Resist chlorides, retain strength and ductility with duplex stainless steel alloys

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Resist Chlorides, Retain Strength and Ductility with Duplex Stainless Steel Alloys

Successfully applying second-generation duplexes to process equipment requires familiarity with their welding and fabrication characteristics

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DUPLEX STAINLESS steels are an alloy family with two phases, ferrite and austenite; the ferrite is normally between 40 and 60%. The ratio is accomplished in wrought alloys by composition adjustment along with controlled hot working and annealing practices at the mill. The alloys could properly be called ferritic-austenitic stainless steels, but the term duplex is more widely used. A typical duplex stainless steel structure is shown in Figure 1. The matrix is ferrite, and the elongated, island-like phase is austenite.

The composition of four present-day (also identified as second-generation) duplex alloys is shown in Table 1. Alloy 2205 (UNS S31803), the most widely used, is available from a number of producers. Comparing the duplex compositions to a fully austenitic stainless steel such as type 316 (UNS S31600), the duplex alloys are higher in chromium and lower in nickel. The nitrogen addition is very critical in duplex alloys, as will be discussed shortly.

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Characteristics of duplex stainless steels

The duplex alloys offer two important advantages over austenitic alloys such as 304L (UNS S30403) and 316L (UNS S31603): greater resistance to chloride stress corrosion cracking (CSCC) and higher mechanical properties. The yield strength of duplex alloys is typically two to three times higher, and the tensile strength is 25% higher while still maintaining good ductility.

The susceptibility of austenitic stainless steels to CSCC at temperatures over about 130°F is well known. On the other hand, the ferritic stainless steels are highly resistant to CSCC but are more difficult to fabricate and weld. The duplex alloys have intermediate resistance to CSCC, which in many environments represents a substantial improvement over the austenitics.

The duplex alloys also offer:

- general and pitting corrosion resistance equal to or better than type 316L stainless steel in many environments,
- the very low carbon level assures resistance to intergranular corrosion,
- high resistance to erosion and abrasion,
- thermal expansion coefficient intermediate between austenitic and carbon steel.

First- and second-generation duplex stainless steels. Duplex alloys date back to the 1930s, and the early alloys are now identified as first generation. They typically had a significant loss in corrosion resistance in the as-welded condition. Type 329 (UNS S32900) is a first-generation alloy, and unless it is given a postweld heat treatment, its corrosion resistance is substantially reduced.

All of the alloys shown in Table 1 are second-generation alloys and typically contain 0.15 to 0.30% nitrogen. The benefit of nitrogen is a sharp reduction in chromium partitioning between ferrite and austenite and improved pitting and crevice

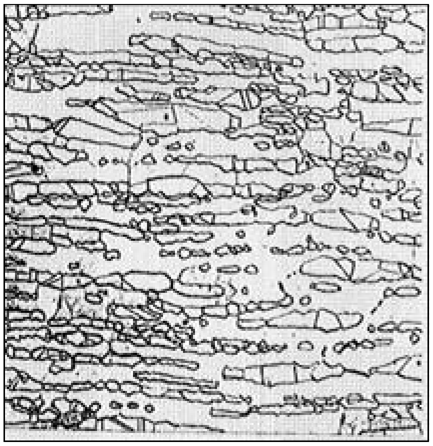

Figure 1. Typical annealed microstructure of alloy 255 plate at 500 × magnification. The matrix is ferrite, and the elongated, island-like phase is austenite. (courtesy of Haynes International)

corrosion resistance of the austenite. With proper welding procedures, as-welded second-generation duplex stainless steels can have nearly the same level of corrosion resistance as mill-annealed material.

There are other differences from the austenitic alloys that should be recognized. Four significant ones are identified below.

1. *Low-temperature toughness:* Like ferritic alloys, the duplex alloys have a definite ductile to brittle transition temperature. For this reason, the duplex alloys are generally not used below about –50°F, whereas the austenitic alloys may be used down to –456°F.

2. *Embrittlement from high-temperature exposure:* A number of undesirable phases can be formed in the duplex alloys after several minutes' exposure at elevated temperatures. In the 1,200 to 1,750°F range, sigma, chi, and Laves phases form; at 600 to 1,000°F, embrittlement occurs. The embrittlement at 885°F is unique to the ferritic iron-chromium alloys and does not form in austenitic stainless steels. While the phases are formed at high temperature, the embrittlement is a loss of toughness at room temperature. Because of these high-temperature reactions, the limit for continuous service is 500°F for alloy 255 and 600°F for the other alloys in Table l. The exposure time at high temperature resulting from welding or fast cooling following a solution anneal is not long enough to cause embrittlement in second-generation alloys.

