

Welding Stainless Steel— Questions and Answers

A Guide for Troubleshooting Stainless Steel Welding-Related Problems

1st Edition

by

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Reviewed by the

AWS Product Development Committee

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Cover: 304L agricultural sprayer with a hemispherical head joined to a cylindrical body by a partial penetration groove weld. Pitting started in the crevice formed by partial penetration, and pitting was promoted by rust trickling out of the crevice pits and depositing on the vertical cylindrical wall which is also heavily heat tinted from the partial penetration weld. The crevice, the rust, and the heat tint all contributed to pitting of the cylindrical wall.

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Preface

It is generally accepted that the history of stainless steels began with the first commercial alloys in 1913, although it was known well before that year that chromium imparted corrosion resistance to iron base alloys. The first commercial alloys were approximately the same as today's Type 410 (martensitic stainless steel) and Type 302 (austenitic stainless steel). Initially, welding of these alloys was a considerable challenge because chromium oxide is quite refractory and interfered with wetting of weld metal to base metal. Arc welding with covered electrodes solved that problem by making use of fluxing ingredients that dissolved chromium oxide.

A second major problem with welding stainless steels was that the heat affected zone tended to become sensitized due to chromium carbide precipitation. For many years, it was quite common that a solution anneal heat treatment had to be applied after welding to remove sensitization, unless much more expensive low carbon alloys were purchased. The very large cost differential between low carbon alloys and non-low carbon alloys virtually vanished with the invention of the argon-oxygen decarburization (AOD) method of refining stainless steels in 1955 and its proliferation around the world in the following fifteen years or so.

By far, the most commonly welded stainless steel grades today are the austenitic alloys such as 304L and 316L. For such alloys, it was learned that slight modification of the filler metal composition to obtain a small amount of ferrite in the otherwise austenitic weld deposit greatly enhanced resistance to solidification cracking. With such filler metals, welding of austenitic stainless steels is as easy, or even easier, than welding of carbon steels. But ferrite is not possible in weld metal of certain austenitic stainless steels, and then solidification cracking problems can arise.

Other stainless steel alloy systems are martensitic alloys, ferritic alloys, and duplex alloys, each with their own special welding concerns. Over the last 40 years, numerous questions have been posed to the author concerning the best way of welding for a given application. Many of these questions have arisen often enough that the "Stainless Q&A" column in the *Welding Journal* was begun in 1999. It was not envisioned in 1999 that the column would prove as popular as it has, nor was it envisioned that the number of questions that can be asked would prove to be nearly limitless, yet such is the case. Over the first few years of the column, most questions came via telephone. However, the world changes, and in recent years, the vast majority of questions come by e-mail. Answers to all questions have been addressed to the inquirer, and those of sufficient general interest have been addressed, sometimes in more depth, in the Stainless Q&A column.

In today's world, people tend to not retain paper copies of journals, so there have been a number of requests to compile the Stainless Q&A columns in one place. It is hoped that this book will provide a useful reference for those with interest in welding stainless steels.

Note: In converting the columns into book form, it proved appropriate to retain original table and figure numbers as were used in the original version of the column. This is a departure from normal book format where figures and tables are numbered sequentially throughout a given book. It is hoped that this will not prove confusing to the reader.

Damian J. Kotecki, Ph.D., FAWS

About the Author

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Introduction

Chapter 1 Welding of Austenitic Stainless Steels

Austenitic stainless steels are by far the most common and the most commonly welded of all of the stainless steel alloy families. A stainless steel is austenitic if its crystal structure is face-centered cubic. These steels are easily identified by the fact that they are usually non-magnetic unless they are cold worked. Cold working tends to induce martensite formation when the austenite is metastable, and martensite is ferromagnetic. It should be noted that the composition of many, but not all, nominally austenitic stainless steels is adjusted by the steel mill so that the alloy solidifies with a small amount of ferrite. This ferrite usually disappears during hot working, but reappears when the metal is autogenously welded, which improves the weldability of the steel.

A first consideration in welding these steels is usually whether or not some ferrite can be obtained in the weld metal. If so, austenitic alloys are usually easy to weld. However, the austenitic alloy weld metals in which the formation of ferrite is not possible are often susceptible to solidification cracking. Therefore many questions relate to the possibility of obtaining ferrite in the weld metal. More information on austenite, ferrite, and other phases can be found in the references listed in Annex A.

Chapter 2 Welding of Ferritic Stainless Steels

A stainless steel is ferritic if its crystal structure is body-centered cubic. These steels are strongly ferro-magnetic and are usually soft. They can be subdivided into three generations. The first generation contains enough carbon so that some austenite forms in the HAZ during welding, and that austenite transforms to martensite upon cooling. As a result, first generation ferritic stainless steels usually require preheat and postweld heat treatment in order to obtain reasonable properties after welding.

The second generation of ferritic stainless steels are those with approximately 12% to 16% chromium and with stabilizing elements such as titanium, which combines with carbon to remove the carbon from solid solution and thereby prevents austenite formation. These are easily welded without preheat and are usable without postweld heat treatment.

The third generation of ferritic stainless steels are extremely low in carbon content and contain 18% or more of chromium and usually considerable molybdenum. Outstanding corrosion resistance is expected of these alloys, especially in chloride-containing environments. They are susceptible to grain growth in the weld metal and heat affected zone which can result in serious embrittlement. These steels need to be welded with low heat input, preferably in a single pass. They can be embrittled by formation of intermetallic compounds during heat treatment, so in general heat treatment is avoided.

Chapter 3

Welding of Martensitic Stainless Steels

Martensitic stainless steels contain enough carbon and nickel to obtain nearly 100% austenite at high temperatures. The austenite transforms to martensite during cooling to ambient temperature or below. These steels are air hardening, which means that they will transform to martensite under almost any conceivable cooling rate. As a result, they are susceptible to hydrogen induced cracking and therefore generally require preheat and controlled cooling after welding to avoid cracking. Most martensitic stainless steels also require postweld heat treatment to obtain optimum properties.

A major concern with these steels is the amount of carbon. As the carbon content is increased, the requirements for preheat, controlled cooling after welding and postweld heat treatment become more stringent in order to avoid hydrogen induced cracking and to obtain useful properties.

Chapter 4

Welding of Duplex Stainless Steels

Duplex stainless steels solidify as essentially 100% ferrite, approximately half of which transforms to austenite during cooling at temperatures above about 1900°F (1040°C). The base metals are held in the temperature range for austenite formation so they can reach this desirable room temperature microstructure. The formation of austenite requires diffusion of alloying elements, so time in the austenite forming temperature range is critical. This time is a matter of seconds for the weld metal and heat-affected zone, while the base metal has many minutes to complete the transformation.

Welding filler metals commonly are enriched in nickel content to assist in austenite formation under the more rapid cooling conditions of welding. However, the critical element in formation of austenite in the weld metal and in the heat affected zone is nitrogen. Nitrogen is a much smaller atom than the iron, chromium, nickel and molybdenum atoms that make up the majority of the duplex stainless steel. As a result, nitrogen can diffuse much faster than any other element which accounts for its ability to speed austenite formation. With insufficient nitrogen, as-welded micro-

structures in the weld and HAZ tend to contain too much ferrite which makes the weldment brittle.

The ferrite in duplex stainless steels can also transform at temperatures below that which forms austenite into intermetallic compounds. The intermetallic compounds severely embrittle the alloy. It is essential to avoid extended time in this intermediate temperature range.

Chapter 5

Welding of Dissimilar Alloys

Dissimilar alloy welding can include both joining two different alloy types and cladding of one alloy with another. The range of possibilities is nearly unlimited. In many cases, both for joining and for cladding, the filler metal is austenitic. Then the emphasis is often on choosing a filler metal that will, under the dilution conditions of the weld, result in weld metal containing a little ferrite to avoid solidification cracking susceptibility. The filler metal selection can become a complex problem because dilution changes from one weld pass to another. Estimates of dilution become essential for selecting filler metal for these applications.

Chapter 6

Odds and Ends

The majority of questions and answers in this book are arranged according to alloy type. However, some questions are not specific to one alloy type. These are collected in this chapter, along with questions addressed to precipitation hardening stainless steels which can have two microstructure types—martensitic and austenitic.

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Basic Safety Precautions

Burn Protection. Molten metal, sparks, slag, and hot work surfaces are produced by welding, cutting, and allied processes. These can cause burns if precautionary measures are not used. Workers should wear protective clothing made of fire-resistant material. Pant cuffs, open pockets, or other places on clothing that can catch and retain molten metal or sparks should not be worn. High-top shoes or leather leggings and fire resistant gloves should be worn. Pant legs should be worn over the outside of high-top shoes. Helmets or hand shields that provide protection for the face, neck, and ears, and a head covering to protect the head should be used. In addition, appropriate eye protection should be used.

Electrical Hazards. Electric shock can kill. However, it can be avoided. Live electrical parts should not be touched. The manufacturer's instructions and recommended safe practices should be read and understood. Faulty installation, improper grounding, and incorrect operation and maintenance of electrical equipment are all sources of danger. All electrical equipment and the workpiece should be grounded. The workpiece lead is not a ground lead. It is used only to complete the welding circuit. A separate connection is required to ground the workpiece. The workpiece should not be mistaken for a ground connection.

Fumes and Gases. Many welding, cutting, and allied processes produce fumes and gases which may be harmful to health. Avoid breathing the air in the fume plume directly above the arc. Do not weld in a confined area without a ventilation system. Use point-of-welding fume removal when welding galvanized steel, zinc, lead, cadmium, chromium, manganese, brass, or bronze. Do not weld on piping or containers that have held hazardous materials unless the containers have been inerted properly.

Compressed Gas Cylinders. Keep caps on cylinders when not in use. Make sure that gas cylinders are chained to a wall or other structural support. Do not weld on cylinders.

Radiation. Arc welding may produce ultraviolet, infrared, or light radiation. Always wear protective clothing and eye protection to protect the skin and eyes from radiation. Shield others from light radiation from your welding operation. The use of filtering masks or airline respirators will be required if it is determined that personnel are being exposed to excessive pollutants.

Additional information on welding safety may be obtained from the American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166. ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, and the *AWS Safety and Health Fact Sheets* are available online and free of charge on the AWS website: <http://www.aws.org/technical/facts/>.

Chapter 1

Welding of Austenitic Stainless Steels

1.1 Sticky Slag in SAW of 347?

 Normally, when I use submerged arc welding for 304L stainless (with ER308L wire), the slag comes off clean. But when I switch to 347 stainless with ER347 wire, there are little bits of slag stuck to the weld metal surface after the bulk of the slag is removed. Why is that, and what can be done about it?

July 1999

This slag removal problem is almost certainly due to the presence of niobium (also known as columbium) in the 347, in combination with your choice of flux. Niobium is present in the alloy to “stabilize” it against chromium carbide precipitation, which can damage corrosion resistance. Niobium also increases the strength of the alloy at high temperatures. It is an integral part of 347 stainless. The niobium is reacting with the flux, and the reaction products are causing the slag to stick. This is a common problem with stabilized stainless steels such as 347 and 321 (321 is stabilized with titanium instead of niobium). Many, but not all, SAW fluxes, whose slag removes cleanly from most stainlesses, will leave residual slag on 347. Since there is no AWS or other classification system that addresses this problem, there is no generic answer to your problem. A change in flux is called for. I suggest that you contact the technical department of one or more flux manufacturers for a recommendation concerning flux whose slag removes cleanly from 347 stainless. You may have to pay more for a different flux to overcome this problem.

