Cost Reductions and Product Consistency Improvements Using Unannealed High- Frequency/Solid State (UHFSS) Welded 409 Stainless Steel Heat Exchanger Tubing

BY

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ABSTRACT

Competitive markets for commercial and residential HVAC systems are demanding higher quality and safer, longer lasting products. Due to increased global competition, HVAC system dealers and end users also demand competitive prices and longer warranties. The common experience of coated carbon steel heat exchangers that suffer corrosion failures in less than ten years will be unacceptable. HVAC manufacturers must find ways to meet both performance and pricing expectations.

The progressive HVAC manufacturer is transitioning to stainless steel tubular heat exchangers for longer service life. However, the higher costs of annealed tungsten-inert gas (TIG) or laser-welded ferritic stainless steel heat exchanger tubing have forced many manufacturers out of this price-sensitive market. These less productive (lower fpm) tube welding processes and an additional post-weld annealing step contribute to the higher costs of stainless steel tubing.

This presentation will introduce a lower cost, high quality alternative to annealed TIG and laser-welded 409 ferritic stainless steel tubing. It will be shown how state-of-the-art, high frequency/solid state welded tubing is manufactured at higher speeds, and why the costly post-weld annealing step can usually be eliminated. In many cases, the HVAC manufacturer can realize significant reductions in heat exchanger tubing costs, and often experience less variation in subsequent tube-bending operations.

BACKGROUND

Commercial and residential HVAC systems have evolved over the years from using predominantly "clamshell" heat exchanger components to the more efficient and cost effective tubular heat exchanger. Figure 1 shows a typical tubular heat exchanger unit.

Figure 1: Tubular Heat Exchanger

The materials used for both clamshell and tubular heat exchangers have progressed from basic uncoated or epoxy-painted plain carbon steels to hot-dip aluminized coated steels. Although the service life of the aluminized steel tubular heat exchanger exceeds that of uncoated steels, increasing heat exchanger firing temperatures for optimum energy efficiencies have pushed aluminized steel past its maximum sustainable surface temperature limits. Once operated over these limit temperatures, the aluminized steel heat exchanger tube suffers catastrophic corrosive attack in a short period of time.

To sustain higher firing temperatures with fewer corrosion issues, the progressive commercial and residential heat exchanger manufacturer has chosen to use an economical ferritic grade of stainless steel that can withstand higher heat without suffering coating degradation problems. Type 409 stainless steel is now being widely used in the tubular heat exchanger market.

While the cost of 409 stainless steel raw material for heat exchanger tube manufacturing is somewhat higher than aluminized carbon steel, the tube welding process can make this heat exchanger component significantly more costly. The inherent challenges of the tube welding process when dealing with high chromium content alloys like 409 stainless steel have led many tube manufacturers to avoid the more productive high frequency/solid state welding process.

The more traditional stainless steel welding technologies of tungsten-inert gas (TIG) welding and laser welding avoid some of these challenges, but typically require slower tube mill speeds for proper seam welds. The laser welding process can be accomplished somewhat faster than TIG welding, and is the most common method used for 409 stainless steel heat exchanger tube welding today.

Recent developments and improvements in high frequency/solid state welding on tube mills have allowed the innovative heat exchanger tube manufacturer to effectively produce 409 stainless steel welded tubing. This tubing can meet and exceed the weld qualities of laser welding without the slower welding speeds and a post-weld annealing process that is required to normalize the laser welded heat affected zone (HAZ). This annealing step adds significant costs and production lead times to laser-welded tubing compared to high frequency/solid state welded tubing. It can also introduce mechanical property variations that have been shown to adversely affect the tube bending fabrication required for both mandrel-bent and wrinkle-bent heat exchanger tubing components.

TUBE CORROSION ISSUES

The primary reason for utilizing 409 ferritic stainless steel heat exchanger tubing instead of hot-dipped aluminized low carbon steel welded tubing is to extend the service life of the heat exchanger. In welded aluminized steel tubing, the aluminum/silicon alloy coating can be exposed to temperatures up to 950^0 F. and still maintain its integrity as a separate, noble corrosion-resistant coating over the substrate low carbon steel.

