HIGH FREQUENCY WELDING OF STAINLESS STEEL TUBES

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INTRODUCTION

This paper is an update of a previous paper authored by Mr. Humphry Udall, former Director of Research and Development for Thermatool.

The welding of stainless steel tubes differs substantially from the welding of high quality carbon steel tubes in a number of ways. The most significant difference is in the melting point of the oxides that are formed on the faying edges during the welding process. The oxides formed on carbon steel generally melt at a temperature lower than the melting point of the steel. Since the oxides melt first and are fairly liquid even before the steel melts, it is easier to squeeze them out in the weld rolls. Actually, it is possible to make a fairly clean weld on carbon steel without actually melting the steel, though this is rarely done.

Stainless steel, either austenitic or ferritic, has substantial quantities of chromium as an alloying element that can oxidize during the welding process. These chromium oxides are “refractory”, that is, they have very high melting points. In fact the melting point is higher than the stainless steel itself. Because of this, the stainless steel becomes soft and even liquid before the oxides melt, making the oxides difficult to squeeze out. If left on the bond plane, these oxides constitute discontinuities that can cause brittle fracture of the weld, low formability, and possibly weld line corrosion.

It is, therefore, essential that enough metal be melted at the edges to flush the oxides out during the weld squeeze. If properly done, all of the oxides will be extruded during the squeeze out and will be contained in the ID and OD flash (Fig 1). Conversely, if too much metal is melted, the HF vee may become unstable leading to possible weld defects. It is a well established fact that the “window of success” for stainless steel is smaller than for carbon steel and greater attention must be paid to the forming and welding parameters.

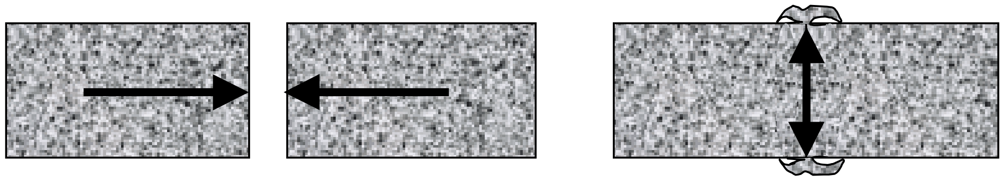


Fig 1 The HF welding process heats only the edges of the strip. The edges are Forced together by the weld rolls causing the molten metal and metal oxides to be ejected. The hot metal below the surface then fuses into a weld.

MATERIAL COMPOSITION

Because carbon can combine with the chromium to form very hard chromium carbides in the weld area, keeping the carbon content low will reduce the incidence of hard welds and cracks. Additionally, when the chromium forms carbides, it is no longer in a form that will help protect the surface of the metal and weld area corrosion is possible. By specifying the L versions such as 304L, the tube producer will reduce the potential for problems without compromising performance of the tube material.

It is possible that excessive unreacted aluminum and titanium can form aluminum and titanium oxides that are also refractory and just as difficult to remove as chromium oxides. The maximum limits for soluble aluminum and titanium may have to be lower than commercial limits. This is an issue to take up with your strip supplier. In addition, large non-metallic inclusions in stainless steel can result in defects known as hook cracks when they are upset in the weld area. Low levels of sulfur and phosphorus should be specified when purchasing strip.

COIL CAMBER AND TEMPER

Flat and straight coil will run better in any mill and this is especially true of stainless. In a properly adjusted mill, soft strip will usually run more smoothly than hard material because of the ability of the mill to correct for slight strip camber. Care should be taken to avoid introducing camber when recoiling strip after slitting.

STRIP EDGE CONDITION

Good strip edges are absolutely essential to achieving a good weld with stainless. The edges should be smooth with a minimum of burr (Fig 2). This requires careful attention to both edge condition and the set up of the slitting knives. Great care must be given to handling and transporting of the slit strip to avoid scraping or bumping of the edges as edge damage is a likely cause for weld defects. Good practice may also include the use of edge trimming on the mill prior to the first breakdown roll. This generates a small amount of trim scrap but this may be paid for by consistently higher quality welds and reduced tubular scrap.

