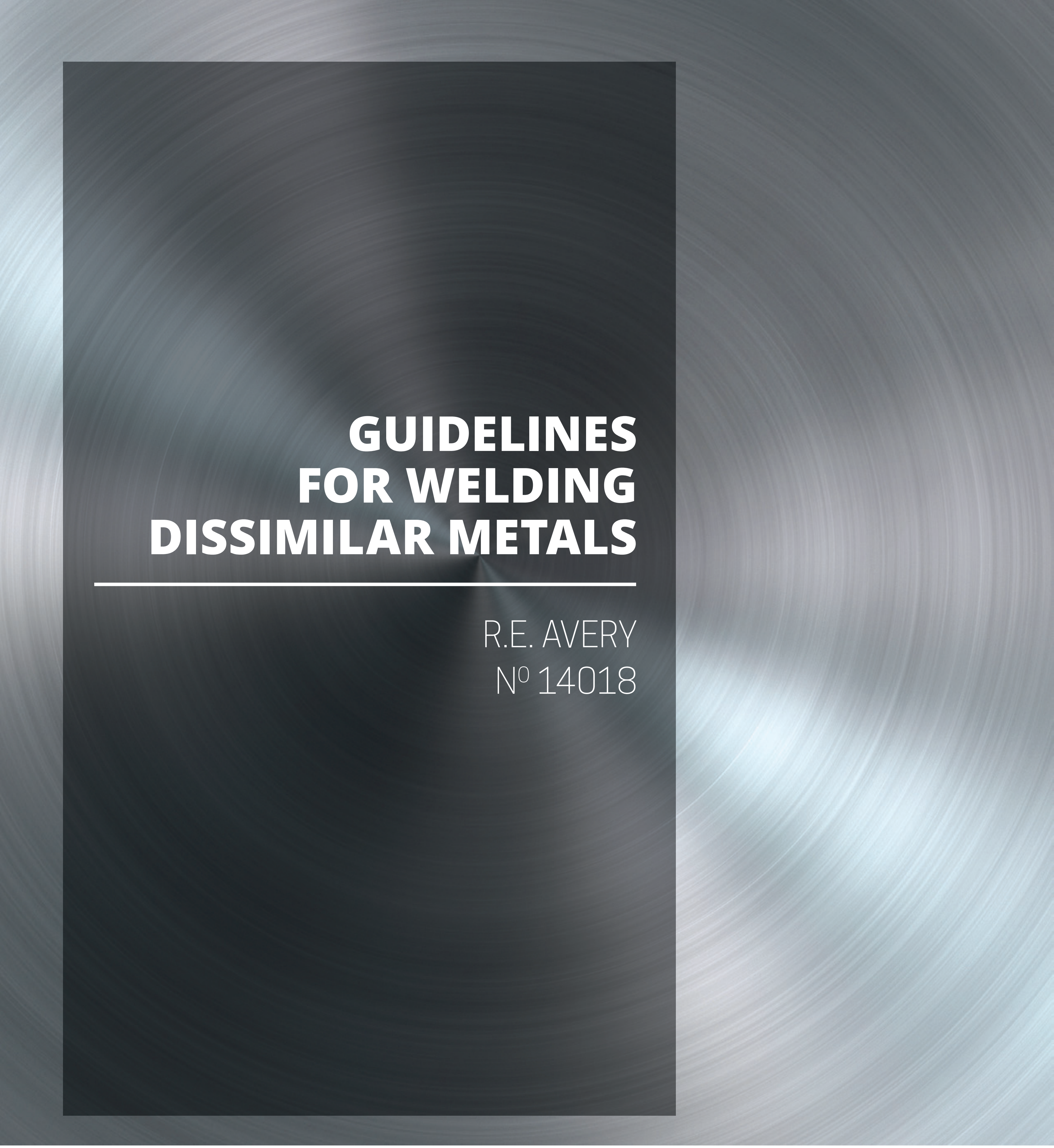

GUIDELINES FOR WELDING DISSIMILAR METALS

R.E. AVERY

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Pay Attention to Dissimilar-Metal Welds

Recent experience with boiler tubing reveals how welding practices affect weld joint performance in service.

