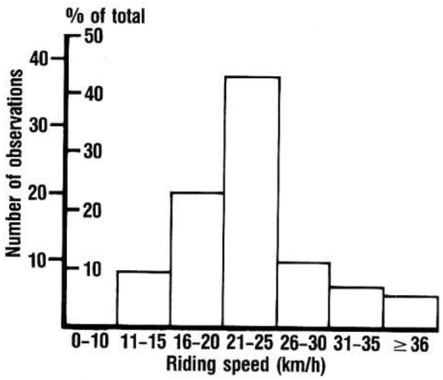


Figure 3: Distribution of riding speeds (84 observations) among 31 randomly selected cyclists.

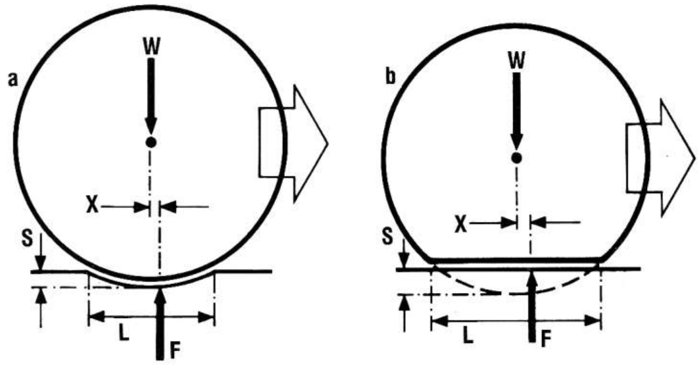


Figure 4: Deformation of wheel or surface due to a load (exaggerated); *a,* wheel harder than surface (approached by railroad wheel and rail), *b,* surface harder than wheel (approximated by bicycle on pavement).

S = sinkage
L = imprint length
F = supporting force for moving wheel
W = load on wheel
X = offset distance from axle to supporting force

haps at speeds up to 27 km/h (17 mph).

To establish what percentage of all cycling this might be, I equipped a bicycle with an electronic speedometer and followed randomly selected cyclists on a still Saturday morning in an essentially flat area in San Mateo County, California. For each cyclist I took three readings (unless the cyclist turned off the main road sooner) and then found a new cyclist.

The results of this test are shown in the graph (Figure 3): of 84 readings, representing 31 cyclists and a total distance of 67 km (42 miles), 66 observations (79 percent) involved speeds below 26 km/h (16 mph) and 28 (33 percent) involved speeds of 20 km/h (12 mph) or less. If these findings are taken to be representative, it seems that most cycling is done at speeds for which rolling resistance is highly significant.

Offset Supporting Force

The rolling resistance of a wheel on a surface results from the deformation of either the wheel or the surface, or both. Usually the deformation is temporary — except in the case of soft ground — and the deformed areas of wheel and/or surface return to their original shapes as the wheel rolls off of them. But since no solid material is perfectly elastic, the force that the deformed areas exert as they recover is less than the force they exert as they are compressed.

As a result the supporting force for a moving wheel is not centered directly below the axle but slightly ahead of it. When combined with the wheel's load, which is centered on the axle, this off-center supporting force exerts a rearward torque which opposes the wheel's motion.

For railway wheels (one of the first cases studied), the forward offset distance of the supporting force is generally about 1/8 of the wheel's imprint length (*Bicycling Science,* p. 108). Whitt, writing for the British magazine *Cycle-touring,* describes how he measured the contact surfaces of different bicycle and railway wheels, and concludes that for wheels with equal diameters the length of the imprint is the clue to reducing the coefficient of rolling resistance.

Bicycle tires have much greater imprint lengths than train wheels — typically 0.1 to 0.3 diameters, as opposed to roughly 0.005 diameters for train wheels (*Bicycling Science,* p. 113). The different behavior of pneumatic tires compensates for much of this difference: for a pneumatic bicycle tire the supporting force is typically offset only 0.02 to 0.04 of the imprint length, instead of the railroad wheels' 0.125. Still, though, the coefficient of rolling resistance for a good tubular bicycle tire is two or three times as great as for a steel wheel on a steel rail.

Why Not Steel?

So why don't we mount steel tires? Obviously things take on a different perspective when we leave the smooth track of the railway and head for the road: roads just are not as smooth nor as hard as steel rails. Whereas surface irregularity of a steel rail is measured in tenths of a millimeter, it is at least 20 times greater even on the best of asphalt roads, not to mention the paving slabs and cobblestone surfaces of many European cities. In addition, while steel rails deform very little, the softer asphalt would deform into a much greater sinkage (thus causing a greater contact length and a higher coefficient of rolling resistance) under the hard steel tire.

Surface irregularities are important because they cause vertical wheel motions, and thereby create a significant retarding force added to the one which results from imprint length. It is this retarding force which is the primary cause of the unpredictability of rolling resistance on ordinary roads.

The effects of wheel diameter and tire pressure have been studied extensively; yet on most modern bicycles the wheel diameter can be regarded as given (approximately 680 mm, ± 15 mm, for almost all adult bicycles in use). Similarly, the effect of tire pressure is simple enough: the higher the pressure, the lower the rolling resistance. By contrast, none of the sources mentioned by Whitt and Wilson, nor any source I have found myself, has systematically compared