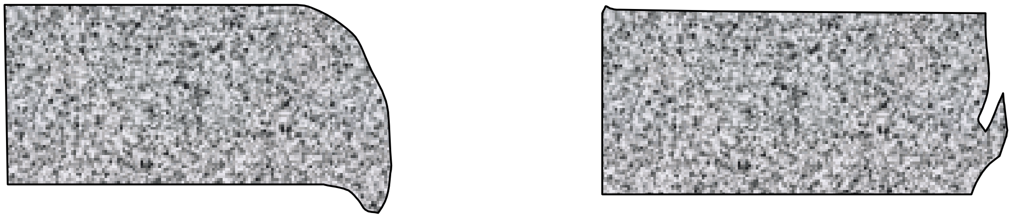


Fig 2. Slitter Burr

Slitter Lap

COIL WIDTH

The designer of the tube mill's roll tooling should provide a list of coil widths for the tube sizes to be produced. These may be only a theoretical dimension as the mill operators control the amount of squeeze out and a large squeeze out may require a wider strip width. It is absolutely essential to good weld quality that adequate squeeze out is achieved.

WELDING VEE GEOMETRY

The recommended vee angle for stainless steel is between 5 and 7 degrees (Fig 3). To determine the vee angle, measure the vee width at a point 2 inches up stream from the weld roll centerline. The gap between the edges should be between .175” and .250”. The vee angle is established by the width of the fin on the last fin pass, the amount of upset in the weld rolls, the distance from the last fin pass to the weld rolls, and the springback of the edges between the last fin pass and the weld rolls.

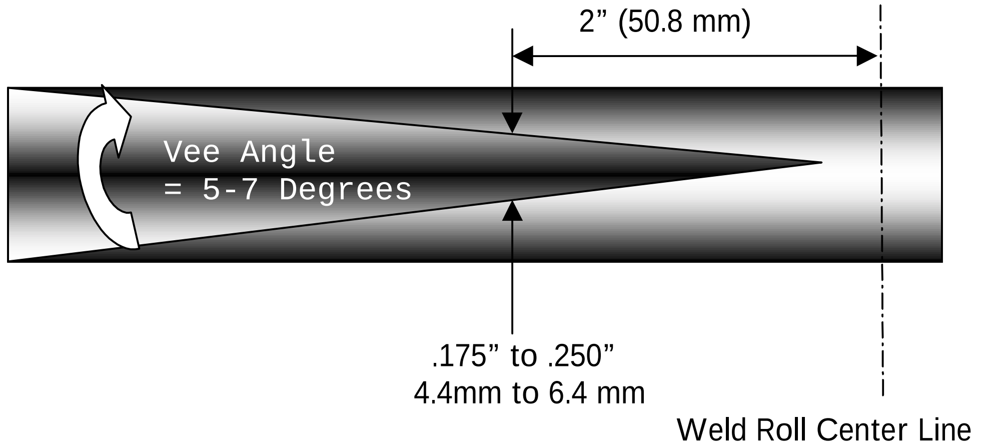


Fig 3. Vee Angle Measurement

In some mills, an insulated seam guide is used between the last fin pass and the weld pressure rolls. It should not be used as a “seam spreader” to open the seam wider than its natural width, which is the width of the last fin plus the natural springback between the edges, since this can lead to production of slivers.

SLIVERS

Slivers are typically small, elongated pieces of metal which can be produced by the rubbing of the strip edges against metal mill parts. There are many places that this can take place, but two of the most likely are the I.D. mandrel support strut and the edges of the seam guide. Another source of slivers is handling damage. The coils are often stacked upright, leaning against one another or against a steel rack. Any rubbing between coils or against the rack can create slivers and edge damage. Use great care when handling the coils with a fork lift. Inserting the forks between the coils can result in slivers and edge damage also.

If slivers are allowed to form and get into the weld area, they are likely to cause welding problems. In some cases they will build up on the induction coil, finally causing an arc either from the coil to the workpiece or from one turn to the next of the coil. This arc will momentarily divert current from the welding vee causing a transient drop in the weld point temperature and possibly a weld defect.

