

**Stainless Steel Feedwater and Condenser Tubing –
Expectations, Results, and Choices**

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Daniel S. Janikowski
Energy Sales Manager
Plymouth Tube
Phone 262-642-8365
djanikowski@plymouth.com

Edward R. Blessman, P.E.
Condenser Sales Manager
Plymouth Tube
Phone 262-206-4516
eblessman@plymouth.com

Abstract

A tubing manufacturer has many alternatives for manufacturing and testing stainless steel tubing for feedwater heater and condenser applications. ASTM/ASME specifications are basic requirements intended to cover all applications. These minimum requirements may not be sufficient for providing the appropriate quality tube for demanding requirements, such as continuous duty for 18 to 24 months common with feedwater heaters and condensers today. This paper summarizes the basic ASTM/ASME requirements with many of the additional property and testing options available to ensure reliable service for today's power plant environment. It identifies the advantages and disadvantages of each and provides suggestions on what could be specified to ensure the best value tubing for your application.

Introduction

The initiation of deregulation has driven a need for all power producers to become more efficient to be competitive. One way to do this is to ensure that base load generation stay on line at full capacity, months at a time. This requires that materials perform at levels not required in the past. The purchaser may need to specify additional processing and testing requirements for additional reliability. ASTM and 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. The expectations for super-critical high pressure feedwater heater tubing are quite different than exhaust pipe. 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. An example of these flaws are shown in Figure 1. The higher chromium level of stainless steels require more care during piercing compared to carbon and alloy steel hollows. And the potential for these flaws is far lower with extrusion than rotary piercing. This can be limited by proper process selection and an additional honing operation after the piercing.

Since welded and cold worked tubing manufacturing was developed 65 years ago, there have been many processing and testing advancements. These have created technical and commercial advantages for the welded and drawn tubing over seamless products. In North America, the vast majority of stainless steel feedwater heater and condenser tubing is used in the welded, cold-worked, and annealed condition. Even though the seamless tubing enjoys an ASME Code advantage allowing a 15% thinner wall, little, if any, is used in 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.



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

At one time, three welded manufacturing plants in the United States 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. The predominately seamless tube mills ignored this market and do not follow these practices.

Seamless 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)
	Highly ultrasonic testable
	Air-under-water test available
	Chemistry optimized for seal welding
	Lower total cost
	Specialized ASME specifications for specific application

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

Common Stainless Feedwater Heater Alloys

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. The ferrite formation in these grades allows a wide processing range during coil processing and welding, because the shrinkage during solidification

is compensated for by the different volume of the two phases. This reduces the risk of weld hot cracking and also helps to allow higher processing speeds. Grades that do not form the compensating second phase during solidification, such as the higher alloyed austenitics, and the ferritics, such as TP 439 and SEA-CURE® require significantly more care. Welding gasses, process speeds, and other parameters are modified from typical 300 series parameters to provide a high integrity weld.

Alloy Name	UNS Number	Major Elements - Percent				
		Chromium	Nickel	Molybdenum	Carbon	Nitrogen
Austenitic 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 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 Stainless Steel Feedwater Heater Alloys

Table 2 lists stainless steels that have been installed in North American feedwater heaters. The most common today are the TP 304 derivatives (TP 304, TP 304L, and TP 304N) and 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 one at the highest temperature in a ultra-critical plant. The “L” grade has low carbon which provides significant extra resistance to corrosion due to sensitization. However, if one specifies “L” tubing, the Code requires the use of lower mechanical properties mandating thicker walls and a resultant 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% thinner walls for the higher strength TP304 N vs. from the non-“N” version. The thinner wall also provides higher thermal conductivity per unit foot, compounding the advantage as less square feet of surface area is needed.

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 \$35/lb 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 usages. Minimum purchase quantities of TP 316N today are the product of a heat. This requires purchase increments of 160,000 lbs, rarely justified by the minimal 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.

