Processing Requirements for Corrosion Resistance Optimization of High Performance Stainless Steel Tubulars

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High performance super-austenitic, super-duplex and super-ferritic stainless steel alloys are widely used in severe service applications. They are selected for their resistance to pitting and crevice corrosion in situations involving high chloride levels, severe microbiological environments, and seawater exposure. These alloys have established a history of reliable performance in severely corrosive environments. High performance stainless alloys have compositions that should allow them to be fully resistant to corrosion in high-chloride water even when scaling and bio-fouling occur.

The processing methods used to convert strip into welded tubing are critical to optimizing the performance of the final product. Unlike the simple single phase commercially pure Ti grades that are used for similar services, the corrosion resistance of these high performance stainless alloys is sensitive to variations in composition and processing. Process variables including chemical composition, control of the welding process, cold working of the welds, annealing, and cleanliness after the annealing are all significant factors that impact corrosion resistance of the finished product.

High performance stainless steel grades offer corrosion resistance and physical properties that make them attractive for use in desalination applications. The long term reliability and economic viability of these alloys depends greatly on the tubing placed into service delivering the expected level of corrosion resistance. A review of the actual chemistries that have been used in these alloys, published corrosion testing data, and data derived from recent testing illustrate the risks of miss-manufactured material and the capabilities of these alloys when they are properly produced.

Introduction and Usage:

There are a number of high performance super-stainless steel (HPSS) alloys that have been used in power plant steam surface condensers. These alloys are listed in Table 1. The total usage of these alloys is now over 155 million feet (47 million meters) and continuing to grow. The most common high performance stainless steel alloy in use is the superferritic, UNS S44660. This alloy has been in use since 1980 with over 70 million feet (21 million meters) in power plant condenser service.[1]

Table 1: Typical Chemistry of High Performance Stainless Condenser Tube Alloys

UNS number	tradename	Cr	Ni	Mo	N	other
Super-ferritic						
S44660	SEA-CURE®	27.0	2	3.7	<0.01	Ti &/or Nb
S44735	AL 29-4C®	28.6	<0.5	3.8	<0.01	Ti
Super-austenitic						
N08367	AL-6XN®	20.8	24.5	6.4	0.21	
S31254	254SMO®	20	18	6.2	0.20	Cu 0.5-1.0
Other Super-austenitic						
N08926	25-6MO®	20		6.2	0.18	
N08367	AL-6XN+®	21.8	25.2	6.7	0.24	
Other High Performance	alloys					
R50400	Ti gr2	Commercially pure Ti				
C70600	90Cu/10Ni		10			Cu 90

The historical usage trends for these high performance stainless grades in power generation steam condenser service are shown in Figure 1. S44660 has seen a surge in usage since 1998 and total super-ferritic usage has surpassed that of the super-austenitic alloys. There are two reasons for this. The first is the wider recognition of the performance of these alloys based on their long and successful record. This applies both to the excellent corrosion resistance and thermal superior performance. These alloys have the best thermal conductivity of any HPSS. The reliability of corrosion resistance is highlighted by the fact that one-fourth of all S44660 in service (roughly 17 million feet or 5.2 million meters) has been in service for more than 20 years without a corrosion failure. The other reason is economic, the super-ferritics have the lowest cost of any high performance condenser tube material.

