MATERIALS

The Metallurgy of Brazing, Part 3

Strength of Joints

Mario Endani

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

Tests to Determine Mechanical Properties

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

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

Combined Loading

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

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

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

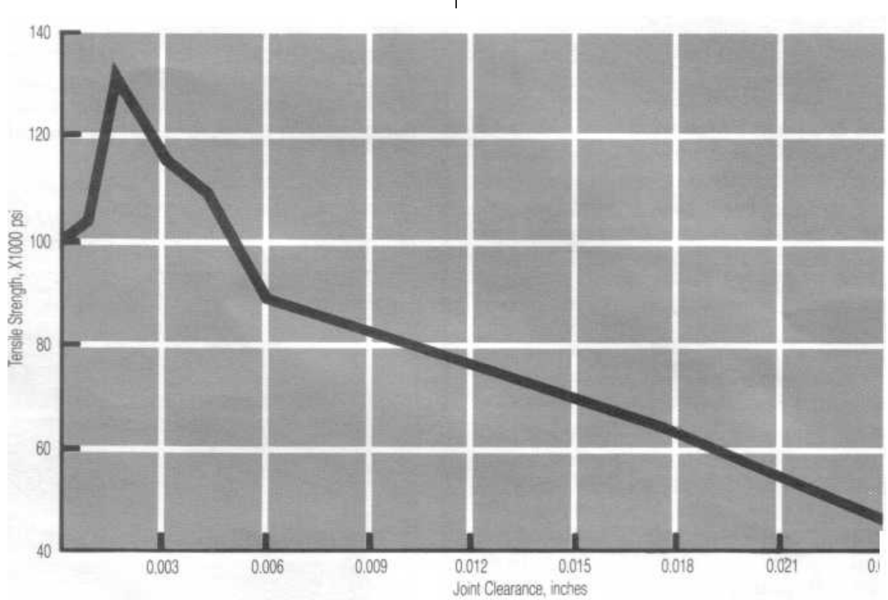


Figure 1: While a joint clearance of about 0.0015 inches produces the strongest possible joint for the conditions in which the joints were brazed, the joint is still very strong for clearances up to 0.005 inches. However, the maximum tensile strength shown here won't be the same for frame joints, since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

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

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

Factors Affecting the Strength of Brazed Joints

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

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

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

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

Tensile Strength

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

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

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

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

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

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

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

Small and Large Clearances

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

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

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

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

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

In the second part of this series, I spoke

Types of Stresses in Frame Joints

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

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

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

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

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

Crispin Mount Miller

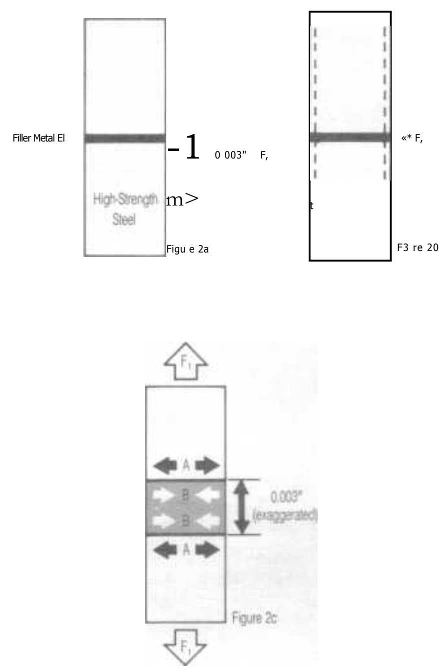


Figure 2: The tensile strength of a butt-brazed joint is two to three times as great as the tensile strength of the filler metal because the steel bars don't allow the filler metal to yield.

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

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

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

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

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

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

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

0.001 Inch

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

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

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

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

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

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

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

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

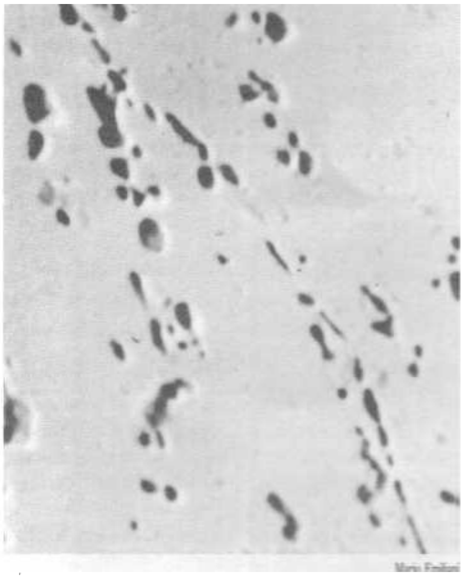
Flux inclusions are usually unavoidable, so some of them are bound to lie at the filler metal/base metal interface. This, of course, will impair the quality of the bond by reducing the area bonded. Porosity has the same deleterious effect.

