Selecting Feedwater Heater Tube Materials for Greatest Efficiency and Reliability

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ABSTRACT

In today's competitive marketplace, it is imperative to minimize the heat rate, and maximize reliability and MW production. Copper alloy tubing in power plant systems create significant restrictions while attempting to do this. Copper will slowly dissolve into the condensate and eventually plate in other parts of the system. When it coats the boiler tubes, it can create a lower melting alloy that can cause premature boiler failure; this is called liquid metal embrittlement. In many plant designs, the copper preferentially coats the HP steam turbine blades which results in significant derates. Additionally, copper alloys are more sensitive to multiple pitting mechanisms and tube leaks are responsible for many unplanned forced outages to plug those tubes.

Modern condensate chemistry control to prevent FAC of the carbon and alloy steel components relies on tight oxygen control and higher pH than traditional values. The chemical additives used to control this cause accelerated corrosion and dissolution of the copper tubing. Although much of the copper is supplied by the condenser, feedwater heater's higher temperatures accelerate this corrosion.

Today, austenitic and ferritic stainless steels dominate use new and replacement feedwater heater tubing for coal fired power plants. ASTM/ASME specification requirements are not sufficient to ensure the reliability needed for an efficient stainless steel heater. In addition to the standard eddy current (ECT) and pressure testing, the user should consider specifying more sensitive ECT testing, ultrasonic testing, maximum residual stress levels, cold working requirements, and limiting delta ferrite in the austenitic alloys for in-service testing. This paper discusses the failure mechanisms, lists the advantages and limitations of each alloy alternatives, and details the requirements needed for new FWH tubing.

Introduction

The initiation of global deregulation has driven a need for all power producers to become more efficient and reliable in order to be competitive. One positive way to do this is ensure that base loaded generation stay on line at full capacity, months at a time. This requires that materials perform at levels not required in the past. To ensure that the materials are of optimum condition for meeting this needs, the purchaser may need to specify additional processing and testing requirements. ASTM/ASME requirements are intended to cover a broad range of products. For example, ASTM A 268 and A 249 are commonly specified for stainless steel automotive exhaust pipe, an application requiring no pressure retention. The expectations for super-critical high pressure feedwater heater tubing are significantly more than for exhaust pipe. However, feedwater heater manufacturers may still order tubing to these specifications today to lower their price.

The stainless steel feedwater heater specifications, ASTM A688/ASME SA 688 and ASTM A803/SA 803[1], were developed over 30 years ago. At that time, no one envisioned the temperatures and pressures that today's super and ultra-critical units would operate. The increased pressures, temperatures, and expectations for reliability require special manufacturing techniques and testing for long tube life. The current ASTM/ASME specifications should be considered minimum requirements, and for long term reliability a number of additional special manufacturing processes and tests are essential.

Many of the comparisons for general tubing applications were covered by Janikowski and Roth[2] in 2006. That paper covered a number of basics in tube making and testing. This discussion extends special requirements to the critical application of feedwater heater tubing. Today, the feedwater heater supply is global, and tubes are being supplied from countries including India and China. Many of the new suppliers have just entered this market and don't have the experience, nor understanding on what it may take to produce a "high reliability" feedwater heater tube. One phrase common to most ASTM tubing specifications is "*It is the responsibility of the purchaser to specify all requirements that are necessary for material ordered under this specification.*" It's up to you!

Seamless or Welded?

The first choice that a user has in selecting the tube material is whether it should be made by a seamless or by a welded process. Traditionally, the seamless product has had a reputation of having higher quality. Seamless tubular manufacturing requires a process to force the hole into the billet. This is done by either a high temperature shearing operation, extrusion; or a internal tearing operation, rotary piercing. Both of these operations have the potential for creating small ID surface flaws, particularly in stainless steels. Examples of these flaws are shown in Figure 1. The higher chromium level of stainless steels require more care during piecing vs. carbon and alloy steel hollows, the potential for these flaws are far lower with extrusion than rotary piercing. This can be limited by proper process selection and an additional honing operation after the piercing.

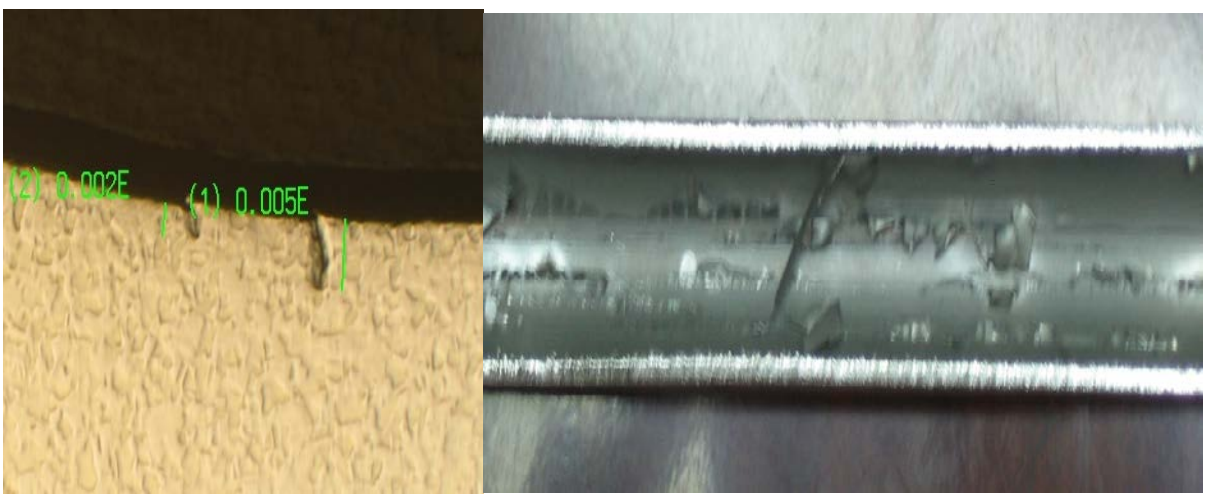

Figure 1 ID flaws in seamless stainless steel tubing. The hollows made by the extrusion process are on the left and the rotary piercing process on the right.

Processing and testing advancements on the welded and cold worked tubing developed over the last 65 years offer many technical and commercial advantages over the seamless product. Although seamless carbon and alloy steel feedwater heater tubing is still used, the vast majority of stainless steel feedwater heater tubing is in the welded, cold-worked, and annealed condition. Even though the seamless stainless tubing enjoys an ASME Code advantage of 15% higher stress level allowing a thinner wall, little, if any, is used in global feedwater heaters. The welded and cold-worked tube manufacturers have developed standard proprietary manufacturing processes and testing focused toward feedwater heater applications that most seamless producers have not followed. A summary of the advantages of each product is listed in Table 1.