AL6XN® and alloy 800 are high performance austenitic stainless steels originally developed for their corrosion and high temperature applications. The two alloys contain higher nickel that makes them resistant 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. AL6XN and TP 439 are often specified when a utility is concerned about chloride SCC. Since TP 439 has a temperature restriction of approximately 600 F, the AL6XN is popular for high pressure heaters. Alloy 800 was used for several heaters in the late 1980's and those have operated without problems. AL6XN has been used in approximately 35 feedwater heaters since 1985. Of those, tubes in two have failed from chloride stress corrosion cracking (at temperatures above the design), and one has had tube cracking that is believed to be related to water chemistry and oxygenated control.

ASME Specifications

Years ago, seamless stainless steel feedwater tubes were originally 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 needed in feedwater heaters. SA 688 was developed for austenitics, and later SA 803 for ferritics, to address the need for additional requirements. These requirements are summarized in Table 3.

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 @ +/- .004"
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	+/- 1/16" maximum
Flattening of bend region	Not addressed	No more than 10% from straight tube
Bend "ski tip effect"	Not addressed	No more than 1/16"
Packaging	Not addressed	Specific to limit problems for bends

Table 3. 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: 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, that rely upon a “mushy” weld zone, do not work well welding stainless steels. 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 feedwater heater tubing, followed by laser welding for less critical applications.

Virtually all welded tubing pressure tube grades that have ASME coverage are produced 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-treated the entire pressure tube, thus 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.

Tungsten Inert Gas (TIG)

Tungsten inert gas (TIG) is the most commonly used welding process (Figure 2) for stainless steel feedwater heater tubing. During TIG welding, an arc is maintained between a shaped tungsten electrode and the tube. Inert gas is used to shield the molten puddle on both the OD and the ID. To provide good weld shape, a tube manufacturer may control the ID pressure by using a ID seal arrangement and controlling pressure. The TIG method provides for a fairly wide (blocky)high quality weld with good penetration. The blocky shape offers two advantages. First it will tolerate minor rolling (misalignment) of the tube during the welding process, and it provides more weld reinforcement which enables greater cold reduction during the in-line cold working operation.

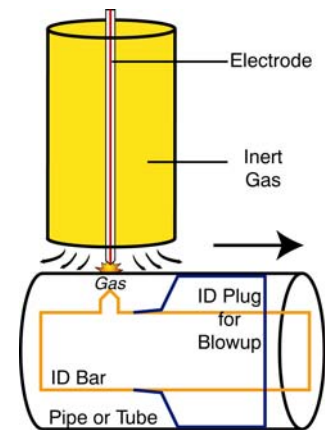


Figure 2 – Schematic of TIG tube welding

Plasma Welding

Plasma welding (Figure 3) is used when greater penetration is needed. In this method, high temperature ionized plasma is used to provide the energy. Because of its very high-localized power, it cannot be used on small diameter tubing if an ID cold working mandrel is on the same piece of equipment. Plasma’s greater penetration develops welds that are narrower than TIG for the same thickness material.

Laser Welding

With the advent of higher power dependable lasers, laser welding (Figure 4) of stainless steel tubing has become a reality. Because of its high energy density, the laser produces the narrowest weld of the three methods. With the increased usage of laser welding, an interesting controversy has developed. The two acknowledged advantages are that it provides the highest welding speed and the least volume of segregated cast material.

