The Metallurgy of Brazing, Part 2

Filler Metal Characteristics

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

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

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

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

Table 1: Filler Metals Commonly Used on Bicycle Frames

Filler Metal'	Average Chemical Composition,'%															Brazing Temperature Rande. °F	AWS
	Ag	Cu	Zn	Cd	Ni	Sn	Fe	Mn	Si	P	Pb	AI	Other Elements	Solidus. °F	Liauidus. °F		
BAg-1	45	15	16	24	-				-		-		015	1125	1145	1145-1400	3A,3B
BAg-la	50	15.5	16.5	18			-			-		-	0.15	1160	1175	1175-1400	3A 3B
BAg-2	35	26	21	18					-			-	0.15	1125	1295	1295-1550	3A,3B
BAg-2a	30	27	23	20		-							0.15	1125	1310	1310-1550	3A,3B
BAg-3	50	15.5	15.5	16	3		-	-		-			05	1170	1270	1270-1500	3A,3B
BAg-4	40	30	28		2		-			-			0.15	1240	1435	1435-1650	3A,3B
BAg-5	45	30	25		-				-			-	0.13	1250	1370	1370-1550	3A,3B
BAg-6	50	34	16		-				-			-	0.15	1270	1425	1425-1600	3A,3B
BAg-7	56	22	17	-		5	-	-	-	-		-	0.15	1145	1205	1205-1400	3A,3B
RBCuZn-A		59	Bal.[3]			0.63	-	-		-	0.05	0 01	0.5	1630	1650	1670-1750	3B 5
RBCuZn-C		58	Bal.	-	-	0.95	0.73	0.26	0.09	-	0.05	0.01	0.5	1590	1630	1670-1750	3B,5
RBCuZn-D	-	48	Bal.	-	10		-	-	0.15	025	0.05	0.01	0.5	1690	1715	1720-1800	3B 5
RBCuZn-E	-	50.5	Bal.		-	-	0.1		-	-	0.5	0.1	0.5	1595	1610	1610-1725	3B,5
BCuZn-F	-	50.5	Bal.		-	3.5			-	-	0.5	0.1	0.5	1570	1580	1580-1700	3B 5

*"B" **designates an** alloy as a brazing alloy; "R" means that it can also be used for braze welding. "Ag," "Cu," "Zn" indicate principal ingredients.*

--1g = silver, Cu = copper, Zn = zinc, Cd = cadmium, Ni = nickel, Sn = tin, Fe = iron, Mn = manganesee, Si = silicon, P = phosphorus, Pb = lead, .-11 = aluminum.

Bal. = Baiancr

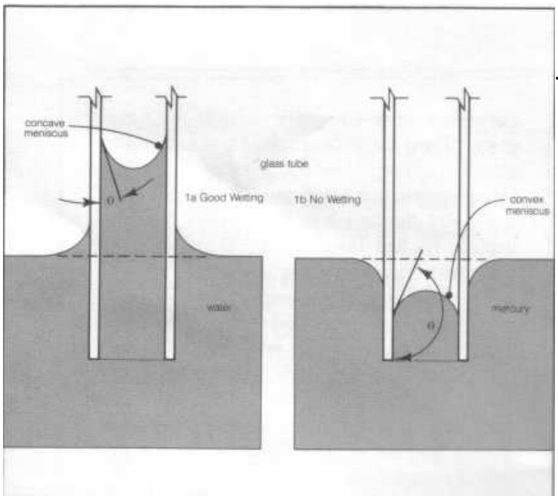

Figure 1: If adhesion between the liquid and tube is greater than the cohesive forces of the molecules, capillary attraction (or wetting) occurs as in 1 a. If cohesion is greater, capillary attraction won't take place. Notice that the contact angle A in 1 a is much less than in 1 b.

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

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

The RBCuZn-type filler metals are very popular (especially with Italian framebuilders) because they cost much less than silver brazing alloys (at today's prices, BAg1 costs 50 times more than RBCuZn-C). But they too have drawbacks; these copper alloys contain large amounts of zinc, which is a very volatile metal. If the filler metal is overheated, zinc fumes will form. This will cause filler metal inclusion (penetration among grains) in the tube or lug, and/or porosity in the filler metal.