Seamless Alloy Steel & Stainless SA 213	**Welded, and Cold Worked SA 688/803**
15 % ASME wall thickness advantage	Excellent eccentricity
Tradition in pressure applications	Low residual stresses available
Available with very thick walls	More stringent eddy current test available (such as SA 688-S1 or S2)
Smaller footprint	Highly ultrasonic testable
	Air-under-water test available
	Chemistry optimized for seal welding
	Lower total cost
	Optimized ASME specifications for feedwater heater application

Table 1. Advantages of seamless vs. welded and cold worked stainless tubing used in feedwater heater applications

At one time, a number of welded and cold-worked manufacturing plants were optimized for stainless steel feedwater heater tubing. This drove the developments of tubing with low residual stress, special eddy current tests, more stringent OD tolerances (over standard welded ASTM A 249 /A 268 material), ability to offer high speed ultrasonic testing, high tolerance u-bending, and special surface cleanliness requirements. However, the seamless stainless tube mills ignored this market and do not follow these practices.

Feedwater Heater Alloy Choices

Alloy Name	UNS Number	Major Elements - Percent				
		Chromium	Nickel	Molybdenum	Carbon	Nitrogen
Carbon and Alloy Steels						
A556 A2 & C2					0.18max, 0.30 max,	
A213 T11	K11597	1.00-1.50		0.44-0.65	0.18 max	
A213 T22	K21590	1.90-2.60		0.87-1.13	0.30 max	…
Austenitic Stainless Grades						
TP 304	S30400	18.0-20.0	8.0-11.0	…	0.08 max	
TP 304L	S30403	18.0-20.0	8.0-13.0	…	0.035 max	…
TP 304N	S30451	18.0-20.0	8.0-11.0		0.08 max	0.10-0.16
TP 316	S31600	16.0-18.0	10.0-14.0	2.0-3.0	0.08 max	
TP 316N	S31651	16.0-18.0	10.0-14.0	2.0-3.0	0.08 max	0.10-0.16
Alloy 800	N08800	19.0-23.0	30.0-35.0	…	0.10 max	…
AL6XN®	N08365	20.0-22.0	23.5-25.5	6.0-7.0	0.030 max	0.18-0.25
Ferritic Stainless Grades						
TP 439	S43035	17.0-19.0	0.50 max	…	0.07 max	0.04 max
SEA-CURE®	S44660	25.0-28.0	1.0-3.5	3.0-4.0	0.030 max	0.04 max

Table 2. Major Chemical Elements of Common Feedwater Heater Alloys

The list in Table 2 includes alloys that have been installed in feedwater heaters globally. The A556 carbon steel alloys are the least expensive of the group. However these alloy free steels are very susceptible to flow assisted corrosion (FAC) as they contain no chromium. Alloy T11 and T22 have more resistance.

Welding techniques matured such that almost every austenitic, duplex, and full ferritic grade that is made in strip form can be manufactured into a high quality tubular product by welding. Common grades, such as TP 304, TP 316, and their derivatives, are chemistry balanced to form a small amount of ferrite during solidification. This ferrite formation in these grades allows a wide range of manufacturing conditions during coil processing and welding because the shrinkage during solidification is compensated for by the different volumes of the two phases. This helps allow higher processing speeds and minimizes the risk of cracking or tearing of the welds. Grades that do not form the compensating second phase during solidification, such as the higher alloyed austenitics and the ferritics, including alloys TP 439 and SEA-CURE® require significantly more care in production. Welding and processing speeds, gasses and other parameters are modified from typical 300 series parameters to provide high integrity welds in these grades.

As can be seen in Table 3, the TP 304 derivatives (TP 304, TP 304L, and TP 304N) dominate the market followed by TP 439. The TP 304 derivatives have a large temperature operation range that allows them to be used in any of the heater locations from the very low pressure to the highest temperature in an ultra-critical plant. The "L" grade has low carbon which provides significant extra resistance to corrosion due to sensitization. However, if one specifies "L" grade tubing, the Code requires the use of lower mechanical properties mandating thicker walls and resulting in a larger heater. One method to get both higher mechanical properties and good sensitization resistance is to specify TP 304 with a carbon content not exceeding 0.035%. Increased nitrogen in 300 series alloys results in higher mechanical properties. ASME allows approximately 9% thinners walls for the higher strength TP304 N vs. from the non-"N" version. The thinner wall also provides higher thermal conductivity per unit foot. This compounds the advantage as less total surface area is then required.

TP 439 has become a very cost effective choice because of it high thermal conductivity, lower cost, and is immune to chloride stress corrosion cracking, and FAC when it is properly made. The higher thermal conductivity allows for a smaller footprint. It is the dominate alloy for all new nuclear power plants; used in both low and high pressure applications. It should only be considered for LP heaters in higher pressure coal-fired plants as it is susceptible to 475^{o} C embrittlement. This can occur with metal temperatures as low as 315^{o} C.

Alloy Group	Meters Sold
TP 304/304L/304N	7,329,393 meters
TP 439	3,987,108 meters
Carbon Steel	1,862,492 meters
"T" Grades	723,238 meters
TP 316/ 316N	267,578 meters
Copper Alloys	195, 075 meters

Table 3 HEI reported feedwater heater tube sales for years 2007 through 2010

TP 316 has been occasionally chosen for feedwater heaters when the user was concerned about the potential for pitting. However as TP 316 has only 16% Cr vs. TP 304's 18%, the overall corrosion resistance improvement is minimal. At today's $38/kg molybdenum cost the justification is difficult. TP316N has been weaned out of the U.S. steel producer's inventory grades because of its very low usage. Minimum purchase quantities of TP 316N today are the product of a heat. This requires purchase increments of 75,000 kgs, rarely justified by the minimal corrosion resistance advantages. The most cost effective option for solving a pitting problem on feedwater heaters is to invest the money into replacing leaking condenser tubing or solving other water chemistry problems.

AL-6XN® (N08367) and alloy 800 are high performance austenitic stainless steels originally developed for corrosion resistant and high temperature applications. The increased nickel content of these two alloys improves their resistance to chloride stress corrosion cracking and provides them with excellent high temperature strength. It also makes them an expensive choice, and results in a lower thermal conductivity. Fortunately, the high temperature strength allows thinner walls and this helps to alleviate some, but not all of the addition cost. N08367 and TP 439 are often specified when a utility is concerned about chloride SCC. As the TP 439 has the temperature restriction, the N08367 is sometimes selected for high pressure heaters. Alloy 800 was used for several heaters in the late 1980's and those operate without problems. N08367 has been used in approximately 30 feedwater heaters since 1985. Of those, tubes in two of the heaters have failed from chloride stress corrosion cracking.