The sliver can also be carried down into the welding vee, causing a short circuit across the vee prior to its closure point. The sliver will rapidly vaporize. However, during the time it takes to do this, the current, which normally flows from this point to the apex of the vee, is momentarily interrupted, and, again we have a potential cause for a weld defect (Fig 4).

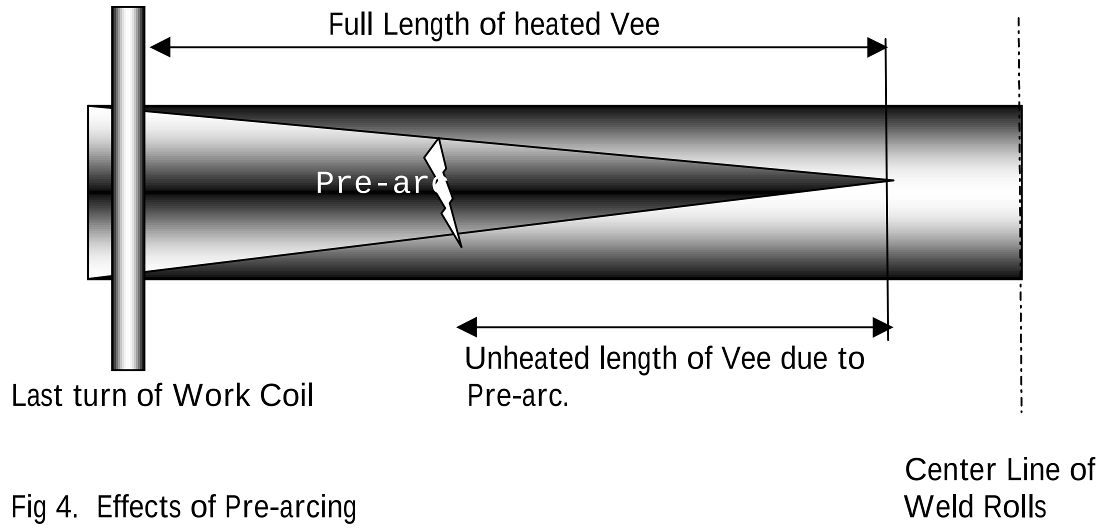


Fig 4. Effects of Pre-arcing

One of the potential benefits of using a solid state welder for stainless steel is the lower coil voltages used. The lower coil voltage is less likely to create the arc that can result in a defect.

COINING OF THE STRIP EDGES IN THE FINPASS ROLLS

If the slitting is good, or if edge trimming is used, no significant working of the edges should be required in the fin passes. If slitting is rough or if there is edge damage from shipping or handling, it may be possible to flatten and square them in the fin passes and still make a clean weld. However, it is also possible that this will lead to production of slivers or laps. A lap is created when a burr is rolled back into the edge but is not fused with the edge metal (see Fig 2).

Parallelism of the edges coming together in the vee is more important in stainless steel than in carbon steel. Because stainless steel generally exhibits more springback than carbon steel, there is a tendency for the edges to close at the inside of the tube first and then at the outside (peaked forming). The overheating at the I.D. can lead to a buildup of melted material on the impeder and/or I.D. mandrel and the lack of heat on the O.D. can cause cold or pasty welds.

Care should be taken to keep the fin rolls clean to prevent pressing dirt, oil, etc. into the edge of the strip. Any foreign material on the strip edge, including paint, will oxidize during heating of the vee and contribute to potential weld defects. Felt wipers may be used on top of the fin rolls to scavenge the corners between the fin blade and the roll radius (Fig 5).

