Welding - It's Not Black Magic

By Budd Davisson

All right, everyone out there who thinks welding was invented by Merlin the Magician and is an exotic combination of alchemy and sorcery, hold up your hands. No takers? Okay, let's put it in other terms which mean the same thing . . . do you view welding as a skill you might (underline "might") be able to learn but would never, as in NEVER, use in building an airplane you yourself would fly? Would you always call in a pro to do the welding?

The foregoing, unfortunately, is the wildly inaccurate mental image many have of welding. For some reason it exudes a mystical aura which says we mere mortals could never get good enough that we would trust our own welds. Hog wash! Welding is a skill like any other and is one of the most satisfying, and useful, you'll ever learn.

Before composites steamrollered over every other type of homebuilt aircraft construction, welded tube structures were by far the most popular and no one, it seemed, feared welding. However, at that time when you spoke about welding, you were only speaking about one type of welding process, oxy-acetylene . . . old fashioned torch welding. Today, however, we have at least three distinct types of welding which are very much a part of the sport aviation scene and each has its devotees and its detractors. Each has its applications, strong points and shortcomings.

Just as the proliferation of materials and aircraft kits has confused the sport aviation builder by introducing so many new decision paths, the same thing has happened with welding. For that reason, we thought we'd touch on welding as a concept and then look at each of the different types of welding and how they fit that concept. All the time we're discussing the subject, however, remember we are speaking about welding as it exists in the sport aviation environment where we're working with relatively thin pieces and the material is usually 4130 chromoly.

Some of the comments we're going to make may not apply when building bridges or battleships.

First: a definition of welding. It is the process of joining two pieces of metal in which a narrow band along the joint is melted so the two pieces of metal flow together. Additional metal is added for strength in the form of filler rod.

The most important word in the foregoing definition and which differentiates it from brazing or soldering is the world "melted." The parent metal is actually melted, rather than just having the two pieces joined by a different material, such as lead or brass, which adheres to the surface acting as a metallic form of glue.

As it happens, there are some applications in aircraft for both soldering and brazing but none of them are in primary structure. Soldering is strictly for sticking avionics wires together and brazing must be limited to attaching non-critical tabs.

As it happens, there is a new form of brazing utilizing Eutectic Corporation's No. 16, nickel-brass rod, which may at some time in the future be usable in light structural applications. It has a cast strength of 30,000 psi, which is all a joint would be good for if a large gap, .025", is bridged and ignored. However, they report if the gap is brought down to .002-.005", the joint strength goes up to nearly 100,000 psi, which is actually better than a normal welded joint. 4130 chromoly, by the way, has a strength of approximately 94,000 psi in the form we usually use it and the most common mild steel alloy, 1020, is in the 60,000 psi range. However, the Eutectic rod should not be considered structural unless the structure was designed specifically for it and the joint allowables lowered to a safe, average number.

When speaking about aircraft welding, it is important we take into account the material characteristics of chromoly because the very factors which give it its high strength-to weight ratio, including its carbon content, are also what make it more critical to weld than lower carbon steels.

For one thing, 4130 is not very tolerant of thermal shock. It doesn't like to be heated up and cooled quickly, especially in a narrow band, as around a weld. When this is done the crystalline structure of the material will be altered. If, for instance, it is heated up to welding temperature and then allowed to cool quickly to room temperature, the weld and the parent material will develop a coarse grainy texture (martensite) internally which makes it brittle and prone to cracking and breakage.

In speaking with various experts in the field, including Bill Ridgway, the Director of Technology for Eutectic Corporation-North America, they all agreed 4130 should be brought up to temperature slowly and left to cool slowly. That is just a characteristic of the material.

The structure surrounding the weld compounds this heating and cooling problem in several ways. One of these is the heat-sinking, or thermal mass, characteristic of the joint. If one tube is being joined to another, the material which is distant from the weld and is still cool, will be trying to soak the heat away from the weld. So, when the heat source is removed, the heat is rapidly sucked out into the rest of the structure and the weld cools quite quickly. The more tubes or the larger mass of metal which is attached to the weld, the larger the heat sink and the more rapidly it will cool. The entire structure is a sponge trying to soak up the heat.