ASME Specifications

Years ago seamless stainless steel feedwater tubes were specified to SA 213, while welded austenitic and ferritic feedwater heater tubes were specified to SA 249 and SA 268 respectively. These specifications were developed for general heat exchanger and boiler tubing. They proved insufficient for the demanding requirements of feedwater heaters. To address the need for additional requirements SA 688 was developed for austenitics, and later SA 803 for ferritics. These requirements are summarized in Table 4.

Requirements	SA 249/ SA 268	SA 688/ SA 803
Non-Destructive Evaluation	Non-destructive electric test or Hydrotest Optional – Air-under-water test	Non-destructive electric test and pressure test Optional –Testing to OD/ID Notches to S1 or S2
OD Tolerances	Standard per SA 1016	More restrictive @ +/- 0.10 mm
Surface Chloride Requirement	Not addressed	1 mg per square ft
Straight tube IGC testing	Not addressed	Required per A262-E each heat
U-bend area IGC testing	Not addressed	Required per A262 on Row 1
Heat treat after bending	Not addressed	Requirements clear defined when specified
Bend radius tolerance	Not addressed	+/- 1.65 mm maximum
Flattening of bend region	Not addressed	No more than 10% from straight tube
Bend "ski tip effect"	Not addressed	No more than 1.65 mm
Packaging	Not addressed	Specific to limit problems for bends

Table 4. Summary of requirement for general tubing specifications SA 249/SA 268 vs. feedwater heater tubing specifications SA 688/SA 803

The Welding Process

Three types of welding processes are commonly used for welding stainless steels feedwater heater tubing: tungsten inert gas (TIG or GTA), plasma welding, and laser welding. All three of these techniques are considered "fusion" methods since the weld is completely molten. Techniques, such as high frequency induction welding or resistance welding, rely upon a "mushy" weld zone. They are not dependable for welding stainless steels because the high chromium content absorbs oxygen that interferes with bonding of the two strip edges. TIG and plasma welding are the most common methods for manufacturing feedwater heater tubing, followed by laser welding for less critical applications. Laser welding's higher speeds produce a narrower weld with less segregation. Sophisticated tracking equipment is mandatory to limit off-seam welding. However, the high speed also restricts opportunity for post-weld cold working. This creates the controversy whether the laser welded product with less segregation and less cold work will perform in critical applications as well as the TIG /plasma welded tubing with more cold work.

Virtually all welded pressure tube grades with ASME coverage are welded without the addition of filler metal. Filler metals are usually used when additional cold working and heat treating may not be available for the final product. This is restricted to large diameter pipe. On power heat transfer tubing today's most common practice includes cold working the weld and heat-treating the entire pressure tube restoring the mechanical and corrosion resistant properties of the original parent material. Filler metal, with the additional needs for quality control, creates more risk than rewards on small diameter product.

Weld Bead Cold Working

The purpose of cold working is to assist with homogenization of the segregated as-cast weld structure and to ensure that the corrosion resistance and mechanical properties are consistent around the tube perimeter. Proper weld bead working is analogous to the tube reducing or drawing of a seamless hollow. Cold working can be grouped into two categories: in-line bead working and cold drawing. Typically the in-line methods are used on feedwater heater tubing with wall thickness up to 2.1 mm. Cold drawing is commonly performed on wall thickness exceeding 1.65 mm, but it can be specified for thinner walls when desired.

OD Sizing and/or Cross-Polishing

OD sizing is the term used for passing the tube through the last stages of rolls on the mill to set the final size of the tubing. This sizing operation reduces the OD of the tubing approximately 0.08 mm to 0.16 mm. All roll form welding mills contain this process stage. When no ID mandrel is used during cold-working, the actual weld cold working is minimal, often less than 1%. This minimal cold working has little impact on the weld refinement that is needed for improved properties and corrosion resistance. To lower cost some tube suppliers use this minimal sizing operation as their sole cold working mechanism. For critical applications, such as feedwater heaters minimal roll sizing should not be considered an acceptable substitute for full cold-working using an ID mandrel. When OD sizing is used the sole method, reduction of cross sectional area should be 20% or more from the starting welded size.

Do not consider using tubing where polishing is used as a substitute for cold working. If seam alignment is not perfect the polishing operation can selectively remove material from one side of the weld. This results in localized regions where the wall may fall below the minimum thickness of the specification (Figure 2). These defects are impossible to detect using either eddy current testing or shear wave ultrasonic testing. A cold working method utilizing ID tooling will correct this imperfection, provided the polishing is not performed.

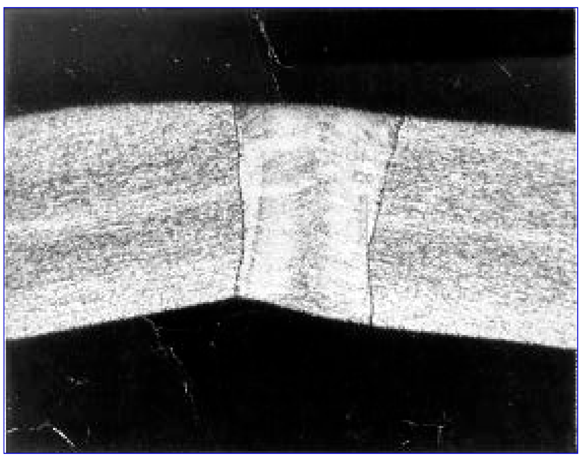

Figure 2 – Photo micrograph of a tube weld where the strip edges were not properly aligned and the OD surface was smoothed by cross polishing. The wall thickness at the left edge of the weld is below the minimum wall requirements

In-line Bead Cold Reduction

The methods of bead working, including bead forging bead rolling, are effective for providing the needed cold work for full homogenation after the heat treating operation. It is critical that these operation are performed using a stiff full support mandrel on the tube ID and roll support on the bottom. Details of these methods were included in the paper by Janikowski and Roth.

Cold Drawing

Cold drawing is a full cross-sectional reduction method. Originally developed for the seamless process, it provides the greatest amount of effective cold work of any feedwater heater tube methods. As seen in Figure 3, the tube is mechanically pulled through a die reducing the OD size. The ID is supported with either a fixed plug or a full length bar.

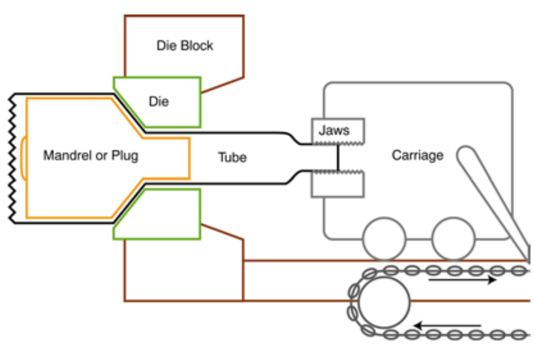

Figure 3 – Schematic of the cold drawing method for cold working of the tube

Advantages

For feedwater heater applications, the following advantages are possible.