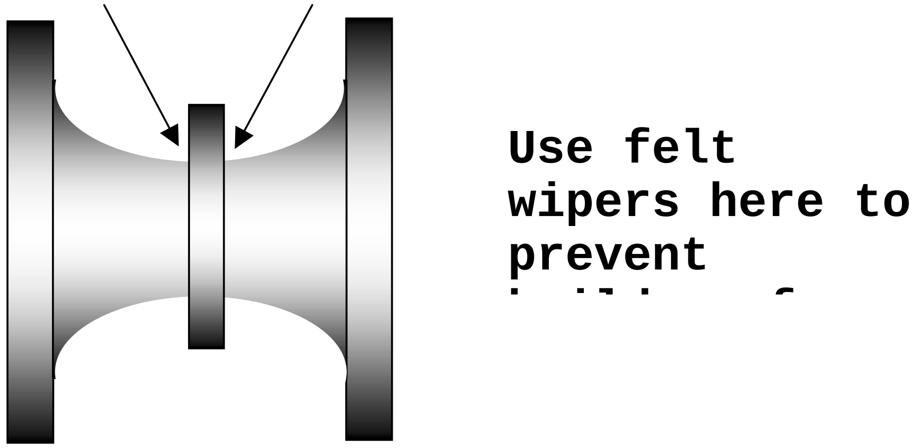


Fig 5. Fin roll

If stiff strip is being used, it is recommended that roll tooling incorporating proper edge forming be used. Without edge forming, efforts to get stiff strip to form properly in the fins may result in edge damage and a less than round shape going to the weld rolls. Because stainless steels work hardens so rapidly, it is important to use well designed tooling to minimize the springback prior to the weld rolls.

INDUCTION COIL

Induction coils can be of the same general design as for carbon steel. If a solid state welder is used, the design may differ from the vacuum tube coil design for the same size. However, the length of the coil should be approximately equal to its inside diameter. The distance from the center line of the weld pressure rolls to the front of the induction coil should be approximately the same as the coil I.D.(Fig 6). If the weld pressure rolls are too large, it may not be physically possible to get the coil this close (Fig 7). The longer vee will require more power to heat and slightly higher temperatures to offset the heat lost due to the longer time it takes the current to travel from the end of the coil to weld rolls.

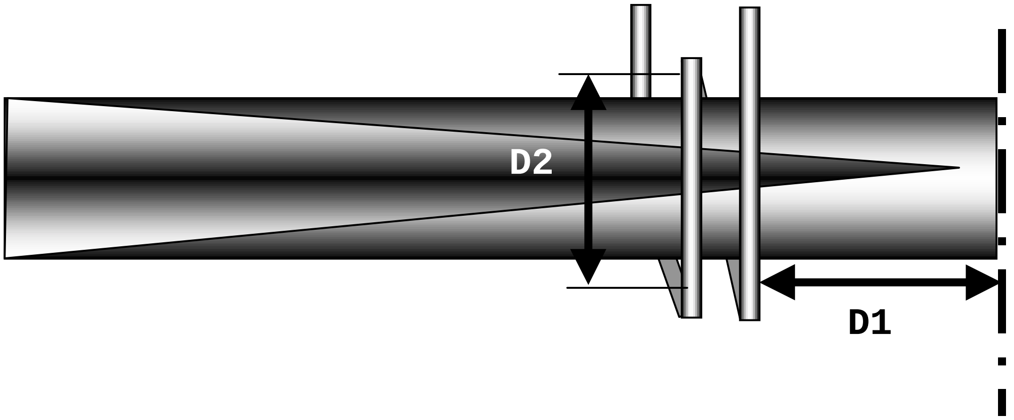


Fig 6. Vee Length (D1) = Coil ID (D2).