3. *Hydrogen embrittlement:* Ferritic stainless steels and to a lesser degree duplex alloys can be embrittled by hydrogen penetrating into the metal. One source of hydrogen can be an overly aggressive cathodic protection system. Austenitic stainless steels are much less likely to be embrittled under similar conditions. Based on recent duplex welding studies, the alloys are not as sensitive as first believed to embrittlement from hydrogen introduced by sources such as the shielding gas or moisture in the coating of covered electrodes.

4. *Ferromagnetism:* With the high percentage of ferrite, the alloys are ferromagnetic and can exhibit welding features of regular steel such as arc blow.

Table 1. Chemical analysis of duplex stainless steels of major elements.

Common Name (UNS)	Percentages (Maximum except as noted)				
	C	Cr	Ni	Mo	Others
7-Mo Plus (S32950)	0.03	26.0–29.0	3.5–5.2	1.0–2.5	0.15–0.35 N
Alloy 2205 (S31803)	0.04	21.0–23.0	4.5–6.5	2.5–3.5	0.08–0.20 N
Ferralium 255 (S32550)	0.03	24.0–27.0	4.5–6.5	2.0–4.0	0.10–0.25 N 1.5–2.5 Cu
SAF 2507 (S32750)	0.03	24.0–26.0	6.0–8.0	3.0–5.0	0.24–0.32 N

Effect of welding on duplex stainless steels

The weldability of second-generation duplex alloys has been greatly improved by controlling nitrogen additions and developing nickel-enriched filler metals. Using a few welding procedure controls, sound welds with corrosion resistance comparable to the base metal are obtained. The importance of controls on heat input, interpass temperature, preheating, and nickel-enriched filler metal follows.

Nickel-enriched filler metal. Duplex alloy autogenous welds (without filler addition) can have 80% or more ferrite in the as-welded condition. Such a structure has poor ductility and often will not negotiate a bend test. An anneal at 1,900–2,100°F restores the desired balance of 40-60% ferrite, but the treatment is expensive and is not practical for many fabrications because of their size or geometry. Increasing the nickel content of the filler metal allows more austenite to form, and welds in the as-welded condition have 40-60% ferrite. Welds made with nickel-enriched filler metals have good as-welded ductility, are able to pass bend tests, and have corrosion resistance comparable to the base metal.

It is important that all weld passes be made with substantial filler metal addition to avoid nickel-lean weld regions. A large amount of base metal dilution will result in welds having a high ferrite content and low ductility. An example is the root pass of a pipe weld made with high base metal dilution and inadequate filler metal addition. Special care must be taken to add nickel-enriched filler metal. Joints with a feather edge and tight fitups favor high dilution and should be avoided. Joints with an open root spacing and a land are preferred because they allow the addition of more filler metal.

Table 2. Typical composition of duplex stainless steel filler metals.

Filler Metal Commercial Name (UNS)	For Welding Base Metal	C	Cr	Ni	Mo	Others
Covered Electrodes						
2209-16 (W32710)	2205 (S31803)	0.03	23	9.7	3.0	0.10 N
22.9.3.L–16 22.9.3.L–15 22.9.3.LR (W32710)	3RE60 (S31500) 2205 (S31803) 2304 (S32304)	0.03	22	9.5	3	0.15 N
7-Mo PLUS Enriched Ni	7-Mo Plus (S32950)	0.03	26.5	9.5	1.5	0.20 N
Ferralium 255 (W32550)	Ferralium 255 (S32550)	0.03	25	7.2	3.1	0.20 N
Bare Filler Wire						
22.8.3L	3RE60 (S31500) 2205 (S31803) 2304 (S32304)	0.01	22.5	8	3	0.10 N
7-Mo Plus Enriched Ni	7-Mo Plus (S32905)	0.02	26.5	8.5	1.5	0.20 N
Ferralium 255 (S32550)	Ferralium 255 (S32550)	0.03	25	5.8	3.0	0.17 N
Flux-Cored Wire						
Influx 2205-0 (W31831)	2205 (S31803)	0.02	22.0	8.5	3.3	0.14 N
Influx 259-0 (W32631)	Ferralium 255 (S32550)	0.02	25	10	3.2	0.14 N, 2.0 Cu

Filler metal products for the duplex alloys are available as covered electrodes, bare filler metal, and open arc-flux cored wire as shown in Table 2. Duplex filler metals are not covered by current American Welding Society (AWS) specifications for stainless steel filler metals but they are expected to be included in future revisions.