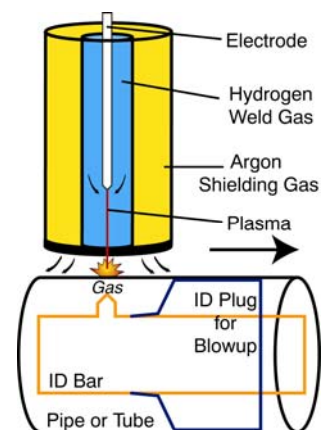


Figure 3 – Schematic of plasma tube welding

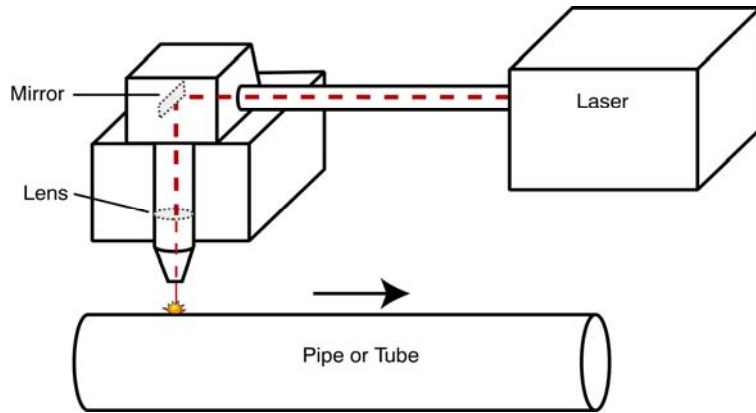


Figure 4 Schematic of laser welding of stainless tubing

However, the very narrow weld has the disadvantages of an increased potential for off-seam welding and little opportunity for cold working the weld. Very sophisticated seam tracking, and edge preparation equipment is mandatory with laser welding. The controversy as to whether less segregation combined with less cold work is better than being able to more heavily cold work a weld with greater segregation has no definitive answer.

Weld Bead Cold Working

The purpose of cold working is to assist with homogenization of the segregated as-cast weld structure ensuring that the mechanical properties, dimensions, and corrosion resistance 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 inline methods are used on feedwater heater tubing with wall thicknesses up to .083". Cold drawing is commonly performed on wall thickness exceeding .065", but can be specified for thinner walls, when desired.

In-Line Bead Reduction

In-line bead reduction is the localized cold working of the weld bead directly on the forming and welding mill. It is performed immediately following welding to ensure that the weld is maintained in a controlled position. The cold working is accomplished by applying pressure with roll tooling on the OD surface, reinforcing the ID with a hardened mandrel, and supporting the opposite side of the tube with another roll.

Roll Forging

Roll forging (Figure 5) is a method where the top and bottom roll are fixed longitudinally and the top roll oscillates vertically hammering or forging the weld. An ID mandrel, usually made of carbide, is centered in the tube under the forge roll providing support for the tube and mandrel.

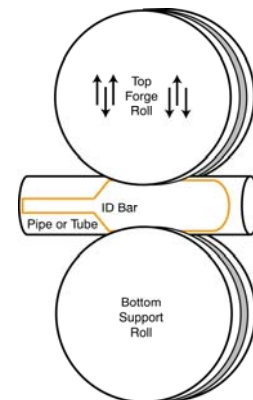


Figure 5 –Schematic of the roll forging method of cold working

Reciprocating Roll Down

The reciprocating roll down method (Figure 6) uses a carriage containing two rolls – the top directly centered over the weld and the other on the bottom side of the tube. The carriage slowly reciprocates back and forth longitudinally. The load is normally applied only when the stroke is in one direction. The mandrel on the ID of the tube is longer than the stroke and is kept firmly in position. The length of the stroke is traditionally related to the OD of the tubing (i.e. larger tubing = longer stroke).

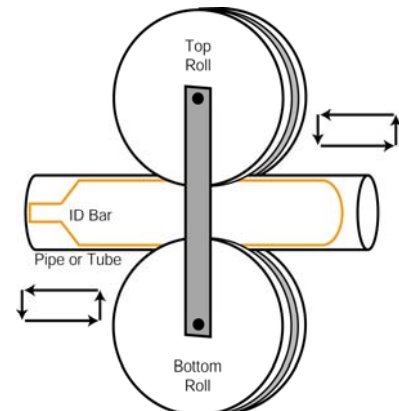


Figure 6– Schematic of the reciprocating roll down method of cold working

OD Sizing and/or Cross-Polishing

OD sizing is the term used by passing the tube through the last stages of rolls to set the final size in the tubing. Typically, this sizing operation reduces the OD of the tubing approximately .003” to .006”. Virtually all roll form / welding mills contain this process stage. As no ID mandrel is used during this operation, the actual cold working is very minimal, less than 1%. This means that cold working has little impact on weld refinement that is needed for improved corrosion resistance and properties. To lower cost, some tube suppliers use this sizing operation as their sole cold working mechanism. It should not be considered as a substitute for full cold-working using an ID mandrel, particularly for critical applications such as feedwater heaters.