- *Tighter Tolerances* - The cold drawn process is capable of providing approximately half of the traditional roll formed OD tolerance. These tolerances can be significantly tighter than seamless cold drawn tolerances since the welded hollow is highly concentric. When this process is performed, the weld can be very difficult to distinguish.
- *Smoother Surface Finishes* - The cold drawing operation provides an ironing effect on both the OD and ID surfaces. This smoothes the surface, thus reducing the roughness as commonly measured in Ra. Typical surface finish of a cold drawn material is in the 0.5 to 0.7 micron Ra or better.
- *Wider OD-to-Wall Ratio Range* - Very heavy or very light wall welded tube can be made by starting with a larger diameter tube and drawing to the final size. This allows the use of thicker or thinner walls than possible with roll forming and welding.
- *Improved Homogeneity of the Weld* - Multiple cold draw passes can provide substantially more cold work than bead working. This can result in a wrought equiaxed structure with no evidence of a prior weld. Other ASTM specifications, such as ASTM A 312, A 249, and A 270, have adopted an HCW class that can be produced using two cold drawing operations or other heavy cold work methods.
- *More Stringent Testing Requirements* – As the process irons the walls, provides a very concentric product and provides better weld homogeneity, more stringent non-destructive testing standards can used on cold-drawn welded product than for tubing made by any other process.

Cold-drawn tubing is higher priced due to the extra processes such as pointing, lubrication, drawing, degreasing, and annealing. However, the advantages often outweigh the small additional cost. The more stringent NDE testing on cold drawn tubing allows the identification of smaller imperfections that would not be recognized on tubing that is roll formed to size. Signals from smaller imperfections on roll formed product may be indistinguishable from the background noise of the tube. As the tube is cold drawn, the signal to noise ratio improves. Any imperfection can be a stress concentrator and elimination of the larger ones can provide a tube with less likelihood of failure

Carburization from incomplete lubricant removal is always a possibility if extra care is not used during the degreasing operation. The result is sensitization and decreased corrosion resistance. Lubricant removal becomes very difficult when the tubing is small diameter and very long, such as in feedwater heater tubing. An intergranular corrosion test in accordance with A262 Practice E should be carefully followed and specified when this process is used.

Heat Treatment Choices

For optimum corrosion resistance, all stainless steel alloys should be annealed after the welding and cold working operations. This homogenizes the weld improving both the mechanical properties and corrosion resistance. Tubes may be annealed one at a time in-line or in multiples using an off-line operation. The optimum method is a function of the alloy, application, and cost effectiveness. Both are considered to be continuous operations.

In-Line Heat Treating

In-line heat treating is the most common method of annealing general purpose stainless steel tubing. In this method, the tube is heated by electro-magnetic induction and then rapidly cooled with either water, convective gas such as hydrogen, or an inert gas such as argon. The time at temperature in this method is very short, typically measured in seconds. Ferritics (TP 439 and S 44660), don't require long homogenization hold times, so the induction anneal works well. In contrast, austenitic alloys solidify with multiple phases and/or high segregation. The short time of an in-line anneal is not sufficient for full homogenation of these grades as the nickel slows diffusion kinetics. Longer heat-treating times are needed to homogenized the austenitic weld when needed for critical applications.

Off-Line Furnace Annealing

The off-line separate "furnace anneal" provides the longer time at temperature needed for the austenitics. While the entire tube may not be in the hot zone at one time, the metal time at temperature in this process is typically in the five to ten minute range. Since these continuous furnaces are designed with rollers or belts and has an open inlet and outlet, tube lengths are not restricted. Multiple tubes are annealed in a single layer in this type of furnace.

During weld solidification, 300 series stainless steels form a duplex structure of ferrite and austenite. This can be detrimental in a feedwater heater application as the duplex structure lowers creep rupture strength. The ferrite can be redissolved using a combination of cold work and furnace annealing. Additionally the ferrite in the weld is ferromagnetic. This can create substantial background noise during subsequent ID eddy current testing. The background noise may be large enough to hide tube problems, such as pits and cracks. This noise can be eliminated with saturation during testing. However, this is only easily accomplished when testing with an external coil at the tube mill. The small hole in feedwater heaters limits the size of saturation magnets that can be used from the ID. A good test to determine residual ferrite in 300 series welds is the A 249 Supplement S7 which will be discussed later.

Austenitics containing higher nickel and molybdenum, such as N08367 form high segregation and other detrimental phases. These can also be eliminated using a combination of cold work and high temperature furnace annealing. Confirmation of homogenation must be done using metallography or an "ASTM G" type corrosion test.

Heat Treat Atmospheres

As the feedwater tubing has clean condensate on both tube surfaces in service corrosion resistance is not a critical requirement in this application. Two atmospheres are common for heat treatment - bright annealing and open air. These atmospheres can be used with either in-line annealing or furnace annealing.

Bright Annealing

Bright annealing employs a reducing gas atmosphere such as dry hydrogen that minimizes surface oxide formation. Because the thermodynamics of the hydrogen/oxygen reaction are not active at lower temperatures, bright annealing is only effective when the annealing temperature is above 1010° C. Alloys that require a lower annealing temperature, such as TP 439, cannot be effectively bright annealed. To keep the tube surface bright, the atmosphere needs to be maintained during both heating and cooling to temperatures below 375° C. Water quenching is not an option as the water will cause scale formation. Therefore, bright annealing quench rates may not be sufficient for some alloys. Since the surface of a bright-annealed tube does not develop a scale the final tube surface finishes may be smoother.

Open Air Heat Treatment

Open air heat treatment allows forced cooling or water quenching. This ensures that ferritic, and heavier wall 6% Mo alloy austenitic alloys that have potential for forming detrimental second phases will not be degraded. However, the exposure to the air and water results in a scale on the tube surface. This scale must be chemically removed in order to restore optimum corrosion resistance.

Chemical Pickle / Passivation

The oxide scale that forms during heat treatment is usually porous and cracked, and therefore not protective. Beneath this scale is a layer of chromium depletion that also degrades corrosion resistance. In applications requiring high corrosion resistance it is important that both the oxide and the chromium-depleted layer be removed (ref. 3, 4). The only sure way to completely remove all depleted material is to use a chemical process. This is commonly accomplished using nitric acid or citric acid solutions. Some guidelines for these solutions and tests for results can be found in ASTM A 380 and ASTM A 967. In feedwater heater applications, the water/steam on both surfaces of the tube is not considered to be aggressive. The oxide scale that forms in the bend region from the stress- relief heat treatment is rarely removed. The authors know of no known tube failures related to allowing the scale to remain in this application.