At temperatures above 950^0 F. for any length of time over a few minutes, the coating starts to metallurgically diffuse into the steel substrate. This irreversible diffusion process results in a corrosion-resistant but brittle layer on the substrate steel made of iron and aluminum in almost equal parts. As the heat exchanger tube expands and contracts during subsequent heating cycles, this brittle layer forms small surface cracks, and the unprotected substrate low carbon steel becomes subject to oxidation/corrosion through the impingement of surface moisture caused by ambient condensation.

Figure 2 shows a view of a commercial rooftop heat exchanger unit that had been replaced after only six years of service. The severe surface oxidation is evident on the weld seams and in other areas that have suffered coating diffusion due to heating above the diffusion temperature. The coating diffusion is evidenced by the lighter/whitish aluminum oxidation and a darker gray surface coloring.

Figure 2: Corroded Aluminized Steel Heat Exchanger

Figure 3 shows an I.D. view of a section of this aluminized steel heat exchanger tube section that was cut from the heat exchanger unit. A heavy layer of corrosion is visible on the inside surface. The tube's I.D. weld seam is noted below the corroded area.

Figure 3: Oxidized Aluminized Steel Tube I.D. Section

Aluminized steel heat exchanger tubing also has a remetallized thermal spray aluminum coating applied over the O.D. weld seam after the welding process. It is not commercially feasible to apply such a coating on the I.D. weld seam, however. In addition to the typical surface corrosion formed as a result of aluminum alloy coating diffusion, it is also possible for the heat exchanger tube's I.D. weld seam to be preferentially attacked in the presence of condensation moisture over time. Figure 4 shows a photomicrographic example of an aluminized steel heat exchanger tube's I.D. weld seam cross-section that has suffered catastrophic corrosion and subsequent weld fracture.

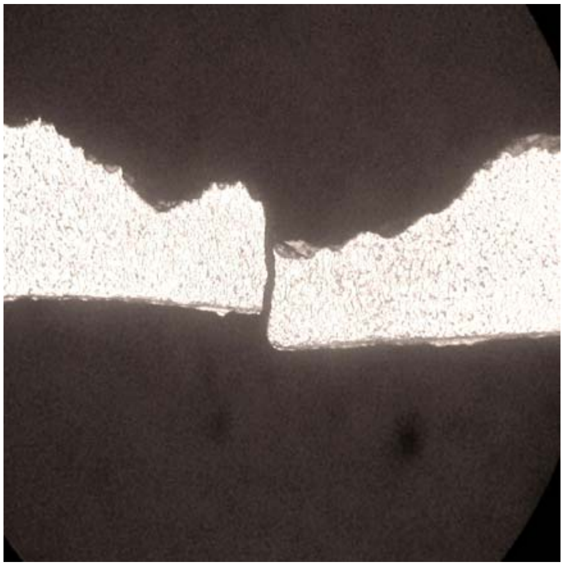

Figure 4: Oxidized Aluminized Steel I.D. Tube Weld Cross-section

It is clear from these examples that for tubular heat exchanger installations that will be exposed to firing temperatures over 950^0 F., and/or installed in locations where abundant condensation moisture will be allowed to accumulate inside the heat exchanger tubes, that a more heat and corrosion-resistant tube material is required for longer service life. It has been proven that Type 409 ferritic stainless steel meets the requirements of such a material.

Early prototype work with 409 stainless steel tubing for HVAC heat exchanger applications was typically done with tubing that was commercially available. In most cases, this would have been either TIG welded, or more commonly laser welded and annealed tubing. In many cases, this type of tubing became the expected norm, along with its high price. It was during this period that the high frequency/solid state 409 stainless steel welded tube option was being developed and perfected.

WELDING METHODS

The most challenging aspect of welding 409 stainless steel on a continuous-seam welded tube mill is the formation of chromium oxides during the welding process. The avoidance of such oxides is critical to making a high quality tube weld. Additionally, the tube must be formed, welded, cooled and sized to the final close tolerances of heat exchanger tubing on a continuous, highly efficient basis to be marketed as a competitive product in the HVAC arena. There are three basic welding methods used to accomplish this task.

