Duplex stainless steel welding: best practices *

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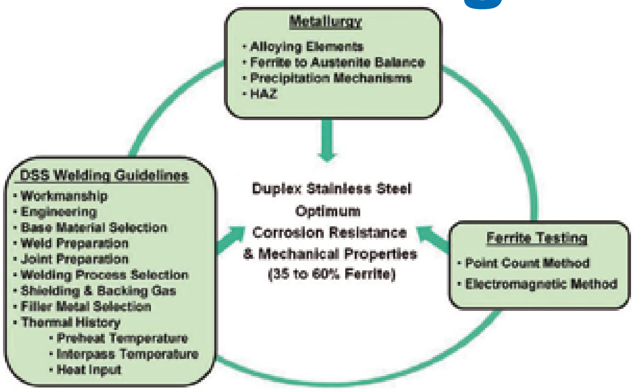

Figure 1 Overview - General Duplex Welding Guidelines

Abstract

Duplex stainless steels have an extensive, successful, track record in a multitude of corrosive and erosive environments up to 315°C (600°F), while providing high immunity to stress corrosion cracking (SCC). Althoughduplex stainless steels are, in many cases, superior in corrosion resistance and strength compared to 304 and 316 austentic stainless steels, many fabricators continue to have difficulties creating welding procedures that yield repeatable weldments with optimum properties. This paper offers practical welding guidelines to new fabricators who want to archieve high quality, robust stainless steel weldments supplementing API 938-C,. "Use of Duplex Steels in Oil Refining Industry". Discussion includes the importance of balancing ferrite to austenite, reducing formation of deleterious intermetallic and nonmetallic phases, measuring ferrite contents, and suggested welding parameters.

Introduction

For many engineering applications in the petroleum and refining industry, duplex stainless steels (DSS) are the preferred material, combining characteristics of both ferritic and austenitic stainless steel (SS) when welded correctly. When welded incorrectly, the potential to form detrimental intermetallic phases drastically increases, which could lead to a catastrophic failure. When comparing DSS to SS, DSS is more resistant than austenitic SS to stress corrosion cracking (SCC) but not as resistant as ferritic SS; also, DSS toughness is typically superior to that of ferritic SS but not as good as austenitic SS.
DSS are two phase alloys based on the iron-chromium-nickel (Fe-Cr-Ni) system. These materials typically comprise approximately equal amounts of body-centered cubic (bcc) ferrite, α-phase and face-centered cubic (fcc) austenite, γ-phase, in their microstructure. It is well documented that maximum corrosion resistance and mechanical

Table 1 Composition and PREN of wrought DSS covered by UNS designation[2].