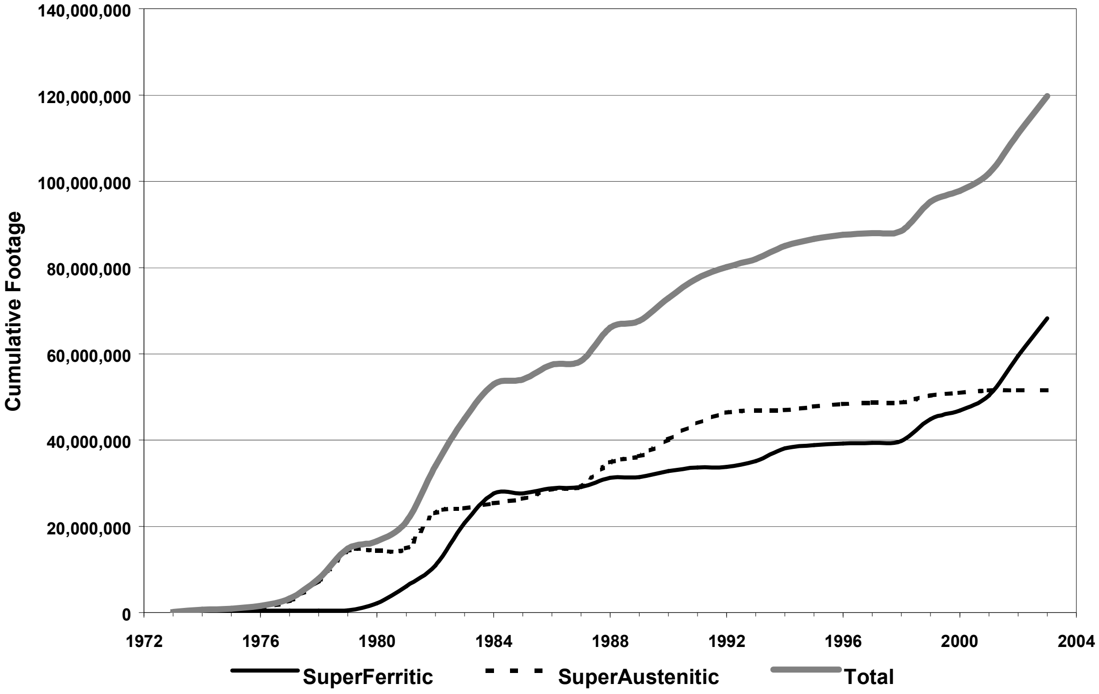

Figure 1: Cumulative Worldwide Historical Usage of High Performance Stainless Steel Condenser Tubing[1]

Corrosion Resistance, Background:

When the HPSS alloys are evaluated using traditional PRE correlation between composition and corrosion resistance it appears that they all should have similar corrosion resistance as shown in Table 2.[3] It should be noted however, that these corrosion resistance ratings represent the optimal values for these alloys based on their chemistry. There are many factors that can lead to the finished product having significantly reduced corrosion resistance. One issue is the exact composition of the alloy. As illustrated in Table 2 the potential variation of corrosion resistance across the chemistry range of these alloys. In practical terms this is not a significant concern in applications since these alloys are each produced by a single steel mill there is minimal variation in chemistry. The chemistries listed as 'typical' are representative of current production material and these alloys need to be compared on the basis of 'typical' composition. Trade names have been used in this table since we are discussing the actual alloy compositions from specific sources.

Table 2: Minimum and Maximum PRE Values for HPSS Alloys

		Cr	Mo	N	PREn
Superaustenitic					
N08367	**AL-6XN**® min	20.0	6.0	0.18	45.2
	Typical	**20.8**	**6.35**	**0.22**	**48.4**
	max	22.0	7.0	0.25	52.6
S31245	**254SMO**® min	19.5	6.0	0.18	44.7
	Typical	**20.0**	**6.2**	**0.20**	**46.5**
	max	20.5	6.5	0.22	48.6
Superferritic					
S44660	**SEA-CURE**® min	25.0	3.0		34.9
	Typical	**27.0**	**3.7**		**39.2**
	max	28.0	4.0		41.2
S44735	**AL 29-4C**® min	28.0	3.6		39.9
	typical	**28.6**	**3.8**		**41.1**
	max	30.0	4.2		43.9

The PREn number is a calculated value that is proportional to the crevice corrosion resistance of the alloy. Since the early publication of this relationship by Rockel [3] and further analysis by Kovach and Redmond [4] this relationship has been accepted as a standard estimate of an alloys potential corrosion resistance. In Figure 2 there are separate lines for the relationship of PRE and actual corrosion resistance for the austenitic alloys and the ferritic alloys. Even though the slope of the lines is the similar, they are offset. There is a difference of roughly 10 points between the superferritic and superaustenitic alloys. For a similar level of pitting/crevice corrosion resistance a super-austenitic alloy needs to have a PREn that is ~10 points higher than a super-ferritic alloy. As reliable as PREn is in estimating relative corrosion resistance of alloys it does not translate directly into a pitting or crevice corrosion temperature. These must be determined by actual testing.