The chemical scale removal method has some additional benefits for tubing. It can act as a 100% corrosion test of the tubing, particularly when performed before the final eddy current test. The acid will aggressively attack any sensitized areas or any inhomogeneities such as manganese sulfide inclusions exposed during prior processing. When an attacked region enters the eddy current coil, the alarm sounds and the tube is rejected.

As a final treatment the tubing should be passivation. This process chemically cleans the surface of the tubing assuring that there is no residual free iron present and it also assists in developing the most robust chromium oxide protective passive film possible. The most common chemical passivation bath contains approximately 20% nitric acid and 3% hydrofluoric acid.

Non-Destructive Testing

Electric Tests

Two types of non-destructive electric tests (NDE) should be considered for feedwater heater tubing; eddy current testing (ET) and ultrasonic testing (UT). Neither technique is totally effective for finding all of the defects that may result on premature failure. The strengths and weaknesses of each are described below.

Eddy Current Testing (ET)

Virtually all feedwater heater tubing is eddy current tested, as it is the lowest cost and a fairly effective method for finding short transverse defects. During production, the tubing is tested from the outside. The method utilizes a full encircling, differential coil that is most sensitive to sharp abrupt defects (Figure 4). The eddy currents are induced by alternating magnetic fields from a driver coil, represented by the yellow coil. In this figure, both the blue and green coils are used for detection of signals produced by imperfections passing through them. The electronics are balanced so that if the signal detected is identical in both the blue and green coils, no net signal is generated to the scope or alarm. The differential coil is not very sensitive to long gradual imperfections that bridge both sections of the detector coils. The amplitude of the signal from the imperfection is related to its volume.

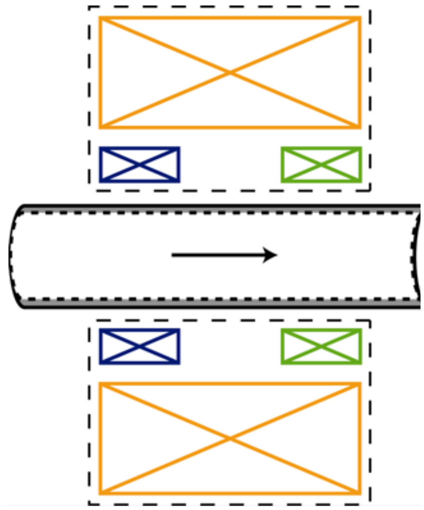

Figure 4 – Schematic drawing of a full encircling differential eddy current testing coil

Advantages

OD eddy current testing can be performed at high speeds at a relatively low cost. Testing speed can exceed 100 meters per minute without a loss of sensitivity. Depending on the contract acceptance criteria, it can find relatively small sharp abrupt imperfections. The defects do not need to be through-wall nor exposed to the OD surface.

Disadvantages

This method does have some limitations. As the signal is proportional to the volume of the imperfection, tight crack-like imperfections may provide little or no signal. Large pit-like defects will produce large signals. Imperfections bridging the differential coil will generate very small signal which may be ignored and not rejected. Additionally, the resistivity of the metal blocks some of the signal from an imperfection that is near the tube ID. This results in a smaller signal than from the same defect near the OD surface. The reduction is called attenuation. The attenuation works in both directions. That is one reason why testing performed from the ID may show significantly different results than that performed from the OD.

Stainless steel tubing is commonly tested using an acceptance criteria using drilled through wall hole no larger 0.031” in diameter. The definition of this is in ASTM A 1016. This criteria allows relatively large imperfections for a critical application such as feedwater heater tubing. It also allows for high eddy current noise levels that will interfere with subsequent ID testing after the tubes are installed. Longitudinal and transverse OD and ID notches as acceptance criteria are commonly specified. These are defined in ASTM A 688 and A 803 Supplements 1 and 2. The S2 supplement provides the greatest sensitivity for finding and rejecting small imperfections. The S2 notch requirement is normally only available on cold drawn tubing where the surface anomalies have been ironed smooth.

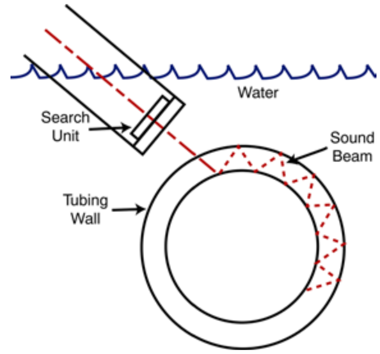

Figure 5– Schematic of an ultrasonic signal propagating through the tube wall

Ultrasonic Testing (UT)

The UT testing method relies on a focused sound wave sent into the wall of the tube and then detection of the echo that is reflected back from an imperfection (Figure 5). The beam is angled to create a shear wave that reflects off of both OD and ID surfaces and provides detection capabilities for quite some distance. Ultrasonic testing relies on the reflection of the sound from a surface. This surface could be an interface of a solid to gaseous/liquid area (pore or crack), or a phase change. The angle of the surface may reflect the sound wave away from the transducer. That requires that a minimum of two transducers be utilized, one from each direction.

In some cases, a four channel (two longitudinal, two transverse) test may be specified. We mentioned earlier that the eddy current test is sensitive to sharp abrupt defects, but not to longitudinal ones. This suggests that the most cost effective multi-directional testing is a combination of ECT plus circumferential UT scanning for longitudinal defects.

Advantages

Assuming the circumferential UT testing is specified, UT examination of feedwater heater tubing is very sensitive to crack-like and longitudinal imperfections. The defect does not require significant volume for detectability like ECT does. It is equally sensitive at detecting flaws near either the OD or the ID surface. The flaws do not need to be through wall.

Disadvantages

The UT test is a slower test than the eddy current test so it will be higher cost. However this additional cost is insignificant when compared to the total installed cost of the heater. The cost of one tube failure from a longitudinal flaw not detected by ECT is far greater than the testing cost. When only circumferential testing is specified, tight, low volume circumferential defect may be missed. Occasionally, oblique oriented flaws will not reflect the signal back to either longitudinal or circumferential transducers. These flaws are more common with seamless tubing than welded or welded and drawn tubing.

The common artificial defect used to calibrate this test is OD and ID longitudinal notches 12.5% as deep as the specified wall thickness. These notches are defined in ASTM A 1016.

Pressure Testing

Three kinds of pressure testing are used on heat exchanger tubing: air-under-water testing, pressure differential/pressure decay testing, and hydrostatic testing. On seamless tubing, only the hydrotest is commonly performed.