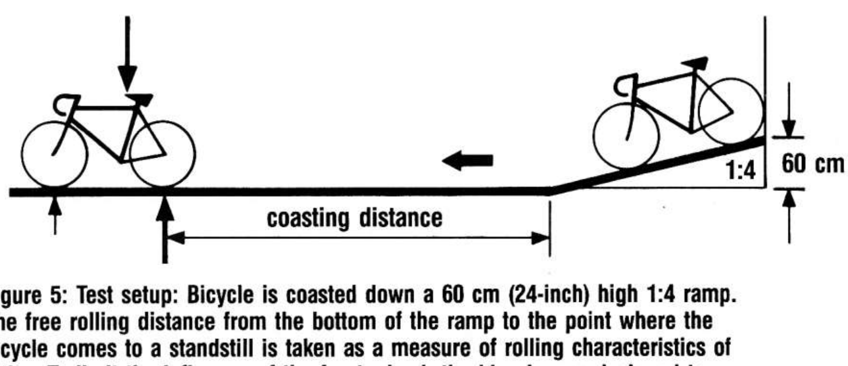


Figure 5: Test setup: Bicycle is coasted down a 60 cm (24-inch) high 1:4 ramp. The free rolling distance from the bottom of the ramp to the point where the bicycle comes to a standstill is taken as a measure of rolling characteristics of a tire. To limit the influence of the front wheel, the bicycle was designed to apply almost the entire load on the rear wheel.

the coefficients of rolling resistance on different road surfaces for pneumatic bicycle tires.

Subway Station

I stumbled upon the effect of road surface quality in conjunction with tire type and quality during simple rolling tests, which I undertook initially to establish whether different tires would have different C_R values, despite identical diameter and tire pressure. My test procedure was as follows:

I built a special extremely-long-wheelbase coasting bicycle (i.e., without a drivetrain) which put most of the rider's weight on the rear wheel (the wheel loading was 58 kg, or 570 newtons). I mounted the sample tires on a group of interchangeable rear wheels. Then with each rear wheel mounted in this bike, I rode down a 60 cm-high ramp with a 1:4 slope and allowed the bike to come to a stop. I recorded the distance from the bottom of the ramp to the point where the bicycle came to a standstill, and took this distance as an indicator of the rear tire's rolling resistance.

Initially I tested two different tubular tires and two different wired-on tires, each inflated to exactly the same air pressure (6.0 bar or 88 psi) in combination with a virtually smooth "road surface" (the marble floor of a new subway station). Later I repeated the test, using only the lighter-running tubular and two different wired-on tires, each in combination with two different tubes, on two different surfaces: the same virtually smooth floor, and a rough concrete floor (of an unfinished subway station) with a surface reminiscent of an asphalt road due for resurfacing.

I made three runs for each combination of tire and surface, and took the mean of each set of three distances. To the shortest mean coasting distance (approximately 12 meters) I assigned the value 1.0; then I expressed the mean for each combination of tire and surface as a multiple of this value (see table). Note that the higher values denote the lower rolling resistances — they can be thought of as relative "mileage" figures, the inverse of drag figures.

Relative Rolling Distances for Various Tires on Two Surfaces

tire	tube	cross-section width	mean distance factor (and standard deviation) smooth surf.	rough surf.
tubular A	—	23 mm	3.1 (0.13)	1.9 (0.15)
tubular B	—	25 mm	2.7 (0.18)	(not tested)
wired-on C	latex	25 mm	2.6 (0.15)	1.7 (0.20)
wired-on D	latex	32 mm	2.3 (0.19)	1.3 (0.18)
wired-on C	butyl	25 mm	2.0 (0.17)	1.5 (0.22)
wired-on D	butyl	32 mm	2.1 (0.16)	1.0 (0.19)

These results allow some preliminary conclusions (which remain to be substantiated by more extensive testing), the most interesting of these being:

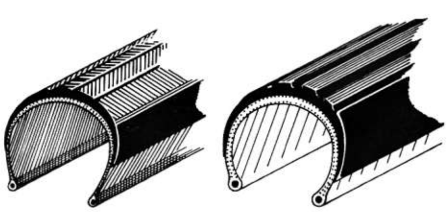
1) At any given pressure there is little difference in performance between tubular tires and light wired-on tires ridden on a smooth surface.

2) At the same pressure tubular tires perform significantly better on rough surfaces than light wired-on tires: the increase in the coefficient of rolling resistance due to surface roughness is much more significant for wired-on tires than it is for tubulars.

3) A given wired-on tire offers significantly less rolling resistance used with a (very flexible and light) latex tube than with a conventional (heavier and "stiffer") butyl tube.

4) A wired-on tire that offers less rolling resistance on a smooth surface than another tire, may actually have a higher rolling resistance than that other tire when used on a rough surface (each time at the same inflation pressure).

In subsequent limited tests on tires available to me in Germany, I attempted to find the lightest running wired-on tire, for both smooth and rough surfaces. (The tires I tested may differ from those available elsewhere: of the tires made in the Far East, I could obtain only the Panasonic Panaracer and the IRC tire, each with a 28-mm cross section.)



a. flexible construction b. less flexible construction

Figure 6: (Left) Tire construction of (wired-on) tires with lowest rolling resistance: very thin fibers which are not interwoven, a protective tape around the beads, gradually thickening tread with relatively unpronounced profile. (Right) Typical construction of tires with higher rolling resistance: thicker cords embedded in rubber, additional layer of fibers under tread, well-defined and more abrupt tread profile.

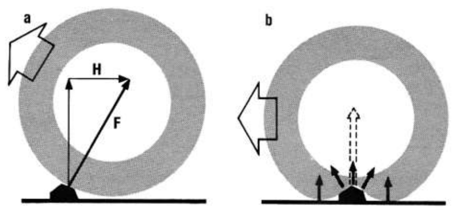
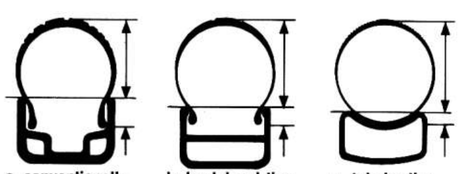


Figure 7: Effect of bumps on (a) rigid wheel and (b) wheel with resilient tire. On rigid wheel bump exerts upward force F with retarding horizontal component H, causing wheel to slow down and often become airborne. Resilient tire "averages" numerous surface forces into smooth supporting force.



a. conventionally seated wired-on tire b. hook-bead tire c. tubular tire

Figure 8: The larger the portion of a tire that is free to flex (i.e., not retained by the rim), the better it can flex, and the less rolling resistance it will offer (all else being equal): the hooked bead wired-on tire is likely to perform better than the conventionally seated tire — though not quite as well as the tubular tire.