The acceptable chloride limits listed on the right side of this figure are based on experience. While under some conditions alloys can be used at levels significantly higher than these values the empirical evidence suggests that these limits are reasonable and will result in reliable service.[5]

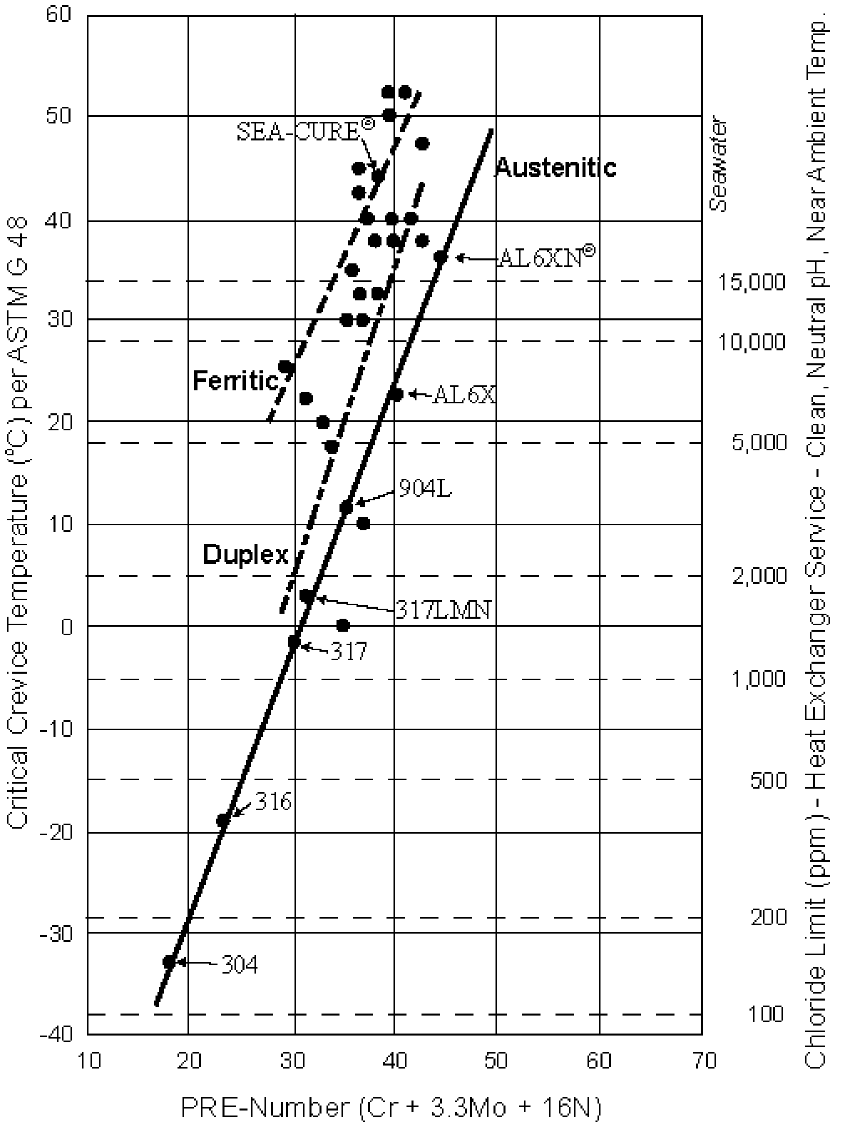

Figure 2: Pitting Resistance Equivalent number versus Critical Crevice Corrosion Temperature and Typical Cooling Water Chloride Limits.

Process Considerations:

Steel Mill Processes:

The steel making, casting, hot and cold rolling, and annealing are the initial stages of steel production. With the advent of modern computer controlled arc melting and AOD refining there is insignificant chemical variation in the basic material. The excellent control in a modern steel mill over the cold rolling and annealing processes also insure that there is minimal deviation in microstructural characteristics of the alloy. As long as the strip is slit cleanly with uniform edges and protected from contamination it will be suitable for tubing production. In many cases the strip does not have the maximum corrosion resistance possible. This can be because the heating and cooling during the strip anneal process were not optimized for corrosion resistance, but for processing or mechanical properties.