Do not consider using a tube 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 7). 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.

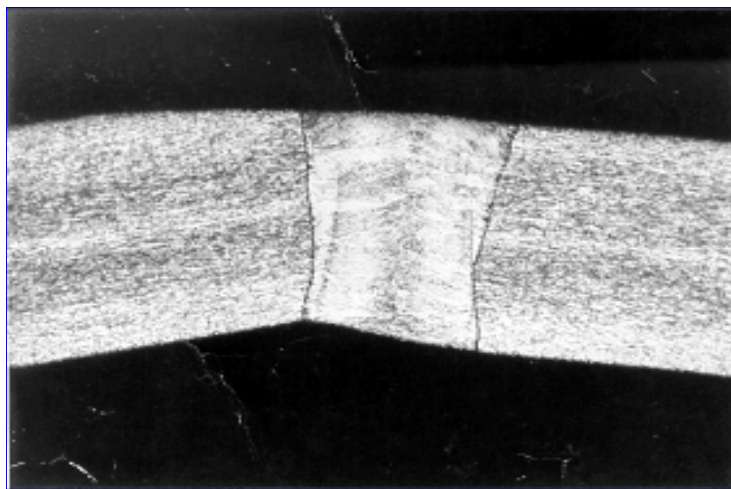


Figure 7 – Photo micrograph of a tube weld where the strip edges were not properly aligned and the OD surface was smoothed by cross polishing. The wall thickness at the left edge of the weld is below the minimum wall requirements

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 8, 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.

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 very 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, commonly measured in Ra. Typical surface finish of a cold drawn material is in the 20-30 microinch 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 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 be used on cold-drawn welded product than for tubing made by any other process.
- *Higher Strength* - Most stainless steels are not heat-treatable for higher strength. For many applications, such as mechanical or aircraft applications, stainless steel tubing is cold drawn to raise the tensile and yield strength. In some cases, the yield strength may be three times the annealed value. However, in most heat exchanging applications, the benefit of cold working is not recognized, especially when ASME Code requirements are needed. This could be an advantage when utilizing the European PED requirements.

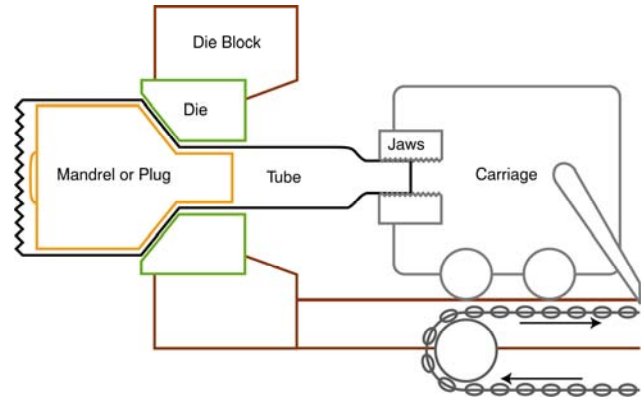


Figure 8 – Schematic of the cold drawing method for cold working of the tube

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 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 seamless or roll formed to size. Signals from smaller imperfections on these products 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 should be carefully followed and specified when this process is used.

Heat Treatment Options

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 stainless steel tubing. In this method (Figure 9), the tube is heated with an induction coil to the desired temperature and then rapidly cooled with either water, convective gas such as hydrogen, or an inert gas such as argon. The heat treatment is performed in-line on the welding mill usually immediately following the in-line cold working operation (if one is performed). Temperature is monitored using optical pyrometry. When induction annealing is performed, the time at which the tube is at temperature is very short. Energy is put into the tube only during the time that the tube is in the coil. The coil is usually only a few inches long. Once the tube leaves the coil, the cooling process starts.