I then analyzed this particular tire to establish what "makes it tick." All these subsequent tests were done with relatively narrow tires (25 to 28 mm), using the latex inner tube and the same wheel, in order to minimize extraneous variables.

The particular tire thus selected (Pariba 25-622 HP, which to my knowledge is not sold in the U.S.) performed marginally bet-

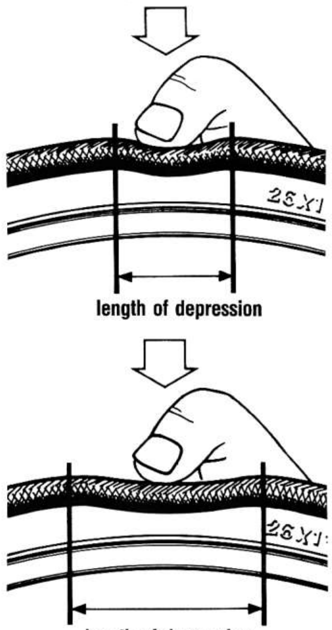


Figure 9: Rule of thumb: if the inflated tire flexes closely around the thumb, it is likely to be more flexible and offer less rolling resistance on rough surfaces.

ter than two other tires, which each appeared similar to it in construction. All three of these tires were constructed as shown in the illustration (Figure 6a) and differed significantly from most of the other tires, which all offered significantly more resistance (Figure 6b). Although I could not test enough tires to obtain statistically significant results, I feel there is enough correlation between tire construction and tire performance to justify these conclusions.

To evaluate a tire properly it seems necessary to cut a section, as I did for this test; since that is a rather expensive hobby, I propose that manufacturers and importers make a habit of cutting up a few tires of each type, to provide four-inch long sections to the dealers for inspection.

Bumps

The theoretical basis for these differences in performance, between tires which are similar in appearance, weight, cross section, and pressure, appears to be as follows:

If a tire were solid and inflexible, any upward projection (bump) in the road surface would force the wheel up, and the force exerted by the bump would include a component opposite to the direction of travel. Some portion of the wheel's forward motion would thereby be lost, or at best converted into vertical motion.

Once the wheel passed beyond the upward side of the bump, gravity would soon convert any upward motion to downward. With luck, this downward motion could then be

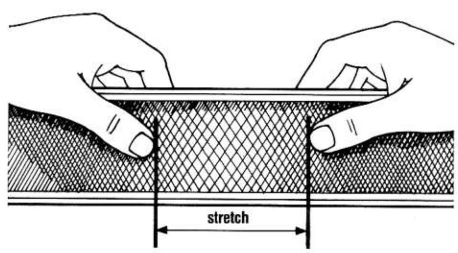


Figure 10: Stretch test on the uninstalled tire: a tire with low rolling resistance on rougher surfaces will flex quite easily without permanent deformation if pulled as shown.

converted back to forward motion by the descending slope of the bump — but only if the bump were so smooth and round that the wheel actually followed the surface as it descended. If the wheel flew clear of the bump and landed on a level surface beyond it, the vertical momentum could make no contribution to forward motion and would be lost. Worse, if the wheel landed on the face of another bump, its downward speed would actually increase the retarding force.

In the case of a downward unevenness, the solid wheel would accelerate down into the dip, but then would have to "climb" back out, with the same retarding effect as for the bump. At best, of course, it would lose as much speed as it had gained; and if the bottom of the dip were sharp it would lose much more.

Floating

A pneumatic tire avoids much of this retarding effect by using a cushion of compressed air, whose elasticity "averages" the forces from bumps and dips into a smoother continuous supporting force. This smoothness enables the tire to stay against the ground over many of the smaller bumps, so that it can press against the downhill side of a bump as well as the uphill side. As long as the wheel stays on the ground, each retarding force is followed by a compensating accelerating force. Ideally, the tire approaches the "floating" effect of the air layer under a hovercraft.

But while the air's elasticity is great, the tire material's elasticity is limited; and the cushion of air can provide only as much elasticity as the tire allows.

A low-pressure tire forms itself into uneven surfaces quite easily, but suffers from large contact area on any surface (the contact length is a function of pressure, when wheel diameter and width are given). A higher pressure tire, on the other hand, has a shorter contact area, so it rolls easily on smooth surfaces. But on rough surfaces, the high-pressure tire can perform well only if it is extremely flexible and has little hysteresis (i.e., friction between molecules, which retards the deformation of a flexible material). Otherwise, the high-pressure tire will "skip" — become airborne and lose the benefit of the downward acceleration. It appears that these criteria are better satisfied by the following methods and materials:

1) Latex or "gum" rubber (i.e., unvulcanized rubber) in preference to vulcanized rubber or butyl — significant for inner tube and carcass.

2) A carcass consisting of two layers of closely spaced thin fibers — in preference to thicker fibers, interwoven fibers, or rubber-covered fibers (such thin carcasses require protective tape around the beads).

3) A tread which is thicker in the middle and tapers off gradually in cross section, in preference to treads with irregular profiles and ridges (from subjective tests, I believe these tread patterns probably also give better traction and handling and perhaps less tire wear).

4) A shape which is free to flex sideways, i.e., a cross section with the smallest possible portion of its height retained within the rim. This criterion is best satisfied by the tubular tire; among wired-on tires, I found that the hooked-bead variety, used with the appropriate "box section" rim, approached this ideal more closely than the conventionally seated tires, used with the deeper rim profile (Figures 8a and 8b respectively).