Richard E. Avery,
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Dissimilar-metal welding refers to the joining of two different alloy systems. Actually all fusion welds are dissimilar-metal welds (DMWs) because the metals being joined have a wrought structure and the welds have a cast structure. Frequently the matching-composition filler metal is deliberately altered from that of the base alloys. For this discussion a dissimilar-metal weld will be that between metals of two different alloy systems.

On this matter, the chemical process industries can learn something from the power industry. A very common DMW application is joining ferritic [*e.g.*, 2 1/4% Cr-1% Mo (UNS K21590)] tubes to austenitic boiler tubes such as 304H (S30409) or a similar austenitic stainless steel. Because these welds are so important, they are treated separately in this article.

Metallugical factors

In dissimilar-metal welding, the properties of three metals must be considered: the two metals being joined and the filler metal used to join them. For example, if one of the metals being joined is welded using preheat when welding to itself, preheat should be used in making a DMW. Another variable might be heat input control. On occasion there may be a conflict in that the optimum control for one metal is undesirable for the other. In this case, a compromise is needed. This is one reason the development of a DMW procedure often requires more study than for a conventional, similar-metal welding procedure.

Fusion welds and other joining methods. The processes available for joining dissimilar metals are:

l. *Fusion welds*. The processes for fusion welds include shielded metal arc (SMAW), gas metal arc (GMAW), submerged arc (SAW), flux cored arc (FCAW), and gas tungsten arc (GTAW). With these processes there is a well-defined weld that preferably contains a substantial filler-metal addition. With the GTAW process, however, the amount of filler added is controlled by the welder. The welder should be trained to make the proper filler-metal addition used for the particular welding procedure.

2. *Low-dilution welds*. Low-dilution welds include electron beam, laser, and pulsed arc; the amount of base metal melted is relatively small, and filler metals are not normally added.

3. *Nonfusion joining*: Typical nonfusion joining processes are friction welding, and explosion welding, diffusion bonding along with brazing and soldering.

Dissimilar-metal joints can usually be made by any of these methods, but low-dilution and nonfusion joining processes are more often used for high-production, special-application joining. DMWs encountered in power and process industries are most often fusion welds made by the more common welding processes.

In fusion welding, the weld metal is a mixture of the two metals being joined and the filler metal. In arc welds made with consumable electrode processes such as SMAW, GMAW, SAW, and FCAW, the weld metal is well mixed or stirred by the arc action and the composition is quite uniform from one area to another. By sampling any place in the weld bead, the weld composition is determined and weld properties reasonably predicted. While the bulk of the weld is well mixed, there is an unmixed zone (UMZ) at the weld interface, which is a very narrow boundary layer of melted base metal that froze before mixing with the weld metal. Fortunately, the UMZ is seldom important in normal service environments but, on rare occasions, has exhibited selected corrosion attack. There is also a zone of unmelted base metal that will have been altered by the heat of welding.

This heat-affected zone (HAZ) can influence service life.

Determining weld composition. It is necessary to know the approximate weld metal composition before the service performance can be predicted. Table 1 lists three methods of determining the weld metal composition along with advantages and limitations. The technique for method 1 is obvious: metal is removed from the weld and an analysis performed. Method 2 approximates weld dilution by area measurement as shown in Figure 1. Method 3 uses the following base metal dilution percentages for some of the common welding processes:

- SMAW (covered electrode): 20 to 25% dilution
- GMAW (spray arc): 20 to 40% dilution
- GTAW: 20 to 50% dilution
- SAW (submerged arc): 20 to 50% dilution

The figures are approximate because the welding technique has a strong influence on the dilution, particularly with GTAW. Dilution in the SMAW process is most predictable, which is an advantage in making DMWs.

When the amount of dilution from the base metal is determined by either method 2 or 3 of Table 1, the average percentage of a specific element, *X*, is determined by the formula below. In this example, the dilution is 15% from each base metal *A* and *B,* while the filler metal contributes 70% of the weld volume.

$$X_X = (X_A)(0.15) + (X_B)(0.15) + (X_F)(0.70)$$

where X_X is the average percentage of element X in the weld metal, X_A is the percentage of element X in base metal A, X_B is the percentage of element X in base metal B, and X_F is the percentage of element X in the filler metal F.

Calculations are normally made for only major alloy constituents, *e.g.,* iron, chromium, nickel, copper, and molybdenum, while elements such as carbon or manganese are seldom figured. Carbon is an important factor in the weldability of iron base alloys, but it is of no more significance in a DMW than in similar metal welding. In other words, it is assumed both metals in a DMW are basically weldable.