Another possibility is that the surface of the strip may not be fully cleaned. These are not always significant issues with tubing performance since the annealing and pickling during the tube manufacturing process can be designed to rectify these conditions. For these reasons, conducting corrosion testing on 'run of the mill' strip samples can lead to inconsistent results and faulty conclusions.

Tube Forming and Welding:

The first tube making process involves the welding of the strip into tubing. The flat strip is formed in to a tubular shape and then the edges are fusion welded together autogenously (without filler metal). The welding can performed using any of the common techniques; GTAW (gas tungsten arc welding or TIG, tungsten inert gas), laser or plasma. In all of these welding processes the molten weld metal is kept clean by the use of inert shield gases. Argon, Helium and mixtures of the two are the most common. The goal is to prevent the formation of oxides in the weld that could result in surface defects that might allow a site for more rapid corrosion initiation. Plasma welding is often used for thicker material. Since these grades have limitations on thickness they are rarely welded by this method. The process can be more difficult to control and often leaves an uneven weld surface with distinct undercut that is difficult to correct in a beadworking operation. These contour variations can make it difficult to roll the tubing smoothly and develop a seal in the rolled tube to tubesheet joint. GTAW is the most common technique used in stainless steel tube welding. The welds are usually slightly wider than the material thickness with a smooth surface and gradual transition from the weld bead to the base metal. The ideal shape after weld is for there to be a slight amount of weld reinforcement. The weld should bulge on both the ID and the OD. Since these welds are fairly wide minor irregularities in the edges of the strip or the alignment of the strip in the mill will not cause significant weld defects. Laser welding is a more recent technique. While this method is used extensively in other tubing applications there is no field experience with laser welded HPSS tubing. The laser welds are very narrow and typically generate almost no dimensional reinforcement, this make beadworking impractical. The high intensity of the laser allows the welding process to be much faster, but it also puts far more stringent requirements on the uniformity of the strip edges and the stability of the tube mill. Any shift in position of the strip edges will result in welds that are misaligned and not being able to fully fuse the edges of the strip. This can cause significant dimensional variation at the weld, crevices along the id surface at the fusion line and the possibility of thin tube wall adjacent to the weld. This line can also provide an initiation site for the tube to split when it is roll expanded into the tubesheet.

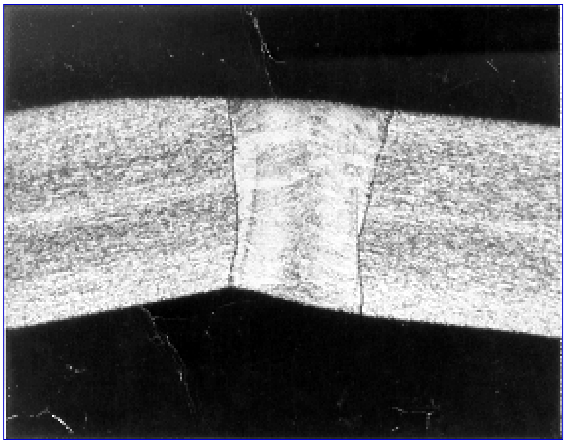

Figure 3: Cross section of a laser welded tube where heavy od bead grinding of a misaligned weld has resulted in a tube that does not meet the minimum wall thickness requirement.

In some tube mills, an abrasive finish is given to the OD of the weld prior to further working of the tube. This can assist in removing oxide if the weld shielding gas was not adequate and in removing any impurities that may have been formed on the surface of the weld. Care must be taken because this polishing can remove a significant amount of material and the result could be tube sections that are below the allowed minimum wall thickness. An illustration of this is seen in Figure 3. This tube was laser welded with the strip edges out of alignment; the left side was higher than the right,. The bead grinding was aggressive enough to restore the OD contour of the tube at the expense of creating tubes that did not meet the required minimum wall thickness. This condition was not detected in the weld mill inspection system and was shipped to the customer. The bead grinding operation is not to be confused with, or used in lieu of mechanical weld bead conditioning.