Fatigue Strength

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

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

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



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

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

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

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

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

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

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

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

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

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

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

Impact Strength

Bicycle frames are often subjected to large

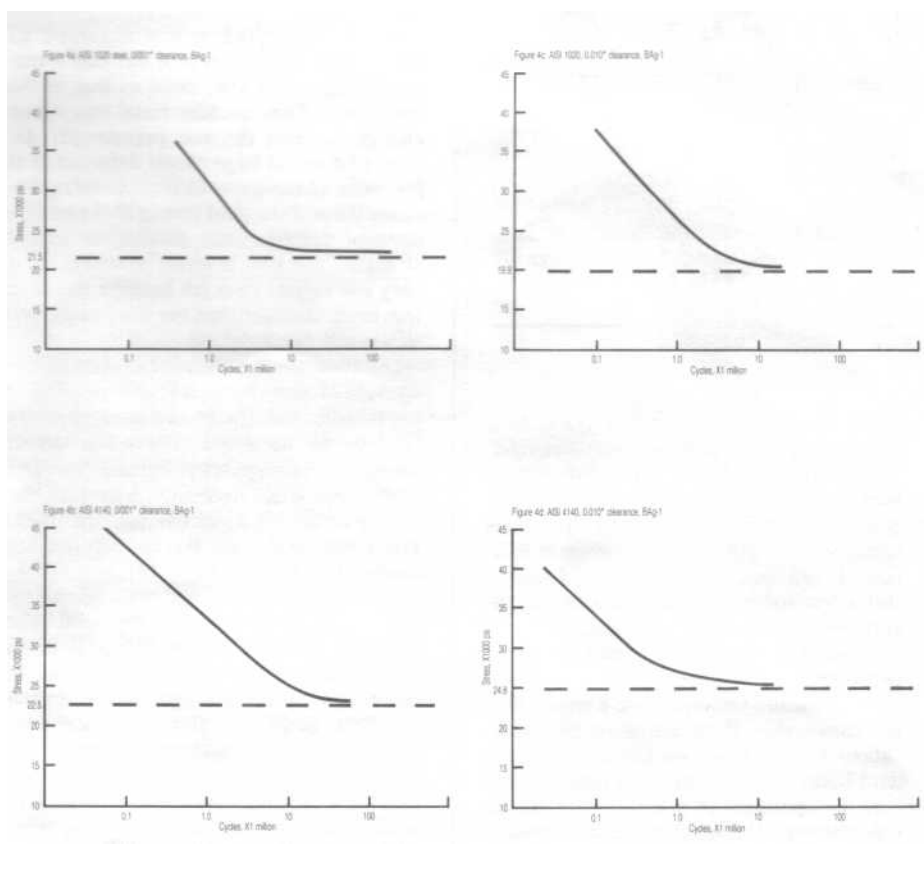


Figure 4: Both the fatigue limit and fatigue strength are not significantly affected by the tensile strength of the base metals. However, the fatigue strength is influenced by the joint clearance, while the fatigue limit isn't. Voids will reduce the fatigue strength of the joint because they act as stress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

'The stress which a specimen can sustain for a given number of loading cycles; the number of cycles must be specified.

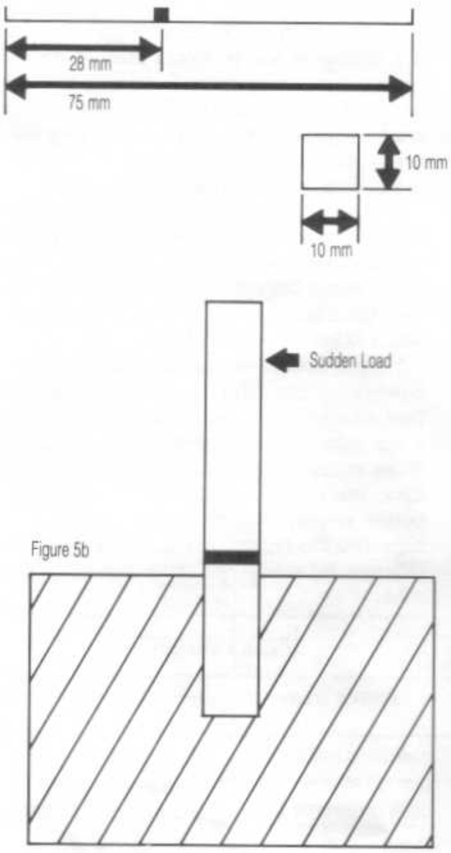


Figure 5: A standard impact specimen is made by butt-brazing two steel bars with dimensions shown in Figure 5a. In Figure 5b the short end of the specimen is held rigidly while a sudden load is applied, usually by a massive swinging pendulum (from "Tentative Methods for Notched-Bar Impact Testing of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