Table 1. Determining DMW composition

Method	Advantages	Limitations
1. Chemical analysis of weld	Most accurate determination	Time consuming Expensive
2. Approximation of base metal dilution by weldcross section and composition calculated	Less expensive and usually shorter than chemical analysis	Estimating the percentage often difficult in welds such as multipass welds
3. Approximate dilution figures for common welding processes and composition calculated	Very fast way of estimating “rough” composition No laboratory work involved	Welding technique can have a strong influence of dilution in some processes, *e.g.*, GMAW, GTAW

Service condition effects. A properly engineered DMW matches weld properties to the service conditions. Some of the more important factors to be considered are mechanical and physical properties and weld corrosion/oxidation resistance.

Mechanical properties. The weld metal should be equal to or stronger than the weaker material being joined, although the American Society of Mechanical Engineers (ASME) code allows a weld strength of 95% in some cases. Ductility comparable to the metals being joined is desirable, but not always possible.

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Physical properties. Weld metal physical properties similar to the base metals are desirable. In joints that are heat cycled, a gross mismatch in the coefficient of thermal expansion can lead to an early thermal fatigue failure.

Weld corrosion/oxidation resistance. The weld should have corrosion and oxidation resistance equal to the least resistant base metal being joined. When a DMW is in an environment where the liquid can be an electrolyte, the weld metal should be cathodic to (more corrosion resistant than) both base metals. If the weld is anodic (less corrosion resistant), it can suffer accelerated galvanic corrosion.

Dissimilar-metal combinations

Nickel-containing and nickel alloys are easily welded to most commercially used metals. Exceptions are fusion welding to aluminum, titanium, and most refractory metals and alloys. Some of the most commonly encountered combinations will now be discussed.

Steel-to-stainless steel welds below 800°F. These are probably the most frequently encountered DMWs in industry, with the possible exception of boiler tube welds. In developing a DMW procedure, it is important to note the welding parameters normally used for each of the metals being joined so that

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those that are appropriate are included in the welding procedure.

Carbon and low-alloy side considerations. A simple guide in making DMWs is to use the same parameters such as preheat, interpass temperature, heat input, postweld heat treatment, etc. that are used in welding the alloys to themselves. Some of these controls are as follows.

1. Carbon steels with less than 0.20% carbon can normally be welded with austenitic fillers without preheat, but when the carbon is greater than 0.30% temperature control is necessary. As alloy content increases, *i.e.*, in the case of low-alloy steels, preheat control is usually essential.

2. Austenitic-covered electrodes or flux-cored wires should have low moisture content to prevent hydrogen-associated defects in the low-alloy HAZ. Coating moisture levels acceptable for welding austenitic alloys may cause hydrogen-related problems such as underbead cracking in the HAZ of a low-alloy steel. Electrodes can be rebaked in accordance with manufacturers' recommendations to reduce moisture.

3. High-restraint joints are susceptible to cracking unless preheat is used. The degree of restraint varies with joint design and metal thickness. Material over about 1 1/4 in. (32 mm) can be highly restrained and usually requires preheat.

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4. When a preheat is needed, a temperature of 300°F is usually adequate with 400°F used in severe conditions. Upon completion, the weld should be slow cooled to allow hydrogen to diffuse from the HAZ.