Cold Work:

The traditional tube making process follows welding with a cold working operation. This beadworking applies sufficient force to the weld bead from both the OD and ID surfaces to reduce the thickness of the weld bead back to a value near the original wall thickness. This operation has two distinct benefits. The first benefit is that it assures that the weld will be dimensionally blended into the tube wall. Any variation in wall thickness at the weld will be gradual and smooth. This will facilitate the rolling of the tubes into the tubesheet. The other benefit is that the cold work put into the weld during this operation enhances the microstrutural recovery during annealing. This will minimize the variations in mechanical properties and corrosion resistance between the weld and the base metal portions of the tube. It is important that the weld be worked from both the inside and outside. If force is only applied to the outside then the extra weld bead metal will be pushed into the ID and not worked by reducing its thickness. The 'OD work' only methods can not provide suitable weld cold working. There are a number of techniques used such as bead forging, bead rolling and bead hammering that do fulfill these cold working requirements. This process is not required by ASTM A268 on the ferritic alloys, however such cold working is required by ASTM A249 and B676 for the austenitic alloys. [6] This is a beneficial process and high quality producers will beadwork both superaustentitic and superferritic alloys.

Annealing Heat Treatment:

Super-austenitic alloys

The selection of an optimum annealing process is highly dependent on the alloy being produced. The superaustenitic alloys have high levels of nickel and molybdenum. These elements slow diffusion within the microstructure. In order to achieve a homogeneous structure these alloys require high anneal temperatures and long hold times than lower alloy austenitic grades. The ASTM specifications contain only minimum annealing temperatures, but no time guidelines. All of the 6% Mo alloy samples evaluated in this testing were annealed at 2150^{O}F. The necessary time at temperature conditions cannot be met with an inline anneal process on the weld mill. In order to optimize the time and temperature requirements it is best to anneal these alloys in an offline continuous furnace. The role of the time that material is held at temperature is demonstrated by test results on some 2" x 0.035" N08367® tubing listed in Table 4. These samples are from the same mill run, the only variation is the annealing process. The requirement for longer time at temperature increases as the alloy content, particularly Ni and Mo increase.

Table 4: Trent Tube Manufactured and Tested

N08367 Tubing 2.000” x 0.035”AW CPT per ASTM G48 Method C
inline oxide annealed and pickled 60ºC
furnace oxide annealed and pickled 70ºC

Since the austenitic alloys are generally not very sensitive to the heating and cooling rates used in annealing there are no special furnace quenching requirements. The superaustenitic alloys are amenable to either bright annealing or oxide annealing. In bright annealing a hydrogen atmosphere is used to keep the furnace environment reducing. The chemically reducing conditions prevent the formation of oxides on the surface and keeps the tubing bright. This atmosphere must be high purity dry hydrogen. The addition of too much nitrogen to the atmosphere can result in the formation of nitrides and the risk of accelerated intergranular corrosion. In oxide annealing you make no special provision to prevent surface oxidation of the tubing. The oxide is chemically removed in a subsequent pickling process.

Super-ferritic alloys

The superferritic alloys are much different in their heat treatment response. They do not need long holding times and the annealing temperatures are lower. This leads itself readily to inline annealing processes. These alloys benefit from rapid heating and cooling during anneal conditions that are readily achievable in an inline process. The rapid cooling rate assures that detrimental secondary phases will not form. Rapid cooling is difficult in the protective atmosphere of the bright annealing process. Inline annealing takes place after the welding and beadworking but prior to the final sizing of the tube. The standard process uses an electromagnetic induction coil driven by a high frequency power supply to rapidly heat the tube. The tube is held at temperature briefly in open air and then force cooled.

The ferritic alloys are better suited to oxide annealing than bright annealing in hydrogen. During bright annealing the ferritic alloys absorb hydrogen upon cooling and become brittle. This is a reversible process and the hydrogen will dissipate and the material will recover its original ductility over time. However, care must be taken since any stress (mechanical or thermal) applied to the tubing during this stage can result in extensive micro-cracking. These cracks are very small and tight making them difficult to detect using conventional NDT techniques. Another issue is that the bright annealed tubing may have a minor amount of colorless surface oxidation. This occurs because the annealing temperatures at the lower end of the range at which hydrogen efficiently reduces chromium oxide. This oxide will inhibit the dissipation of hydrogen expending the time for recovery of ductility from a matter of hours to a time period measured in months. Testing on properly bright annealed strip samples show harmfully low ductility levels from hydrogen embrittlement as long as 6 months after annealing. If tubing in this condition was installed there would be severe cracking of the tube ends on expansion in to the tubesheet. This thin oxide film will also have a negative impact on the corrosion resistance of the tubing.