1.2 Magnetism in ER308LSi Filler Metal?

 I recently noticed that my ER308LSi wire sticks to a magnet. I thought 308L is an austenitic stainless and therefore nonmagnetic. Could something be wrong with the wire?

July 1999

In the annealed condition, 308L or 308LSi is fully austenitic and therefore nonmagnetic. However, 308L and 308LSi are rather low-alloy austenitic stainless steels, and

the cold working that occurs during drawing of the wire to final size can induce the austenite to transform in part to martensite. Martensite is ferromagnetic, so it is attracted to the magnet. When the wire is melted in the arc, the martensite disappears. The resulting weld metal will consist mainly of austenite, with, usually, a small amount of ferrite to prevent hot cracking. The ferrite is also ferromagnetic, so the weld metal will likely be slightly attracted to a magnet, but not as strongly as the wire.

If you want to check this, cut a 2–3 ft length of the wire, clamp one end to a steel plate connected to your welding power source ground cable and slip the other end into the welding gun contact tip with no other wire in the gun. Don't hold on to the wire. Pull the gun trigger to let current flow through the wire, and let it heat up to a bright yellow color (but don't allow it to melt). The heating will cause the martensite to revert back to austenite. Release the trigger and let the wire cool. Now you should find that the wire does not stick to a magnet. The wire should also be much softer than it was before you heated it. The wire has now been annealed. If the magnetic attraction has gone, it is very unlikely that something is wrong with the wire.

On the other hand, if the magnetic attraction is still there after annealing, the problem could be with the wire composition—it might not be 308L or 308LSi. The wire should be checked further.

Note also some higher alloyed stainless steel wires, such as 309L or 309LSi, can contain some ferrite in the wire. This ferrite may not be removed by annealing, so the wire can continue to be attracted to a magnet after annealing.

1.3 Why is 304L Limited to 0.03% C while E308L-16 is Limited to 0.04% C?

❓ Type 304L or 316L base metal is limited to 0.03% carbon maximum. I understand that this limit is imposed to prevent sensitization during welding. But the corresponding weld filler metals in AWS A5.4, E308L-16 or E316L-16, for example, are allowed to reach 0.04% carbon. Is the weld metal less affected by sensitization, or is 0.04% carbon maximum only an acknowledgement that the filler metals can't do better than that?

September 1999

Chromium and carbon combine in stainless steels to form a series of carbides. The carbide that causes the most trouble in stainless steels has approximately the formula Cr_{23}C_6 , although some of the chromium atoms are replaced by iron and molybdenum if present. This is a dangerous carbide because one atom of carbon can tie up almost four atoms of chromium, and because carbon atoms diffuse much more rapidly than do chromium atoms. In stainless steel base metals, these carbides tend to form along grain boundaries. The problem they cause is most severe when the metal reaches a peak temperature in the range of 900 to 1600°F (480 to 870°C). Invariably, a portion of the weld heat-affected zone (HAZ) reaches peak temperatures in this range. Carbon,

which is a very small atom compared to the matrix atoms of iron, chromium and nickel, diffuses rapidly in this temperature range, so the entire grain is a source of carbon for the carbides. But chromium, a large atom, diffuses slowly, so that only the part of the grain very nearby the grain boundary is the source of the chromium for the carbides. The result is a chromium-depleted zone adjacent to the grain boundary. This zone is then preferentially corroded in an aggressive environment. When the corrosive media dissolves the material adjacent to the grain boundaries, the grains themselves fall out and corrosion advances. This phenomenon is called sensitization.

The corresponding weld metals (308L for 304L base metal or 316L for 316L base metal) normally contain some ferrite. When heated by a subsequent weld pass into the sensitization temperature range, they provide an alternative to grain boundaries as chromium carbide precipitation sites. The alternative is in the ferrite itself. On a microscopic scale, the ferrite is richer in chromium, by several percent, than the matrix austenite. So carbides prefer to form in the ferrite rather than at grain boundaries. Since the ferrite is richer in chromium than the austenite, and since chromium diffuses much faster in ferrite than in austenite, there is little or no problem with sensitization of these ferrite-containing weld metals. Sensitization is then largely a problem only in the base metal HAZ, which contains no ferrite. It is, therefore, technically correct to allow for more carbon in low-carbon weld metal than in low-carbon base metal.

1.4 Can I Use ER308LSi for SAW?

 Our shop has been using GMAW with ER308LSi and 99% argon-1% oxygen shielding on a seamer for joining 304L sheets up to 1/4 in. thick. We use 0.045 in. and, for the thicker material, 1/16 in. wire. Now we want to seam some 3/8-in. thick material. It's been suggested to use the lower silicon ER308L for submerged arc welding (SAW) because the weld will have too much silicon in it if the higher silicon wire is used, but, because of inventory control problems, I don't want to have both ER308L and ER308LSi in the shop. Is there any harm in using ER308LSi in SAW for this thicker material?

September 1999

There is a well-known association of high silicon content with hot cracking in austenitic stainless steel welds when there is no ferrite in the weld. But if you weld 304L base metal with ER308LSi filler metal, using either GMAW or SAW, you can expect ferrite in the weld metal. Therefore, there is no metallurgical problem with using ER308LSi in SAW. However, a chemical analysis of such a weld showing more than 1% silicon might raise a few eyebrows if the weld ferrite content is not being checked. You can keep those eyebrows in place by a judicious choice of flux for SAW.

There is no good classification system for SAW fluxes used with stainless steel weld metals, so it is not possible to give a generic answer about flux choice. But in general terms, SAW fluxes for stainless steel can be loosely fit into one of three categories. There are fluxes high in silica content, which burn out a significant amount of chromium from the weld metal and replace some of it with silicon. Such fluxes are metal-

lurgically described as acid fluxes. Second, there are fluxes that contain very little silica. These burn out only a small amount of chromium and add very little silicon. They are metallurgically described as basic fluxes. Third, there are fluxes that contain metallic chromium as well as slag-forming materials. The metallic chromium alloys in part with the weld metal so that the undiluted weld metal composition equals or, more usually, exceeds the chromium content of the wire. Such fluxes are usually described as chromium-compensating, but they are also usually somewhat acidic and cause significant silicon pickup in the weld metal.

From the point of view of keeping eyebrows in place, you might want to select fluxes that fit only the metallurgically basic description. The weld deposit with such a flux and ER308LSi wire will not exceed 1% silicon content, and you won't have to explain about more than 1% silicon not producing hot cracks when the weld contains some ferrite. Talk to a technical representative of your flux supplier to determine which fluxes are metallurgically "basic" and suitable for stainless steel.

1.5 Hot Cracking in 320?



While trying to weld Type 320 stainless by GTAW using a matching filler metal (ER320), I am getting a lot of weld cracking. What can be done to avoid this?

September 1999

Type 320 stainless steel is nominally 20% Cr, 34% Ni, 2% Mo, 3% Cu with some Nb (Cb) for stabilization. Because of the high nickel content, it is not possible to obtain any ferrite in this fully austenitic steel weld metal. I assume that your cracking is mainly along the weld centerline, which is most common in such alloys.

There are two things you can do to improve the likelihood of crack-free welding. The first is to change to ER320LR filler metal. The "LR" means "low residuals," i.e., reduced levels of carbon, silicon, sulfur, phosphorus, and niobium. These five elements are known to promote hot cracking, which occurs during solidification. Reducing these elements reduces hot cracking tendencies.

The second thing you can do is "weld ugly." Most welders like to make pretty beads that wash out well and have little or no convexity. In fully austenitic steels like Type 320, this practice promotes hot cracking. "Weld ugly" means deliberately using too much filler metal so a strongly convex bead results. The extra metal acts much like a riser on a casting by supplying extra metal during weld shrinkage as solidification progresses. In the same vein, make certain the crater is filled, or, better, is overfilled, at each arc stoppage. While no one likes to grind welds, it is cheaper to grind off excessive filler metal than it is to cut out cracked weld metal and weld again. Also, it is beneficial to use low travel speed so the crater has an elliptical tail. If the travel speed is higher, the crater tail and the weld ripples will form a series of sharp Vs along the weld centerline, a shape that promotes hot cracking.

1.6 Ferrite Standards?



What are ferrite standards for stainless welds, and where do I get them?

October 1999

There are written standards and physical standards. The written standards tell how to use the physical standards for calibration of instruments to measure ferrite in nominally austenitic and duplex ferritic-austenitic stainless steel weld metals.

The written standards are AWS A4.2, available from the American Welding Society in Miami, Fla., and ISO 8249, available from the ISO in Geneva, Switzerland, or from a national standards body that is an ISO member, such as ANSI in the United States, BSI in the United Kingdom or DIN in Germany. At the present time, the published AWS A4.2 covers Ferrite Number (FN) measurements from zero to 100 FN, while the published ISO 8249 only covers zero to 30 FN. ISO 8249 is currently being revised to expand the range of calibration to 100 FN as well. This revision will probably be published in 2000. The two standards are technically equivalent, though the wording is different.

There are two types of physical standards, referenced in both written standards as “primary standards” and “secondary standards.” A number of primary standards, or a number of secondary standards, are required by the written standards for proper calibration.

The primary standards consist of an iron substrate that is ferromagnetic, covered by various thicknesses of nonmagnetic material. The nonmagnetic coating thickness of a given primary standard is precisely controlled. A table in the written standard provides a calibration between Ferrite Numbers and nonmagnetic coating thickness. The greater the nonmagnetic coating thickness, the lower the FN. The table is specific to a particular instrument, the Magne-Gage^{®1}. Because the coating thickness standards do not have the same microstructure as weld metal, different instrument probes respond differently to a given nonmagnetic coating thickness; therefore, the calibration with primary standards cannot be extended to all instruments. There are also calibration tables in the AWS A4.2 standard, but not in ISO 8249, for a limited number of other instruments.

To provide for calibration of numerous instruments in addition to a Magne-Gage[®], secondary standards were devised that have the same microstructure as weld metal. The FN of a given secondary standard is first assigned as the average FN obtained by Magne-Gages[®] calibrated by primary standards. Then the secondary standards can be used to calibrate any of a large number of suitable commercial instruments.

Both primary standards and secondary standards are available from the U.S. National Institute of Standards and Technology (NIST), in Gaithersburg, Md. The primary standards have many uses other than calibration of instruments for ferrite measurements, so they are not offered by NIST according to Ferrite Number, but according to

1. Magne-Gage is a registered trademark of Magne-Gage Sales & Service Co., Inc.

coating thickness. At the present time, applicable sets of three or four primary standards are identified by NIST as SRM 1357, 1358a, 1359, 1360, 1361a, 1362b, 1363a, and 1364a. To decide which sets you need, you should first examine the calibration table in the written standard for thicknesses corresponding to the Ferrite Number range of interest to you. The secondary standards (eight per set) specific to the range of 0 to 30 FN are identified by NIST as SRM 8480, and those specific to the range of 30 to 100 FN are identified as SRM 8481. You can obtain pricing and other information from the NIST Standard Reference Materials Web site at: <http://ts.nist.gov/srm>.

Prior to NIST involvement in providing secondary standards, secondary standards were available from The Welding Institute (TWI) in the United Kingdom. At the time of this writing, TWI had a very limited number of sets remaining, with no plans to renew its supply.

1.7 Low FN in Vertical-Up in SMAW Welding?



I'm using some E308L-16 electrodes with a certification that indicates about 8 FN in the weld metal. I'm welding on 304L pipe, mostly in the 5G position, and am required by contract to have 5 FN minimum in the welds. In the parts of the welds around the 12 o'clock position, I'm doing okay, but in the parts of the welds around 3 o'clock or 9 o'clock, I sometimes get less than 5 FN. Why? And what can I do about it?