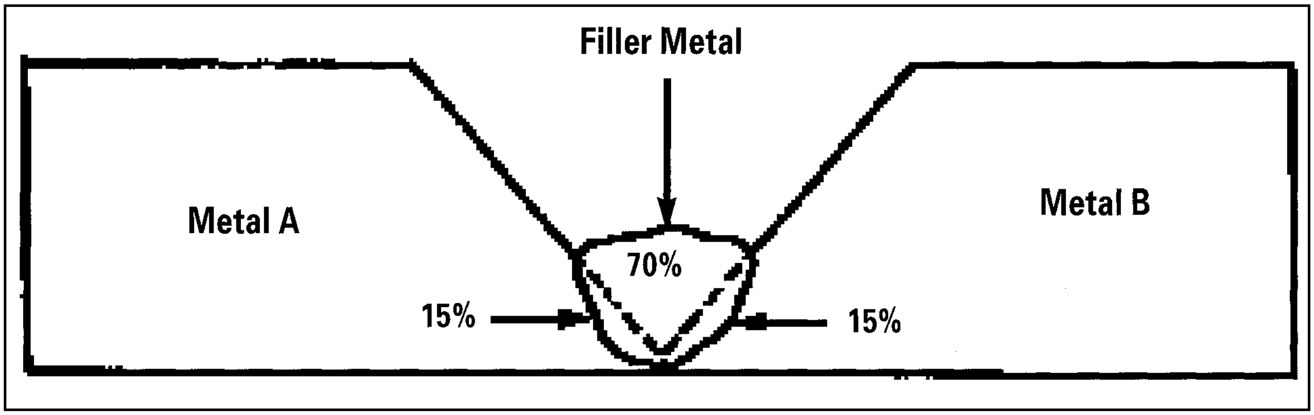
Stainless steel side considerations. As with welding stainless steel to itself, good practice includes such items as proper cleaning before welding, good fitup, and proper shielding gases. Other considerations include the following:

1. Postweld heat treatments such as a 1,100-1,300°F stress relief are often beneficial in improving HAZ properties in ferritic steels. This heat treatment can, however, reduce the corrosion resistance and adversely affect the mechanical properties of many standard grades of stainless steel.

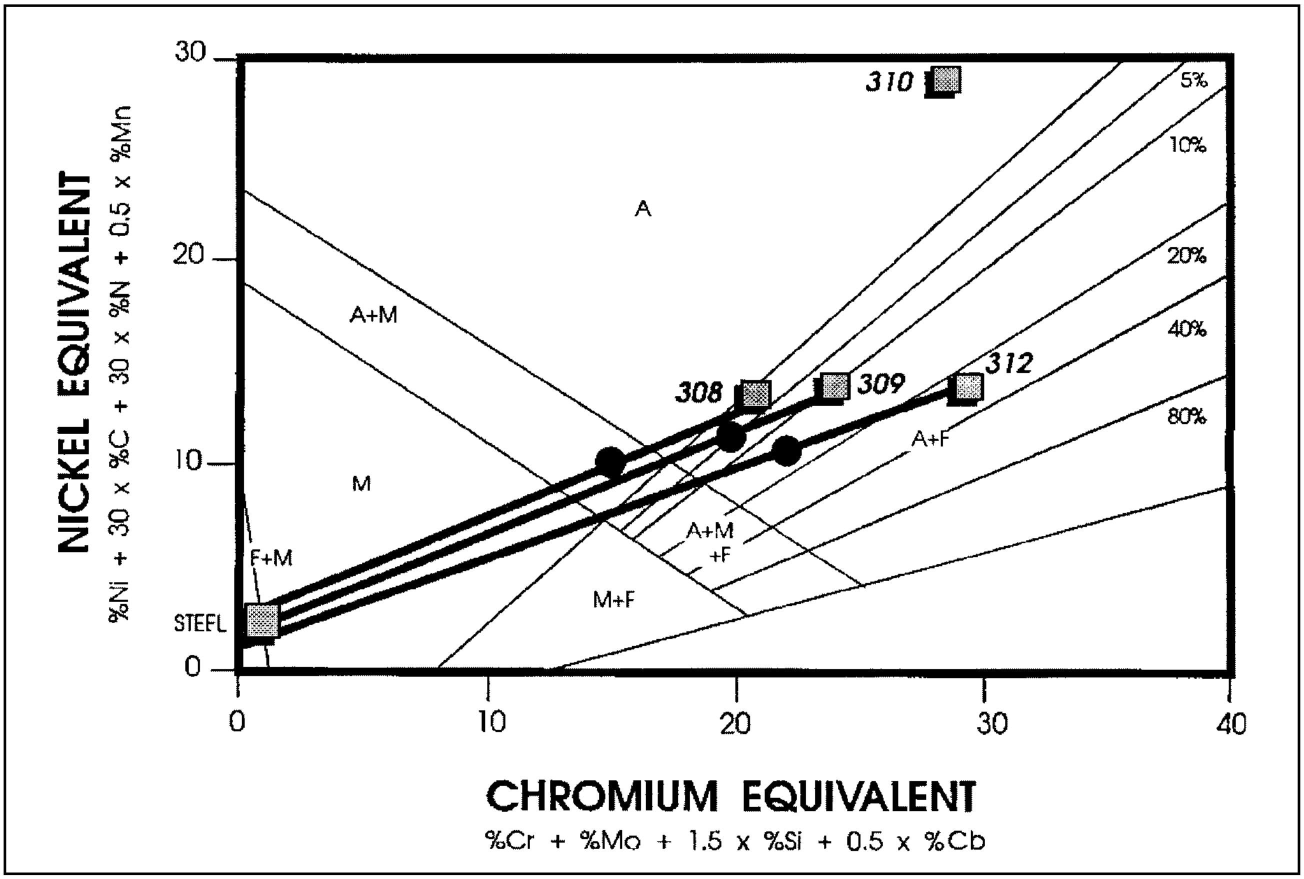
2. Heating unstabilized stainless steels that have a carbon content of 0.03% or higher can significantly reduce the intergranular corrosion resistance. If heat treatment is a necessity and full corrosion resistance of the austenitic stainless steel is needed, columbium- or titanium-stabilized types or the low-carbon grades (less than 0.03% C) should be used.