Heat input control. There has been a great deal of disagreement on the part of producers and welding investigators as to the proper limits on heat input. The argument for high heat input is that it allows more time for ferrite to transform to austenite, particularly in the heat-affected zone (HAZ). The concern for high heat input is that it allows more time for embrittling phases, such as sigma and 885°F embrittlement, to develop. With the second-generation duplex stainless steels, the time at temperature during welding is short enough that there is no significant embrittlement. A generally accepted heat input range in kilojoules (kJ) is 15 to 65 kJ/in., although levels as high as 152 kJ/in. have been successfully used. When welds must be made with less than 15 kJ/in., preheating to 200–400°F helps reduce the cooling rate and reduces the portion of ferrite in the weld.

The heat input in kilojoules per inch is calculated as follows:

$$\frac{\text{voltage} \times \text{amps} \times 60}{\text{travel speed (in./min.)} \times 1{,}000}$$

Interpass temperature control. An early concern in welding the duplex alloys was that a high interpass temperature could result in 885°F embrittlement; so a maximum limit of 300°F was suggested. It is now generally agreed that a maximum of 450 to 500°F is acceptable. In practice, however, fabricators often specify the same value used for austenitic stainless steel, 300 or 350°F, in the interest of consistency.

Preheat. There is no reason for a preheat on thicknesses of ¼ in. and less made with nickel-enriched filler metals. In heavier sections and high-restraint welds, preheat can be used to minimize the risk of weld cracking. When a low-heat-input welding process (below 15 kJ/in.) must be raised, a preheat of 200–400°F reduces rapid cooling and decreases the amount of ferrite.

Welding

The commonly used welding practices for austenitic stainless steels, other than those noted previously, are also applicable to the duplex alloys.

Preparation for welding. The important rules to observe in welding duplex alloys include careful preparation prior to welding.

Cutting and joint preparation. The alloys can be cut and the edges can be prepared by machining, plasma-arc cutting, grinding, or abrasive cutting. Thermal cut surfaces should be ground to bright metal. Carbon air arc can be used for back gouging weld root passes but not cutting. Surface contamination by free iron should be avoided. In service, embedded free iron will often cause rust spots and, in turn, become the site of a corrosion pit. Iron can be embedded as a result of handling with carbon steel tools – cutting tools or grinding wheels contaminated with iron or from abrasive blasting with iron-contaminated abrasives.

Joint designs, fitting, and tack welding. Duplex weld metal is somewhat

Internal baffles or lifters constructed of Ferralium 255 for a cylindrical dryer.

less fluid than the 300 series stainless steel, such as type 308 (UNS S30800); so the weld joints should be more open and accessible to allow manipulation of the electrode. Nickel alloy joint designs with wider bevels and thinner lands work well for duplex alloys. Because most duplex weldments will be placed in corrosion environments, butt welds should be full penetration with weld surfaces free of crevices, undercut, and other irregularities. When back gouging and welding on the reverse side are not possible, the root side should be protected during welding with an argon purge. The use of copper chill bars, with or without an inert gas, is not encouraged because the rapid cooling increases the amount of ferrite in the weld and heat affected zone.

Fitting and tack welding practices are essentially the same as with other stainless steel alloys. In making gas tungsten arc tack welds, however, it is important to add an ample amount of filler metal. Tack welds made by only melting the base metal can be high in ferrite and prone to cracking.

Cleaning in preparation for welding. Prior to tack and fill welding, the weld joint and 2 in. on either side should be cleaned of foreign materials such as oil, grease, paint, marking ink, machining lubricant, and general dirt. Failure to do so can result in welds containing cracks, porosity, and other defects. Cleaning can be done by vapor degreasing, with alkaline cleaners, or with a suitable solvent.

Duplex alloys are normally supplied in the pickled or abrasive cleaned condition and are free of surface oxides. If oxides are formed during fabrication, for example from annealing, the oxide must be removed prior to welding. Acceptable removal practices include pickling, abrasive blasting, or grinding.