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

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

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

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

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

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

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

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

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

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

Shear Strength

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

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

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

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

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

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

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

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

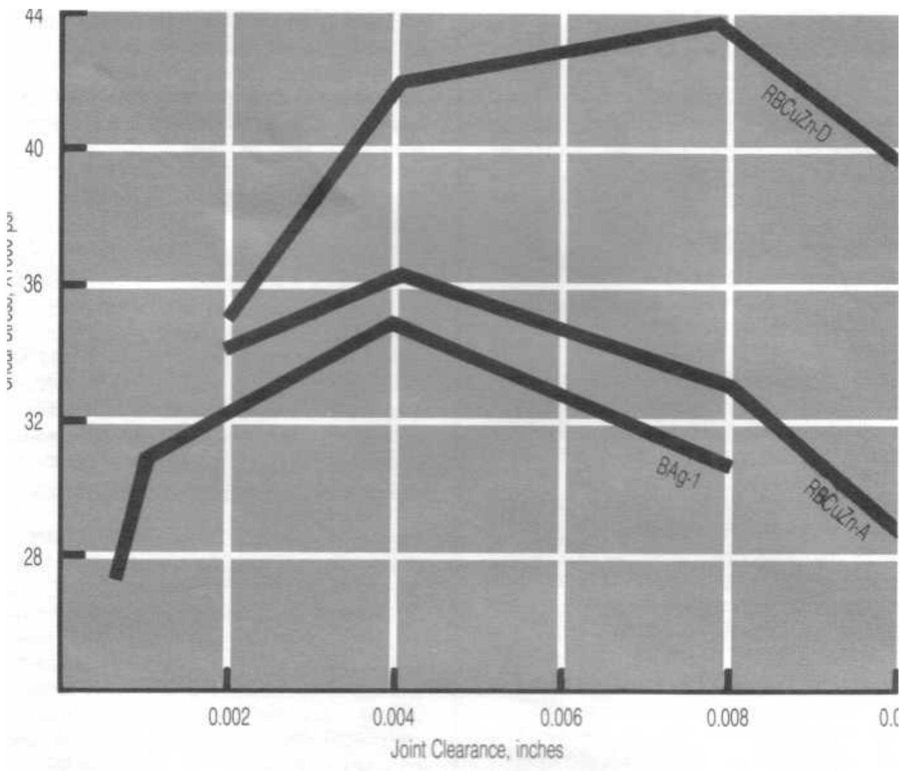


Figure 6: The maximum shear strength occurs at clearances considerably greater than the maximum tensile strength in Figure 1; yet another reason why it's not worthwhile to try and achieve a uniform clearance in frame joints (from J. Cobus et al., VVblding *Journal* vol. 41. no. 9, p. 415s; by permission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

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

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

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

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

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

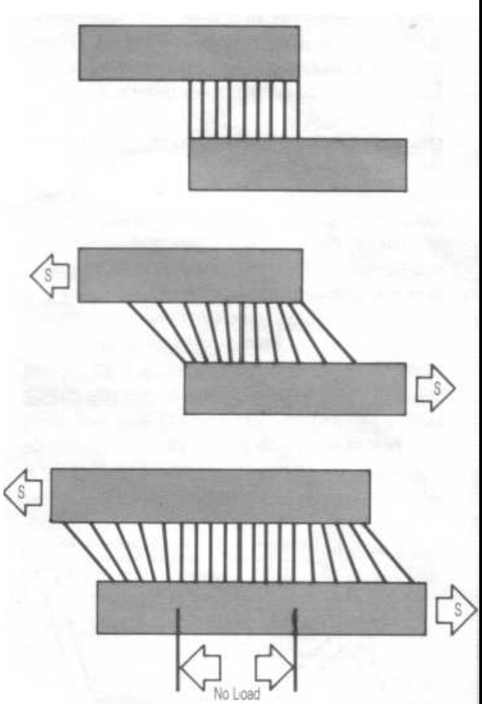
[5] *J. Colbus, et al.,* Welding Journal, *Vol. 41, No. 9, p. 415-s.*

[6] *See footnote 3.*

Summary

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

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



Igure 7: (Top) The parallel lines between the plates repre;ent the filler metal in an unstressed state. (Center) When a ;hear stress S is applied to a lap whose joint area is small, he stress is distributed evenly throughout the joint. (Bottom) Vhen the joint area increases, a portion of the lap in the ;enter doesn't carry any load. Thus, lengthening the lap foesn't guarantee a stronger joint simply because the bond yea is greater. (from H.R. Brooker and E. V. Beatson, *Indus*rial *Brazing,* 'Butterworth Group, Seven Oaks, England, 975).