Filler-metal considerations. One of the most common DMW combinations is type 304 (UNS S30400) stainless to a low-carbon or mild steel. Type 308 (S30800), the standard filler metal for welding type 304 to itself, should not be used to make this weld. Some type 308 welds may be satisfactory, but eventually there will be quality problems because of iron dilution.

A higher alloy filler metal such as type 309 (S30900) with a ferrite number (FN) over 10 or type 312 (S31200) with an FN over 25 should be used. The effect of dilution on an austenitic stainless steel weld can be illustrated using the WRC 1988 diagram in Figure 2. The structure of a stainless steel weld may be fully austenitic, such as type 310 (S31000), or contain varying amounts of delta ferrite, as with types



■ ***Figure 1. Weld bead with 30% dilution, 15% from Metal A and 15% from Metal B.***



■ ***Figure 2. Effect of 25% mild steel dilution types 308, 309, and 312 weld metals. Structure of the diluted 308 is austenite and martensite while 309 and 312 austenite and ferrite.***

308, 309 or 312. The amount of ferrite is determined by the composition and weld cooling rates; the faster the cooling, the higher the ferrite content. Fully austenitic welds are more susceptible to hot cracking or fissures than welds containing about 5% or more ferrite.

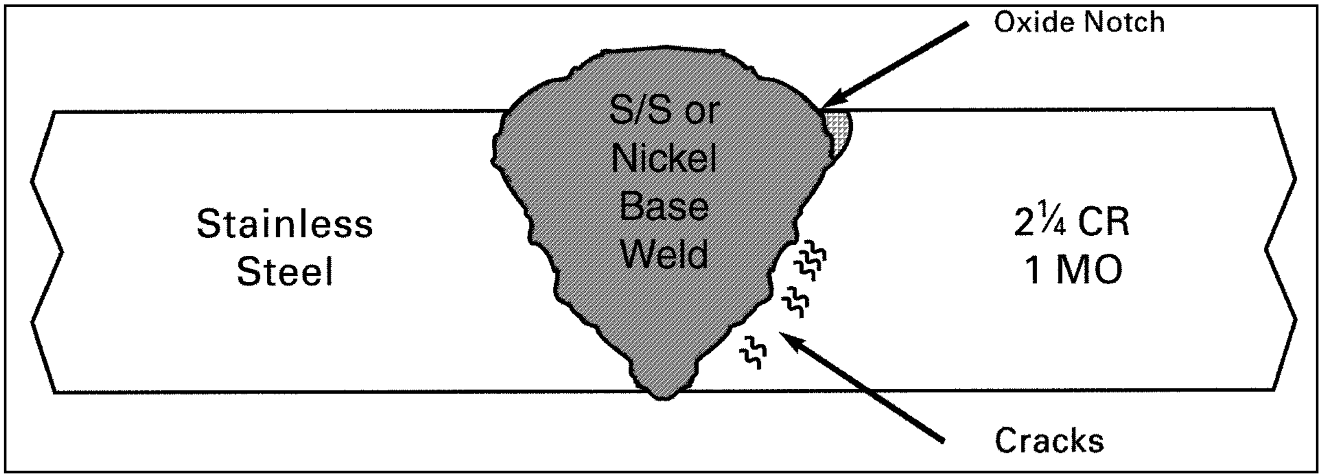
Figure 2 also shows that martensite (M) may be formed as the nickel and chromium equivalents are reduced. Martensite is a hard, low-ductile phase that is prone to hydrogen-related defects. In DMWs, it is best to avoid martensite. If type 308 filler metal is diluted by 25% with mild steel, the weld metal is in the austenite–martensite (*A* + *M*) phase area of Figure 2. Types 309 and 312 electrodes both have more nickel and chromium and when diluted by carbon steel are still in the austenite–ferrite (*A* + *F*) phase area and maintain excellent crack resistance.