Welding processes. Duplex stainless steels may be joined by the following arc welding processes: shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), flux-cored arc welding (FCAW), and submerged arc welding (SAW). Autogenous welding – that is, GTAW without the addition of filler metal – and plasma arc welding (PAW) should be avoided. Welds from both processes have excessive ferrite and consequently lower corrosion resistance and poor bend ductility unless a full post-weld anneal is performed.

Shielding and backing gases. Shielding gas for GTAW and GMAW spray arc is 100% argon. With the GMAW in the short-circuiting or pulsed-arc-transfer mode, shield gas is usually a mixture of either 75% Ar-25% He or 90% He-7½% Ar-2½% CO_2. Additions of oxygen, hydrogen, or nitrogen to the shielding gas are not recommended.

The pitting resistance of duplex alloys is reduced by the presence of oxide films such as formed during welding. Therefore, it is important to provide good backing gas protection where cleaning after welding is not possible, for example, the inside root surface of a pipe weld. Pure argon provides good protection against oxide formation, as does pure nitrogen, but nitrogen has also been found to offer increased safety against pitting attack. The mechanism of improved pitting resistance is rather complex. It has been found that chromium nitrides in the ferrite phase lower the pitting resistance of the weld metal and HAZ in duplex alloys. Nitrogen in backing gas diffuses into the weld metal and HAZ and increases the austenite content at the root surface. With increased austenite, chromium nitrides in ferrite are reduced and pitting resistance is improved.

Welding procedures. An excellent starting point for the development of a duplex stainless steel welding procedure is a proven and qualified austenitic stainless steel procedure. Because the basic principles for welding stainless and nickel alloys are covered elsewhere, they are not repeated here. Comments that follow are special to duplex alloys.

GTAW. The foregoing comments on shielding and backing gases are particularly important in GTAW. Other suggestions include using as large a gas cup size as practical to minimize surface oxidation. The welding operator should also be thoroughly instructed in the need and reason for ample filler metal (nickel-enriched) addition. This applies to both tack and fill welding.

GMAW. With its characteristic high heat input, the spray-arc-transfer mode is well suited for welding duplex alloys. The short-circuiting mode produces sound welds, but because of fast cooling rates, the joints are high in ferrite, which results in lower toughness and corrosion resistance. With some of the benefits of both, pulsed arc transfer is an intermediate choice and allows welding of sheet gauges along with all position capability. Another consideration in GMAW is that the shielding gas is usually pure argon for spray arc or an argon-helium mixture for flatter beads. Argon–helium mixtures (75% Ar–25% He and 90% He–7½% Ar–2½% CO_2) are commonly used with short circuiting or pulsed arc. While an argon shielding gas with 1-2% oxygen is used for better arc stability in spray arc welding the 300 series stainless steels, an oxygen addition should not be used with the duplex alloys.

SMAW. The electrode manufacturer's recommended instructions on amperage, electrode storage, handling, rebaking, etc. should be followed. Since duplex alloys contain at least 50% ferrite, hydrogen from moisture in the electrode coating might cause porosity or hydrogen embrittlement of the weld. Electrode storage and rebaking procedures in accordance with the manufacturer's recommendation should, therefore, be a part of the welding procedure.

Duplex-covered electrodes are mainly designed for welds to be used in the as-welded condition. Depending on the particular electrode, base metal, and welding parameters, the weld may or may not be suitable in the solution annealed condition. When post-weld solution annealing is performed, such as in the repair of castings, a detailed review of the materials used is in order.

FCAW. Most of the flux-cored wire products are self-shielding (open arc) to be used without shielding gas. In fact, the addition of a shielding may be detrimental by offsetting the ferrite balance. Users should follow the cored wire producer's recommendations for the particular product and alloy being welded. As with SMAW, a check should be made with suppliers if a post-weld solution anneal is to be performed.

In conclusion

The second-generation duplex alloys offer unique advantages to the process industries as a material of construction for process equipment. Some major differences from the austenitic stainless steels, such as type 316, include the following.

1. The useful temperature range of duplex alloys is more restricted than the austenitic alloys, namely, from about –50 to +600°F.

2. Duplex alloys have excellent resistance to chloride stress corrosion cracking and two to three times higher yield strength than austenitics.

3. The second-generation duplex alloys with controlled nitrogen additions are readily welded without impairing corrosion resistance.

4. By controlling welding parameters and using nickel-enriched filler metals, weld ferrite levels are able to be regulated and ductile welds with good corrosion resistance obtained. ■