Weld Roll Center Line

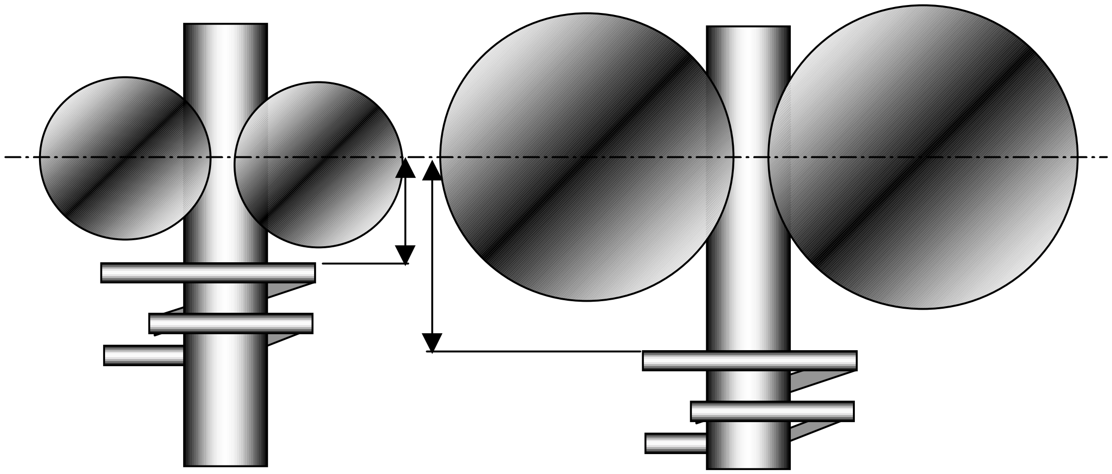


Fig 7. The effect of weld roll diameter on Vee Length.

The longer welding vee can result in a wider heat affected zone since the heat will have a longer time to diffuse into the edges of the strip. In extreme cases the temperature at the weld point may drop below the critical temperature needed to achieve a good weld. The merits of a wider heat affected zone are widely debated in the industry. Some feel that a wider HAZ will improve ductility needed for forming and bending. Others counter that the HAZ is a weak link in the tube, representing a potential point of corrosion which should always be kept at an absolute minimum.

WATER IN THE VEE

One of the most important requirements of making high quality welds in stainless steel is the elimination of oxygen from the weld area. Water dissociates at the welding temperature into hydrogen and oxygen that provides plenty of oxygen for the formation of metallic oxides. Therefore it is essential that the weld area be kept as dry as possible. This means that water used to cool the weld rolls must not get into the weld vee and that coolant used to cool the impeder must be routed backwards by using a return flow impeder. Coolant from the upstream forming rolls must not be allowed to flow into the weld area and fill the tube to overflowing.

SPUME

Spume is the name generally given to the small particles of metal that are ejected from the welding vee during the high frequency welding operation as a result of the high electromagnetic forces produced by the current flowing in the work coil (Fig 8). This spume tends to be in the form of very small, spherical particles of metal and metal oxides. They can be very hard and abrasive and if they are allowed to accumulate on the weld rolls, marking of the tube is likely.

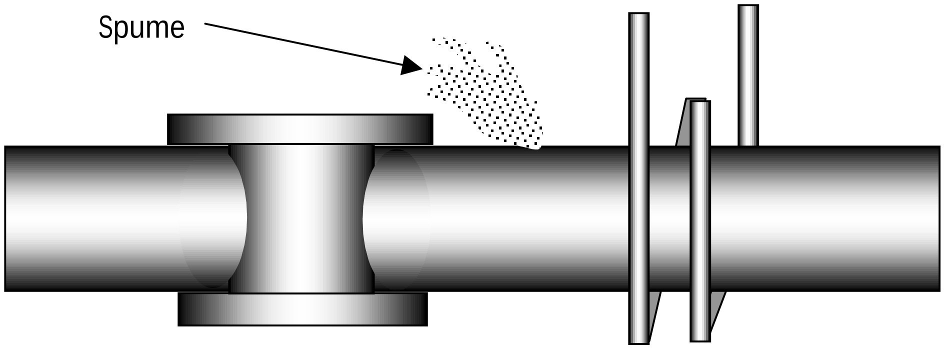


Fig 8. Spume is ejected from the apex of the Vee.

The metal particles can also blow backwards and accumulate on the coils, and even on the edges of the strip, both of which can cause weld defects. The spume can be removed with felt wipers on the weld rolls, and in some cases, literally vacuumed up by using a fume collector placed over the weld area.

INTERNAL BEAD

The internal bead formed during the HF welding operation can be removed by scarfing with a carbide tool or by rolling into the I.D.. Many manufacturers leave the bead in place when the tube is to be used for decorative applications. If a high quality weld is required, scarfing is highly recommended as rolling the bead into the I.D. can create cracks and stress risers on the I.D. where the hard oxidized bead material is rolled into the softer weld area.