The TIG Welding Process

The TIG welding process utilizes a non-consumable tungsten electrode with an argon or argon-hydrogen mix shielding gas to prevent chromium oxide formation. TIG tube welding is usually done in one bead, and can use from one to four electrodes combined in a multiple torch arrangement.

TIG welding speeds are generally in the 10/15 feet per minute (fpm) range for 409 stainless steel sheet thicknesses up to 0.060". This slow tube welding speed required to establish the wider weld bead necessary for a high quality TIG welded tube seam will often make the TIG welding method the least desirable choice for competitive 409 stainless steel heat exchanger tube manufacturing.

Figure 5 shows a typical stainless steel tube TIG weld pattern (1.750" O.D. X 0.42" wall SS heat exchanger tube). Note the typical wide hourglass shape of the HAZ, approximately 0.035" wide at the top/widest area of the weld zone.

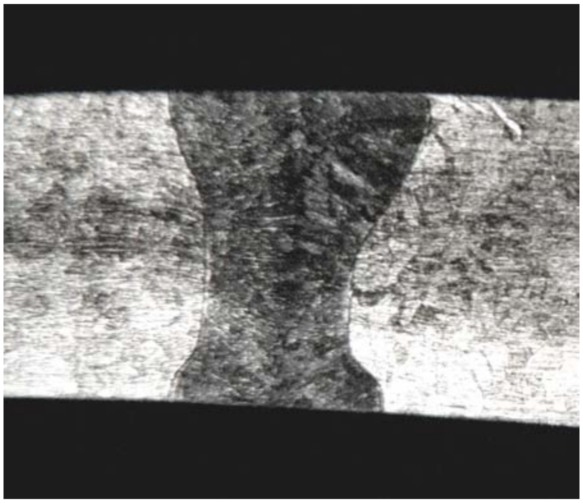

Figure 5: TIG Stainless Steel Tube Weld Pattern

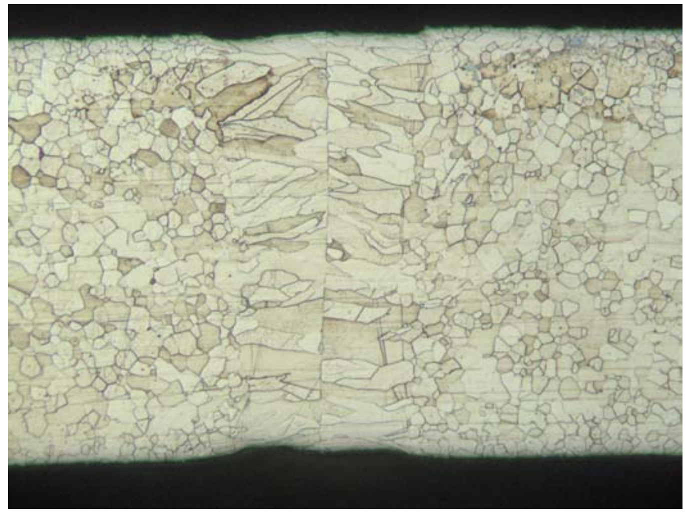

Figure 6: Laser Welded Stainless Steel Tube Weld Pattern

The Laser Tube Welding Process

The laser tube welding process utilizes a highly concentrated beam of light with a power density that can be up to 1,000 times higher than a TIG welding arc. A laser-welded tube seam will have a narrower pattern, and for a 0.060" tube wall thickness, will often be only 0.015"/0.020" wide.

The laser weld seam displays very little HAZ, and in 409 stainless steel heat exchanger tubing, often appears to contain relatively few very large, horizontally-oriented recast grains with a well-defined, thin weld centerline. Figure 6 shows a typical laser weld in a 409 stainless steel heat exchanger tube. Note the horizontal weld zone recast grains, the abruptly segregated weld seam/centerline, and the almost immediate transition from the horizontal recast grain structure to the fine grained, equiaxed microstructure of the tube's raw material.