Air-Under-Water Testing

The air-under-water testing method (Figure 6) is performed by placing air-pressurized tubes in a well lit tank of water while an operator walks the length of the tank looking for bubbles. Typical pressures are 1000 to 1700 kPa. Because of its low cost and high sensitivity, this is the most common pressure test used for welded heat exchanger tubing. When pressurized at 1000 kPa, tube leaks as small as 0.05 mm can be regularly found (ref. 5).

Figure 6 – Air-Under-Water Testing

The air-under-water test is the most sensitive of the commercially available pressure tests. Because large quantities can be tested at one time, it is a very inexpensive test, costing only a few dollars per hundred meters. One disadvantage is that the detection for very small leaks may be operator dependent as it is a visual method. As with all pressure methods in order to fins a defect the flaw needs to be through-wall.

Pressure Differential /Pressure Decay Testing

The pressure differential testing method became a production reality with the development of high sensitivity electronic pressure sensors. Currently, it is commonly used for testing welded titanium tubing. The pressure differential test is performed by pressurizing two tubes to the same pressure, closing off the pressure source, and monitoring the differential pressure between the two tubes. If the differential exceeds a predetermined limit, an alarm sounds. A description of the methods have now been developed in ASTM A 1047. It has now been adopted into several tubular product specifications.

As the pressure differential method is highly automated, it is a low cost method with repeatable results. It is not subject to operator fatigue. The parameters must be selected carefully to ensure good testing. As of this date, an acceptance criteria has not yet been agreed in ASTM. The smallest calibration hole allowed by A 1047 is 0.08 mm.

However, larger holes may be required for reasonable cost. As the time of the test is a function of pressure drop, tubes with larger volume require longer times for the same acceptance criteria. The environment also needs to be carefully controlled at the test is very sensitive to changes in temperature. Again, the defect needs to be through wall to be detected.

Hydrostatic Testing

Traditionally considered the workhorse of pressure testing, the hydrostatic testing method is gradually being phased out when other methods are available. For many years, hydrostatic testing had been the required NDE for a seamless product. ASTM and ASME have now adopted ET as an alternative test for most seamless products. Hydrostatic testing is significantly less sensitive than air-under-water testing. At normal production rates, only fairly gross defects are found. In the ASTM NDE task group work (ref. 5), hole sizes of 0.1 mm, are almost undetectable.

In general, on welded product, hydrostatic testing is performed only when required by the specification. The hydrostatic is slower and more expensive than the other methods. It is subject to operator fatigue and also requires a through wall defect.

Residual Stress Testing

Many stainless steels, particularly the 300 series alloys are susceptible to chloride stress corrosion cracking. This may occur when the tubing is exposed to three factors; trace amounts of chlorides, high stresses, and a temperature above 60^o C. A variety of stress sources are possible: residual stresses from the tube manufacturing, thermally induced stresses, pressure induced stresses, and other mechanical stresses from operations. The sum of all stress sources is what drives the cracking. However, residual stress in the tube can be the primary source if they are not controlled. Rotary straightened tubing may have residual hoop stresses over half of the yield strength of the tube.

All stainless steels are not equally susceptible to chloride stress corrosion cracking (SCC). Copson and Chang (ref. 6) determined that the alloys most susceptible to racking in boiling magnesium chloride were those containing 8% nickel, not unlike TP 304. Both lower and higher nickel content resulted in a longer time to failure. Crucible Materials Research performed a series of test duplicating heavily faulted feedwater applications (ref. 7). These tests were performed in high temperature autoclaves that ensured that the water was in a liquid state at the high temperatures of the test. The pH was controlled between 9.0and 9.5 and the solution was oxygenated. The chloride was added in the form of ASTM artificial sea salt. The samples were created by using strip samples and bending them in the shape of a "C" and holding the shape using an insulated bolt. This develops stresses in the outer fibers at the yield strength of the material. The samples exposed to three levels of chloride at three different temperatures. The results of that test are shown in Table 5.

This data shows that the susceptibility is a function of nickel content, chloride content, and temperature. The results parallel the work of Copson & Chang; the potential for failure due to chloride SCC is a function of nickel content. The highest potential is when the nickel content is approximately 8%. TP 439, which has a nickel content of less than 0.5% did not crack even in the most extreme conditions. UNS S44660, which has a nickel content of approximately 2%, cracked under the most extreme conditions. Alloy 2205, a duplex stainless steel commonly used in HRSG's, was slightly more susceptible, cracking at the highest temperature but lowest chloride content. TP 304, an alloy containing 8% nickel, cracked at the lowest test temperature and highest chloride level (it also cracked at the lowest chloride level at the intermediate temperature). The nitrogen containing TP304LN failed in a lower chloride content than TP 304L. This is attributed to the combination higher stresses from the higher yield strength of TP304LN and the design of the test, causing stress levels at the yield strength. This implies that when TP 304LN is used at the higher Code allowable stresses over TP304L, it is even more important to limit controllable stresses such as residual hoop stress. Alloys containing nickel content above 8% have decreasing sensitivity as the nickel content increases.

		Test Temperature Degrees F						
		250			350		450	
		Chloride Content (ppm)						
Grade	**Ni %**	**100**	**1,000**	**10000***	**100**	**1,000**	**100**	**1,000**
TP 439	0.4	nt	nt	nt	nt	OK	OK	OK
S44660	2	nt	nt	nt	nt	OK	OK	Cracked
2205	5	nt	nt	nt	nt	OK	Cracked	nt
TP 304L	8	OK	OK	Cracked	Cracked	Cracked	Cracked	Cracked
TP 304LN	8	OK	Cracked	Cracked	Cracked	Cracked	Cracked	nt
TP 316L	11	OK	OK	OK	Cracked	Cracked	Cracked	nt
S31254	18	nt	nt	nt	nt	OK	Cracked	Cracked
N08367	25	nt	nt	nt	nt	OK	Cracked	Cracked

* ***Testing Terminated in 15 days***

Table 5. Stress corrosion cracking testing of various alloys using "C" ring samples held with insulated bolts. The testing was performed for 28 days unless otherwise indicated using artificial sea salt as the chloride source. The testing was performed in high pressure autoclaves to ensure that the test solution was always liquid. The term "nt" means that samples were not tested in those conditions.