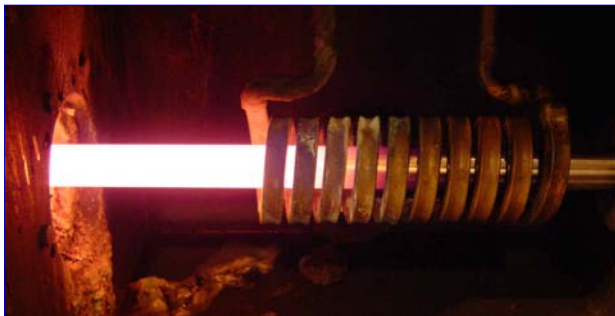


Figure 9 Induction annealing of stainless steel tubing



Figure 10 – In-line water quenching

Following are a summary of the advantages and disadvantages of the method:

Advantages

- *Low Cost* - Since it is in-line with the welding operation, additional costs are minimal.
- *Highest Quench Rate* – When combined with a high pressure encircling ring, the highest quench rate of any method is possible. Some alloys, like the super ferritic and super duplex

alloys, require this method to guarantee sufficient quench (Figure 9) for prevention of detrimental second phases. These secondary phases significantly reduce corrosion resistance.

Disadvantage

- *Short Homogenization Time* – Stainless steels containing more than 6% nickel have slower diffusion kinetics. The in-line anneal will not completely homogenize these grades. Homogenization should not be confused with solution annealing. The term “solution annealing” normally refers to dissolving of chromium carbide particles that lower intergranular corrosion resistance. When overall corrosion resistance or long term performance is the primary concern, a separate furnace homogenizing anneal should be considered. Furnace annealing should always be specified on higher alloyed austenitic alloys or the heavier wall thickness 300 series feedwater heater tubing.

Off-Line Furnace Annealing

The off-line separate “furnace anneal” provides a significantly longer time at temperature than the in-line anneal, typically in the five to ten minute range. This is the time frame needed for full weld homogenization of the alloys containing greater than 6% nickel. 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 (Figure 10).



Figure 11 – Off-line furnace annealing of feedwater heater tubing

Advantages

- *Greater Homogeneity & Corrosion Resistance* - The longer hold time provides for greater homogeneity and general corrosion resistance for the austenitic grades. This is especially important for alloys with higher nickel and molybdenum concentrations and feedwater heater tubing.
- *More Predictable & Consistent Properties* - This may be important if high ductility and low hardness is needed for forming operations. Tubing to be u-bent for feedwater heater applications benefits from this method, as the predictable properties are needed to produce bends with very consistent dimensions.

Disadvantages

- *Higher Cost* – Off-line furnace annealing has a higher cost especially at today’s higher natural gas, hydrogen, and electrical costs.
- *Additional Operations* – Tubes may need additional straightening, sizing, and cutting operations after anneal.
- *Slower Quench Rates* - Quench rates are not as quick as induction anneal. Although sufficient for austenitic alloys, the furnace anneal should not be used for the super ferritics and super duplex grades.

Heat Treat Atmospheres

Two types of atmospheres are commonly used during 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 hydrogen, that minimizes the formation of oxides. 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 approximately 1850° F. Alloys that require a lower annealing temperature, such as TP 439 and super ferritics, 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 700 F. Water quenching is not an option as the water will cause scale formation. Therefore, bright annealing quench rates may not be sufficient for some ferritic and duplex alloys when corrosion resistance is critical. Since the surface of a bright-annealed tube does not develop a thick scale, the final tube surface finishes may be smoother.

Open Air Heat Treatment

Open air heat treatment allows water quenching. This ensures that ferritic, duplex, and heavier wall higher 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 for optimum corrosion resistance.

Chemical Pickle / Passivation

When an oxide forms on the surface of a stainless steel tube during heat treatment, it is predominately chromium oxide. The scale is usually porous and cracked, and therefore, not very protective. Beneath this scale is a region of chromium depletion that has inferior corrosion resistance. In applications requiring high corrosion resistance, it is very important that this chromium-depleted layer be removed (ref. 2, 3). Mechanical polishing may re-embed these chromium-depleted layers in the surface, having little beneficial effect. 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 condensate 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. 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) are commonly used for stainless steel tubing - eddy current testing (ET) and ultrasonic testing (UT). Each has advantages and disadvantages.