UNS No.	Common Designation	C	Mn	S	P	Si	Cr	Ni	Mo	Cu	W	N	PREN (b)
		Composition (a), wt%											
Low-alloy grades (PREN <32)													
S31500	3RE60	0.03	0.2-2.0	0.03	0.03	1.4-2.0	18.0-19.0	4.25-5.25	2.5-3.0	...	...	0.05-0.10	28
S32001	19D	0.03	4.0-6.0	0.03	0.04	1.00	19.5-21.5	1.0-3.0	0.60	1.00	...	0.05-0.17	23.6
S32304	2304	0.03	2.5	0.04	0.04	1.00	21.5-24.5	3.0-5.5	0.05-0.60	0.05-0.06	...	0.05-0.20	25
S32404	UR50	0.04	2.0	0.01	0.30	1.00	20.5-22.5	5.5-8.5	2.0-3.0	1.0-2.0	...	0.20	31
Intermediate-alloy grades (PREN 32-39)													
S31200	44LN	0.03	2.0	0.03	0.045	1.00	24.0-26.0	5.5-6.5	1.2-2.0	...	...	0.14-2.0	33
S31260	DP3	0.03	1.0	0.03	0.03	0.75	24.0-26.0	5.5-7.5	2.5-3.5	0.20-0.80	0.10-0.50	0.10-0.30	38
S31803	2205	0.03	2.0	0.02	0.03	1.00	21.0-23.0	4.5-6.5	2.5-3.5	...	...	0.08-0.20	34
S32205	2205+	0.03	2.0	0.02	0.03	1.00	22.0-23.0	4.5-6.5	3.0-3.5	...	...	0.14-0.20	35-36
S32550	255	0.03	1.5	0.03	0.04	1.00	24.0-27.0	4.5-6.5	2.9-3.9	1.5-2.5	...	0.10-0.25	38
S32900	10RE51	0.06	1.0	0.03	0.04	0.75	23.0-28.0	2.5-5.0	1.0-2.0	...	...	...	33
S32950	7-Mo Plus	0.03	2.0	0.01	0.035	0.60	26.0-29.0	3.5-5.20	1.0-2.5	...	...	0.15-0.35	35
Superduplex grades (PREN ≥40)													
S32520	UR52N+	0.03	1.5	0.02	0.035	0.80	24.0-26.0	5.5-8.0	3.0-5.0	0.50-3.00	...	0.20-0.35	41
S32750	2507	0.03	1.2	0.02	0.035	1.00	24.0-26.0	6.0-8.0	3.0-5.0	0.5	...	0.24-0.32	≥41
S32760	Zeron 100	0.03	1.0	0.01	0.03	1.00	24.0-26.0	6.0-8.0	3.0-4.0	0.5-1.0	0.5-1.0	0.30	≥40
S32906	Safurex	0.03	0.8-1.5	0.03	0.03	0.50	28.0-30.0	5.8-7.5	1.50-2.60	0.80	...	0.30-0.40	≥41
S39274	DP3W	0.03	1.0	0.02	0.03	0.80	24.0-26.0	6.0-8.0	2.50-3.50	0.20-0.80	1.50-2.50	0.24-0.32	42
S39277	AF 918	0.025	...	0.002	0.025	0.80	24.0-26.0	4.5-6.5	3.0-4.0	1.2-2.20	0.80-1.20	0.23-0.33	≥41

(a) Single values are maximum
(b) PREN = %Cr + 3.3x(%Mo + 0.5x%W) + 16x%N

**Stainless Steel World had intended to publish this article in two parts. The first part of which was published in the November 2007 edition of the magazine on pp. 43, 45, 47, and 49. Unfortunately this contained mistakes resulting from incorrect processing of the material at Stainless Steel World's offices. We would like to express that these mistakes in no way relect upon the the work of the Fluor Corporation. As a result we would like to rectify the situation by publishing the correct version of the entire paper in this December edition of Stainless Steel World.*

Element	Weight Percentage (wt %)	Elemental Role	Alloying Characteristics
Chromium (Cr)	18 to 30%	Ferrite former	• Increasing Cr will increase corrosion resistance. • The ferrite content increases with increasing Cr; however, too much Cr will decrease optimal phase balance.
Nickel (Ni)	4 to 8%	Austenite former	• Ni promotes a change in crystal structure from ferrite to austenite. • Ni delays the formation of intermetallic phases.
Molybdenum (Mo)	Less than 5%	Ferrite former	• Enhances pitting corrosion resistance. • Increased tendency to form detrimental intermetallic phases if Mo content is too high.
Nitrogen (N)	Minimum of 0.14%	Austenite former	• N causes austenite to form from ferrite at elevated temperatures, allowing for restoration of an acceptable balance of austenite to ferrite after a rapid thermal cycle in the HAZ after welding. • Additions of N increase pitting and crevice corrosion resistance and strength. • Delays the formation of intermetallic phases. • Offsets the formation of sigma phase in high Cr, high Mo steels.

Table 2 Importance of alloying elements of DSS.

properties throughout a DSS weldment are achieved when the phase balance of ferrite to austenite is 50:50. However, achieving a 50:50 phase balance of ferrite to austenite ($\alpha \rightarrow \gamma$) in a weldment has proven to be difficult due to many variables such as metal chemistry, welding processes, and thermal history of the steel. Experience coupled with testing has shown that DSS have optimal corrosion resistance and mechanical properties when 35 to 60% ferrite content is maintained throughout the weldment. Figure 1 illustrates the factors that contribute in achieving the optimal weld properties.

Many fabricators lack sufficient experience controlling heat input that achieves a balanced microstructure in DSS weldments. Duplex guidelines (Figure 1) supplement API 938-C[1] and suggest parameters for welding procedure specifications (WPS) that will assist welders achieve the optimum ($\alpha \rightarrow \gamma$) balance.