Another characteristic of a rapidly heated or cooled weld is the internal stresses which are locked into it by expansion and contraction. As the metal around the joint is heated in preparation for welding, it expands and the narrower the band heated, the more violent the difference is between the expansion right in the weld area and the expansion further away in the structure. One part of the metal is pushing hard on the other. Then, when the weld is completed and the molten metal of the bead and the parent metal cool, they contract. The real problem is they contract at a different rate than they expanded because much of the material is now locked in place by the weld and can't move. As if that isn't bad enough, much more of the structure is now part of the heat sink so the weld area has the potential of cooling more rapidly than it was heated.

What we have in a weld is a situation not unlike an earthquake which is about to happen. The Earth's tectonic plates are pushing against one another like crazy and eventually, usually at a fault line where the stresses are focused, movement occurs causing an earthquake and earthquakes are always accompanied by cracks. That's what happens in a 4130 weld in which the contraction and expansion are ignored. All those stresses are locked in and are a mini-earthquake just waiting to happen.

So, how do you avoid or get rid of the stresses? According to the experts, the first step in keeping 4130 happy is to preheat it before welding. Put plenty of heat in the metal covering a sizable distance (1" or more) from the point of welding. That accomplishes two things. First, it puts heat into the rest of the structure so it isn't so heat hungry that it sucks heat out as fast as you can put it in. This makes the weld go easier and slows cooling down. Secondly, preheating expands a much larger area and sets the stage for a more gradual contraction over a larger area as the weld cools. If only the narrow band of the weld is heated, when it cools, all the contraction is concentrated in that one tiny area and the interface between the hot and cool areas really gets tweaked from the contraction stresses. Every metal acts the same in this situation, but with high carbon steels like 4130 the stresses right at the interface are more violent. By spreading out the expansion/contraction area, we've spread out the area to transfer the stresses and they don't concentrate as much.

Preheating helps avoid stresses by spreading everything out, but if the weld is left to cool too rapidly, the stresses can still be quite high. On top of that, rapid cooling promotes martensite build-up in the weld which makes it more brittle. To put it simply, 4130 prefers to cool down gradually.

If a weld is kept hot, letting the red color remain over the entire weld for 10-20 seconds and then the heat is gradually moved off over the next 20-30 seconds, the material is allowed to move around and seek its own comfort level before it is completely locked in place. Many welders will finish the weld and then play the torch on the area, raising all of it up to a uniform dull red, then let it cool slowly while playing the torch on it. Others will come back later with a rosebud heating tip and bring the entire joint back up to dull red and give everything a chance to re-align before letting it slowly cool off. This is called stress relieving and the term says it all.

Now that you know how finicky 4130 can be, let's talk about the various different types of welding open to us in sport aviation.

Oxy-Acetylene

The old fashion oxy-acetylene torch has been with us since around the turn of the century and it hasn't changed much, other than becoming more and more precise and compact. This has worked to the sport aviator's advantage in that it has given us a number of nice little torch handles like the Smith Airline series. They work best for us because of their relatively small size and light weight and the placement of the adjusting knobs up front where we can reach them without changing hand position.

We also have a few new exotic pistol-grip torches which involve a trick new tip design which works well in some areas. The ergonomics of the handle, however, make them difficult to use in tight quarters.

To get into the game, the prospective welder needs two tanks, acetylene and oxygen, which may be owned or rented, a regulator (dual or single stage), torch handle, tips (size 0, 1, 2, 3), 15 feet of hose, glasses or goggles and in-line check valves. The entire rig should cost about $250 or less plus a welding cart.

Oxy-acetylene is the type of welding usually seen in sport aviation for a lot of reasons, tradition and cost being the first two. Also, it has been around so long it is easy to find someone to teach you and it's relatively easy to learn.

In terms of heating aspects of a torch, they are crude to the extreme when compared to the pin-point heat sources of both TIG and MIG welding, the other two processes we'll discuss. A torch blows heat all over the place, which is precisely why it works so well for the amateur welder. It takes so much heat to get a weld going and it covers such a large area that it has the least preheating problems of any of the methods. However, it is still advised that he entire area be brought up to a dull red before the bead is started. With an oxy-acetylene torch all that requires is playing the flame around the area for a while before actually welding.

The typical join welded with oxy-acetylene has much more heat pumping through its various bits of tubing and steel than the other two types because the torch can't bring a narrow area up to welding temperature without also blowing heat into surrounding areas. This means the heat sink of the surrounding area has absorbed much more heat so it won't be so heat-thirsty when the weld is finished. Still, it will be thirsty.