Laser tube welding does allow a considerably higher tube production speed compared to the TIG welding process, in the neighborhood of approximately 50/60 fpm. However, the tube mill's line speed must be adjusted for the proper timing of the tube's post-weld annealing (for on-line annealers). For the laser tube weld to adequately normalize at a low level anneal/stress relieve temperature of approximately 1,400^0 F., the tube must travel through an induction heating coil slowly enough to soak the tube wall at temperature thoroughly. This often slows the tube welding process significantly.

Alternatively, the 409 stainless steel laser welded heat exchanger tube may be annealed/stress relieved off-line in a separate heat treating furnace. This allows maximum laser tube welding speeds on the tube mill, but causes additional production delays, higher energy costs and possibly tube straightness problems after the stress relieving step.

One disadvantage of the post-weld annealing/stress relieving process for laser welded 409 stainless steel heat exchanger tubing is the significant and varying surface discoloration that the heat treatment step causes. Since the tube is typically heated in the open air, not in an atmosphere-controlled furnace, the surface of the laser welded 409 stainless steel tubing usually develops a darker surface oxide hue ranging from a medium copper color to a very dark brown color, often with lighter streaks usually caused by dripping tube mill coolant. Figures 7 and 8 show views of these discoloration conditions.

Figure 7: Dark and Streaky Surfaces of Laser Welded and Annealed Tubing

While it may seem trivial that a tubular heat exchanger component that may be enclosed inside the HVAC cabinetry is discolored, the weld seam becomes very difficult if not impossible to locate while fabricating the tubing. In those cases where the tube seam is required to be specifically aligned relative to the tube bends, this may well be an important issue.

Figure 8: Varying Degrees of Surface Staining/Coloring in Laser Welded and Annealed Tubing

Heat exchanger tube bending personnel have also found that the different hues of the surface discolorations in annealed 409 stainless steel tubing can foreshadow significant variations in the abilities of the different tubing to be bent to final configurations. In some cases, laser welded and annealed tubing with a very light copper color was much more difficult to bend than tubes with darker-hues. It is hypothesized that the difference in coloring corresponds to variations in the annealing/stress relieving temperature actually achieved by the tubing during the annealing process.

The higher cost, lower tubing production speeds, annealing/stress relieving requirements, surface discolorations and tube bending variations of laser welded and annealed 409 stainless steel heat exchanger tubing make the search for a viable and lower cost alternative very desirable.

High Frequency Welded Tubing

Unannealed high frequency/solid state (UHFSS) welded 409 stainless steel tubing has a fairly long history of use in the automotive exhaust market. Although not as dimensionally precise as HVAC heat exchanger tubing, this welded tubular product has met the demands of the automotive market for weld quality, bending ability and tube end formability. In fact, the evolution of heat exchanger tubing materials has closely patterned that of automotive exhaust with regard to corrosion challenges and product warranty issues.

The challenge of welding 409 stainless steel without the inherent atmospheric protection of the TIG process or the ultra-high power density of laser welding needed to be addressed to take advantage of the high speed processing possible with high frequency welding. After many months of process improvements, in-process evaluations, prototype tube trials and actual production heat exchanger tube testing, these problems were solved. A new state-of-the-art in high frequency/solid state welded 409 stainless steel heat exchanger tubing was finally realized.

Argon gas shielding, improved weld roll cooling methods, carbide weld roll materials and innovative forming roll geometries have all been implemented to produce an acceptable and robust high frequency stainless steel welding process. Combined with stringent in-process testing and inspection procedures, these process improvements have helped the high frequency welded tubing manufacturer meet the HVAC market's need for a lower cost alternative to laser welded and annealed 409 stainless steel heat exchanger tubing.

UHFSS tube welding mills generally run at much higher speeds than either TIG or laser welding tube mills, usually in the 150 to 220 fpm range, depending on the O.D. size and wall thickness of the tube being produced. The high frequency solid state welding systems used are typically much less complicated than TIG or laser systems, and are easier to maintain and change over. The advent of variable power (adjustable kW) high frequency heating systems has also allowed significant improvements in stainless steel weld qualities vs. older "single kW" power systems. Figure 9 shows a basic view of a typical high frequency/solid state tube mill's weld box area.