Two Tests

In addition to a visual inspection, with which most of these criteria may be verified, two simple checks may be useful — certainly after the tester has developed some "feel" for the appropriate qualities:

1) On the inflated tire, push perpendicularly down with the thumb: the more desirable flexing of the tire follows the thumb quite closely, in contrast to a tire which (inflated to the same pressure) deforms more gradually, as illustrated in Figures 9a and 9b respectively.

2) On the uninstalled tire, check for elasticity by pulling in the direction represented by the arrows in Figure 10.

Finally, it may be necessary to explain the relationship between cross sectional width, weight, and allowable pressure for different tires. The reason for the use of narrower tires (20 - 28 mm, as opposed to the 32 mm of earlier 27 × 1¼ and 700C tires) is not a (presumed) relationship between tire width and rolling resistance, but a simple physical principle: at any given pressure the stresses

Shop Talk

Spoke Tension: How Tight Is Right?

Eric Hjertberg

Widely misunderstood and often ignored, tension is the bicycle wheel's secret force. Investing the spokes with tension can make this delicate-looking structure into a unit of immense strength.

Optimum tension is, in general, the highest tension the wheel can support indefinitely. Appropriately high tension gives the longest possible wheel life but even so most wheels are built loose because it is quicker and requires less precision and less expensive parts.

Building to high tension is slow, cautious work because, like a brick wall, the higher it gets the more important it is that each additional layer be deliberate and even. Let's examine why it is worth the extra effort to build to high tension.

Chance of Reaching Zero

The tighter wheel is stronger. It can support greater weight without sustaining damage. As weight is applied to the hub the bottom several spokes experience a decrease in tension. If tensions are greater to begin with there is less chance they will reach zero, and allow the rim to become permanently flattened or twisted. A tighter wheel can also withstand greater side loads for the same reason, like a tent pitched with taut guy lines.

In addition to its strength, the tight wheel will last longer because it flexes less. Flexing, however minute, causes metal fatigue and eventual spoke breakage.

During building and early riding, spokes, hub, and rim yield and deform. Tighter building extracts more of this change during the building process itself so less can occur later. A tighter wheel is less likely to settle with use.

Tight spokes are also more likely to hold their nipples still. During hard riding a spoke that occasionally goes slack for an instant can eventually lose a few turns of its nipple due to vibration. Tighter wheels loosen less and are more vibration-proof and so more stable.

But beyond these practical advantages, tight wheels just feel better. They possess a crisp, bright resonance that seems stiffer and more efficient. The lively, responsive ride of a top quality bicycle is owed in part to its well-built wheels. Cycling may be our most efficient form of transportation but most of us ride more for the quality of the experience than for sheer economy, so virtues like stiff and snappy feel rate highly.

Since tight wheels seem to possess every advantage, why are so many built loose? Besides extra time, are there risks in approaching maximum tension?

Fidgets

The greatest economic impediment to building to high tension is the strength, time, and experience required. Although most people are strong enough to build a good

Continued from page 11

on the tire are reduced in the same proportion as the cross section width (Figure 11). Consequently, a lighter and more flexible tire is much easier to manufacture if a narrower cross section is selected — the alternative of using stronger fibers has its limitations.

I do not claim to have covered everything relating to rolling resistance of bicycle tires in this article, nor that my limited testing so far is adequate and conclusive. More extensive testing (e.g., at different inflation pressures, with different riding speeds and loadings, and with more different standardized surface qualities) would certainly help to get a more definitive answer to the question: which is the best tire for which use? Wear and puncture-resistance properties should probably be considered, too (what's the use of saving seconds, if you have to spend hours fixing flats?). However, I feel that I have shown two things: that tire rolling resistance is quite a significant factor in most bicycle use, and that some recognizable features of bicycle tires and inner tubes allow the user to select a combination of tire and tube which is very likely to have a low rolling resistance.

I have neither the funds nor the patience to continue my experiments in this field, having arrived at reasonably accurate criteria for my own use. Just the same, I am anxious to see more (and especially more quantitative) experiments concentrated on this subject. Keep me posted!

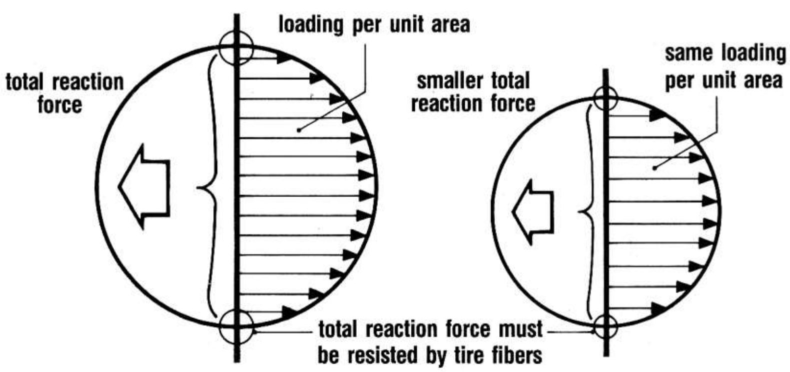


Figure 11: Wide tire versus narrow tire: inflated to the same pressure (i.e., force per unit of area), the total force on the wider tire is greater. Consequently, the wider tire must be made stronger and heavier and will therefore end up being less flexible. It may roll well on smooth surfaces, even feel comfortable on rough surfaces, but it will probably offer more resistance on this rougher surface.

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For additional tires, see the bibliography to chapter 5 in Whitt and Wilson.

Rob van der Plas is the author of the recently published Penguin Bicycle Handbook, *Penguin Books, London, 1983.*

wheel they might be unable to build as quickly and frequently as necessary to earn a living. Even an exceptionally strong and experienced builder would be hard pressed to complete a first class rebuild to high tension in less than one-half hour even under perfect conditions. Most such jobs occupy a solid hour or more.