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

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

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

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

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

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

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

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

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

Capillary Attraction

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

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

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

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

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

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

The magnitude of the pressure difference, called AP, depends on three variables: the surface tension of the liquid, y; the contact angle, 0; and the distance between surfaces, d (see Figure 3). Written as an equation,

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

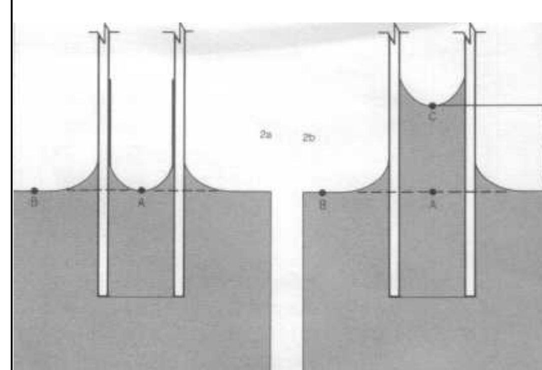

Figure 2: The moment the tube is immersed, a thin film of liquid travels up its walls (2a). This causes a difference in pressure which makes the liquid rise to a height h, so that the pressures are again balanced (2b).

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

If a joint is cleaned and fluxed properly prior to brazing, most molten brazing alloys compatible with low-alloy and plain carbon steels form a contact angle approaching zero. As 0 approaches zero, the cosine of 0 approaches 1. Thus, the cos 0 term does not significantly affect L P for a well-prepared joint.

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

For bicycle frame brazing, there is a high y, low 0, and small d. Thus if no problems arise (like de-wetting of the flux or filler metal, burning of the brazing alloy which may change y, or joint clearances outside the range of 0.002-0.005 inches), capillary attraction will be close to the maximum possible value. For example, if we have a joint as in Figure 3, and assume that at 1740°F RBCuZn-C has y* = 0.0031 lb$_($/in; 0 = 5°; and d = 0.004 inches; L P turns out to be 1.54 psi (or 0.0106 N/mm^2). Thus, there is a pressure of 1.54 psi pulling the molten filler metal into the joint.

The viscosity of brazing alloys is also an important factor. As the brazing temperature increases, the viscosity of the filler metal decreases. Thus, the filler metal becomes more fluid, and is able to penetrate the joint more easily. But remember, filler metals should never be overheated.

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

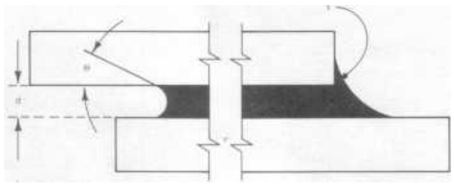

Figure 3: the magnitude of capillary attraction depends on three variables: y, 0, and d. When brazing bicycle frames, y is high, 0 is low, but d can vary considerably.

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

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

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

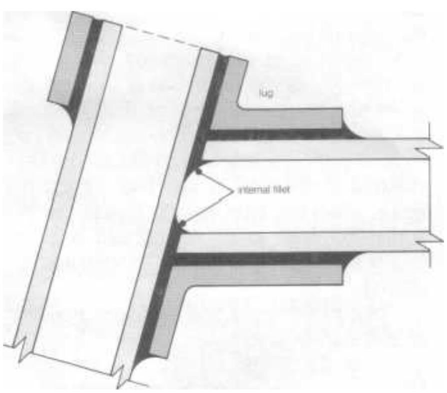

Figure 5: The lack of an internal fillet may be due to changes in filler metal composition. By the time the brazing alloy reaches the miter, its liquidus may be high enough to solidify it.

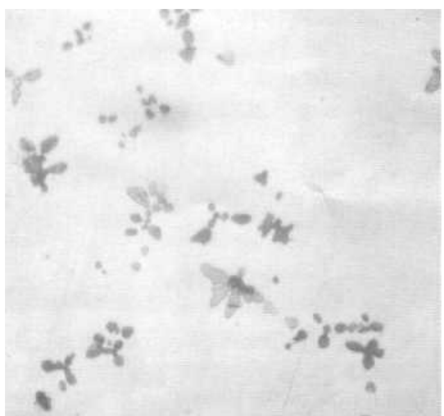

Figure 6: These flower-like crystals were found in the fork crown joint of a well-known production Italian racing frame. The filler metal is an (R)BCuZn-type, and the base metal is Columbus SL. The average diameter of the crystals is about 0.00085 inches (magnified 240 times).