October 1999

It is a rather common experience with SMAW to find less ferrite in uphill, vertical-position welding than in the flat position. This is usually due to nitrogen pickup from the air outside the arc. In SMAW, some air always gets into the arc. In the uphill, vertical position, a welder tends to hold a longer arc than in the flat position. When the arc is longer, the shielding from the coating is stretched thinner, so more air gets into the arc. Whipping the electrode from side to side aggravates this problem. The nitrogen molecules from the air are broken apart by the arc into single atoms, which easily dissolve into the weld metal. Nitrogen is a very powerful alloying element in stainless steel weld metal in terms of promoting austenite at the expense of ferrite. A drop in ferrite from 8 to 4 FN would correspond to a nitrogen pickup of only 0.06%.

With the electrodes you have, the best solution is to concentrate on welding technique. Keep as short an arc length as possible, especially in the uphill, vertical position. Avoid inclining the electrode steeply upward when welding uphill in the near vertical position as this tends to open the weld pool to more air. Instead, try keeping the electrode nearly perpendicular to the surface of the joint so the electrode obstructs air from getting into the arc. When weaving, travel slowly from side to side of the bead, not rapidly. These techniques will minimize the nitrogen pickup, and you should be able to stay above 5 FN.

In the future, you might want to consider using E308L-15 electrodes instead of E308L-16 electrodes. The -15 coating type is usually more efficient in terms of excluding nitrogen from the weld pool, though most welders don't like the operating characteristics of the -15 coating as well as the -16 coating.

1.8 Filler Metal for 6% Mo Stainless?

 I have to weld a 6% molybdenum super austenitic stainless steel. I've been told to use high molybdenum nickel-based alloy filler metal, which is very expensive. Is this necessary?

November 1999

In a word, yes. The super austenitic stainlesses, such as UNS S31254 (nominally 20% Cr, 18% Ni, 6% Mo, 1% Cu, 0.2% N) or UNS N08367 (nominally 21% Cr, 25% Ni, 6% Mo, 0.2% N) are almost always chosen for pitting corrosion resistance. Molybdenum and nitrogen together are mainly responsible for the pitting corrosion resistance. Molybdenum segregates on a microscopic scale during solidification of weld metal, so the dendrite cores (first bits of solid to form) are lower in Mo than the average composition. Without the benefit of an extensive solution anneal, such as the base metal gets during processing, this segregation remains when the weld is cooled to ambient temperature. Then, the dendrite cores become preferential pitting sites. The solution to the problem is to over-alloy the weld metal with molybdenum so the dendrite cores have at least as much Mo (6%) as the nominal composition of the base metal. This requires something more than 8% Mo in the weld metal. Unfortunately, when more than 8% Mo is present in an iron-based alloy, it becomes impractical to avoid formation of chi phase (an intermetallic compound of approximate composition Fe_3CrMo) during cooling. Chi phase formation severely embrittles the metal and damages corrosion resistance. Limitation of iron, as occurs when a nickel-based alloy filler metal is used instead of a stainless steel, prevents chi phase from forming, so the high-Mo filler metal has acceptable as-welded properties. As a result of all of these considerations, the normal filler metals specified are the nickel-based alloy electrodes given in AWS A5.11 as classes ENiCrMo-3 (nominally 21% Cr, 9% Mo, 3.5% Nb, 60% Ni) and ENiCrMo-10 (nominally 21% Cr, 13% Mo, 4% Fe, 3% W, 55% Ni), or the corresponding wire classes ERNiCrMo-3 or ERNiCrMo-10 specified in AWS A5.14. Yes, they are expensive as compared to the “super austenitic” stainless steel base metal.

1.9 No Ferrite but Centerline Cracking in GMAW?

 I'm making outside corner welds on 304L stainless boxes using ER308LSi. Most of the welds are fine, but I occasionally get a centerline crack. Would a change to ER308L help?

January 2000

I doubt it. A centerline crack in such a weld is almost invariably the result of no ferrite in the weld. Both ER308LSi and ER308L are controlled ferrite products, typically having a composition that calculates to about 8 to 12 Ferrite Number on the WRC-1992 Diagram. The 304L base metal composition is likely to predict a little less ferrite, typically 3 to 6 FN. So the diluted weld metal in your corner weld should contain

enough ferrite for freedom from hot cracking (the centerline cracking you occasionally observe).

When a centerline crack occurs in these materials, loss of ferrite due to contamination is most likely the cause. The usual suspect is nitrogen. Nitrogen is a very powerful austenitizer. A nitrogen pickup on the order of 0.06%, as compared to the wire content, could be enough to suppress ferrite and lead to hot cracking. You could cut some chips from a cracked weld and have them analyzed for nitrogen, then compare the results with the wire manufacturer's certified composition, or analyze the wire yourself for this information, to be sure nitrogen is the culprit.

There are two likely possibilities for nitrogen contamination. One is plasma arc cutting the joint edge without subsequently grinding to clean metal. Plasma arc cutting of stainless is usually done with either nitrogen or air as the cutting gas, so nitrogen contaminates the cut edge. If you are welding over the kerf without first grinding to clean metal, the nitrogen in the kerf will contaminate the weld, which could be responsible for your cracking.

The other likely cause of the problem is disturbance of the shielding gas. An outside corner weld is more prone to this than most other joints, because the gas has to cover 270 deg of space, instead of only the usual 180 deg for a butt-weld or 90 deg for an inside corner or fillet weld. Are there fans or other sources of air movement around the welding area? If so, try putting up baffles or shields to protect the arc from the draft. Or, if there is a local exhaust for fume control near the arc, try moving it a bit farther away.

One other possibility is that you are using an inappropriate shielding gas. Gases with high carbon dioxide content (for example, 75% argon-25% carbon dioxide) will produce carbon pickup in GMA welding. Carbon is an austenitizer, just like nitrogen, and carbon pickup can also lead to loss of ferrite, with resulting centerline cracking. For GMA welding of stainless, there should be no more than 5% carbon dioxide in the gas shielding. (This is not true for flux cored arc welding [FCAW]—the slag in FCAW limits contact of the metal with the gas, so carbon pickup is not a problem with even 100% carbon dioxide shielding.)

1.10 HK-40 Repair Welding?



I am trying to weld HK40 pipe, but the joint keeps cracking beside the weld. What can I do?

January 2000

Essentially, HK40 is a high-carbon version of 310 stainless. The nominal composition is 0.4% C, 25% Cr, 20% Ni. The usual welding filler metal is E310H-15, although some nickel-based alloy filler metals have also been used. Normally, this alloy is used for creep resistance at temperatures like 1600°F (870°C). In the solution-annealed condition, in which this pipe is normally supplied, the ductility of the material is comparable to that of other austenitic stainless steels, and it is readily weldable. However, at high service temperatures, chromium carbides precipitate throughout the microstructure.

ture. This causes the ductility at ambient temperatures, where repair welding might take place, to approach zero. The base metal is then unable to accommodate any shrinkage strains associated with welding. From your description of the cracking, I assume your pipe has been in elevated temperature service and is now embrittled.

Harry Ebert wrote a paper titled “Solution Annealing in the Field” for the February 1974 *Welding Journal*. He showed an annealing procedure using electric heaters to achieve a temperature of approximately 2150°F (1175°C). At this temperature, the carbides dissolve. For a complete solution anneal, after the time at annealing temperature, HK40 is water-quenched to prevent re-precipitation of carbides during cooling and obtain maximum ductility. However, Ebert showed that removal of the heaters and air cooling, while producing some carbide precipitation, resulted in enough ductility for successful repair welding of the embrittled pipe. I’d suggest examining Ebert’s paper to see if this method can be applied to your situation.

1.11 Filler Metal for 1/4 Hard 304L?



I’m attempting to develop a welding procedure for 1/4 hard 304L sheet, but the transverse tensile strap always breaks in the weld. The fracture surfaces appears ductile, and there are no defects. I’ve tried ER308LSi and ER309LSi. What filler metal can I use to pass this test?

February 2000

The problem stems from a strength mismatch between the as-deposited weld metal and the cold-worked base metal. The 1/4 hard 304L sheet, if bought to the ASTM A666 specification, is required to have tensile strength of at least 125 ksi (860 MPa) and yield strength of at least 75 ksi (515 MPa). This is a considerable increase in strength, induced by cold working, from the requirements of ASTM A240 for annealed 304L sheet, which is 70 ksi (485 MPa) tensile strength and 25 ksi (170 MPa) yield strength. In the as-welded condition, the weld metal doesn’t get the benefit of cold working, so it can’t match the strength of the cold-worked base metal.

There are two possible approaches to solving the problem, and both are imperfect. One is to cold work the weld area. Roll planishing has been used on welds in stainless steel sheet metal to increase the strength of the weld area. This cold works the weld by squashing the weld reinforcement, and it can produce considerable weld area strengthening. Roll planishing works acceptably for butt-joint welds, but it is virtually impossible to apply to fillet welds.

The other possible approach is to choose a compatible higher-strength filler metal. AWS A5.9, which is the specification applicable to such GMAW wires as ER308LSi and ER309LSi, doesn’t address strength, so it is useful to look to the AWS A5.4 specification for covered electrodes for SMAW as a guide to what can be expected from GMAW wires. From A5.4, one can see 308L and 309L are required to meet 75 ksi (520 MPa), with no yield strength requirement. A martensitic filler metal, such as 410NiMo, which is required to provide at least 110 ksi (760 MPa) tensile strength, is not appropriate for welding austenitic stainless steel. But the very high ferrite duplex ferritic-austenitic stainless steel filler metals are quite compatible with austenitic

stainless steels. While not normally thought of in that sense, 312 is, in fact, a duplex stainless steel, and it provides at least 95 ksi (660 MPa) tensile strength. Type 2209 provides at least 100 ksi (690 MPa) tensile strength, and 2553 provides at least 110 ksi (760 MPa) tensile strength. Of these, ER2553 is difficult to find, but ER312 and ER2209 are reasonably available. Another possibility is the high nitrogen austenitic compositions ER209 and ER240, whose SMAW counterparts are required to provide at least 100 ksi tensile strength. Unfortunately, these are also hard to find. All of these filler metals are stronger than ER308LSi or ER309LSi, but they still are likely to undermatch the 1/4 hard 304L base metal.

Actual weld metal strength of these filler metals can be appreciably higher than the specified minimum values. But there is also the matter of the heat-affected zone. Welding of the 1/4 hard 304L will produce some annealing in the HAZ, which will reduce its strength. So you may find that the fracture in a transverse tensile test shifts from the weld metal to the HAZ when you change to higher strength weld filler metal.

Unless you can cold work the weld deposit and HAZ, I don't think you can consistently match the strength of the 1/4 hard 304L. You will then have to take some degree of undermatch into account in your design.

1.12 High Silicon vs. Normal?



High silicon wires such as ER308LSi or ER309LSi wet better in GMA welding than their lower silicon equivalents such as ER308L or ER309L, but is there a downside to using these wires in gas metal arc or gas tungsten arc welding?

February 2000

The silicon limits specified in AWS A5.9 for all the high silicon wires, such as ER308LSi or ER309LSi, are 0.65 to 1.00%. The silicon limits for the non-high silicon wires, such as ER308L or ER309L, are 0.30 to 0.65%. All other chemical composition limits are identical for the high silicon wires as compared to their non-high silicon counterparts. For comparison, the silicon requirement for a covered electrode deposit of, for example, E308L-1 6 is 0.90% maximum, which is expected to be raised to 1.00% maximum when the AWS A5.4 specification is next revised. There is no minimum silicon content, nor is there a division in silicon contents, for covered electrode deposits. You can expect more silicon with E308L-17 than with E308L-16 or E308L-15, but no distinction is made by the specification. Correspondingly, for flux cored wires classified according to AWS A5.22, the silicon requirements are 1.0% maximum, with no minimum, for E308LT0-1 and other classifications. Again, there is no distinction made regarding silicon levels.