Beyond the strength and time required, there is the risk of spontaneous wheel collapse: an *overtight* wheel can fail dramatically. If a builder seeking optimum performance makes the spokes too tight, or tightens them unevenly, the wheel may begin to appear uncooperative or unstable — as the builder trues one spot, for example, other parts of the wheel may go out of true which were in line a moment before. Then with no further warning the rim can suddenly pop into a potato-chip shape, leaving many of the spokes loose and bending the rim.

During building, there are few signs that the average tension may be too high because it rises very suddenly as the wheel becomes tight. If the wheel begins to "fidget," it's been taken too far already, or tightened very unevenly. For a professional builder it's a useful exercise to do this deliberately from time to time, to maintain a sense of how far it's safe to go — but for people who build fewer wheels this may be an expensive form of education.

A more cautious approach is to start at the low end of the acceptable range and work up with experience — true up a wheel with moderate tension and ride it for a while. If the wheel loosens after the first few miles of hard riding, that's an indication that it could have been built tighter in the first place.

Frequently one spoke, often near the joint in the rim, will need to be significantly tighter than the others to hold the wheel true. In such a case, this one spoke will limit the tension of the whole wheel — when it cannot be tightened further, neither can the others if the wheel is to be true.

Rapid Tightening

When a spoke is tightened the tension rises slowly at first, because much of the distance taken up comes from settling-in of the spokes where their ends seat in hub and rim, from the new "set" the spoke elbow takes as it adjusts to the exact angle between spoke and flange, and from puckering of the rim surface near each spoke. These initial deflections exhibit much less "stiffness" (in the direction of the load) than do the spokes themselves, but the take-up they offer is limited.

When the builder tightens the spokes beyond this amount, any further length removed must come from elongation of the spokes themselves (and lengthwise compression of the rim), and the tension rises at a rapid rate, determined by the "stiff" lengthwise elasticity of these parts. Diagram 1 shows how between points D and F the average tension nearly doubles with only one turn of each nipple. Since both rim type and spoke number affect this rate, only more experienced builders should approach this zone. Those lacking time or experience should stay in the shaded region where overtightening is a small risk.

Local Deformations

Excessive tension can also cause deformation and eventual rim cracks near each nipple. A key sign of potential trouble is excessive puckering and bulging of the rim surface at the nipple. Rims without secondary supporting sockets can withstand little deformation. Those with full sockets can tolerate more bulging. Some of the new heat-treated rims, despite their strength, are actually brittle and cannot deform without producing small cracks that will eventually grow.

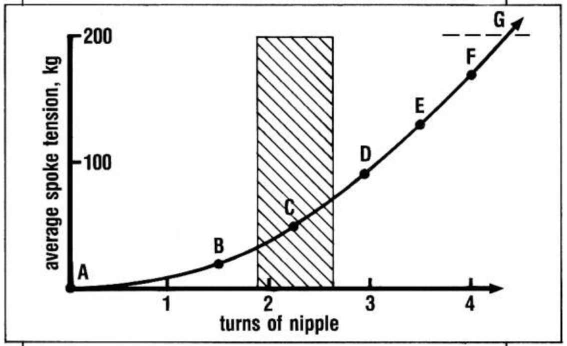
In addition to cracks, some rims are limited by their stiffness. Wood rims, for example, were very resistant to radial blows but less strong for sideways forces. They did not prefer as much tension or as few spokes as are now common. Lessons learned during the wood rim years are followed still. In those days, looser wheels were not only preferable, they were necessary. Modern rims with such features as better alloys, full sockets, and large cross section styles are stiffer and can support higher spoke tension than wood rims.

Very tight spoke nipples can deform during building. High tension brings greater friction to the spoke threads and requires lubrication and a close fitting wrench. Increased thread friction also causes spokes to wind up. Unless unwound this twist can make a wheel untrue when later released. Twist can be monitored by feeling the shaft of the spoke with two fingers to see if it turns with the nipple, or minimized by holding forcefully with a smooth-jawed plier.

Stability When Damaged

Ironically, while high tension strengthens the wheel and reduces the chance of spoke breakage, it increases the trauma when a spoke does fail. This is a good reason not to build to maximum tension. If a spoke does break, the sudden loss of all that tension, combined with the still-powerful neighboring spokes, can produce an uncorrectable kink in the rim. This helps explain why lower tension racing wheels are common in Europe. In the rough and tumble world of foul weather and cobbled road racing, broken spokes and crushed rims are inevitable results of bumps and crashes. Lower tension wheels with heavy rims and straight 2.0-mm spokes make reliable battle irons because they are so stable when damaged and are usually retired before spoke fatigue catches up. And the mechanics rebuilding them are freed from the time consuming task of achieving high but not excessive tension.

Spoke tension gives the bicycle wheel strength, stability, longevity, and good feel. Today's rims can withstand greater tension but it must be applied selectively, slowly, and patiently. In spite of its cost, a well-built wheel with high spoke tension has more to offer the serious rider. And hard riders are wheelbuilding's most realistic judges. In future Shop Talk columns we will explore some actual building techniques, guidelines, and shortcuts for achieving high tension.