When using internal bead removal tooling, it is essential that the tool be kept cool with sufficient clearance around the tool for coolant to freely circulate. If there is insufficient clearance, the coolant will back up into the weld and may create defects. It is also important to realize that when scarfing stainless steel, the speed at which the bead moves relative to the tooling is important. Generally, the faster the speed of the tube, the better the quality of the scarf and the longer the life of the tool. It has been recommended that a minimum welding speed of 125 FPM be maintained when I.D. scarfing stainless steel.

WELD POWER, RIPPLE, AND FREQUENCY

The optimum weld power is the minimum power at which a satisfactory weld is being obtained. Adjustment to the weld power is generally done by observing the spume which occurs at the apex of the weld. The spume, which appears yellow or orange, usually spurts downstream of the weld on both the inside and outside of the tube. A moderate spume is the best indication of adequate weld power and steady mill conditions. Uneven spume is an indication of uneven welding conditions and usually of poor weld quality. It can be caused by mechanical irregularities in the mill, such as eccentric rolls, or by excessive weld power or both.

Some manufactures of ferritic stainless tube for automotive applications have applied an automated weld power control system based on a two-color pyrometer that is integrated into the welders speed/power control system. The pyrometer can be set to maintain a consistent weld temperature once the proper temperature has been determined. This diminishes the variability introduced when using several operators on the weld mill, all of whom see the color of the spume slightly differently.

One of the advantages of the new solid state welders is the availability of very low ripple output power as a standard feature. Welders with a .2% ripple are routinely delivered and even lower numbers are possible with new IGBT (Isolated Gate Bipolar Transistor) technology. The low ripple is mainly of concern if you are leaving the weld bead in the tube. Low ripple results in a smoother bead but it does not affect the amount of bead formed. The amount of bead formed is a function of squeezeout that is influenced by strip width, weld power, and frequency (Fig 9).

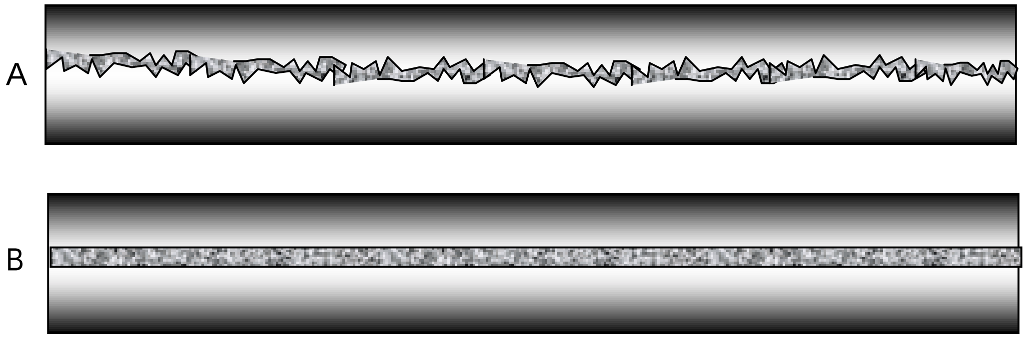


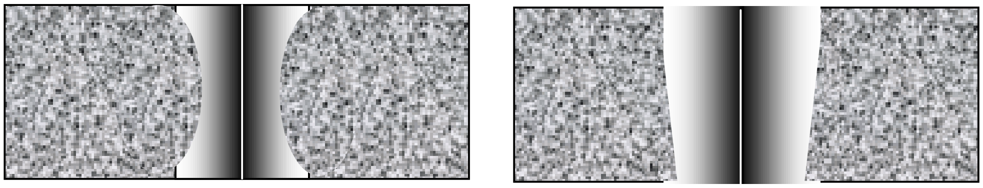
Fig 9. The effects of Ripple on bead shape: A - High Ripple, B – Low Ripple.

When using a vacuum tube welder at low power, the SCRs are phased back and this will maximize the ripple effect. To minimize the ripple, run the welder at higher power settings, at least 80% or better. Solid State welders operate at lower voltages and are equipped with better filtering to ensure low ripple over the entire power output range.