If you examine AWS A5.9 further, you will notice there is no high silicon version of the fully austenitic alloys ER310, ER320 and ER330. Weld metals from these alloys cannot contain any ferrite, so their weld metals are somewhat sensitive to hot cracking. In this case, higher silicon would be detrimental because it increases the tendency for hot cracking. But ER308L, ER308LSi, ER309L and ER309LSi filler metals are designed to provide some ferrite in the weld metal. When there is a little ferrite in the

weld metal (only about 3 FN is necessary), there is no tendency to hot cracking, and high silicon has no adverse effect.

So, unless you manage to eliminate the ferrite from the as-deposited weld metal, there is no downside to using the high silicon wires as compared to the non-high silicon wires.

1.13 Welding Free-Machining Stainless?



I am trying to make fillet welds of 303 stainless steel threaded fittings to 304 stainless heads and shells. I've tried both SMAW and GTAW with 308L, 316L and 309L filler metals, but the welds frequently crack and leak. Would 312 filler metal be a better choice?

March 2000

Types 304 and 303 are, at first glance, compositionally almost the same (nominally 18% Cr, 8% Ni). But the 303 stainless steel, as specified by ASTM A581 or A582, must contain at least five times as much sulfur as the maximum amount of sulfur allowed in ASTM A240 Type 304 (0.15% S minimum in 303 vs. 0.030% maximum in 304). This sulfur exists in the steel in the form of sulfides. The sulfides break up chips during machining operations. As a result, machining of 303 and other so-called “free-machining” stainless steels is much easier than machining of 304 stainless steel. So it is attractive to make parts such as threaded fittings, intended for mechanical joints, of 303 or similar stainless steel.

But the sulfur that makes the 303 steel easy to machine also promotes hot cracking during welding. Normally, filler metals such as 308L, 316L or 309L contain enough ferrite that their welds are free of hot cracking tendencies. But a normal ferrite-containing weld cannot handle as much sulfur as is present in 303 stainless. Such steels are normally considered to be unweldable due to their hot cracking tendency. Brooks and Lambert (*Welding Journal* 57(5): 139-s to 143-s) developed a relationship between the total of phosphorus and sulfur in the weld metal and the required minimum amount of ferrite necessary to prevent hot cracking. Their work showed that, when the total of P+S exceeded about 0.05%, 13 to 14 FN was necessary to prevent hot cracking in their austenitic stainless steel welds. The sulfur alone in 303 considerably exceeds the P+S limit of Brooks and Lambert.

Type 312 filler metal (nominally 29% Cr and 9% Ni), undiluted, is very high in ferrite, typically on the order of 70 FN. So 312 filler metal can provide some improvement in hot cracking resistance as compared to the filler metals you have already tried. However, the filler metal choice cannot affect the sulfide stringers in the hottest part of the heat-affected zone (HAZ). These stringers produce liquid films that wet grain boundaries at welding temperatures and cannot resist shrinkage stresses during cooling. So you are likely to then find HAZ cracks in place of weld metal cracks. A much better solution is to replace the 303 fittings with 304L fittings. You may pay more for machining the 304L fittings than you would the 303 fittings, but you will be able to use 308L filler metal without fear of hot cracking. The reduction in repairs or scrap should more than offset the increased cost of 304L fittings.

A change to another grade of free-machining stainless steel, such as 303Se, is unlikely to improve your cracking situation. Whatever inclusions are deliberately added into the steel, to make it free-machining, also make the steel sensitive to hot cracking.

1.14 Best Electrode to Use for Long-Term Exposure?



What would be the best austenitic stainless steel electrode to use for long-time exposure in the temperature range of 1400 to 1600°F?

March 2000

This is a very complicated question because the answer depends strongly upon the base metal(s) to be joined, the service environment and the design mechanical property requirements. The common austenitic stainless steel base metals, such as 304, 316, 16-8-2, or 347, have barely adequate oxidation (scaling) resistance to survive in air at 1600°F (870°C) for extended periods. But if the base metal oxidation resistance is adequate, then matching filler metals (308, 316, 16-8-2, 347) would be appropriate. Normally, higher carbon versions of both the base metal and filler metal would be chosen for higher strength (304H, 316H, 16-8-2H, or 347H base metal and 308H, 316H, 16-8-2, or 347 filler metal).

On the other hand, if the environment contains sulfur (SO₂ or H₂S), then these stainless steels would have inadequate resistance to scaling at these temperatures. A higher chromium stainless steel such as 309 (nominally 23% Cr, 13% Ni) or 310 (25% Cr, 20% Ni) would likely be chosen. Again, a matching filler metal would normally be selected.

If a matching filler metal were chosen, it would be appropriate to specify a limit on weld metal ferrite content, because, in this temperature range, transformation of ferrite to sigma phase is quite rapid, and these filler metals, except for 310, are normally designed to contain some ferrite in their as-deposited condition. Sigma phase in large amounts can severely embrittle the steel. An upper limit of 10 FN in the as-deposited weld metal is often specified, although limits of 12 and 15 FN have also been used. A ferrite limitation on 310 stainless steel filler metal is unnecessary because the weld metal is fully austenitic.

A major concern about the austenitic stainless steels mentioned above is their very low resistance to creep above about 1300°F (700°C). Creep is plastic deformation under prolonged loading at stresses well below the yield strength measured in a short time tensile test. The ASME *Boiler and Pressure Vessel Code*, Section II, Part D, provides design-allowable stresses for such steels on the order of 2100 lb/in.² (14 MPa) or less, depending upon ASTM specification and product form of the steel, at 1400°F (760°C), 1300 lb/in.² (9 MPa) at 1500°F (815°C), and nothing above that temperature. The Code considers 1500°F to be the maximum service temperature for all of these

austenitic stainless steels, even 310. The Code appears to prefer nickel-based alloys over austenitic stainless steels in the 1400 to 1600°F temperature range.

If your weldment is not covered by the ASME Code, and if these property limitations are acceptable in your design, then the “best” filler metal for service in the temperature range of 1400 to 1600°F would normally be the filler metal that most closely matches the base metal, with a ferrite limitation of 10 FN maximum. Further, this limit should be applied to actual measured ferrite content, determined on all-weld metal with an instrument calibrated according to AWS A4.2. The WRC-1992 Diagram should be used only for specifying ferrite in the form of bare solid wire or consumable inserts. It is not safe to assume that off-the-shelf electrodes or consumable inserts will meet this limit. Since the AWS filler metal specifications do not specify ferrite requirements, this requirement should be specified in your purchase order, as provided for in AWS A5.01, *Filler Metal Procurement Guidelines*.

If you can make your question more specific, I should be able to make my answer more specific.

1.15 How to PWHT 304L Weldments for Dimensional Stability?



After making a large and rather complicated weldment of 304L stainless steel, the weldment has to be machined to very tight tolerances. Is it advisable to stress relieve after welding to improve dimensional stability during machining, and, if so, at what temperature?

April 2000

Postweld heat treatment (PWHT) is commonly applied to large, complex weldments of carbon steel or low-alloy steel to improve dimensional stability during machining. A large, complex weldment can be expected to contain yield point residual stresses somewhere within it. Machining away some metal containing residual stresses causes redistribution of stresses, which often results in the metal moving slightly during machining. A PWHT before machining produces stress relaxation by creep and local yielding because the yield strength of the metal falls with increasing temperature. So, after a properly controlled PWHT, the maximum residual stress should be on the order of the yield strength of the metal at the PWHT temperature, which is a fraction of the room-temperature yield strength. The result is a greatly reduced tendency for the metal to move during welding, and dimensional stability is improved. In principle, PWHT can do the same for austenitic stainless steel weldments.

With carbon steel or low-alloy steel, PWHT is commonly applied at temperatures such as 1150°F (620°C). However, this temperature is dangerous for 304L austenitic stainless steel and similar weldments for two reasons. First, the weld metal, which is

normally 308L, typically contains some ferrite for resistance to hot cracking. At temperatures around 1150°F, the ferrite transforms to sigma phase, a brittle intermetallic compound, which embrittles the weld metal. Second, at the same temperature, the 304L base metal experiences chromium carbide precipitation on the grain boundaries, which depletes the chromium in solution in the metal immediately adjacent to the grain boundaries. This makes the metal sensitive to intergranular corrosion. Type 304L stainless is quite immune to sensitization during the very short thermal cycles of welding, but it is not immune to sensitization during the much longer thermal cycle of PWHT at 1150°F.

If the weldment is not yet made, you can improve the situation relative to sigma phase by using relatively low ferrite filler metal. Normal 308L weld metal often contains more than 10 FN. But 308L filler metals of 4 to 9 FN are available, and use of these can reduce the damage from sigma phase to acceptable levels. If the weldment is already made, of course, there is nothing you can do about the ferrite level.

A safer approach is to reduce the PWHT temperature, I'd suggest PWHT at 800 to 900°F (425 to 480°C) for 2 to 4 h. With this PWHT, 304L base metal welded with 308L filler metal should not form any sigma phase, and the extent of chromium carbide precipitation should be minimal. In this temperature range, the yield strength of the 304L base metal and matching 308L filler metal should be about one half of what it is at room temperature, so considerable stress relaxation can occur. There will not be as much stress relief as at 1150°F, but there should be a big improvement in dimensional stability.

1.16 Can I Break the Coating off a 347 Electrode and Use the Core Wire for GTA?



I am required to make some girth welds in 347 stainless pipe. I plan to put in a GTA root pass, then finish with SMAW. I only need a few pounds of 347 rod for the GTA root. Is it acceptable to break the coating off of a few of my 347 coated electrodes and use the core wire for the filler metal?

July 2000

Type 347 filler metal is almost identical in composition to 308 filler metal. The difference is mainly the 347 contains about 1/2% niobium (Nb, a.k.a. columbium or Cb). So many producers of 347 covered electrodes use 308 or 308L core wire and add the necessary niobium through the coating. Then if you break off the coating, you lose the Nb. The niobium is important for high-temperature strength and low-temperature corrosion resistance of the weld metal. So you could end up with an unsatisfactory root pass composition. I suggest you discuss this with a responsible person in the R&D department of the manufacturer of the covered electrodes you are thinking of decoating for GTAW use.

1.17 Can I Purge with Nitrogen Instead of Argon?

② Our shop welding procedure specifications for GTA welding of austenitic stainless steel pipe, such as 304L or 316L, always call for argon purge of the root. Argon is more expensive than nitrogen, which, I am told, has also been used for root side purging. But I have been told by others nitrogen is risky for purging because it sometimes causes welds to crack. Is nitrogen an acceptable purging gas for stainless?

July 2000

In a word, yes. But nitrogen requires a little more caution than argon. Nitrogen is normally a diatomic molecule (two atoms per molecule), and in that form is nearly insoluble in molten stainless steel. Nitrogen, when confined to the root side of the joint, causes no trouble then, because the two atoms stick together.

A potential for trouble arises if the nitrogen passes through the root into the arc. The arc energy is enough to separate the diatomic nitrogen into monatomic nitrogen ions, which are highly soluble in molten stainless steel. Then nitrogen becomes an alloying element. As an alloying element, nitrogen acts to reduce ferrite in the weld metal. If the ferrite content drops too low (typically less than about 3 FN), the weld may solidify as primary austenite and be sensitive to hot cracking.