Spoke tension vs. nipple tightening — In a typical (but imaginary) wheel we can see how quickly average tension rises in the higher portion of its range. From point "A" of zero tension but no spoke slack, tightening initially produces gradual increases in tension. Then, much more quickly, the tension rises beyond the maximum safe level. The values below are examples but not recommendations, since the appropriate magnitudes depend on the specific components:

A — zero tension
B — 20 kg, inadequate tension, 1½ turns
C — 50 kg, adequate tension, 2¼ turns
D — 90 kg, good average tension, 3 turns
E — 130 kg, optimum tension for a very well-balanced wheel, 3½ turns
F — 170 kg, excessive tension, 4 turns
G — 200 kg, wheel failure

Tension Measurement

One of the most important lessons in a traditional wheelbuilding apprenticeship is calibration of the builder's hand so he can judge spoke tension by squeezing adjacent spokes much as a mechanic can feel tire pressure with his fingers. Plucking spokes produces a tone which is also closely related to tension. Similar spokes in like lacing patterns produce equivalent tones for the same tension if plucked near the nipple.

At present there is only one commercially available spoke tension measuring device, made by Hozan Tool of Japan. Though expensive, it gives good numerical readings on a dial. A second by Wheelsmith is scheduled for introduction this year.

Ergonomics

Physiology of Cyclist Power Production

John Forester

The statements on the physiology of cyclist power production by David Gordon Wilson and by Crispin Mount Miller (December 1982 *Bike Tech,* Volume 1, Number 4) illustrate the misconceptions caused by current assumptions of exercise physiologists. At least those authors recognized that a problem existed and asked for answers.

Exercise physiologists measure oxygen efficiency and make much of it. They require a cyclist to ride at 25 mph in a 140-inch gear, because that is the most oxygen-efficient gear, and wonder why he collapses in ten minutes. So what? Any person looking at actual road racing and endurance cycling data and techniques must conclude that the hypothesis of oxygen efficiency is at least irrelevant. Successful cyclists ride at oxygen-inefficient cadences, a fact for which a new hypothesis must be created.

I propose a new hypothesis which considers instead the acquisition, digestion, storage and use of food, the other side of the chemical reactions that produce power.

Power is force times speed. The speed of muscle contraction (within the range of cycling cadences) has little effect on muscle performance, but the force has considerable effect. Low forces are developed by only the aerobic muscle fibers, while large forces require both the aerobic and the anaerobic fibers.

The aerobic fibers are powered by blood-carried glucose and triglycerides; the anaerobic fibers by muscle-stored glycogen. Blood-carried glucose can be replenished during cycling, first from the liver and then by eating carbohydrates. Blood-carried triglycerides and fatty acids are practically inexhaustible because they come from body fat, but the rate at which fat can be converted to them is relatively inflexible. Hence most of the fuel for high-power long-duration exercise is glucose, because the triglyceride and fatty acid production rate does not climb much during a few hours of exercise.

Muscle-stored glycogen cannot provide much of the energy for road racing and endurance cycling, because it cannot be replenished during exercise and the supply lasts for only about ten minutes of hard exercise. Glycogen is merely polymerized glucose, taken from blood glucose and polymerized in the place of use so it won't get loose. The body will not take glucose from the blood for storage in the muscles when exercise requires that the glucose be used directly to power those muscles. Muscle glycogen is replenished largely during sleep, and it takes two nights to fully replenish the muscle-stored supply after exhaustion.

Therefore it is impossible that muscle-stored glycogen can be a major factor in events lasting from one hour to many days, but it can be a winning factor if properly used. This is not a contradiction, as I will explain.

Since anaerobic work can supply only a small portion of the energy needed for an extended event, the successful cyclist arranges to spend most of the event using only his aerobic fibers, supplying the glucose fuel first from his body stores and then from food he eats during the event. Sparing the anaerobic fibers conserves the muscle glycogen for the critical parts of the event, when high-power short-term sprinting to surmount a hill, make a break, or win a sprint provides the winning margin.

Using only aerobic fibers means using low muscle forces to avoid recruiting the anaerobic fibers and using glycogen. For a given level of power, low muscle force requires high muscle speed, and therefore high cadence. This strategy is so advantageous that the cyclist adopts it even though it requires more oxygen, and in the end more food. (Why else would experience have shown that winners waste time and effort eating?) Spinning on glucose keeps the cyclist in contention with sprint power in reserve, while sprinting on glycogen gives him the winning advantage.

Triglycerides and fatty acids have their importance, too. It is practically impossible to eat sufficient carbohydrates for complete replenishment of glucose during longer cycling events. Cyclists who are successful in 24-hour and multi-day events have trained their fat-metabolic processes to operate at higher-than-normal rates day in and day out. Thus they obtain a higher proportion of their "normal" power from fat conversion than do less highly trained cyclists, so that for a given level of carbohydrate intake they produce greater power, and can keep it up as long as their body fat lasts.

It is my opinion that training this system is the most painful experience for a cyclist, for only by forcing himself to keep going after his normal stores have been used can the cyclist "convince" his fat-metabolic processes that normal living involves damn hard work for days on end.

For a more complete discussion, including related hypotheses (on bicycle design and proportions, implications of neurological function for cycling, and why exercise physiologists have missed the point), see the chapter on The Physiology of Hard Riding in my book *Effective Cycling,* to be issued by The MIT Press during spring, 1983.

Letters

Striving for Stability

I've been enjoying *Bike Tech* and want to send encouragement to keep up the good work. I especially liked the "Balancing and Steering" piece in the August 1982 issue.

I hope you continue to look into questions regarding handling. I've designed and built a couple of frames and find frame design to be both an interesting and complex subject.

I'd particularly like to see some treatment of wheel flop. I realize that the handling article by Whitt and Wilson represents only part of their work and that they probably talk about wheel flop. But this particular article could lead to the conclusion that bicycles with the same or near same stability index handle alike. I don't think that's true. A bike with a shallow head angle, such as 70 to 72 degrees, wants to "dive" into corners more than a bike with upright angles.

I hope you'll also address the question of wheelbase. It's been my experience that wheelbase is not nearly so important as head angle and fork rake. And we're seeing that in some Italian road bikes made to be comfortable over long distances with longer chainstays, but also made for fast handling with 74-degree head angles and shorter fork rakes.