Figure 9: UHFSS Coil and Weld Box Area

ADVANTAGES OF UHFSS TUBING

UHFSS welded 409 stainless steel heat exchanger tubing offers several important benefits when compared to laser welded tubing. These benefits include significantly lower tubing costs, a more homogenous and stronger weld microstructure, better surface cosmetic appearance and more consistent bending properties than laser welded and annealed tubing.

Tube Cost Comparisons

In general, UHFSS 409 stainless steel heat exchanger tubing is priced from 20% to 30% lower than comparable laser welded and annealed tubing, depending on O.D. size and wall thickness. Although the raw material to produce the tubing is identical (typically an annealed, "high formability" grade of 409 stainless steel sheet in slit coil form), the costs to produce laser welded and annealed tubing are far greater than UHFSS tubing. Lower tube mill speeds (50 fpm vs. 180 fpm on average for UHFSS), higher equipment and maintenance costs for laser units, either in-line or off-line annealing/stress relief systems and less productive cutoff and end-conditioning processes all contribute to the higher costs of laser welded 409 stainless steel tubing.

UHFSS Weld Zone Microstructures

The UHFSS tube weld is vastly different than either TIG welding or laser welding in the 409 stainless steel material. As seen in Figure 10, the weld zone and HAZ is almost indistinguishable from the base material of the tube wall. This maintenance of a generally fine-grained equiaxed microstructure in the ferritic stainless alloy means that the resulting weld will be stronger and less prone to fatigue failure. The need for a post-welding anneal or stress relieve has been virtually eliminated due to this resulting uniformity in the weld zone.

Figure 10: Typical UHFSS 409 SS Tube Weld Zone/HAZ

In addition to the superior microstructural uniformity of the UHFSS tube weld, the actual strength and ductility of the high frequency 409 stainless steel tube weld has been found to be consistently better than annealed laser tube welds. Table 1 lists the comparable uniaxial tensile test properties for both 1.750" O.D. and 2.00" O.D. 409 stainless steel heat exchanger tubes, tested across the weld zones. Figure 11 shows the actual circumferential tensile test bars machined from the tube samples.

Table 1

Tube O.D.	Yield	Tensile	Elong.
1.750" (Annealed)	51,240 psi	61,205 psi	50%
1.750"- (UHFSS)	53,406 psi	62,670 psi	56%
2.000" (Annealed)	39,238 psi	65,785 psi	50%
2.000"- (UHFSS)	46,377 psi	67,203 psi	62%

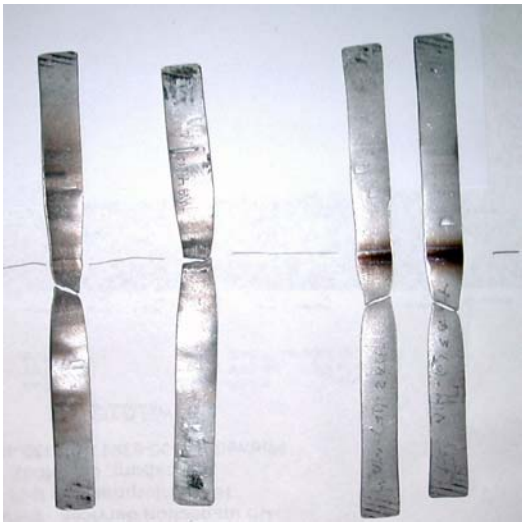

Figure 11: Laser welded/annealed and UHFSS circumferential 409 SS tensile test specimens (laser set on left)

The laser welded and annealed test bars on the left side of the photograph have broken in or near the softer and weaker laser weld zones. The UHFSS weld specimens on the right fractured in the tube's base material, away from the stronger welds.

Surface Cosmetics

Although most tubular heat exchanger components are hidden inside the HVAC cabinet, the dark, mottled surface of laser welded and annealed 409 stainless steel heat exchanger tubing has caused some concerns regarding consumer impressions. Most other metallic components in the HVAC system are bright copper, stainless or aluminized steel, which makes the darker annealed tube components stick out as "different". In fact, some new HVAC models designed by a major manufacturer will have some visible components that cannot utilize the unsightly surface common to annealed 409 stainless steel tubing. Bright-surface UHFSS 409 stainless steel tubing was chosen as a much lower cost alternative to an austenitic stainless steel component.