Not all stainless weld metals are intended to contain ferrite. Nitrogen pickup makes little difference in welding fully austenitic stainless steels such as 310 or 320. Such fully austenitic stainless steels require more care in any event to avoid hot cracking during welding. Nitrogen pickup with duplex stainless steels, such as 2209, is actually beneficial because those steels have very high ferrite content, which cannot be reduced to near zero by nitrogen, and nitrogen improves their corrosion resistance.

But nitrogen pickup does make a significant difference with the more common austenitic stainless steels such as 304L and 316L, whose weld metals are normally designed to contain a small amount of ferrite. Nitrogen pickup can cause the solidification mode to change from the normal primary ferrite mode to primary austenite mode. Then they become sensitive to hot cracking.

Obviously, welding with a root opening makes it easier for nitrogen from the root to get into the arc. Therefore, a tight root is safer than an open root. Another thing to beware of is use of excessive nitrogen flow to speed up purging. High flow rate, with restricted venting of the purge gas, can force the nitrogen out through the weld root into the arc, even if the root is nominally tight. Fitup is almost never perfect, and a root that is tight in some areas is likely to be not so tight in other areas. A useful practice, after the required root gas purity is obtained, is to reduce the purge gas flow rate to just produce a mild, soft flow out the intended vent opening when welding is to begin.

With proper care and a tight root, including good fitup, nitrogen purge is acceptable for austenitic stainless steels, such as 304L and 316L, whose weld metals are normally designed to contain some ferrite. I would advise against the use of nitrogen for open root GTA welding of these steels.

1.18 Can I Weld Safely on Cold Stainless?

 I need to cut into a 304L stainless pipe that is part of a large system containing water. I then want to GTA weld a T fitting with a shut-off valve already welded to it in place of the segment I cut out for the branching line. To do this without draining the system, I plan to wrap copper tubing around the pipe on either side of the zone where I need to cut and weld, insulate around that and run liquid nitrogen through the copper tubing to freeze the water on either side of the area where I need to cut. This will plug the pipe so the water doesn't run out, except for the liquid between the two frozen plugs. I've used this freeze-plug technique in the past, putting in a threaded fitting and a coupling. But I dislike having to thread the stainless pipe and add the coupling. Also, there is evidence of crevice corrosion at the threaded connections. No doubt, there will be some chilling of the pipe at the cut ends. Is there any harm in welding while the pipe is chilled, or must I preheat the area where I want to weld back to room temperature?

July 2000

First of all, 304L stainless is remarkably tough and ductile, even at the temperature of liquid nitrogen, which is -320°F (-196°C) at normal atmospheric pressure near sea level. This probably accounts for the fact the pipe didn't burst when you froze it. It also accounts for why you don't have to worry about brittle fracture when welding. There is also no concern about hydrogen-induced cold cracking in austenitic stainless steels like 304L. So welding on cold 304L, by itself, isn't a problem. But there is a concern with water, either from some melting of the ice plugs or from condensation from the air on the cold pipe, reaching the joint area. Water getting into the arc or weld pool is likely to produce porosity in the weld. If you freeze-plug the water line about a foot (30 cm) from where you cut and maintain the liquid nitrogen flow until you are done welding, you should be able to keep the freeze-plug from partially melting and letting water run toward the welding area. Fortunately, 304L stainless steel is a rather poor heat conductor.

Once the segment to be replaced with the T is cut out, clean and dry the inside of the pipe for several inches back from the intended joints. Then, preheat the cut pipe for 3 in. (75 mm) back from the intended joint to a temperature slightly above the dew point of the ambient air. This will inhibit condensation in the joint area. The dew point depends on the relative humidity and temperature of the air—if you are in Arizona, the dew point could easily be well below freezing, but if you are in Houston, the dew point could be 60°F (16°C) or higher.

Before beginning welding, gas purge the inside of the pipe between the freeze plugs. The fact that you have seen crevice corrosion at the mechanical connections indicates you need a completely penetrated and oxidation-free weld root. Before physically putting the T into the space between the cut ends of the pipe, place two flexible metal gas purge lines into the T through the valve so one line will place gas near one of the freeze plugs and the other line will place it near the other. Thin-wall copper tubing with a 1/4-in. (6-mm) inside diameter should be flexible enough to be pulled out through the valve after you are done. So the opening for purge gas and air to exit is

about the same as the cross-sectional area of the two purge lines, add wads of fiber-glass or some other noncombustible compressible material into the valve seat to obstruct most of the valve opening. Then partially close the valve to hold the flexible lines and the compressible material in place, but not so tightly that one or both gas lines is pinched closed. Put tape over both joints to keep air out. Plan the application of this tape so that, when peeled back to begin welding, you will begin on the bottom part of the pipe. Run the purge gas (argon is safer than nitrogen, but either can be used—see the next question) through both lines at about 10 to 20 ft³/h (5 to 10 L/min) per line, until the gas coming out the opening in the valve reaches 10 ppm oxygen or less. You will need an oxygen detector to determine the oxygen level is that low—seeing that the exit gas will snuff out a match is not nearly good enough.

When the exiting purge gas is sufficiently low in oxygen, start peeling back the tape over one joint so the bottom half of the girth can be welded first. That way, if the welding does manage to cause some ice to melt, the resulting water inside the pipe will only reach an already completed weld. Weld the second joint with this same sequence.

You should be able to successfully weld the T into the line following this procedure. And the resulting welds, properly purged, will have much less sensitivity to crevice corrosion than your former mechanical connections. I hope my readers will find your freeze plug approach as interesting as I did.

1.19 What is the Right Covered Electrode Filler Metal for 321 Stainless?

❓ We have been making stainless steel components from 304 or 304H stainless using E308H-16 covered electrodes. The customer now wants to replace some of the 304 or 304H base metal with 321 stainless. This means we must make 304 or 304H to 304 or 304H joints, 321 to 321 joints and 304 or 304H to 321 joints. Is there one covered electrode that can be used for all of these joints?

October 2000

Type 321 stainless is essentially Type 304 or 304H with an addition of titanium. The titanium was originally added to the basic 304 composition with the intention of preferentially combining with carbon to produce titanium carbides instead of chromium carbides, thereby virtually eliminating grain boundary corrosive attack in the weld heat-affected zone (HAZ) in aqueous service. In this respect, Type 321 is conceptually very similar to Type 347 stainless, which uses niobium instead of titanium for this purpose. Table 1 compares the compositions of 304, 304H, 321 and 347, as given in ASTM A240.

Today, Types 321 and 347 stainless are not so much used for aqueous corrosion resistance as they are used for high-temperature service. The titanium or niobium carbides

**Table 1—Comparisons of 304, 304H, 321, and 347
Compositions as Given in ASTM A240**

	% C	% Mn	% P	% S	% Si	% Cr	% Ni	% Mo	Other, %
304	0.08 max.	2.0 0 max.	0.045 max.	0.030 max.	0.75 max.	18.0 to 20.0	8.0 to 10.5	—	—
304H	0.04 to 0.10	2.00 max.	0.045 max.	0.030 max.	0.75 max.	18.0 to 20.0	8.0 to 10.5	—	—
321	0.08 max.	2.00 max.	0.045 max.	0.030 max.	0.75 max.	17.0 to 19.0	9.0 to 12.0	—	Ti = 5× (C + N) to 0.70
347	0.08 max.	2.00 max.	0.045 max.	0.030 max.	0.75 max.	17.0 to 19.0	9.0 to 13.0	—	Nb = 10×C to 1.00
ER321	0.08 max.	1.0 to 2.5	0.03 max.	0.03 max.	0.30 to 0.65	18.5 to 20.5	9.0 to 10.5	0.75 max.	Ti = 9×C to 1.0
E347-XX	0.08 max.	0.5 to 2.5	0.04 max.	0.03 max.	0.90 max.	18.0 to 21.0	9.0 to 11.0	0.75 max.	Nb = 8×C to 1.00

that prevent chromium-carbide precipitation also provide improved resistance to creep at elevated temperature. The two steels are largely interchangeable.

Matching ER321 stainless filler metal (classified in AWS A5.9) is available for GMAW and GTAW. However, matching filler metal is not available as covered electrodes because the titanium does not transfer well across the arc of a flux shielded process such as SMAW. But 347 filler metal, as covered electrodes, works quite well and is recommended for 321 base metal. It is also quite acceptable for 304 or 304H joining and for joining these base metals to 321 stainless. Therefore, I suggest you use 347 covered electrodes for all of the joints you described.

1.20 What is the Difference Between Percent Ferrite and Ferrite Number?



I understand a little ferrite in a nominally austenitic stainless steel weld is helpful in preventing hot cracking. But why are there two measures—percent ferrite and Ferrite Number? What is the difference? Does it matter which I specify?

December 2000

You are quite correct, a little ferrite in a nominally austenitic stainless steel weld metal, such as 308L or 316L, is very helpful in preventing hot cracking. So, of course, the various organizations involved in provision of a welding filler metal have a vested interest in how the ferrite requirements for a filler metal are specified. This has an important bearing on whether or not a given lot of filler metal is accepted for use.

By the time of World War II, the desirability of ferrite in nominally austenitic stainless steel welds as a means of preventing hot cracking was recognized. The ferrite was originally detected by metallographic examination. The weld metal examined had to be cut into a specimen suitable for polishing, etched carefully to differentiate between ferrite and austenite and then some means of determining the volume fraction of ferrite had to be applied. Usually, this involved point counting, in which a grid of orthogonal intersecting lines would be overlaid on a photograph of the microstructure. Then, the percent ferrite would be obtained as the number of grid intersection points falling on ferrite as a percentage of the total number of grid intersection points. The method of point counting to estimate volume percent of a given phase is defined in the ASTM E562 standard. Manual point counting is laborious, but the job can be automated by using an image analyzing microscope, following the method of ASTM E1245. A major drawback to point counting is that it is a destructive test—the weld metal actually sampled usually can't be the weldment put into service. A second major drawback is that point counting results are very sensitive to the quality of the etching of the sample and to interpretation of points falling on boundaries between phases.

In 1949, Anton “Tony” Schaeffler published the well-known Schaeffler Diagram that linked chemical composition to percent ferrite determined by metallographic methods (*Metal Progress*, 56(11): 680–680B). While the Schaeffler Diagram was originally conceived as a predicting tool to provide guidance in filler metal design and selection, people started to apply it for specification, e.g., the filler metal shall provide 5 to 10% ferrite when its composition is plotted on the Schaeffler Diagram. While simple in concept, this led to numerous problems. A major problem is there are usually several organizations concerned with the safety of a weldment that goes into, for example, a power plant. No one organization entirely trusts the other, so chemical analysis might be provided by the filler metal manufacturer, checked by the fabricator and rechecked by the master contractor. Not surprisingly, when three organizations independently perform chemical analysis on anything, they don't all arrive at the same conclusion. Therefore, they don't get the same predicted percent ferrite. Also, the correlation between chemical composition and percent ferrite is imperfect—significant elements such as nitrogen were not part of the Schaeffler Diagram, and there are inaccuracies in any such diagram. For example, the Schaeffler Diagram is clearly incorrect in its treatment of manganese in the Nickel Equivalent.

Determination of ferrite by metallographic means turned out to be equally non reproducible. In the late 1960s and early 1970s, round robins of ferrite determination by metallographic means were run in the Welding Research Council, Subcommittee on Welding Stainless Steel, and in the International Institute of Welding, Commission II. These round robins showed, for example, that several laboratories might measure anywhere from 3 to 8% ferrite on a single sample of weld metal. So it was difficult for several organizations to agree that a specification like 5 to 10% ferrite was actually met. When they didn't agree, delays in construction resulted while the disagreeing parties attempted to resolve their differences.