It seems that some so-called touring bikes could do with higher stability indexes. Bicycling is, of course, a tradition-honoring sport and it seems that touring machines often are made with shallow head angles and longer fork rakes because they're supposed to look that way. On fast, downhill runs, however, that can mean a squirrelly ride on a loaded bike. Whitt and Wilson say that Stability Index values from -1.85 to -2.3 "give lighter, more responsive steering." I translate that as meaning that they're difficult to control on fast downhill runs, especially fast corners. The whole style of "touring geometry" most likely started with riders and framebuilders looking for comfortable machines to handle long-distance tours over rough roads. They found, of course, that more fork rake and shallower head angles transmitted less road shock. I don't think handling really was a consideration.

But you're the guys with the answers. I'd like to see some more handling stories to find out if my gut level reactions to frame geometry and my experience, building and riding bikes, are correct.

Incidentally, I think the values for Fork-offset ratio in Table 1 in the Whitt-Wilson article were incorrect. They should decrease as head angle steepens and stability index increases. (See corrected table in the letter from Brad Butler. — Editor)

One other subject that might provide an interesting story is maximum cornering angles. Criterium bikes are designed with higher bottom brackets to clear the pedals in the corners. This also raises the center of gravity (the rider sits slightly higher). What are the tradeoffs here? All else being equal (tires, road conditions, etc.) how does frame geometry effect cornering?

Ed Stiles
Tucson, Arizona

Corrections

In the excerpt from the new edition of *Bicycling Science* titled "Balancing and Steering" (*Bike Tech,* August 1982) there are some miscalculations of the stability index *u*. Enclosed is a revised table. [Editor: see box, "Revised Table 1."]

Brad Butler
Laurel, Maryland

Revised Table 1: Steering geometries and stability indices of high-quality bicycles; u calculated from Equation 1, $(y/d) = 0.00917\ [(90°\text{-}H)(\sin H) + 4u]$, inverted to give $u = 1/4\ [109.1\ (y/d) - (90°\text{-}H)(\sin H)]$ *(Figures supplied by Brad Butler)*

Bicycle type	Head angle	Fork-offset ratio[a]	Stability index u[b]
Touring	72°	0.0736	-2.27
	72°	0.0740	-2.26
	72°	0.0692	-2.39
	73°	0.0845	-1.76
Road-racing	73°	0.0837	-1.78
	74°	0.0729	-1.86
	74°	0.0976	-1.18
	74.5°	0.0804	-1.54
Track	75°	0.0759	-1.55
	75°	0.0953	-1.02

a. Fork offset/Wheel diameter.
b. $u = [\delta^2(f/d)/\delta\alpha\delta L]_{\alpha=0.}$

Interrelations

Whitt and Wilson's "Balancing and Steering" (*Bike Tech,* August 1982) gives the impression that choice of head angle (H) is determined primarily by the fit of rider to bicycle. In reality, racers use a bicycle with steeper H than tourists use because they need quicker steering. That is, they need a greater turn of the front wheel for a given shift in rider weight. Given a suitable stability index (u) or trail (t) in each case, $1^1/_2$ or 2 degrees change in H makes the difference between a bike that will take a fast corner effortlessly and a bike that will be impossible to keep on the road.

Perhaps t is a "dependent variable," as Whitt and Wilson state; trail is much easier to work with than the stability index for two reasons: first, calculating t involves only trigonometric functions. Second, Banton and Miller's ("The Geometry of Handling, *Bicycling,* July 1980) explanation of the interrelation of H and fork offset (y) in terms of t has great power. In fact, t and u complement each other, as the attached graph ("Relations of Three Steering Geometry Parameters") shows:

Note first that the slopes of the constant-u and constant-t lines are virtually identical. Even the numbers are almost identical, if you ignore the change in sign. The equation for t gives a way of easily arriving at a suitable offset y, given the knowledge that a t of $2\text{-}2^1/_2$ inches will yield best results. And because of the similarity of line and value, the value of u is determined in the process.

Also on the graph is a plot of the formula appearing in DeLong (*Guide to Bicycles and Bicycling*) and plotted in Talbot (*Designing and Building Your Own Frameset*):

$$y = R \cdot \tan \frac{90 - H}{2}$$

This formula is supposed to yield neutral steering — i.e., no frame drop as the wheel is turned. Talbot suggests subtracting 0.75 inch from this value for quick steering (racing) bikes, about half that much for touring bikes. Note that for H = 75° or 74°, Talbot's suggested y is close to that the Banton and Miller t = $2^1/_2$ inches line would suggest. But note too that Talbot's formula decreases t as H increases, contrary to stability goals, and suggesting Talbot's formula is less perfect.

Sherman Coventry
Portland, Oregon

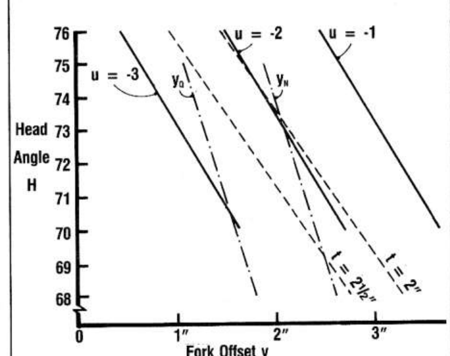
DGW Responds:

Bike Tech is already showing the maturity that one finds in the proceedings of the most prestigious professional societies, where the discussions of papers are often more illuminating than the papers themselves. I have greatly enjoyed, and learned from, letters commenting on two of my articles.

One group of letters gave me embarassment rather than enjoyment. My calculations of the stability index, u, in table 1 of "Balancing and Steering" in the August 1982 *Bike Tech* (and unfortunately in table 9.1 in the second edition of *Bicycling Science*) were incorrect. Not only did I set my calculator incorrectly in some way, but I did not notice that the stabilities obtained were varying in the wrong direction. Many apologies! Brad Butler's values are correct.