It has been noted that some stainless steel tube producers prefer 200 kHz for a welding frequency stating that it provides a more ductile weld. Others insist on 400 kHz because of the narrower heat affected zone produced. At least one HF welder manufacturer can provide frequencies of 100 kHz to 800 kHz depending on customer needs and product demands.

Very little research has been done on which frequency really works best because product application, strip width and width control, welding speed, squeezeout, vee length, frequency, and welding temperature all affect weld quality. It is not likely that we will ever be able to accurately evaluate all of the possible interactions of the various parameters and establish the optimum welding frequency. One experiment was performed on 304 stainless where all parameters were held constant and only the frequency was changed. One run was made at 355 kHz and another was made at 155kHz. The microstructural analysis showed very little difference except for the amount of upset and flow angles.

As would be expected the lower frequency heated more metal, resulting in more squeezeout. Because more metal was heated, more of the edge was softened and the flow angles were steeper with the lower frequency. The differences were definable but it was not possible to categorically state that in all cases one weld would perform better than the other (Fig 10).



Typical Heat Affected Zone for a 400 kHz welder.

Typical Heat Affected Zone for a 200 kHz welder.

Fig 10. The effect of frequency on Heat Affected Zone.

It has been shown that for different sizes of pipe and different welding speeds, there is a critical welding frequency, above which the welder will operate more efficiently with less sensitivity to variations in weld parameters. This is true for carbon steel and for stainless steel. It remains true that while it is possible to achieve a satisfactory weld at virtually any frequency, welds made at higher frequencies generally are easier to control. Since control of the welding parameters is more critical with stainless, it would suggest that higher frequencies would give better long term results because of the reduced incidence of weld defects and scrap tube.

INERT GAS

It has been often said that if the HF weld is properly executed, no cover gas is necessary. In many cases, this may be true. However, recent developments indicate that the use of a cover gas may have significant advantages when the product is intended for critical applications, such as automotive exhausts. Typically, the cover gas of choice is argon or an argon mixture.

Years ago, many experiments were conducted to develop a delivery system that would blanket the weld area without chilling the weld pool. The problem was that the argon, in its liquid state for storage, was very cold. If applied to the weld area directly, it could freeze the weld pool. If it was applied at a high pressure or velocity, it would entrain air and the oxides would still form in the weld. Additionally, the nozzle had to be non-metallic so that it would not be subject to inductive heating. Getting the argon to the I.D. of the weld was not very successful so that even under the best conditions, the results were not significantly better than not using a cover gas.

Recent trends are directed towards enclosing the coil and the weld rolls in an airtight box and gently purging the box with Argon. A gas dam must be incorporated onto the I.D. trim bar to prevent excessive loss of gas down the I.D. of the tube. The current philosophy is simple: if you prevent any oxides from forming during the welding process, the chances of oxides being trapped on the bond plane are nil.

Having gone through the trouble of gas shielding to prevent weld defects, it should be clear that the mill environment must be kept meticulously clean also. Of critical importance is the rule of thumb that carbon steel must not be run on a stainless mill. The iron oxide (scale) that will contaminate the mill coolant is a great source of two problems. First, iron oxide scale can be rolled into the surface of the stainless and cause a rusty discoloration and second, particles of scale can be entrapped in the weld vee to create weld defects. It is just as important that any part of your mill made of iron or steel be kept clean and its contact with the strip edges be minimized.

WELD TESTING

The design of weld test procedures is extremely important, since a poorly designed test can lead to either rejection of material which is actually within product specifications, or to approval of rejectable material.

The most common tests are flare tests and expansion tests (Fig 11). On heavier wall material, flattening tests are also often used. As a general rule the test should be designed to subject the tubing to elongations similar to those required for its production processing. Thus, if the final product involves flaring, a flare test is clearly appropriate. If it involves expansion, the expansion test is appropriate.