Besides etching appearance, ferrite has another property that allows it to be differentiated from austenite—ferrite is ferro-magnetic, while austenite is not. To a first approximation, the magnetic properties of a ferrite/austenite mixture of weld metal are proportional to the ferrite content. (There is also a compositional effect—in general, ferrite higher in alloy content has a somewhat weaker magnetic response than lower alloy ferrite, but this effect is not important in interpreting the measurements.) A magnetic scale for ferrite determination was developed by the Welding Research Council, and was published as the AWS A4.2 standard in 1974. The A4.2 standard has been updated several times since 1974, and the latest edition was published in 1997. The magnetic method has become an international standard, ISO 8249, which was first published in 1985, and was updated in 2000. While the words in AWS A4.2 are not identical to the words in ISO 8249, the standards are technically identical, as are the test results obtained by following the two standards. The magnetic scale describes its measurements in terms of Ferrite Numbers (FN), which were originally believed to numerically approximate percent ferrite. However, it is quite clear today that, at least at higher Ferrite Numbers, the FN overstates the volume percent ferrite. From the point of view of whether or not a specification requirement is met, the exact amount by which the FN overstates the percent ferrite is unimportant. Of primary importance is that the various parties in the supply and consumption chain for weld metal can reproduce the ferrite measurement results, so there is no disagreement about whether or not the specification was met. And, of course, links must be established between the specified ferrite range and acceptable weld properties. After more than 25 years of experience with Ferrite Numbers, the links between FN and properties are well established.

Round robin studies of FN determination by the Welding Research Council, and by the International Institute of Welding, for samples in the 5 to 10 FN range, demonstrated the reproducibility among a number of measuring laboratories is better than ± 1 FN. So, the reproducibility of FN measurements is considerably better than that of percent ferrite determinations. In addition, FN measurement is nondestructive. That is, the actual weldment can be evaluated, not only a prefabrication weld sample.

Predicting diagrams for welds, relating Ferrite Number to chemical composition, have been developed experimentally. The DeLong Diagram (*Welding Journal* 52(7): 281-s to 297-s) of 1973 was updated by the Welding Research Council in 1988 (*Welding Journal* 67(12): 289-s to 298-s), and again in 1992 (*Welding Journal* 71(5): 171-s to 178-s). Today, the WRC-1992 Diagram is the official method of the ASME Code, for predicting FN when FN cannot be measured. But FN measurement is preferred to prediction from a Diagram.

So, to summarize, Ferrite Number measurement is more reproducible than ferrite percent measurement. Ferrite Number is more conveniently measured than ferrite percent. And, because the Ferrite Number measurement is a non-destructive test, it is suitable for in-process quality assurance, while ferrite percent is generally not. Specification of a Ferrite Number minimum, or of a FN range when necessary, is far preferable to specifying a percent ferrite minimum or range. For most weldments in nominally austenitic stainless steels, where the main concern is freedom from hot cracking sensitivity, specification of 3 FN minimum is all that is necessary. For 347 weld metal, and for some higher alloyed weld metals such as 317L and 309LMO, 5 FN

minimum provides assurance of freedom from sensitivity to hot cracking. Where elevated temperature service and/or postweld heat treatment are to be applied, an upper limit of 10 or 15 FN is often appropriate to avoid embrittlement due to phase transformations at high temperature. And for duplex ferritic-austenitic stainless steel weld metals such as 2209, a specification range of 30 to 70 FN has been found to correlate well with good corrosion resistance and good mechanical properties.

The Welding Research Council, the International Institute of Welding and the ASME Code strongly recommend specification of ferrite in stainless steel weld metals by Ferrite Number, not by percent ferrite.

1.21 Corrosion Resistance of 304L to 316L Joints with 308L vs. 316L?



I have to make a number of joints of 304L pipe to 316L pipe. From the standpoint of corrosion resistance, does it make any difference if 308L filler metal or 316L filler metal is used?

January 2001

To begin, let's look at some compositions. Since you indicate the base metals are pipes, and the service is corrosion, I'll look to ASTM A312, *Standard Specification for Seamless and Welded Austenitic Stainless Steel Pipes*. I should note that different ASTM stainless steel base metal specifications sometimes have different composition limits for nominally the same grade of steel. For filler metal compositions, I'll look to AWS A5.4 for covered electrodes; AWS A5.9 for bare wires for gas metal arc, gas tungsten arc and submerged arc welding; and AWS A5.22 for gas shielded flux cored wires. The compositions are listed in Tables 1 and 2 for both base metals and filler metals.

The elements responsible for corrosion resistance are chromium, nickel and molybdenum. Looking at either table, it can be noticed that the minimum chromium and the minimum nickel for the filler metals tend to be higher than the corresponding minimum of the base metals. This provides some assurance the weld metal will at least match the corrosion resistance of the corresponding base metal.

In general, since 316L contains more alloy, it has slightly better corrosion resistance than 304L in most applications. But the corrosion resistance of a joint between the two base metals can be no better than the corrosion resistance of the less resistant base metal. If the filler metal corrosion resistance at least matches the corrosion resistance of the less resistant base metal, then the weld metal corrosion resistance should be adequate for the intended service, as long as both base metals are adequate.

So, the conclusion is, in virtually all joints between 304L and 316L stainless steels for corrosion resistant service, it does not matter if the filler metal chosen is 308L or 316L, except 308L is generally less costly.

Table 1—304L Base Metal vs. 308L Filler Metals

	C, %	Mn, %	P, %	S, %	Si, %	Cr, %	Ni, %	Mo, %
A 312 TP304L	0.035 max.	2.00 max.	0.040 max.	0.030 max.	0.75 max.	18.0 to 20.0	8.00 to 13.0	Not Specified
A5.4 308L	0.04 max.	0.5 to 2.5	0.04 max.	0.03 max.	0.90 max.	18.0 to 21.0	9.0 to 11.0	0.75 max.
A5.9 308L	0.03 max.	1.0 to 2.5	0.03 max.	0.03 max.	0.30 to 0.65	19.5 to 22.0	9.0 to 11.0	0.75 max.
A5.22 308L	0.04 max.	0.5 to 2.5	0.04 max.	0.03 max.	1.0 max.	18.0 to 21.0	9.0 to 11.0	0.5 max.

Table 2—316L Base Metal and Filler Metal

	C, %	Mn, %	P, %	S, %	Si, %	Cr, %	Ni, %	Mo, %
A 312 TP316L	0.035 max.	2.00 max.	0.040 max.	0.030 max.	0.75 max.	16.0 to 18.0	10.0 to 15.0	2.0 to 3.0
A5.4 316L	0.04 max.	0.5 to 2.5	0.04 max.	0.03 max.	0.90 max.	17.0 to 20.0	11.0 to 14.0	2.0 to 3.0
A5.9 316L	0.03 max.	1.0 to 2.5	0.03 max.	0.03 max.	0.30 to 0.65	18.0 to 20.0	11.0 to 14.0	2.0 to 3.0
A5.22 316L	0.04 max.	0.5 to 2.5	0.04 max.	0.03 max.	1.0 max.	17.0 to 20.0	11.0 to 14.0	2.0 to 3.0

1.22 Ferrite Limits for 4K Fracture Toughness?

 I am trying to qualify welding procedures for 304L and 316L equipment for cryogenic service in liquid nitrogen or liquid hydrogen. The December 2000 Stainless Q&A column proposed 3 FN minimum for 308L and 316L weld metals for freedom from hot cracking. But when I test welding procedures using covered electrodes or submerged arc with 5 to 10 FN, I fail toughness requirements of 15-mils lateral expansion at -320°F (-196°C , or 77 K). I have no trouble with the base metal tests. How can I meet this toughness requirement in the welds without hot cracking?

February 2001

Austenitic stainless steels, including their weld metals, do not undergo the rather abrupt transition from ductile fracture to brittle fracture with falling temperature that is experienced by common mild steel and low-alloy steels. Rather, they experience

a gradual decline in toughness, measured as either absorbed energy or lateral expansion in the Charpy V-notch impact test, with falling temperature. At cryogenic temperatures, the fracture mode in austenite is still normally ductile tearing, not brittle cleavage. However, the ferrite in a nominally austenitic stainless steel weld metal can experience cleavage fracture, so it is often essential to limit the amount of ferrite to increase the fracture energy at cryogenic temperatures.

Also, keep in mind that the Charpy V-notch impact test becomes invalid at temperatures much below -320°F . It is valid for liquid nitrogen testing but not for liquid hydrogen testing since liquid hydrogen temperature at atmospheric pressure is about -423°F (-253°C , or 20 K). Colder still is liquid helium, at -452°F (-269°C , or 4 K). The problem with Charpy impact testing at these very low temperatures is that the thermal capacitance of the metal approaches zero, so as plastic deformation begins in the root of the notch during the impact test, adiabatic heating occurs, which raises the temperature of the metal. The only valid tests at these very low temperatures are slow strain rate fracture toughness tests, where liquid hydrogen or liquid helium can extract heat fast enough to overcome adiabatic heating. But fracture toughness tests are highly specialized and expensive, so the average, or even above average, fabrication shop can't afford them. The ASME Code Committee, after examining correlations between fracture toughness tests at liquid helium temperature and Charpy V-notch results at liquid nitrogen temperature, proposes to require 21-mils (0.53-mm) lateral expansion, not 15-mils (0.38-mm) lateral expansion, at liquid nitrogen temperature to qualify a welding procedure for service at liquid helium temperature. As a result, your problem could become even more difficult in the future than it is now.

Coming back to the topic of toughness of nominally austenitic stainless steel weld metals, there have been a number of studies on cryogenic toughness. One of the best known is that of Szumachowski and Reid (*Welding Journal*, November 1978 and February 1979). This work showed ferrite and nitrogen are detrimental to Charpy V-notch impact toughness at liquid nitrogen temperature. It also showed the lime-fluoride slag system (e.g., AWS A5.4 E316L-15 electrodes) produced better toughness at a given ferrite and nitrogen level than did a rutile slag system (e.g., AWS A5.4 E316L-16 electrodes). The difference between a -15 coating and a -16 coating is due to the oxygen (inclusion) content of the weld metal. The -15 coating produces lower oxygen (about 400 ppm) vs. the -16 coating (about 600 ppm) or -17 coating (about 900 ppm). Therefore, to improve your chances of meeting cryogenic impact requirements, choose low-ferrite, low-nitrogen filler metal with a lime-fluoride (-15) coating. Or, in submerged arc welding, choose a high-basicity flux with a low-ferrite, low-nitrogen filler metal.

But you can do better. The effect of oxygen continues below 400 ppm. A slag-free-inert-gas-shielded process (GTAW or GMAW) can produce on the order of 150 ppm or less of oxygen in the weld metal. I've routinely found low-nitrogen (0.04% or 400 ppm) AWS A5.9 ER308LSi and ER316LSi wires with about 10 FN, welded GMAW, spray transfer, with 98% argon-2% oxygen shielding gas, that produce Charpy V-notch toughness of about 30-mils (0.76-mm) lateral expansion at liquid nitrogen temperature. This is not specially melted material, just commercial quality. At this ferrite level, there are no fears of hot cracking.