When the weld is finished, all the welder has to do to stress relieve the joint is back the torch off a little and play it around the bead just as he did when preheating. Heat will be put into the joint at a decreasing rate until the torch is totally removed. By that time all the microscopic bits and pieces inside the joint will have had time to find a comfortable place to sit before the whole joint is cooled and locked up tight.

As a normal rule the rod used in the weld is copper coated mild steel. The copper is there to prevent rusting. There's been a lot of discussion about using 4130 rod or worrying about the copper contaminating the weld. In discussing these factors with the metallurgists, they said the bead will probably be diluted approximately 50% with the melted 4130 anyway, so we shouldn't worry.

Contamination and dilution might be a worry, if we were driving tiny little beads down into the openings in the joints. But we're not. The width of the bead is always enormous compared to the thickness of the material. We have a 5/16" bead running around .035" or .049" material, so the size of the bead by itself outweighs any serious concern. This factor alone is why so few welds, even the really ugly ones, break.

TIG (Tungsten Inert Gas) Welding

A lot of folks call TIG "Heli-Arc" which is actually a trade name, but it all means the same thing. In this system the torch held by the welder is an electrode holder that in some versions looks suspiciously like a wood burning set. A non-consumable tungsten electrode is centered in the middle of a ceramic housing and connected to the power unit by an electrical cable and several small hoses. Electricity is pumped through the electrode and an arc is struck between the electrode and the grounded parent metal. Heat is generated instantaneously and is usually controlled by a foot pedal which is actually controlling the juice going to it.

When the parent metal is melted by the arc, which can be the instant the arc is struck if the pedal is to the metal, filler rod is fed in not unlike using a conventional torch. While all the fireworks are going on, an inert gas (Argon) is being pumped through the ceramic housing and down over the weld in process. This puts the actual welding process in a little dome of inert atmosphere and keeps it from being contaminated by outside elements. This gives even a better view of what is actually happening in the weld puddle than an oxy-acetylene torch which is already excellent. The view of the puddle is critical because the entire character and strength of the weld is determined by what is happening in the tiny band at the leading edge of the puddle.

The better TIG torches have a cooling fluid pumped through the handle to keep it cool. This isn't really necessary for aircraft welding because our welds are so short, but it sure makes things more comfortable. The cost of the entire rig varies greatly but bottoms out at about $850 with $1200-$1500 being more average.

The Eutectic folks say they often suggest TIG welding 4130 with a 312 stainless steel rod because it is more ductile and tolerates the internal stresses better than mild steel or chromoly.

The devotees of TIG have some pretty good points in their favor. For one thing, if you're working a joint that has a lot of mass connected to it and is tough to weld for a normal torch because it takes so much heat you can hop on it with a TIG torch and almost instantly be welding. It can really bring the surface up to temperature in a hurry so it is a much faster means of welding.

TIG also generates a really nice, clean weld and it is possible to make tight, beautiful little beads.

The foregoing two strong points are also pointed to by detractors as the method's shortcomings. The very fact that a stone-cold joint can be welded instantly means a huge amount of heat is being driven into a tiny band so quickly the weld is finished before the area is even close to being finished expanding.

Then, because the heat zone is so narrow and surrounded by nice cool steel, the heat is sucked out like it is attached to a vacuum cleaner. In this situation, the experts say the internal stresses are enormous because they are concentrated in such a tiny area.

An additional danger mentioned by the professionals is the possibility of hydrogen embrittlement. If there are any oxides, oil or moisture on the metal when it is welded, the heat can be so instantaneous the hydrogen in the compounds may become trapped in the weld. When that happens, the finished weld may look and test just fine but if the tests are repeated a few days later, microscopic cracks may be found.

Hydrogen problems don't usually exist with gas welding because so much heat is driven into the area prior to welding much of the hydrogen present is cooked off. TIG is also fairly slow, when compared to MIG, so the heat build-up will cook off a lot of the hydrogen, but not necessarily all. It depends on how quickly the weld is started.

So, here we see the experts making two different arguments for preheating when using TIG: it reduces both thermal shock and hydrogen embrittlement. They also make the same arguments as before for stress-relieving the welds afterwards by reapplying heat.