Metallurgy

Alloying Elements

For DSS producers there is no difficulty in meeting standard specifications of chemical compositions. Individual steel producers have narrow target compositions within ASTM/ASME specifications to meet different criteria. DSS are sensitive to variations in composition, particularly of those elements controlling the phase balance. The relatively broad chemical limits permit large variation in properties.
There are three basic categories of DSS, low-alloy, intermediate alloy, and highly alloyed, or superduplex stainless steel (SDSS) grades, grouped according to their pitting resistance equivalent number (PREN) with nitrogen and are shown in Table 1. The most widely used alloys are DSS-grade 2205+ and SDSS-grade 2507.

The remarkable corrosion resistance and mechanical properties of DSS are attributed to the rich alloy content of chromium, nickel, molybdenum, and nitrogen that form austenite in a ferritic matrix. The combination of high chromium and high molybdenum is a cost-efficient way to achieve good chloride pitting and crevice corrosion resistance because of the reduced amount of nickel compared to austenitic SS. The superior attributes of DSS are credited to the interactions of alloying elements forming complex microstructures. The importance of alloying elements is explained in Table 2.

Optimum ($\alpha \rightarrow \gamma$) Balance

Ferrite content of DSS will indicate whether proper welding and/or heat treatment techniques result in corrosion resistance and mechanical properties that fulfil engineering requirements. The presence of ferrite in DSS imparts the superior chloride stress corrosion cracking (CSCC) resistance and high strength. An increase of ferrite content causes behaviour similar to a ferritic SS. When the amount of austenite in DSS increases, strength will decrease while corrosion resistance and susceptibility to CSCC increases. As a consequence, ferrite limits should be specified within a reasonable range and be used as a control measure.
When low temperature impact properties are required, ferrite content must be carefully controlled.

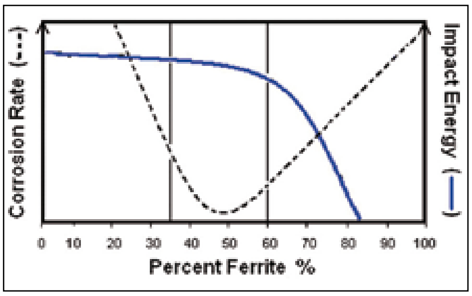

Figure 2 Corrosion rate and impact energy vs. percent ferrite of DSS.

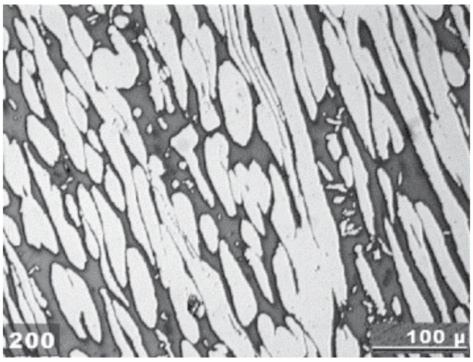

Figure 3: DSS micrograph (200X)[4]

As the ferrite content exceeds approximately 60%, there will be a noticeable decrease in the ductile behaviour and pitting resistance. Sources indicate there may be a negative effect on ductile behaviour with ferrite levels below 35%, and reduced resistance to SCC due to a change in the solidification mode causing segregation and precipitation of intermetallic phases[3]. Although it is common to see 30-65% ferrite specified for base and weld metal and 30-70% ferrite HAZ, our experience shows a range between 35-60% ferrite provides optimal results.
Figure 2 is a theoretical diagram that illustrates how ferrite content affects DSS materials. The dotted curve represents the corrosion rate in chloride containing aqueous envi-

	Duplex Stainless Steel	
	°C	°F
Solidification range	1445 to 1385	2633 to 2525
Scaling temperature in air	1000	1832
Sigma phase formation	700 to 975	1292 to 1787
Carbide precipitation	450 to 800	842 to 1472
475C/885F embrittlement	350 to 525	662 to 977

Table 3 Typical precipitation temperatures for DSS.

ronments with respect to percentage of ferrite within the material. The corrosion rate is greatest below and relatively moderate above 35% ferrite. The solid curve represents impact energy at ambient temperatures with respect to the percentage of ferrite in DSS. Impact energy is at its greatest magnitude at lower ferritic levels right through to approximately 60% ferrite, at which point, the impact energies begin to significantly decrease.