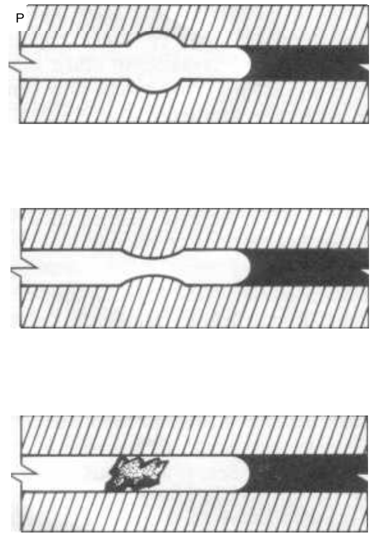

Figure 4: Capillary dams can be caused by sudden increases in clearance, sudden decreases in clearance, and foreign material lodged in the gap. Too many of these dams will result in a poorly bonded joint.

Capillary Dams

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

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

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

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

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

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

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

Changes in Composition

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

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

The amount of iron dissolved depends on the chemical composition of the brazing al

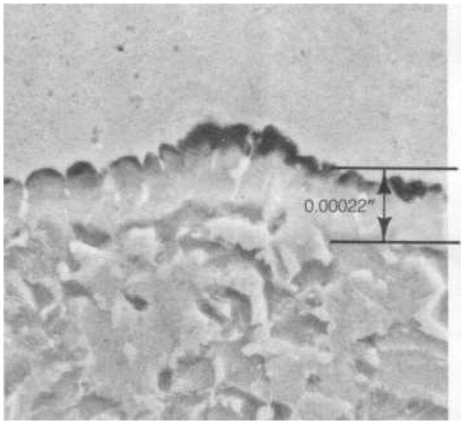

Figure 7: This is a Scanning Electron Photomicrograph of the alloying which can take place at the filler metal-base metal interface. The region above the interface is RBCuZn-A filler metal, while the region below the interface is Reynolds 531 tubing. The average thickness of the intermetallic layer is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

loy, and especially its liquidus. The higher the liquidus, the more iron will be dissolved. That's why incomplete filleting is usually more common in brass-brazed joints. The filler metals listed in Table 1 dissolve any where from 1/2°70 to 4% iron.

When a frame brazed with RBCuZn-A gets in an accident and needs a new tube, the joints to be dismantled have to be heated

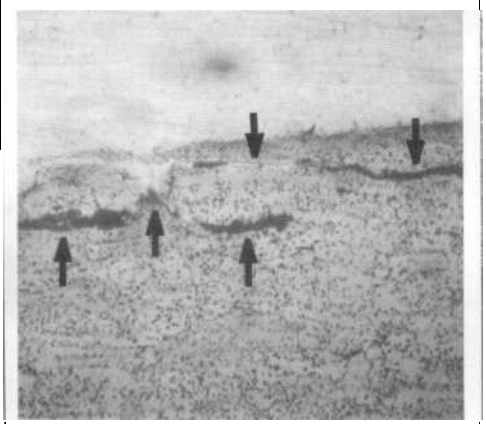

Figure 8: This photo, from the fork blade-dropout joint of another custom American frame, shows that filler metal inclusion doesn't affect just brass-brazed frames. The arrows point to areas where BAg-1 has entered the grains of Reynolds 531. The maximum depth of the inclusions is only about 4.5% of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

well above 1650°F (the original liquidus of RBCuZn-A). This can cause extensive filler metal inclusions in the lug and adjacent tube because zinc fumes are likely to form. This makes brass-brazed frames more difficult to repair than low-temperature silver-brazed frames.

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

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

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

Intermetal ics

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

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

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

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

Another example occurs when steels are joined with BCuP filler metals (copper-phosphorus brazing alloys that contain a minimum of5% phosphorus). At brazing tempera

tures, the phosphorus combines with iron to form the brittle intermetallic iron phosphide.

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

Filler Metal Inclusions

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

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

Surface Finish

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

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

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

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