Eddy Current Testing (ET)

Eddy current is the dominate test used for almost all stainless steel tubing. 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 12). The eddy currents are developed by an induced alternating magnetic driver coil which is 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 detection is identical in both the blue and green coils, no signal to the scope or alarm is generated. 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 directly related to its volume.

Advantages

- *Cost* – ET testing is fast and therefore, relatively inexpensive. Testing rates can exceed 100 meters per minute.
- *Locates Partial Wall Defects* – This method finds imperfections that are not through wall.
- *Volume Sensitivity* - This testing is most sensitive to sharp abrupt imperfections with volume.

Disadvantages

- *Volume Required* - Defects must have volume in order to be identified. Tight narrow defects may be missed.
- *Insensitive to Longitudinal Defects* – Since the signal is generated from volume differences between the two differential sensing coils, longitudinal gradual imperfections may produce little or no signal, and are unlikely to be rejected. Ultrasonic testing should be specified when longitudinal defects are a concern.
- *Attenuation* - This causes OD defects to be more easily found than ID defects.

The most common acceptance criteria is the use of a drilled through wall hole no larger 0.031” in diameter. The definition of this is in ASTM A 1016. Longitudinal and transverse OD and ID notches can also be specified. These

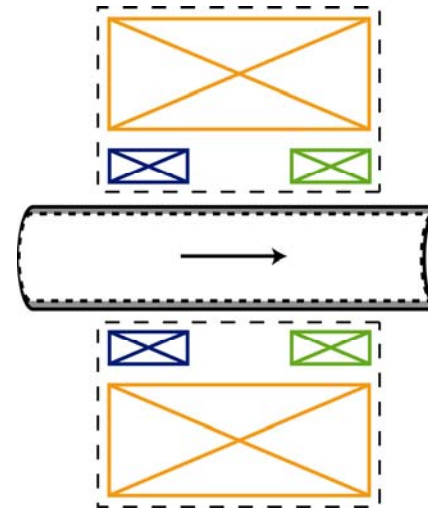


Figure 12 – Schematic drawing of a full encircling differential eddy current testing coil

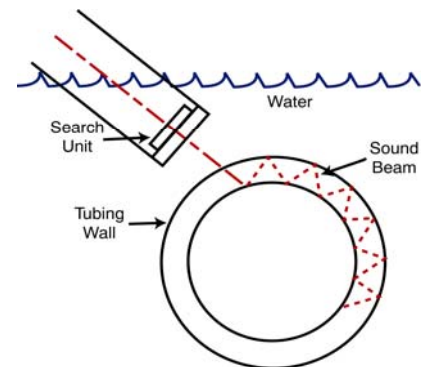


Figure 13– Schematic of an ultrasonic signal propagating through the tube wall

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.

Ultrasonic Testing (UT)

The UT testing method sends a focused sound wave (called a shear wave) into the wall of the tube and then detects the echo that is reflected back from an imperfection (Figure 13). It is normally performed by sending the sound wave in a circumferential direction around the tube. As angular defects may reflect the sound wave differently, the tube should be tested in both directions.

Advantages

- *Finds Longitudinal Defects* – Contrary to differential eddy current testing, UT testing is most sensitive to longitudinal straight defects such as cracks and incomplete welds. The technique is not particularly affected by the defect volume like ECT. Tight narrow defects are easily found.
- *Dependable for Heat Exchanger Sizes* – This testing provides a good signal from ID defects on standard heat exchanger sizes. As the depth of the signal can be orders of magnitude greater than ECT, attenuation is not a significant issue.
- *Finds Partial Wall Defects* – This method finds imperfections that are not through wall.

Disadvantages

- *Cost* - The test is slower and relatively more expensive than ECT. However, for feedwater heater applications, the small additional cost could be well justified.
- *Limited Sensitivity* – This method is not normally sensitive to short transverse defects or defects not oriented to reflect the sound wave directly back to the transducer. These defects are commonly detected by ECT.
- *Requires Furnace Anneal* – The ultrasonic signal can be reflected by changes in crystal structure or significant grain size differences. This may require a full furnace anneal.

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 commonly used on welded heat exchanger tubing: air-under-water testing, pressure differential/pressure decay testing, and hydrostatic testing.