Tube Bending and Formability Issues

As mentioned earlier, the variability introduced to the tube properties due to in-line or off-line tube annealing/stress relieving processes can often be seen in the coloring of the laser welded and annealed 409 stainless steel heat exchanger tubes. Tube bending personnel have found that the consistency of the unannealed 409 stainless steel tubes makes their job significantly easier.

This is due to fewer setup changes and/or mid-shift adjustments being required to the bender when a new lot of tube is loaded in the machine. It is not uncommon for a tube bender to need significant adjustments each time a new load of annealed tubing is started. Tests have shown that the properties of the as-welded 409 stainless tubing are much more consistent than those of multiple annealing lots, even when made from the same heat of raw material. Figures 12 through 15 show just a few of the many difficult bending configurations where UHFSS welded 409 stainless steel heat exchanger tubing has been successfully used.

Regarding tube bending and tube end formability issues ("swaging"), many HVAC manufacturers have discovered the fact that 409 stainless steel heat exchanger tubing does not always form the same as the much softer aluminized steel tubing it is replacing. In some cases, this has caused some difficulties.

Figure 12: Wrinkle-bent "U-bend" tube

Figure 15: Wrinkle-bent and "pointed" U-bend tube

Figure 13: Serpentine Wrinkle-bent tube

Figure 14: Wrinkle-bent and flattened tube

The biggest difference between aluminized low carbon steel heat exchanger tubing and UHFSS welded 409 stainless steel tubing formability is often found in the tube end forming/ swaging process. Changes to the speed, force and total percentage deformation induced by the swaging process are often required for the successful swaging of UHFSS welded tubing.

Tubular HVAC heat exchanger manufacturers who regularly utilize lower swaging expansion percentages (less than 15%) do not usually encounter problems with UHFSS welded 409 stainless steel tube swaging. Well-maintained, balanced and aligned swaging machines are also important, as the work hardening rate of 409 stainless steel tubing does exceed that of typical aluminized steel tubing.

The softer low carbon aluminized steel is much more forgiving than 409 stainless steel in the event of misaligned swaging or excessively high expansion rates, speeds and swaging forces. In many such cases, the extremely ductile aluminized steel will deform without fracturing, while a 409 stainless steel tube may not.

CONCLUSIONS

In the highly competitive HVAC heat exchanger market, the manufacturer that can economically meet customer demands for extended warranties and longer unit life will likely earn more market share. Today's workhorse tubular heat exchanger made with aluminized steel welded tubing can no longer meet the higher firing temperature requirements of high efficiency furnaces.

Type 409 stainless steel welded heat exchanger tubing has been proven to be an effective corrosion-resistant component for longer-life HVAC systems. Laser welded and annealed 409 stainless steel tubing has been the component of choice while the more productive process of unannealed high frequency/ solid state (UHFSS) welding of heat exchanger grade tubing was being developed and perfected.

Production-qualified and life tested heat exchangers utilizing UHFSS welded 409 stainless steel tubing have proven capabilities as a lower cost alternative to expensive laser welded tubing. Documented testing has shown that the UHFSS weld zone is more homogenous and stronger than laser welds. The expensive and time-consuming post-weld anneal/stress relieve heat treatment common to laser welding is not required for UHFSS welds.

Avoiding the costly annealing process improves the surface cosmetics of UHFSS welded 409 stainless steel tubing. Unannealed tubing also has less mechanical property variation that can be caused by a variable annealing process, as evidenced by a wide variety of different surface colors and hues.

Some adjustments to standard tube end forming/swaging processes used for aluminized steel heat exchanger tubing may be required for optimum results with UHFSS welded 409 stainless steel tubing. However, many manufacturers have proven this tubing grade to be capable of effective tube end formability.

A decision to switch from high priced laser welded and annealed 409 stainless steel heat exchanger tubing to a high quality UHFSS welded tubing at a 20-30% savings can be one of the best choices an HVAC manufacturer can make in 2006.