Pickling:

The dependence of corrosion resistance on the surface finishing method is clearly indicated by the data in Tables 5 and 6. Removing all surface oxides and any chromium depleted layer is needed to achieve optimal corrosion resistance. [7] Mechanical cleaning methods do not reliably provide an optimal surface. Just because a surface looks bright and shiny doesn’t assure that they surface is clean. The pickled finish assures that you will be able to achieve the highest level of corrosion resistance for the particular alloy.

One caution is that sometimes samples for corrosion testing are pickled in order to clean them. If the material did not have a pickled finish to start with then this cleaning will raise the corrosion resistance of the sample but it will not be representative of the actual tubing. A solvent cleaning is permissible to remove any organic residues from the surface of samples, but a more aggressive chemical cleaning or pickling before testing is not acceptable.

Table 5: Crevice corrosion resistance of S44660 as a function of Surface finish

Test Temperature	30^{O}C		35^{O}C		40^{O}C	
Condition	% CC	Rate	% CC	Rate	% CC	Rate
Welded, oxide annealed	50	1	72	4	99	35
Welded, oxide annealed, mechanically ground	4	<1	34	2	49	17
Welded, oxide annealed, pickled	0	<1	0	2	0	3

ASTM G48 'B' Crevice Corrosion test for 72 hours.
%CC is the fraction of the crevice with corrosion
Rate is the weight loss in mg/dm2/day

Table 6: Crevice corrosion resistance of N08367 as a function of Surface finish

Test Temperature	24^{O}C		35^{O}C		40^{O}C	
Condition	% CC	depth	% CC	depth	% CC	depth
As oxide annealed	100	<25	100	<25	100	100
Oxide annealed, sand blasted	0	0	100	100	100	900
Oxide annealed, sand blasted, pickled	0	0	11	<25	30	<25

ASTM G48 'B' Crevice Corrosion test for 72 hours.
%CC is the fraction of the crevice with corrosion
Depth is maximum of pits in µm. <25 is insignificant surface etching.

Corrosion Testing Results:

The most informative techniques for evaluating the corrosion resistance of an alloy is obtained by testing actual manufactured products. There are many corrosion tests described in the literature. Many of the tests only reflect material's performance in a very specific environment. Since resistance to pitting and crevice corrosion in chloride environments is usually the limiting factor for the application of stainless steels, tests that measure performance in these environments are the most commonly applied. For the highly corrosion resistant HPSS alloys the most widely accepted tests are the ones listed in ASTM G 48. These tests utilize a solution of 6% wt $FeCl_3$ (10% $FeCl_3$+$6H_2O$). The low pH (<0.7) and high chloride level (~34,000 ppm) was selected to resemble the environment at an actively corroding pit or crevice. These conditions will stress the alloys ability to repassivate and resist further corrosion. The results of these tests are usually reported as a critical corrosion temperature. **The Critical Pitting Temperature (CPT) and the Critical Crevice Temperature (CCT) are the temperatures where corrosion is first noted.** [8] The test designated as Practice C is the best suited to testing these HPSS alloys. It is a 72 hour pitting test and can be performed on samples of almost any geometry and size. This allows the testing actual tube samples in the as manufactured condition. It also does not require the use of artificial crevice forming blocks and the related variations that this introduces in test conditions.

This test uses an $FeCl_3$ solution acidified with HCl. This acidified solution makes the test slightly more aggressive, keeps the test solution stable at higher temperatures, and minimizes lot to lot and lab to lab variations in the testing. For some historical results G48 Practice A (pitting test) or G48 Practice B (crevice corrosion test) data is all that is available. These tests do not use the acidified test solution and result in higher reported critical corrosion temperatures.