We did not mean to imply, as Sherman Coventry wrote, that one chooses head angles on the basis of rider size. We do believe, however, that part of the reason for the smaller angle used by tourists and commuters is to keep the front wheel (and possibly a fender or mudguard) away from the pedaling circle. Personally, I believe that we learn to compensate for an extraordinarily wide range of steering geometry and wheelbase, as David Jones discovered. Ed Stiles gives at least partial agreement. My first recumbent was made (to my rough sketches) by Frederic Willkie III for his own use, and

Relations of Three Steering Geometry Parameters



Stability Index Lines ———
Based on Whitt and Wilson, Table 2.

Constant Trail Lines — — — — — —
Based on the Banton and Miller equation

$$t = \frac{R}{\tan H} - \frac{Q}{\sin H}$$

$$\text{or } y = Q = -\sin H\left(t - \frac{R}{\tan H}\right)$$

Steering Lines - · — · — · —
Based on Talbot's equations

$$y_Q = R \cdot \tan\left(\frac{90 - H}{2}\right) - .75''$$

$$y_N = R \cdot \tan\left(\frac{90 - H}{2}\right)$$

he was (and I hope still is) considerably lighter than I. When I bought it from him, I found that the front fork would gradually bend until the front tire began hitting the forward frame tube. I would then put it into a jig and bend it back through at least an inch and a half, which, with a 16-inch wheel, translates to a large variation in (y/d). I could detect no significant effects on steering. I also brought the rear wheel forward by about 12 inches to decrease the large front-wheel loading, and again found no significant effects although the bike was, naturally, livelier in the short-wheelbase version.

Some other questions and comments by Ed Stiles and others may be responded to by an improved steering analysis sent in by Raymond Pipkin: I hope that you will have space to publish this soon.

With regard to the questions raised about pedaling on hills, I liked both of John Allen's points (letters, *Bike Tech,* February 1982). One certainly notices a difference in standing on the pedals of a heavily loaded bike and a light one, in that one loses the ability to get quickly over top dead center because a heavy bike cannot be induced to shoot a little forward or lag back. I'd suppose, also, that the influence of the direction of the gravity vector would have a different effect for a rider pushing with more than his/her weight from that for one who wasn't.

John Forester makes several points about pedaling, some, but not all, of which I agree with. It's certainly true that racing bicyclists are trying to go at maximum speed, and they will therefore not use their maximum-efficiency pedaling cadence. As race distances increase, I'd guess that the optimum speed would change from the maximum-output pedaling speed for sprints toward, but never reaching, the maximum-efficiency speed for transcontinental distances. He implies that much ergonomic data, including the Japanese graph given in the December 1982 *Bike Tech,* are for anaerobic work, if I understand him correctly. The Japanese data were telemetered from bicyclists riding on a track, and from my memory of the article being translated for me by an obliging Japanese student, I believe they are for medium-duration, aerobic work.

John Forester gives a rather extreme example of using a 140-inch gear at 25 mph, which I don't believe any data would support — or if they do, I'd certainly go along with his belief that such data were for anaerobic work. I'd like to state again that when we quote these data we have some ideal subject (maybe ourselves?) in mind. But we are all built along very different lines, and we'll have different optimum curves. My legs are more like those of cart-horses than race-horses, so that I tend to show a bias in favor of lower-frequency pedaling as a reaction to being continually compared with the race-horse type of rider.

David Gordon Wilson
Contributing Editor
Cambridge, Massachusetts

Thanks to everyone for the observations and corrections. We'll continue to pursue the subject in future issues. I have two remarks to add about points raised by Sherman Coventry:

The similarity between u values and trail values is quite striking. It may be that the units of u are of an arbitrary size chosen to be equivalent to inches of trail at some typical head angle (apparently about 73 degrees), since the numbers for u would be very different if expressed in terms of diameters and degrees or radians. (The head angle and fork offset whose action is plotted in Figure 3 of the "Balancing and Steering" excerpt correspond to a u of about -2.1 — but from the graph in Figure 3 it appears that the derivative

$$\left(\frac{\delta^2\,(f/d)}{\delta\,\alpha\,\delta\,L}\right)_{\alpha=0}$$

that defines u has a magnitude of roughly $0.000047\ \frac{\text{diameters}}{\text{degree}^2}$ *or* $1.53\ \frac{\text{diameters}}{\text{radian}^2}$ *.)*

The formula from Talbot, also known as the Davison Formula — $y = R\tan\left(\frac{90 - H}{2}\right)$ *— is indeed an imperfect specification for steering behavior. What it specifies is a wheel placement at which rake equals trail. This condition causes the frame height to be the same for a steering angle of 90 degrees as for a steering angle of zero. According to Khris Kvale and John Corbett ("A Fresh Look at Steering Geometry,"* Cycling USA, *February 1981), Davison assumed that with this geometry the frame height would also stay constant for all steering angles* between *zero and 90 degrees, and the result would be "neutral" steering. But as Jones's work demonstrates, this assumption is mistaken. Kvale and Corbett suggest that Davison's theory was accepted because when it was published — in 1935 — head angles were relatively shallow, so that the formula specified a relatively large, "well-behaved" amount of trail, as opposed to the somewhat skittish amount it would specify today.*

Crispin Miller

Let Us Hear

We'd like *Bike Tech* to serve as an information exchange — a specific place where bicycle investigators can follow each other's discoveries. We think an active network served by a focused newsletter can stimulate the field of bicycle science considerably.

To serve this function we need to hear from people who've discovered things. We know some of you already; in fact some of you wrote articles in this issue. But there's always room for more — if you have done research, or plan to do some, that you want to share with the bicycle technical community, please get in touch.