This work indicates that tubes in those grades containing 5% to 15% Ni should be manufactured to restrict residual stress. This is done using proprietary annealing and straightening operations. Residual stress should be measured on a regular basis during production; typically every 200 tubes. The most common method for hoop (circumferentual) stress is the Thirkill split ring method shown in Figure 7 (ref. 8)

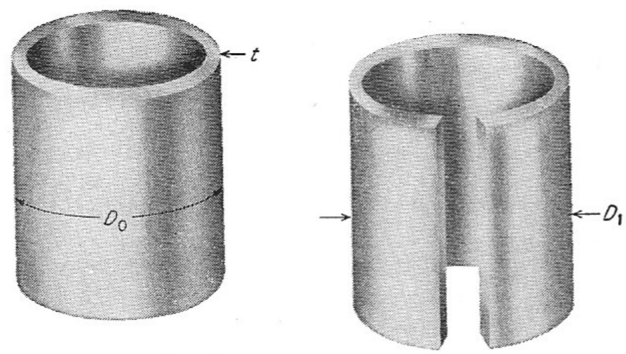

Figure 7. Thirkill split ring sample for measurement of residual hoop stress

Although when the tube is properly processed the longitudinal stress is normally lower than the hoop stress, the specifier may want to require occasional measurements for longitudinal stress. This can be accomplished using the tongue deflection test shown in Figure 8. When the tube is properly processed, the longitudinal residual stress is 14 MPa or less.

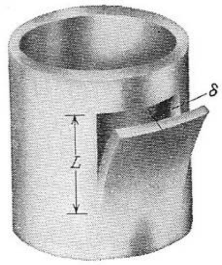

Figure 8. Tongue deflection method for determination of longitudinal residual stress

Measuring residual stresses in a compound curved region is much more challenging. Neither the split ring nor the tongue deflection methods are effective in the u-bend region. Even though a separate stress relief anneal is commonly performed on the bend area after bending, in some cases a user may want know if the heat treatment was effective. A strain gage technique, described in ASTM E 837 utilizes an attached strain gage that monitors the deflection while a hole is drilled through its center. An example is shown in Figure 9. This method does not have the precision that the previously two methods described. Typically, the residual stress range for this method is reported to be +/- 35 MPa. This test is also relatively expensive, in the $1000 per sample range.

Figure 9. A u-bent tube containing a the drilled-hole strain gage method for determination of residual stresses

Typically on grades that are susceptible to cracking the EPRI's feedwater Guidelines (ref. 9) recommend a maximum residual stress of 35 MPa. The ability to meet this requirement is a function of OD to wall ratio. It is more difficult to prevent higher residual stresses on thin wall tubes. Fortunately, the lower stresses available on heavier walls are needed on products that are used in higher pressure and temperature applications. Today, 21 MPa maximum residual stress is can be specified.

Some specifiers require the ASTM G36 boiling magnesium chloride test for determining residual stress. Although this is a good test for identifying if enough stress is present in the manufactured for cracking, it is not sufficient for measuring the low levels needed to reduce the potential for cracking in service. Cracking in service is the result of stress from multiple sources, including residual, pressure induced, thermally induced, and others. It is important to mandate a maximum stress level in your specification to allow a cushion for the service induced sources.

Feedwater Heater Design Stress Considerations

Over the years, ASME has allowed options to provide alternative designs in pressure vessels to lower cost provided they do not reduce safety. One of these is Note G5. This note allows the use of 35% higher stress levels in vessel design. The caveat is that the higher stress levels allow some minor permanent deformation in the structure. A number of feedwater heater manufactures have been using Note G5 in design to significantly reduce cost with devastating results. Figures 10 and 11 show cracks found in the desuperheating zone of two different high pressure feedwater heaters. There were multiple cracks in both heaters and all of the cracks propagated in a circumferential direction. They had identical signatures when ECT tested. Both utilities assumed that the indications were due to SCC. However, they had significantly different root cause.

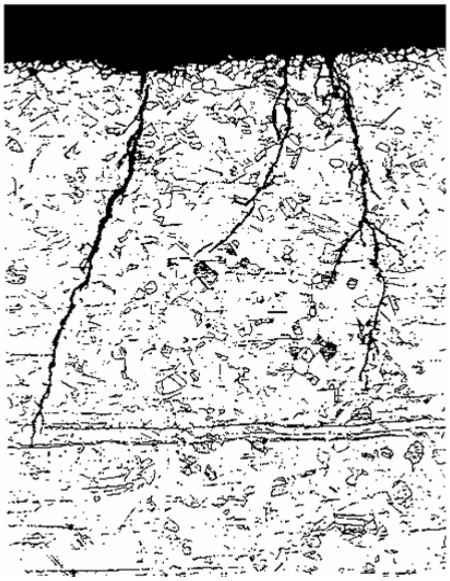

Figure 10 Chloride SCC of TP 304N **Figure 11 Thermal Fatigue Cracking of TP 304N**

The stress corrosion cracks propagate without internal corrosion and have multiple branching. However, the cracks in Figure 11 are wide and have no branching. They were also only on the side of the tubing facing the steam inlet. The tubing in Figure 10 had high residual stress and were in a heater built without Note G5. The tubing in Figure 11 was in a heater built to Note G5 and had no evidence of the presence of chloride.

What seems to be occurring is that G5 is allowing deformation of the bundle that interferes with the expansion and contraction of the tubing during thermal transients. This causes the tube to bend during heating and straightens during cooling developing the fatigue mechanism. The binding is confirmed as the tube in Figure 11was very difficult to remove for the evaluation. Now that G5 has been used for about 20 years, we are now seeing multiple bundles with tube failures due to this cause. DO NOT ALLOW NOTE G5 TO BE USED FOR YOUR HEATER!

In-Process Mill Quality Control Practices

Reputable tube mills use a combination of visual inspection, in-process eddy current testing, and manipulation (destructive) samples to continuously monitor the quality of the weld.

Manipulation (Destructive) Testing

Manipulation tests are designed to specifically test the ductility of the weld in various directions. Although these tests were described in the earlier paper, this testing is critical for feedwater heater tubing. The weld is bent in a manner to strain a specific surface (OD or ID) in a specific direction (in the direction of the weld or transverse to the weld). Detailed explanations for how each test is to be performed is included in ASTM A 1016. Manipulation tests include:

- *Flatten Test* - This test is designed to test the transverse weld ductility on the exterior surface (Figure 12).
- *Reverse Flatten Test* - This test was developed to test transverse weld ductility on the ID surface (Figure 13).
- *Reverse Bend Test* - For austenitic stainless steels that are considered to have a greater ductility than others, this test is a higher strain version of the reverse flatten test (Figure 14).