Corrosion resistance: Historical reported data

Allegheny Ludlum AL-6XN® Source Book ASTM G48-A (pitting) [9]

AL-6XN®	annealed and pickled	75ºC
AL-6XN Plus®	annealed and pickled	90ºC

ASTM Interlaboratory Test Program G48-C (pitting)

N08367	annealed and pickled	
	Lab 1	75ºC
	Lab 2	70ºC
	Lab 4	75ºC
	Lab 5	75ºC
	Lab 6	80ºC

Trent Tube Manufactured and Tested ASTM G48-C (pitting)

N08367	furnace oxide annealed and pickled	70ºC
N08367 Plus	furnace bright annealed	80ºC

Plymouth Tube Manufactured and Tested ASTM G48-C (pitting)

S44660	inline oxide annealed and pickled	75ºC

TMR/Copperweld S44660 paper ASTM G48-A modified* (pitting) [10]

S44660	strip samples	60ºC
	As welded tubes	55ºC
	Welded and annealed tubes	55ºC

* test was modified by shortening the test period from 72hr to only 24hr.

Allegheny Ludlum Technical Data Blue Sheet ASTM G48-A and B (pitting and crevice) [11]

AL 29-4C®	no CCT reported	samples passed 50ºC
AL 29-4C®	no CPT reported	samples passed 50ºC

ASTM Interlaboratory Test Program G48-C (pitting)

S44735	annealed and pickled	
	Lab 1	85ºC
	Lab 2	80ºC
	Lab 4	80ºC
	Lab 5	75ºC
	Lab 6	80ºC

Valtimet Ti and Super Stainless Tubing paper ASTM G48-A and B modified† (pitting and crevice) [12]

S44660	strip samples	No corrosion at 50ºC in either test

S44735	strip samples	No corrosion at 50ºC in either test
S44735	reannealed sample, bright anneal	No corrosion at 50ºC in either test
S44735	reannealed sample, air annealed	pitting and crevice corrosion at 50ºC

†test was modified by shortening time from 72 hours to 24 hours

Summary for N08367:

The reported CPT values determined using G48-C for N08367® uniformly fall into the range of 70ºC–80ºC. This includes results from many different laboratories and data from many years of testing on many different sizes of finished products. Based on these test results it is reasonable to expect a large number of production samples to pass the G48-C test at a temperature of 60ºC with no pitting. The richer composition of N08367 Plus® clearly improves the pitting resistance of this grade by approximately 10ºC over the standard material. While there have been very limited applications for the Plus version of the alloy it does offer improved corrosion resistance.

Summary for S44660:

The 75ºC reported by Plymouth Tube for S44660 covers many different product sizes tested over many years. Comparison of the older Trent Tube S44660, current Plymouth Tube S44660, to the Copperweld S44660 and Valtimet S44735 data illustrate the combined effect of composition, welding, annealing, and pickling. While the alloys in these tests conform to the ASTM specification and should all have similar corrosion resistance, there is clearly a significant difference in their corrosion performance. In testing the Copperweld tubing a CPT value of only 55ºC was obtained. And that was using a shortened version of the less aggressive test. Looking at published data for other alloys it appears that the G48-A test will result in a reported CPT that is 5ºC–10ºC lower than tests using the G48-C method. The difference in processing results in Plymouth Tube's S44660 the having a CPT that is approximately 25ºC higher than could be attained by the Copperweld tubing. The Plymouth manufactured tubing will consistently pass a G48-C test on samples of tubing in the as shipped condition at 65ºC with no pitting. The actual critical pitting temperature will be in the range of 70ºC–80ºC.

A similar result is seen in the Valtimet S44735 data. Their reannealed samples showed an interesting variation in results. The bright annealed sample shows similar corrosion resistance to the original strip (undefined heat treatment and surface condition) with both passing a shortened G48-A at 50 ºC. The oxide annealed and pickled sample shows crevice corrosion in a G48-B test at 50ºC. Since the alloy composition is identical the difference in performance is related to improper heat treatment and/or pickling of the air annealed samples. Allegheny Ludlum literature and the ASTM Interlaboratory Testing both show this alloy having no problem passing a more severe test at this temperature.