On the other hand, if you want to use a flux-shielded process, you will have to look at filler metals below 5 FN, with highly basic slag systems. As a result of the Szumachowski and Reid work, AWS A5.4 E316L-15 covered electrodes and AWS A5.22

E316LT-3 self-shielded flux cored wires with a highly basic slag system were produced to 2 FN maximum. These were used for fabrication of 304L stainless steel magnet cases for superconducting magnets for the fusion energy program at Lawrence Livermore National Laboratory. Note that, today, the E316LT-3 filler metal would be classified as E316LT0-3 because the AWS A5.22 standard, as revised in 1995, now includes a welding position indicator (“0” for downhand and horizontal positions only), which it did not when the filler metal for Livermore was manufactured. The steel ranged up to 4 in. (100 mm) thick. Welds were qualified by testing both for 15-mils lateral expansion at liquid nitrogen temperature and for fracture toughness at liquid helium temperature. The welds met the toughness requirements and did not hot crack. The 316L filler metals were chosen because 316L seems to be more resistant to hot cracking than 308L when the ferrite is very low. Low phosphorus, low sulfur and high manganese are also important to the hot cracking resistance of such weld metals.

Nickel-based-alloy filler metals (e.g., AWS A5.11 classes ENiCrFe-2, ENiCrFe-3, and ENiCrMo-3) can also meet the cryogenic toughness requirements. These have no ferrite, but are crack resistant. They cost considerably more than stainless steel electrodes.

To sum up, your choices for meeting cryogenic toughness requirements are GMAW or GTAW with filler metals of normal FN or slag-shielded filler metals with below 2 FN.

1.23 Matching Filler Metal for 310H Base Metal— Not 310H Filler Metal, but 310 Filler Metal?



Is 310H the correct filler metal for welding 310H base metal? I can find 310H filler metal in the covered electrode standard only, but that does not seem to match the base metal carbon content

June 2001

Your observation is correct, 310H base metal and 310H filler metal do not match. Type 310H base metal is designated with an “H” only to differentiate it from Type 310S, which has no minimum carbon requirement. Type 310H base metal has a minimum carbon requirement. AWS filler metals bearing the 310 designation also have a required minimum carbon content, except for flux cored wire classified according to AWS A5.22. There is a much higher carbon version of 310, known as HK40, for which the 310H filler metal in AWS A5.4 is intended. Table 1 lists the compositions of 310S base metal, 310H base metal, 310 filler metals from the three relevant AWS standards, HK40 base metal and 310H filler metal.

Type 310 filler metal is generally made to a target carbon content of 0.10 to 0.12% (even with flux cored wires) because, way back in the B.C. (before computers) era, Hallock Campbell and R. David Thomas, Jr. (*Welding Journal*, November 1946), and confirmed by G. E. Linnert and F. K. Bloom (*Welding Journal* February, 1947), deter-

Table 1—310 Base Metals and Filler Metals

	C, %	Mn, %	Si, %	Cr, %	Ni, %
ASTM A240 Type 310S	0.08 maximum	2.00 maximum	1.50 maximum	24.0 to 26.0	19.0 to 22.0
ASTM A240 Type 310H	0.04 to 0.10	2.00 maximum	0.75 maximum	24.0 to 26.0	19.0 to 22.0
AWS A5.4 E310-XX	0.08 to 0.20	1.0 to 2.5	0.75 maximum	25.0 to 28.0	20.0 to 22.5
AWS A5.9 ER310	0.08 to 0.15	1.0 to 2.5	0.30 to 0.65	25.0 to 28.0	20.0 to 22.5
AWS A5.22 E310TX-X	0.20 maximum	1.0 to 2.5	1.0 maximum	25.0 to 28.0	20 to 22.5
ASTM A608 Grade HK40	0.35 to 0.45	1.5 maximum	0.50 to 2.00	23.0 to 27.0	19.0 to 22.0
AWS A5.4 E310H-XX	0.35 to 0.45	1.0 to 2.5	0.75 maximum	25.0 to 28.0	20.0 to 22.5

mined that tensile elongation in 310 weld metal was maximized at that carbon level. Lower carbon deposits tend to contain many microcracks, which reduce tensile elongation. So the matching filler metal for 310H base metal is 310 filler metal.

1.24 What is the Correct Filler Metal for 316LN?



I have to weld 316LN base metal but find there is no AWS classification for 316LN filler metal. What is the correct filler metal to use? 316L? 317L?

July 2001

Normally, there are two possible concerns about joining 316LN—strength and corrosion resistance. The nitrogen addition to 316LN enhances both strength and corrosion resistance as compared to 316L. Table 1 compares composition and strength of 316L and 316LN, along with AWS A5.4 E316L-XX and E317L-XX covered electrodes.

You will find the E316L-XX electrode strength requirements a bit short of those for the 316LN base metal, while the E317L-XX strength requirements match. So, there is a tendency to select E317L-XX. However, it should be kept in mind that E316L-XX

Table 1—Composition and Strength Requirements for 316L and 316LN Base Metals, and 316L and 317L Electrodes

Element	C, %	Mn, %	Si, %	Cr, %	Ni, %	Mo, %	N, %	Tensile, ksi (MPa)	Yield, ksi (MPa)	% Elong.
316L	0.030 max.	2.00 max.	0.75 max.	16.00 to 18.00	10.00 to 14.00	2.00 to 3.00	0.10 max.	70 (485) min.	25 (170)	40 min.
316LN	0.030 max.	2.00 max.	0.75 max.	16.00 to 18.00	10.00 to 14.00	2.00 to 3.00	0.10 to 0.16	75 (515)	30 (205)	40 min.
E316L-XX	0.04 max.	0.50 to 2.50	0.90 max.	17.00 to 20.00	11.0 to 14.0	2.00 to 3.00	N.S. ^(a)	70 (490)	N.S.	30 min.
E317L-XX	0.04 max.	0.50 to 2.50	0.90 max.	18.00 to 21.00	12.00 to 14.00	3.00 to 4.00	N.S. ^(a)	75 (520)	N.S.	30 min.

N.S. = Not Specified.

electrode deposits typically exceed 80 ksi (560 MPa) tensile strength and 50 ksi (340 MPa) yield strength, so there is not a real mismatch, only a specification requirements mismatch.

The corrosion resistance is a bit more complicated because it depends strongly upon the corrosive medium. One measure of corrosion resistance is the Pitting Resistance Index, or PRE_N . This is often defined as the following:

$$PRE_N = \% Cr + 3.3 \times \% Mo + 16 \times \% N$$

From Table 1, the nitrogen content of 316LN is likely to be about 0.10% higher than that of E316L-XX weld metal, which increases the PRE_N of 316LN by 1.6 (16×0.10) over that likely with E316L-XX weld metal. However, 1% more molybdenum in E317L-XX increases its PRE_N by 3.3 over that of E316L-XX, which more than compensates for the lack of nitrogen. So, again, there is a tendency to select E317L-XX filler metal.

Before making a final selection, also consider there are other effects of the composition difference between 317L filler metal and 316L filler metal. For example, E317L-XX filler metal tends to contain considerable ferrite. 316LN base metal is sometimes selected for use at cryogenic temperatures, where ferrite is detrimental to toughness. So, I can't make a carte blanche recommendation to use 317L filler metal. You need to consider the service environment to be sure there are no important disadvantages to using 317L filler metal for your application.

1.25 Why is 308L Required to Meet 35% Elongation While 316L is Only Required to Meet 30% Elongation?

 I just noticed in AWS A5.4 that the tensile elongation requirement for 316L stainless weld metal is only 30%, while that of 308L weld metal is 35%. I have always considered 316L to be a high-quality stainless steel weld metal, so why should it be inferior to 308L in this respect?

January 2002

To put things in perspective, I ought first to point out that our highest quality structural steel weld metals, such as those from AWS A5.1 E7018, are required to meet 22% tensile elongation. Even the E7018M for naval combat vessels is only required to meet 24% tensile elongation. So, in that respect, the 316L requirement of 30% elongation hardly seems to reflect inadequate or inferior ductility.

What you have noticed is a legacy of the 1940s, before the role of ferrite in preventing microfissures in nominally austenitic stainless steel weld metal was fully understood. As far as I know, no one who served on the joint ASTM and AWS committee that, in 1946, published ASTM A298-46T AWS A5.4-46T, *Tentative Specification for Corrosion-Resisting Chromium and Chromium-Nickel Steel Welding Electrodes*, is alive today. However, the late R. David Thomas served on that committee, and his son, R. David Thomas, Jr., still active and residing in Vermont, participated in the work that led to this specification. I am indebted to Dave, Jr., for his recollections of that time and his willingness to share them with my readers.

It seems the 316L weld metals of the 1940s normally did not contain ferrite. As a result, they commonly contained some microfissures (short hot cracks, commonly perpendicular to the weld interface, in weld metal reheated by a subsequent weld pass). The microfissures, also perpendicular to the tensile stress of an all-weld-metal tensile specimen, tended to slightly reduce the tensile ductility. So, those 316L weld metals could consistently exceed 30% elongation, but 35% was inconsistently met. On the other hand, the 308L electrode deposits of that day commonly contained a little ferrite, in which condition, they were free of microfissures. Without microfissures, the weld metal easily exceeded 35% elongation. If, however, the 308L contained no ferrite, microfissures would occur and the weld metal would not consistently meet 35% elongation. Therefore, 35% elongation was chosen as a way of conveniently discriminating between 308L weld metal without microfissures and 308L with microfissures.

Times changed and today, 316L weld metal is commonly, but not always, designed to contain a little ferrite. There seemed to be no reason to change the elongation requirements of AWS A5.4, so the 316L elongation requirements remain as they were written in 1946. There is no technical reason today for 308L elongation requirements to be different from 316L elongation requirements. The difference is purely a legacy from the state of the art of the 1940s.

I note further that AWS D1.6, *Structural Welding Code—Stainless Steel*, does not differentiate between weld metals with 30% elongation requirements and those with

35%. Weld metals with 30% elongation requirements are prequalified for structural welds in the same base metals as weld metals with 35% elongation requirements.

Elongation of at least 30% indicates quite ductile material, and I would not consider 316L weld metal to be inferior to 308L weld metal.

1.26 Lamellar Tearing in 304L Stainless?

 We are preparing to fabricate some rather heavy-section 304L stainless. Fillet-welded stiffeners will be on both sides of some approximately 2-in.-thick plates. Years ago, we had trouble with lamellar tearing in weldments of somewhat similar geometry but made of mild steel. This cost us a lot of money and created a time delay. Should we be concerned about lamellar tearing in the stainless?

January 2002

Lamellar tearing occurs when weld shrinkage imposes tensile strains in the through-thickness direction of steel plate or shapes containing inclusions aligned or elongated parallel to the surface. The strain tends to separate the inclusions from the matrix, which opens a crack. Additional strain can cause the cracks to grow into inclusion-free regions and can also cause linkage between a number of cracked regions, creating much larger cracks. The tendency for lamellar tearing depends strongly upon inclusions oriented parallel to the steel surface. Steels with poor deoxidation practice are especially prone to lamellar tearing.

ASTM A770/A770M, *Standard Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications*, can be used to assess the tendency for lamellar tearing of plates 1 in. (25 mm) thick or greater. A test specimen is produced by making a pair of full-penetration welds to opposite surfaces of the plate sample under test, then machining two round tensile specimens whose reduced section length is in the through-thickness direction. The specimens are then pulled to fracture and the reduction of area is determined for each. A minimum of 20% reduction in area is specified by the standard to indicate a plate resistant to lamellar tearing. This standard and the test requirement are primarily intended for carbon-manganese and low-alloy steels, but the results could be applicable to stainless steels as well.

However, stainless steels such as 304L are invariably produced using argon-oxygen decarburization, or some similar refining method. As a result, these steels tend to have very low levels of inclusions, and there is little tendency for the inclusions to align parallel to the plate surface. Therefore, the reduction in area in the through-thickness direction of austenitic stainless steels like 304L is generally high. I think it highly unlikely you will encounter lamellar tearing in 304L. In my opinion, requiring the ASTM A770/A770M test of 304L stainless steel is likely to be a needless expense.