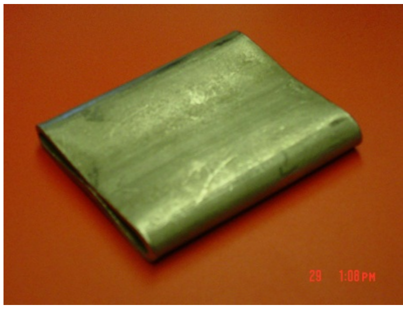
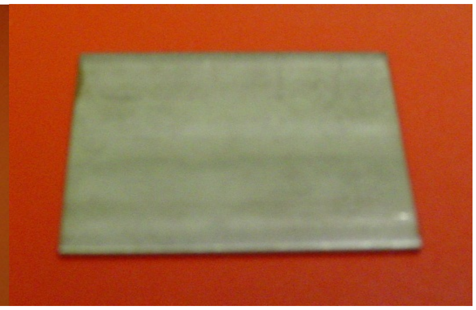


Figure 12. Flatten test **Figure 13. Reverse Flatten test** **Figure 14. Reverse Bend Test**

- *Flange* - This test, which starts out as a flaring operation, is the test to check for the tube's ability to expand (Figure 15).
- *Tensile Test* - Although not generally considered a "manipulation test" (since the tensile sample on welded tubing requires the weld to be tested), it is a test of longitudinal weld ductility.

Figure 15. Flange Test

The minimum sampling rates for the various manipulation tests are specified in the appropriate ASTM product specification. These rates are not sufficient to ensure reliability for feedwater tubing. These are listed as a test per maximum of length or maximum number of pieces. High quality welded tube producers will perform manipulation tests at a much higher frequency during the welding process, in addition to the ASTM required certification tests on the final product. Before you purchase your tubing, evaluate your supplier and testing.

Corrosion Testing

Stainless steel is chosen for resistance to corrosion. Unfortunately, few ASTM/ASME specifications require a corrosion test. Several types of corrosion test options are possible.

Weld Decay (A 249-S7) Tests

The weld decay test was developed as a quick test for monitoring the presence of residual ferrite in a weld. The boiling HCl readily attacks the ferrite, and if present in the weld, will cause thinning of the weld at a much faster rate than the base metal. For a properly annealed weld, the ratio should be 1.0 or less (Figure 16). This test is only effective on austenitic grades that form ferrite during solidification, such as TP 304 and TP 316 derivatives. However, for feedwater heater applications, the ferrite has an additional problem. It is ferro-magnetic! This produces irregular spurious signals during ID eddy current testing. The signals interfere with defect interpretation. Elimination of the ferrite is critical for noise elimination.

Figure 16 – Weld Decay Test

Intergranular Tests

Intergranular corrosion tests are tests specified in ASTM A 262, A 763, or A923 that are designed to detect sensitization from slow cooling rates, insufficient annealing, or carbon and nitrogen contamination. With feedwater heater tubing, these tests take on a different importance than for traditional stainless steel tubing. When feedwater heater tubing is cold drawn specialized techniques are require to ensure removal of the ID lubricant so that the tubing is not sensitized during the subsequent anneal. This is not easily accomplished when a tube 50 to 90 ft long and the inside diameter can be less than ½".

"G" Type Tests

As corrosion resistance of feedwater heater tubing is not as critical as for condenser tubing, the ASTM "G" type tests may not be needed on this product. They may be considered in unusual cases.

Summary

The feedwater heater owner is the expert on how the unit will be operated and should specify the optimum processes and tests on his feedwater tubes to ensure that the heater will perform as expected. If no specials are specified, the tube producer may assume that the lowest price product is desired. Ordering to a basic ASTM/ASME specification does not guarantee a good tube, whether seamless or welded. To meet the demanding requirements for this application, the following supplemental purchasing requirements should be considered:

- *ASME Feedwater heater specifications*- Require SA 688/ SA 803 specification as a minimum. Do not allow tubing to be certified solely to SA 213, SA 249 or SA 268.
- *NDE* – One NDE test is not sufficient to find defects in all orientations. For sub-critical power plants, consider the A 688/A 803-S1 eddy current as a minimum. For super or ultra-critical applications, consider both an ultrasonic test and the S2 eddy current test for the high pressure units.
- *Pressure Testing* – Consider specifying an air-under-water test. It has the ability to find very small leaks that neither the eddy current nor UT will detect. The price is minimal. The hydrostatic test that is required by ASME is only sensitive to relatively gross defects.
- *Cold Working* – Require that the weld be cold worked using OD and ID tooling. Simple sizing with OD tooling only does not provide a wrought weld structure that was the original basis for the ASME design allowable stresses. For super and ultra critical high pressure tubing you may what to specify that the tubing be cold drawn. Do not allow cross polishing. The localized wall thinning it causes is almost impossible to detect.
- *Specify Maximum Residual Stress* – Austenitic 300 series tubing is susceptible to chloride SCC. When using these grades in feedwater heater applications residual hoop stress should be restricted to 21 MPai maximum. You may also want to consider optional testing in the bend area. Do not allow the G36 test as a substitute.
- *Specify Weld Decay Testing* – Although A 688 and A 803 require minimal intergranular corrosion tests, you may want to specify additional testing. The A 249 weld decay test should be considered on all welded 300 series tubing to keep ID ECT noise to a minimum.
- *No Note G5*- Do not allow Note G5 to be used in the construction of your heater. Many heaters are now failing prematurely due to thermal fatigue.
- *Require Test Plan Approval* – Prior to product, require a test plan that you can review. Verifying the sampling rates for in process destructive tests and other inspections are critical.
- *Know the supplier* - There are no ASTM police! Interpretations of what may be required run the whole gamut. Your expectations may be far higher than what the supplier believes is sufficient. You may have to live with those materials for 30 years.

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A 249/A 249M Specification for Welded Austenitic Steel Boiler, Superheater, Heat-Exchanger, and Condenser Tubes
A 262 Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels
A 268/A 268M Specification for Seamless and Welded Ferritic and Martensitic Stainless Steel Tubing for General Service
A 270 Specification for Seamless and Welded Austenitic Stainless Steel Sanitary Tubing
A 312 Specification for Seamless, Welded, and Heavily Cold Worked Austenitic Stainless Steel Pipes
A 370 Test Methods and Definitions for Mechanical Testing of Steel Products
A 380 Specification for Cleaning, Descaling, and Passivation of Stainless Steel Parts, Equipment, and Systems
A 668/A 668M Specification for Welded Austenitic Stainless Steel Feedwater Heater Tubes
A 763 Practices for Detecting Susceptibility to Intergranular Attack in Ferritic Stainless Steels

A 789/A 789M Specification for Seamless and Welded Ferritic/Austenitic Stainless Steel Tubing for General Service
A 803/A 803M Specification for Welded Ferritic Stainless Steel Feedwater Heater Tubes
A 923 Practices for Detecting Susceptibility to Intergranular Attack in Duplex Stainless Steels
A 967 Specification for Chemical Passivation of Stainless Steel Parts
A 1016/A 1016M Specification for General Requirements for Ferritic Alloy Steel, Austenitic Alloy Steel, and Stainless Steel Tubes
E 837 Standard Test Method for Determining Residual Stresses by the Hole Drilling Strain Gage Method
G 48 Standard Test Method for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by the Use of Ferric Chloride Solution

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