Air-Under-Water Testing

The air-under-water testing method (Figure 14) 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 150-250 PSI. Because of its low cost and high sensitivity, this is the most common pressure test used for welded



Figure 14 – Air-Under-Water Testing

heat exchanger tubing. When pressurized at 150 PSI, tube leaks as small as .001” can be detected and those as large as .002” can be regularly found (ref. 4).

Advantages

- *Sensitivity* – This is the most sensitive of the common pressure methods.
- *Cost* - Air-under-water testing is low cost – currently a few pennies per foot.

Disadvantages

- *Operator Dependant* – The sensitivity of this method may be subject to fatigue of the operator.
- *Defect Limitations* - The defect must be through wall in order to be detected.

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. However, as of the time of publishing of this paper, no acceptance criteria is defined.

Advantages

- *Cost* – This is a low-cost method.
- *Sensitivity* – Pressure differential testing is the second most sensitive common test when used at production rates.
- *Operator Independent* - This method is not subject to operator fatigue.

Disadvantages

- *Defect Requirement* - Defects must be through wall in order to be detected.
- *Parameters* - These 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 .003”. However, larger holes may be required for reasonable cost.

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. 4), hole sizes of 0.002”, are almost undetectable. In general, on welded product, hydrostatic testing is performed only when required by the specification.

Advantage

- *Meets ASME Code* – Hydrostatic testing is used to meet Code requirements.

Disadvantages

- *Lowest Sensitivity* – This method is the least sensitive of the common pressure methods.
- *Cost* – Hydrostatic testing has the highest cost of pressure test methods.
- *Operator Dependant* - This method may be subject to fatigue of the operator.
- *Defect Requirement* - Defects must be through wall in order to be detected.

Residual Stress Testing

Most stainless steels are susceptible to chloride stress corrosion cracking. This occurs when the tubing incurs a combination of three factors; trace amounts of chlorides, high stresses, and a temperature above a minimum of at least 150 degrees F. 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 not controlled. Rotary straightened tubing may have residual hoop stresses near the yield strength of the tube.

All stainless steels are not equally susceptible to chloride stress corrosion cracking (SCC). Copson and Chang (ref. 5) determined that the alloys most susceptible were those containing 8% nickel, not unlike TP 304. Lower and higher nickel content resulted in more resistance. Crucible Materials Research performed a series of test duplicating heavily faulted feedwater applications (ref. 6). 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 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 4.

This data shows that the susceptibility is a function of alloy, chloride content in the water, 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%, only 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 will be more

susceptible to failure when chlorides are introduced to the condensate. Alloys containing nickel content above 8% have decreasing sensitivity as the nickel content increases.

Grade	Ni %	Test Temperature Degrees F						
		250			350		450	
		Chloride Content (ppm)						
		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 4. 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. 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 when used in elevated temperature applications, such as feedwater heater tubing. 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 (circumferential) stress is the Thirkill split ring method shown in Figure 15 (ref. 7)

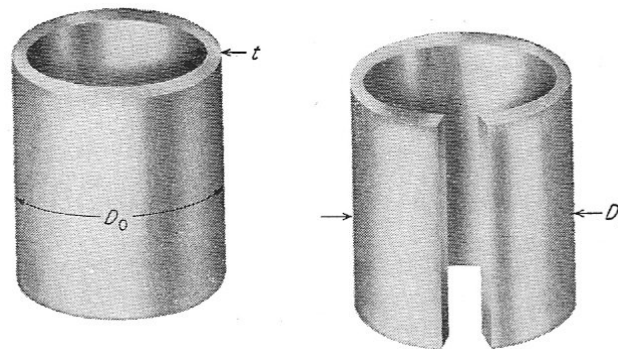


Figure 15. Thirkill split ring sample for measurement of residual hoop stress

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 16.

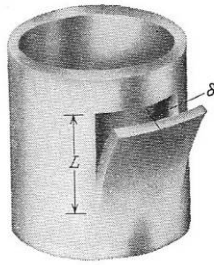


Figure 16. Tongue deflection method for determination of longitudinal residual stress

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 the center. An example is shown in Figure 17. This method does not have the precision that the previously two methods described. Typically, the residual stress for this method is reported to be +/- 5000 psi. This test is also relatively expensive, in the \$600 to \$1000 per sample range.