Martensite is a hard, low-ductile phase that is prone to hydrogen-related defects.

While types 309 and 312 are now widely used for DMWs, type 310 has a long history of use in dissimilar-metal welding and for welding difficult metals including high-hardening alloys such as tool steels. Type 310 welds often have given excellent service in spite of minor fissures detectable by liquid penetrant testing. One caution in using 310 for "weathering" steels containing 0.07–0.15 % phosphorus is the probable weld metal cracking. Type 309 or 312 filler metals can better tolerate this level of phosphorus and should be used.

Steel-to-stainless steel welds over 800°F. When service temperatures are above 800°F, the ideal filler is a nickel–chromium or nickel–chromium–iron metal such as American Welding Society (AWS) A5.14 Class ERNiCr-3 bare wire or AWS A5.11 Class ENiCrFe-2 or Class ENiCrFe-3 electrodes. Nickel alloy welds have a coefficient of thermal expansion (COE) between ordinary steel and austenitic stainless. With the higher COE type 309 and 312 welds, there is a high stress concentration at the steel-side fusion line that, during thermal cycling, invites thermal fatigue failures.

Another caution in using stainless steel filler metals occurs when the weldment is heat treated between 1100 and 1300°F. Welds containing higher amounts of delta ferrite, *e.g.*, type 312 (FN more than 25) or type 309 (FN more than 10), can lose room temperature ductility and suffer reduced corrosion resistance as a result of sigma formation in this temperature range. If postweld heat treatment in this range is required, a low-ferrite composition weld metal reduces the chance of sigma formation. Another method is to first "butter" (surface by weld overlay) the ferritic side with type 309 followed by the heat treatment for the ferritic



■ *Figure 3. Typical dissimilar-metal weld defects in boiler tubes after a long time in service.*

side. The butt weld is then made using using a conventional filler such as type 308. An alternative is a nickel alloy filler metal that is not subject to sigma formation.

Other dissimilar-metal combinations. Nickel- and copper-base alloys are often welded to carbon and low-alloy steels as well as to each other. After determining the approximate composition of the DMW, the approximate maximum tolerance limits for major alloying elements can be determined; see Table 2.

Inspection and testing

In qualifying a welding procedure specification, DMWs are usually evaluated by tensile and bend tests like similar-metal welds. When either of the base metals or the weld metal is significantly weaker, which is often the case, a longitudinal bend test is preferable because all elements are forced to elongate the same amount and a better evaluation is possible. With a transverse bend test, the specimen may move in the bend die, causing all of the elongation to take place in the weaker member and often resulting in fracturing.

DMWs can be inspected using the same inspection standards employed in similar-metal joints.

Nondestructive surface inspection. Magnetic particle testing is not possible if one or more parts of the joint are nonmagnetic. Even when all of materials are magnetic, the degree of ferromagnetism can vary because of composition differences, and the magnetic differences can give false indications at the fusion line. Because of this, liquid penetrant inspection is most frequently used for surface inspection.

Nondestructive radiographic inspection. DMWs can be inspected using the same procedures and inspection standards employed in similar-metal joints. The exposure should be selected for the material and thickness of greatest interest. Because of differences in the radiographic density, interpretation of radiographs can be somewhat different than with similar metal welds.

Nondestructive ultrasonic testing. When the weld metal is coarse grained (such as an austenitic stainless steel, nickel–chromium or nickel–copper weld joining a ferritic alloy), there is a major problem with interpretation at the fusion line. For this reason, the ultrasonic testing of DMWs is seldom practical.