Precipitation Mechanisms

Optimum phase balance ($\alpha \rightarrow \gamma$) of a DSS is shown in Figure 3. The light globules in the dark body are unetched austenitic grains within the etched ferritic matrix respectively.

DSS alloys solidify primarily as ferrite at approximately 1425°C (2597°F) and partially transform to austenite at lower temperatures by a solid state reaction[4]. If the cooling rate is rapid, very little ferrite will transform to austenite resulting in an excessive ferrite phase at room temperature. Consequently, the cooling rate of duplex welds must be slow enough to allow the transformation of approximately 50% of the ferrite to austenite and, at the same time, fast enough to prevent the formation of intermetallic phases and deleterious microstructures. Unwanted phases may occur during fabrication when welding differing section sizes or heavy sections with very low heat input.

The high alloy content and the presence of a ferritic matrix render DSS susceptible to embrittlement and loss of mechanical properties, particularly toughness, through prolonged exposure at elevated temperatures. As cooling proceeds to lower temperatures in the range of 475-955°C (887-1750°F) for short periods of time the precipitation of carbides, nitrides and intermetallic phases, all of which can be detrimental, will occur. The most notable phases are alpha prime (α'), sigma (σ), chi (χ), and Laves (η) phases. For this reason, DSS are generally not used at temperatures above 315°C (600°F).

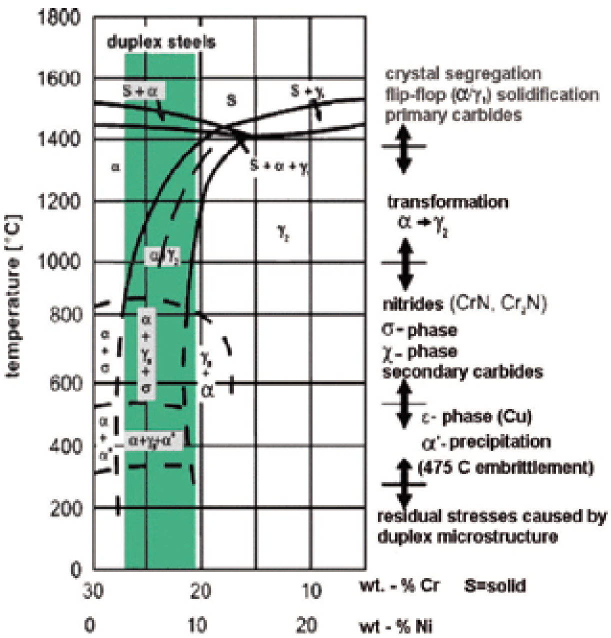

Figure 4 Pseudo-binary Fe-Cr-Ni phase at 70% Fe section illustrating areas of detrimental phase formation[5].

Cooling provided by the work piece itself is the most effective method of reducing the time that the HAZ is in the temperature range formation of these intermetallic phases. The pseudo binary phase diagram, Figure 4, is a roadmap of the metallurgical behaviour of DSS, and may be used to extrapolate the temperatures at which precipitation reactions and other characteristics occur (Table 3).

Heat Affected Zone (HAZ)

The HAZ is the area of the base metal that has its microstructure and properties altered by inducing intensive heat into the metal. The HAZ should have corrosion resistance and impact toughness comparable to the base material minimum requirements. DSS and SDSS exhibit a narrow-HAZ, in comparison to austenitic-SS, due to the low heat input welding processes and the high thermal conductivity of the material. Typically an austenitic-SS HAZ is in the order of 500 µm in width (approximately 20 grains), whereas a DSS HAZ is often as small as 50 µm in width (2 grains). For this reason, it is extremely difficult to measure the narrow-HAZ of DSS in commercial and industrial settings. The morphology of a DSS HAZ is more important than estimating ($\alpha \rightarrow \gamma$) values. A low heat input welding process has sufficient heat to promote the transformation of discontinuous ferrite in the HAZ, and will contribute to the fine grain size responsible for the increase in toughness of the region (Figure 4). Caution is necessary when using too low a heat input associated with rapid cooling as a narrow and predominantly ferritic HAZ may be produced. Sufficient micrographs demonstrating the presence of discontinuous ferrite in the HAZ may be required to ensure a robust welding process.