Figure 17. 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, EPRI's feedwater Guidelines (ref. 8) recommends a maximum residual stress of 5000 psi. 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.

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.

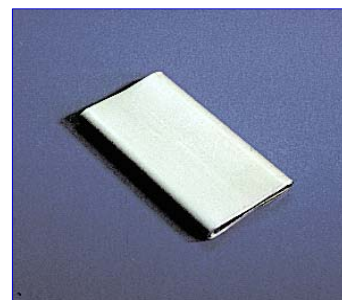


Figure 16 – Flatten Test

Manipulation (Destructive) Testing

Manipulation tests are designed to specifically test the ductility of the weld in various directions. 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 18).
- *Reverse Flatten Test* - This test was developed to test transverse weld ductility on the ID surface (Figure 19).
- *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 20).
- *Flange* - This test, which starts out as a flaring operation, is the test for longitudinal weld ductility, primarily on the ID surface (Figure 21).
- *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.

Minimum sampling rates for the various manipulation tests are specified in the appropriate ASTM product specification. These are listed as a test per maximum of length or maximum number of pieces. Most 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.

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



Figure 19 – Reverse Flatten Test



Figure 20 – Reverse Bend Test



Figure 21 – Flange Test



Figure 22 – Weld Decay Test

than the base metal. For a properly annealed weld, the ratio should be 1.00 or less (Figure 22). This test is only effective on austenitic grades that form ferrite during solidification. This restricts the test to primarily 304 and 316 derivatives. The test does not provide meaningful results on austenitic grades with higher Mo and Ni, ferritic grades, and duplex grades. The test is most commonly used in the paper and sugar industries where it is common to clean tubing with muratic acid to remove deposits.

Intergranular Tests

Intergranular 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. This test is normally called for to check if an alloy is “solution annealed”. The “solution annealed” term is most often designated for dissolving chromium carbides, which ensures that the chromium is available to keep the stainless “stainless”. These tests may not be meaningful for determining whether an alloy is suitable for an application and cannot determine if a weld is adequately homogenized for optimum corrosion resistance.

“G” Type Tests

ASTM “G” type tests are acid based pitting and crevice corrosion tests that are intended to mimic potential applications. The G 48 test is often used testing high performance stainless when chloride pitting or crevice is a concern. Because of the difficulty of controlling a “crevice” on a tube, the “pitting” method C of G-48 should be specified for accurate results. These tests are probably the best choices for applications requiring corrosion resistance. If a project is large enough to justify some developmental work, the acid blend could be developed to be process specific.

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 strongly considered:

- *ASME Feedwater heater specifications*- Require SA 688/ SA 803 specification as a bare minimum. Do not allow tubing to be certified solely to 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 does not provide a wrought weld that the ASME design allowables were based on. For super and ultra critical high pressure tubing, you may want to specify that the tubing be cold

drawn. Do not allow cross polishing and the localized wall thinning it causes is almost impossible to detect.

- *Specify Maximum Residual Stress* – Austenitic 300 series tubing is very susceptible to chloride SCC. With use these grades in feedwater heater applications, residual hoop tensile stress should be restricted to 5000 psi maximum or lower.
- *Specify Corrosion 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 may be a good choice on austenitic feedwater heater tubing to ensure that the weld is homogenized. G type tests may be need for applications where corrosion is the major concern.
- *Require Test Plan Approval* – Prior to product, require a test plan that you can review. Sampling rates of internal destructive tests and other inspections are critical.
- *Know the supplier* - There are no ASTM police! This is your job as the purchaser. 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.

References

1. ASTM Standards:

- 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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4. O'Donnell, D., Lee, T., Testing performed for the ASTM A01.09/A01.10 NDE Task Group, April 30, 2001.
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8. "Feedwater Heaters: Replacement Specification Guidelines", Part 1.4- Tubing Selection and Preparation, EPRI Final Report GS-6913, Project 2504-5, August 1990.