Boiler tube DMWs

To make the most effective use of the materials in modern boilers, tubes range in composition from carbon steel to various grades of chromium-molybdenum steels to austenitic stainless steels such as type 304H (UNS S30409). This involves a number of DMWs. The ferritic-to-austenitic welds have experienced early service life failures. These welds have traditionally been made with either an austenitic stainless steel or a nickel–chromium alloy filler metal. Failures that occur after about five years have not been related to ordinary weld defects such as slag, lack of fusion, or porosity but are related to metallurical changes due to service conditions. The number of DMW failures increased significantly in the mid to late 1970s, and investigations were initiated in North America under the direction of the Electrical Power Research Institute (EPRI). A brief summary of their findings follows.

Nature of failures. Typical DMW defects in boiler tubes after long times in service are shown in Figure 3. Through an examination of numerous DMWs with 50,000 to 200,000 h of service, the EPRI studies identified three distinct failure modes, all in 2 1/4 Cr–1 Mo next to the fusion line.

1. Failures that occur along prior austenite grain boundaries in the low-alloy steel about one or two grains away from the weld fusion line; this failure is most commonly seen in DMWs made with stainless steel filler metal and occasionally in nickel-base filler-metal welds.

2. Failures along a line of globular carbides, formed in service, next to the fusion line; this is more common in DMWs made with nickel-base filler metal.

3. Failures that result because of an oxide notch formed on the outside of the tube at the weld to low-alloy junction. The notches do not usually propagate to failure, but can in the case of thin wall tubes subject to high bending stresses; this failure can occur in both stainless steel and nickel base welds.

There is a difference in the service life of stainless steel and nickel base welds. The nickel joints last three to five times longer. Another finding was that a wider bevel on the ferritic side extended service life.

Service conditions and predicted life. The service life of a boiler tube DMW is strongly influenced by the following factors:

•*operating temperature*: higher temperatures shorten life;

•*number of thermal cycles*: the greater the number of cycles, the greater the damage;

•*type of thermal cycles*: the cycle can be cold, warm, or hot; cold cycling causes the most stress;

•*temperature excursions*: the higher the temperature and. number of excursions, the greater the damage;

•*total time at temperature*: service life is shortened by longer times at temperature.

By using these factors and other engineering data, EPRI developed a software program called Prediction of Damage in Service (PODIS) that estimates the remaining life of a given DMW. PODIS can be helpful in establishing a monitoring inspection program for DMWs as they approach the end of their expected life.

Replacement weld joints. Various utilities employ different practices in making replacement boiler tube DMWs, which probably indicates that there is no single best method. Some of the following approaches are used:

Knowing the composition, weld properties can be predicted for a wide range of DMWs.

Table 2. Approximate limit of diluting elements in welds.*

	Diluting Elements			
Weld Metal	**Iron**	**Nickel**	**Chromium**	**Copper**
Nickel	**30%**	**—**	**30%**	**Unlimited**
Nickel-Copper	**2.5% SMAW** **15% GMAW**	**Unlimited**	**8%**	**Unlimited**
Ni-Cr-Fe†	**25%**	**Unlimited**	**30%**	**15%**
Copper-Nickel	**5%**	**Unlimited**	**3-5%**	**Unlimited**

* The limit values should be treated only as guides. Absolute limits are influenced by the welding process, weld restraint and small variations in weld filler and base metal compositions,

† Silicon should be less than 0.75% in the weld.

1. Shop-welded transition pieces, often called "dutchmen," are used because the DMW can be made under optimum conditions, *e.g.*, down hand, automatic welding, etc.; the i.d. root can be machined or ground to provide a smooth surface; and inspection is easier. The field welds are then between similar metals, *i.e.*, stainless steel to stainless steel and low alloy to low alloy.

2. Making the DMW in the boiler; some companies prefer making one DMW field weld rather than the total of three welds described previously.

3. Nickel-base filler metals are used by most utilities intead of stainless steel. The most widely used filler metals are AWS A5.14 Class ERNiCrFe-2 for the GTAW root and covered electrodes conforming to AWS A5.11 Class ENiCrFe-2 or ENiCrFe-3.

In conclusion

The nickel-containing stainless steels, nickel- and copper-base alloys are readily fusion welded to carbon and low alloy steel and to each other. Methods are described to estimate the weld metal composition of DMWs. Knowing the composition, weld properties can be predicted for a wide range of DMWs.

In establishing a DMW procedure, the more restrictive requirements for each base metal (such as preheat, temperature control, weld heat treatment, etc.) should be used. On occasion, there will be a conflict that needs special study and testing.

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