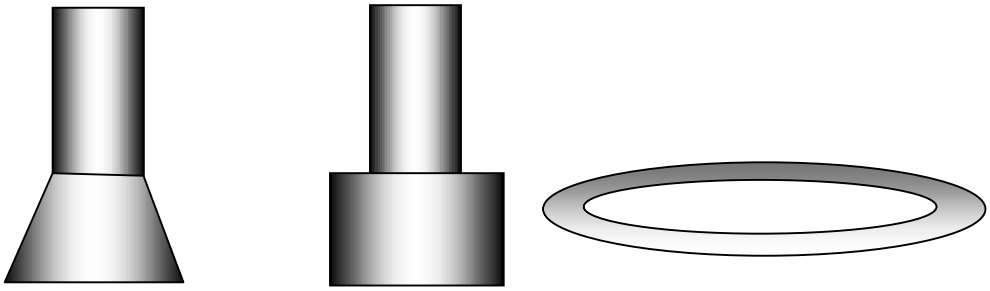


Fig 11. Flare Test Expansion Test Flattening Test.

It is essential that the test tooling be properly designed and well maintained so that consistent results will be achieved. The test procedures must be carefully defined and followed so that variations introduced by human influence are minimized. For example, when flaring tube from which the I.D. bead has not been removed, small grooves must be cut in the flare mandrel to provide clearance for the bead. If this is not done, the bead will be forced into the I.D. of the tube causing stress risers which can cause premature failure.

The speed and possibly even the temperature at which the test is performed must be defined and controlled.

Metallographic sectioning of the weld will reveal the degree of upset that has been achieved as well as the width and uniformity of the bond region. In austenitic stainless steel, the metal on the bond line acquires a dendritic structure. This structure will recrystalize during annealing. Before annealing, however, examination of the dendritic structure is useful in evaluating the uniformity and squeezeout of the weld. A narrow uniform layer is desirable. “Hairy” margins of the dendritic region represent grain boundary liquation and should not be confused with carbide grain boundary precipitation which generally cannot be resolved with a light microscope.

The degree of upset can sometimes be observed by examining the flow lines visible from the slight banding that occurs in most stainless steels. While it is difficult to measure quantitatively, a moderate amount of upset is essential to achieving a good weld. Generally, micros are taken prior to any subsequent annealing so that the microstructure is well defined and flow angles can be observed and measured.

Non-destructive testing has evolved much like high frequency solid state welding has, gaining wider usage and acceptance. However, despite gratifying technological advances, no NDT manufacturer has been able to create a system that will absolutely guarantee weld quality. NDT systems work very well when they are a part of a well-executed quality program that includes metallographic, mechanical, and destructive testing of the product.

PROCEDURES

Because the consequences of making a poor weld are very expensive, it is economically imperative to exercise special care at the mill when welding stainless steel tube. A standard mill set up sheet is absolutely necessary to ensure consistent and repeatable setups. The setup sheet should include all standard roll, spacer and shaft information, fin roll fin widths, girth after each pass, girth prior to weld and circumference after weld, coil and impeder dimensions, vee length, speed, power, weld temperature, gas type (if used) gas flow and pressure, sizing dimensions, etc. Each of the defined parameters must be listed with an aim and a tolerance. Each parameter should be measured and recorded at the start of each shift and after lunch break.

Purchasing should be ordering the material to written specifications which include melting, casting and rolling methods, chemistry limits, gage and gage tolerances, coil size, slit width and width tolerances, camber limits, shipping, loading and storage instructions, etc.

Test and inspections should be detailed on a list that defines which test procedure is used, by whom, where, how often, and provide accept/reject tolerances. Each test procedure should be written to include methodology, equipment used, calibration procedures, and what to do if the test fails or passes.

Each operator or inspector should have a job description that defines the tasks to be performed, personnel qualifications, and special training or education required.

CONCLUSION

High frequency welding of stainless steel is more difficult than welding carbon steel. Mill cleanliness, exclusion of oxygen from the weld area, adherence to the best procedures, a highly disciplined and well trained crew, and a fully functioning quality program will help to ensure the maximum yield of high quality tubing.

THERMATOOL
WELDING AND HEATING SYSTEMS

High Frequency Welding
Of
Stainless Steel Tubing

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