1.27 Stainless Filler Metal to meet 15 mils Lateral Expansion at -320°F?

Ⓚ Although our shop has built mainly mild steel vessels, we are considering bidding to build a 304L stainless steel vessel for very low-temperature service. The contract will include a weld metal toughness requirement of at least 15 mils lateral expansion at -320°F. What is this requirement, and is it hard to meet? Also, what filler metals will meet this requirement?

May 2002

By far, the most common way to specify toughness for mild steel and low-alloy steel is by the energy absorbed in breaking the standard Charpy specimen at a particular temperature. This energy requirement is usually 20 ft-lb (27 J) at a temperature such as -20°F (-9°C). However, the yield strength of austenitic stainless steels increases markedly at cryogenic temperatures such as -320°F (-196°C), so that 20 ft-lb at that temperature is not considered to provide sufficient evidence of toughness. Therefore, the ASME Code uses the lateral expansion criterion instead.

The standard Charpy specimen is 10-mm (0394-in.) square in cross section. When it is struck while conducting the test, the face opposite the notched face mushrooms a bit. The extent of mushrooming is related to the toughness. This mushrooming can be measured as the lateral expansion. After the mushrooming, the width of the specimen at the struck face is measured with a micrometer and the increase in width, as compared to the original width, is the lateral expansion figure reported. The most common lateral expansion requirement is 0.015 in. (0.38 mm) minimum, or your stated 15 mils. For conducting the test at -320°F (-196°C), liquid nitrogen is the ideal temperature-control bath for the specimen immediately prior to the test because liquid nitrogen boils at that temperature.

Unlike mild steel, austenitic stainless steel does not normally experience a sharp transition from ductile fracture to brittle fracture with falling temperature. Instead, there is usually a very gradual decrease in toughness, as measured by the Charpy V-notch impact test (either as energy for fracture or lateral expansion), with falling temperature. When a mild steel or low-alloy steel is broken in the Charpy V-notch test and a low energy fracture is obtained, cleavage facets normally appear as bright crystal facets on the fracture surface. This seldom happens with austenitic stainless steel, even at cryogenic temperatures. But there is still some risk of fast-propagating fracture at cryogenic temperatures with austenitic stainless steels, and the 15 mils lateral expansion requirement seems to correlate well with resistance to fast-propagating fracture.

Szumachowski and Reid, in a two-part report (*Welding Journal*, November 1978 and February 1979), studied factors that influenced Charpy V-notch lateral expansion and fracture energy of austenitic stainless steel weld metals deposited from covered electrodes. They found that 15-mils lateral expansion could be met with 308L or 316L filler metal provided that:

1. Ferrite was maintained low (less than 2 FN was preferred)
2. Nitrogen was maintained low (less than 0.06%)
3. A DC-lime coating (-15 type) improved the results.

Further studies have found the rules developed by Szumachowski and Reid are generally applicable to submerged arc welding and flux cored arc welding as well. However, there are two problems with applying these rules. The first is that low-ferrite, low-nitrogen filler metals are not readily available. Often, special orders with long lead times are required to obtain such filler metals. In the case of submerged arc welding, you may have to purchase a large amount of wire in order to get low-ferrite, low-nitrogen wire. The second problem is that austenitic stainless steel weld metal with less than 2 FN has a pronounced tendency towards hot cracking.

There is a better way. The clue is in the Szumachowski and Reid finding that DC-lime coatings gave better results than rutile coatings at the same ferrite and nitrogen level. They just didn't explore far enough. The toughness difference between the DC-lime coatings and the rutile coatings studied by Szumachowski and Reid is explainable by weld metal oxygen level. The weld metal oxygen is mostly present as oxide inclusions, which help to nucleate and grow the fracture in a Charpy V-notch test, or in a real service fracture. Typical weld metal oxygen levels from a stainless steel DC-lime coating (E308L-15 or E316L-15, for example) are about 450 to 500 parts per million (ppm). Typical weld metal oxygen levels from a stainless steel rutile coating (E308L-16 or E316L-16, for example) are about 600 to 700 ppm. Typical weld metal oxygen levels from a rutile-silica coating (E308L-17 or E316L-17, for example, which Szumachowski and Reid did not study) are about 900 to 1000 ppm.

Submerged arc welding with high basicity fluxes produces weld metal oxygen content no lower than that obtained with DC-lime coated electrodes. Submerged arc welding with more acid fluxes produces higher weld metal oxygen content. Flux cored arc welding with the common stainless steel wires made today produces weld metal oxygen content comparable to that of rutile-silica covered electrodes, or even higher. So the better way does not lie in the flux-shielded welding processes.

The better way lies in getting rid of the flux. Because they have no slag, gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) typically produce weld metal with about 100 to 150 ppm of oxygen. At such oxygen levels, weld metal with more reasonable levels of ferrite can produce well over 15 mils lateral expansion. In several tests I've run, I have found well over 15 mils lateral expansion at -320°F (-196°C) with weld metal of up to 10 FN, or even more. With such weld metal, there is no tendency toward hot cracking. This means you can buy readily available ER308LSi, ER308L, ER316LSi, or ER316L filler metal for these inert gas (or nearly inert gas) welding processes with good assurance that you can meet the toughness requirement. The use of argon with 1 or 2% oxygen does not seem to raise the weld metal oxygen level sufficiently to do any damage to the toughness. The higher silicon of the ER308LSi or 316LSi does not seem to matter either and is very desirable from the point of view of weld metal wetting.

I suggest you run the procedure qualification with these solid stainless steel wires and an inert gas of no more than 2% oxygen in argon.

1.28 305 Tube Welding vs. 304?

 We have a contract to fabricate 4-in. Schedule 40 Type 305 stainless steel tubing. The assembly is to carry compressed air. We have previously welded Type 304 and Type 304L pipe and tubing, but not 305. The composition of 305 looks similar to that of 304. We plan to make a gas tungsten arc (GTA) root pass (argon purge), then fill with covered electrodes. Can we use 308 filler metal? Are there any pitfalls in welding 305 that make it different from welding 304?

September 2002

Four-inch Schedule 40 tubing has an actual OD of 4.5 in. (114 mm) and wall thickness of 0.237 in. (6.02 mm) (ASTM A813/A813M, *Standard Specification for Single- or Double-Welded Austenitic Stainless Steel Pipe*). A GTA root followed by SMAW fill passes is entirely reasonable. There are a couple of pitfalls, however, that should be taken into consideration.

Type 305 stainless can be a bit higher in nickel and lower in chromium than Type 304. The higher nickel gives Type 305 the property of a lower rate of work hardening than that of 304. So Type 305 is generally better suited to cold bending or deep drawing, which may be the reason your customer has called for Type 305. Type 305 can also be higher in carbon content than Type 304, although that is not necessarily so. Table 1 compares the composition requirements of these two alloys as given in the ASTM A554, *Standard Specification for Welded Stainless Steel Mechanical Tubing*. Also included in Table 1, for comparison, are the composition requirements for 308 rods for GTA welding and 308 covered electrodes as given in the AWS A5.9, *Specification for Bare Stainless Steel Welding Electrodes and Rods*, and AWS A5.4, *Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding*, respectively.

Note from Table 1, there is some overlap in all of the composition ranges of the MT-304 and MT-305, so it is possible for certain compositions to be classified as either

Table 1—Chemical Composition Ranges for ASTM A554 MT-304 and MT-305 Tubing, AWS A5.9 R308 Rods, and AWS A5.4 E308-XX Electrode Deposits

Product	C, %	Mn, %	P, %	S, %	Si, %	Cr, %	Ni, %
MT-304	0.08 max.	2.00 max.	0.04 max.	0.03 min.	1.00 max.	18.00 to 20.00	8.00 to 11.00
MT-305	0.12 max.	2.00 max.	0.04 max.	0.03 max.	1.00 max.	17.00 to 19.00	10.00 to 13.00
ER308 or R308	0.08 max.	1.00 to 2.50	0.03 max.	0.03 max.	0.30 to 0.65	19.50 to 22.00	9.00 to 11.00
E308-15, -16, or -17	0.08 max.	0.50 to 2.50	0.04 max.	0.03 max.	0.90 max.	18.00 to 21.00	9.00 to 11.00

MT-304 or MT-305. There are no differences in mechanical property requirements between MT-304 and MT-305 (75 ksi [517 MPa] minimum tensile strength, 30 ksi [207 MPa] minimum yield strength, and 35% minimum elongation in 2 in. [100 mm]).

The first potential pitfall with 305 stainless tubing lies in the GTA root pass. Under ordinary circumstances, a GTA root pass in stainless tubing is generally made with little or no filler metal. That means the composition of the root pass is largely, or entirely, that of the base metal. The composition of 304 base metal almost always results in a little ferrite in a GTA root pass without filler metal, so there is no tendency for hot cracking. But that is not necessarily the case with 305. Assuming a low nitrogen content such as 0.02%, the higher nickel and lower chromium limits of 305 when plotted on the WRC-1992 Diagram would indicate the greater part of the possible composition ranges would contain no ferrite. The possibility of centerline cracking is rather high if the weld solidifies without ferrite. So the GTA weld root in the 305 could be sensitive to hot cracking.

One way to deal with the possibility of centerline cracking is to specify 3.0 FN minimum, calculated using the WRC-1992 Diagram from the composition of the 305 stainless tubing. To do this accurately, you will need the manufacturer's certified material test report, including nitrogen, for the tubing.

But, if you are buying off-the-shelf 305 tubing, you may not be able to find it with non-zero calculated FN. In that case, your best (safest) course of action is to force the welder to use a lot of 308 (or 308L) filler metal in the root pass. You can do this by opening the joint so there is a root opening of 1/8 to 5/32 in. (3 to 4 mm). Welders don't like such wide-open root openings, however, because a lot of skill and attention are required to produce a good root profile with an open root. Another alternative is to set up the Welding Procedure Specification (WPS) to require a consumable insert of the IN308 or IN308L classification according to AWS A5.30, *Specification for Consumable Inserts*. The composition of IN308 is identical to that of the ER308 of AWS A5.9 (typically, IN308 is produced by roll forming the same rod stock used to make ER308), and is designed to provide ferrite in the root pass. AWS B2.1-8-216, *Standard Welding Procedure Specification (WPS) for Gas Tungsten Arc Welding with Consumable Inserts followed by Shielded Metal Arc Welding of Austenitic Stainless Steel (M-8/P-8/S-8, Group 1), 1/8 through 1-1/2 inch Thick, IN3XX, ER3XXX, and E3XX-XX, As-Welded Condition, Primarily Pipe Applications*, addresses this exactly, except that 305 is not one of the base metals listed. Just as Type 304, Type 305 stainless would be categorized as a P-8 material because it falls within the 14.5 to 30% Cr and 7.5 to 15% Ni composition ranges of P-8.

If you use GTAW for the joint root, I suggest using an IN308 or IN308L consumable insert for the root pass as part of your WPS.

The second possible pitfall lies in the carbon content range of the 305 base metal. Carbon is allowed to be as high as 0.12%, versus 0.08% in 304 base metal. This, coupled with the slightly lower chromium content of 305 versus 304, may possibly make the 305 more susceptible to sensitization in the weld heat-affected zone (HAZ). Sensitization occurs in the HAZ during exposure of the material to peak temperatures in the approximate temperature range of 900 to 1600°F (500 to 807°C), where chromium carbides precipitate on austenite grain boundaries. Because carbon atoms diffuse much faster in this temperature range than do chromium atoms, chromium-depleted regions form adjacent to the grain boundaries, making the metal susceptible to inter-