Such reported data is useful in comparing alloys to each other. But it is limited in answering some key questions such as how much performance variation can be expected from a specific manufacturers' production material. While producers try to make sure that test samples accurately reflect the condition of production material, we decided that it would be beneficial to record the corrosion resistance of a large number of production lots of tubing.

Recent Corrosion Test Results

Over the last three years, samples from over 80 individual heat lots of S44660 tubing were corrosion tested. Samples from 3 of the heats were re-tested after they had been cold drawn to a smaller diameter and re-annealed. We used the G48-C test since it straightforward, requires minimal sample preparation, and accurately reflects the preformance of the tubing in the as shipped condition. Duplicate samples from each heat were tested for 72 hours at 65ºC (selected based on a CPT of 75ºC or higher). None of the tested heats tested in this project failed by pitting corrosion. Two sets of samples were re-tested after one of the samples failed due to crevice corrosion where the samples were touching each other or the sample holders. The typical weight loss of the samples was only $0.04^{mg}/_{cm}2$. Out of the samples 5 had weight loss higher than $0.10^{mg}/_{cm}2$. Detailed investigation of these samples with greater weight loss indicates that they had significantly more end-grain attack than samples with lower weight loss. There was no pitting on these samples. The edge attack was not a consistent; there was no case where both samples from one heat had this condition.

This level of constancy illustrates the reliability of the corrosion resistance of this alloy when the process is optimized and properly controlled.

While there has been a substantial amount of literature published over the years concerning corrosion resistance as a function of chemistry[13] there has been much less data published focused on the dependence of corrosion resistance on processing variables. In order to emphasize the critical nature of process control in the manufacturing of super-ferritic alloys we have under taken a series of trials.

The first trial utilized 1.000” (25.4mm) x 0.028” (0.71mm) tubing. Trials were conducted examining variations both anneal temperature and the severity of the quench. These samples were evaluated utilizing the standard G48 C test method.

Table 7: Pitting Resistance of S44660 Tubing as a Function of Annealing Conditions
italics indicate visible pitting on samples

Test temperature	145 F	150 F	155 F	160 F
Annealing conditions	(63 C)	(66 C)	(68 C)	(71 C)
Standard anneal / standard quench	0.00004	0.00008	0.00024	***0.021***
Anneal -125F (-70C)/std quench	0.00014	***0.0028***	***0.0446***	
Anneal +100F (+55C)/std quench	0.00013	***0.0021***	***0.0432***	
Standard anneal / delayed quench	0.00036	***0.0309***	***0.0246***	

1” x 0.028” tubing, oxide annealed and pickled; G48 “C” 72 hours, weight loss in g/cm2

These anneal temperatures all fall well within the requirements of the specification. This testing indicates the need for tight process controls with these super-ferritic alloys. This testing also reveals why it is necessary to conduct corrosion testing at an appropriate temperature. Testing at a lower temperature will not provide the sensitivity need to distinguish between material that can achieve optimal corrosion resistance and poorly processed material.

Conclusions:

The super-austenitic and super-ferritic alloys have an excellent service record in general heat exchanger applications and steam condenser service. Over 82% of all condenser service that uses HPSS tubes is using S44660 or N08367. These alloys have the distinction of having been supplied for projects requiring corrosion testing of every production heat lot to a minimum CPT. As a result there is a long record of corrosion testing and consistently high performance for these two alloys.

It should be clear from the corrosion test data that just meeting the minimum ASTM chemistries and basic mechanical properties are not enough to assure adequate corrosion resistance. It is not unreasonable for a purchaser of high alloy stainless tubing to require multiple corrosion tests on actual

tubing samples in order to verify the performance of the product. When tubing is produced using the appropriate 'best practices' the result is a constant product with excellent corrosion resistance.
Experience producing the super-ferritic alloys is also critical. A lack of experience with these grades may lead a manufacturer to select sub-optimal processing methods. The combination of inferior production methods and a lack of understanding of suitable corrosion testing methods may result in both the producer and their customers being misinformed concerning the performance of the product that has been delivered.

The combination of a long successful installation record, a strong ongoing testing program, and a firm technical knowledge of the alloy are all critical factors in selecting a supplier of a HPSS alloy. While no alloy or production method can be perfect for every application these are steps that you as a user can take to assure the best performance possible.

Bibliography to follow