It is theoretically possible to preheat and maybe even stress relieve to a certain extent with the TIG unit by keeping the arc flame playing over the area but with the power too low to melt the surface. However, the area being affected is still fairly small. That's why some TIG welders who have concerns in this area come back in with a rosebud tip on an acetylene torch and heat a larger area in a more uniform fashion.

MIG (Machine Inert Gas)

Currently MIG welding is a controversial welding technique because it is fairly new to the aviation industry and has the ability to violate some of the long held tenets of 4130 welding unless great care is taken. One of the primary concerns in sport aviation applications by the amateur welder is that the basic units are relatively inexpensive ($300-$400) and appear easy to use. There is a real temptation to use it without understanding some of the caveats involved.

In many ways the system resembles TIG in that an arc is struck between the parent metal and an electrode in the handle while an inert gas is flowing over it. The big difference, however, is that the electrode in this case is a consumable filler rod which is being fed through the handle automatically as it is being melted into the weld. There is no separate filler rod so it is a one-handed operation.

Because it is a consumable electrode, the weld commences almost as soon as the arc is struck, so the weld moves very quickly. This is why MIG was developed in the first place: It was designed as a production system for assembly lines where time really counted. It is also better suited to joining material in which both pieces are approximately the same thickness or have the same thermal mass because it is difficult to direct the heat.

It is hard to see exactly what is happening in the puddle so it is difficult to judge the actual penetration of the weld. Also, everything is happening quite quickly so it is easy to screw up before you realize it.

It is the instantaneous heating nature of the MIG weld that concerns those who say 4130 requires preheating and stress relieving. The heat goes in instantly, the weld is finished quickly, and then the rest of the structure is free to quickly suck as much heat out as it can. Also, any hydrogen which may be present in whatever form doesn't have a chance to escape, so the metal has to be as clean as possible, inside and out, to eliminate the possibility of embrittlement.

According to Eutectic's Bill Ridgway, MIG also has the ability to produce welds with an elevated hardness which affects the ductility and brittleness of the joint. He says a hardness over Rc 30 indicates a possibility of martensite build-up caused by too rapid air cooling of the weld. The American Petroleum Institute has apparently set a max limit of Rc 27-30 for their pipeline welds for this reason.

For comparison, most sources say a piece of 4130N tubing will test Rc 19-23 before welding.

On the other side, it is of interest to note that according to Jerry Mehlhaff at American Champion, the entire Citabria line has been MIG welded since the 1960s. He also says they don't stress relieve and their welders are re-certified every six months. They say the FAA tests their welds and are happy with Rc 38-41 in the weld. The tubing will test about Rc 3 next to the weld while the same tubing next to a gas weld will test almost zero.

Many kit manufacturers are using MIG in their airframe fabrication because it is fast and becomes a major cost factor. Some of them report they stress relieve specific components while others don't.

Obviously what we have here is a serious difference of opinion concerning MIG welding on 4130. However, if a general statement can be made about it, it is that it appears to require an experienced hand to produce a weld that is correct and safe. Even then certain preparation techniques must be followed and stress relieving seems advisable.

The biggest single danger of MIG welding in the sport aviation environment is that it gives the initial impression it is easy to do. That may be the case when doing body work or building wrought-iron stairs, but it is definitely not the case when welding up a 4130 structure on which your life depends.

Summary

In reality, it is extremely difficult to find an aircraft weld which has actually broken in flight. This is in part because the way structures are designed welds usually spend most of their lives in compression, so they don't see much load. Also, the way most joints are designed there is easily 200-300% more weld length than is necessary, even after applying normal safety factors.

However, we have an unknown when it comes to locked-in stresses and possible hydrogen embrittlement, especially in MIG welds. The experts tell us the types of failures we'll see from improper heating and cooling as well as embrittlements will almost always be fatigue failures. That being the case, flight time is the only true judge of what works and what doesn't. Many kit builders can point at the hundreds of MIG welded airplanes they have flying which have had no failures. That is true this year. What about next year, or the year after that? Kit planes don't fly very much and those which use MIG welding fly even less than the average. So, if an airframe has a point at which it will begin experiencing failures, we may not reach that point for years to come. That being the case, it would appear we don't have enough experience in the sport aviation environment yet to say whether the possible problems associated with TIG or MIG pose a threat or not.

Since what we're talking about here are flying machines, which are generally unforgiving of structural failure, it seems to us we ought to err on the side of conservatism. This is another way of saying regardless of the type of welding system employed, when in doubt preheat and then stress relieve.