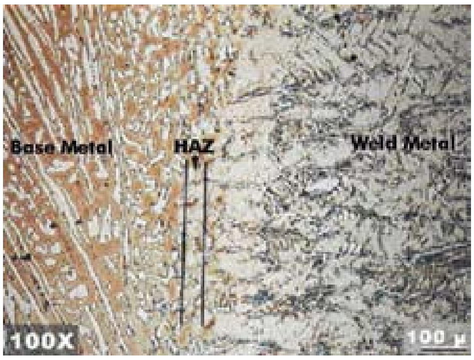

Figure 4: Light optical micrograph of a 50mm 2205 DSS material.

Table 2 indicates the effects of N in DSS; furthermore, N additions to

Test	Purpose	Additional Details
ASTM A923 Method B or C	Determines if any intermetallic phases or precipitates were formed during welding process	Must have predetermined acceptance criteria Determine if precipitates affect corrosion resistance and mechanical properties
Ferrite Readings		WPS and PQR generally uses point count method
(1) Point Count Method	Determines % ferrite	Check α–γ balance for entire weldment thickness. Optimal ferrite content between 35-60%
(2)Electromagnetic Measuring Method	Determines % ferrite or FN	Used during production welding to verify % ferrite in accordance with WPS and PQR Sample preparation according to manufacturer's recommendations Use for WPS and PQR for comparison with production welds Device measurements of the weld cap and root should be within 35–60% ferrite content
Hardness survey	Check maximum allowable hardness	Depends on DSS grade and service environment Recommended not to exceed HV_{10} 310 Caution: Conversion from Vickers hardness to Rockwell for DSS is not represented by ASTM E140. Refer to API-938C, Figure 2, for hardness conversions.
Impact Testing	Toughness measurement	Typically associated with minimum design temperature and engineering recommendations EN specifies minimum 60J at room temperature Frequent requirements for parent and weld metal are minimum 45J average at -46°C per ASTM A923 Method B. The narrow HAZ precludes accurate impact measurements in isolation.

Table 4: Additional details to ASME Section IX in the development of a WPS and PQR.

the shielding gas further support formation of austenite during cooling so that the weld and HAZ are more easily converted back to the optimal austenitic to ferritic balance. It is difficult to test the toughness in the HAZ by traditional methods since the zone is often not more than one or a few grain sizes wide[4].

DSS General Welding Guidelines

Acceptable welds do not depend solely on a welder's ability to weld DSS; it also depends on a range of variables such as base and filler material selection, pre/post-weld cleaning, joint preparation and, most importantly, choice of the most suitable welding process for a specific job. Historically, fabricators new to welding DSS spend a significant amount of time fine tuning their WPS to achieve optimal weldments. The following guidelines are intended to supplement API 938-C. The guidelines, suggest parameters for weld procedures as well as providing knowledge to create welds with excellent properties, with reasonable production, and low repair rates.

Workmanship

The most important factors in successfully welding DSS are quality workmanship and welder education. Rewards are significant when welders are informed and involved in the details of the weld procedure since even the best welder can create marginal welds with an excellent WPS. An informed and proactive welder can create successful, repeatable, welds when there is an understanding of the important role the variables play in achieving an optimum ($\alpha \rightarrow \gamma$) balance in DSS.

Engineering

The key to obtaining well balanced ferrite proportions within the base-metal, weld-metal, and HAZ is to perform Welding Procedure Specifications (WPS) and Procedure Qualification Records (PQR) that address DSS welding issues as well as all requirements and codes for weld joints and applications. According to code requirements, a WPS and PQR must meet only the minimum requirements specified in the design code. The welding of DSS demands that additional tests be conducted to ensure that the weld will be suitable for the intended service and exhibit the same physical and corrosion resistant qualities as the base metal. In particular, heat inputs should be well documented in the WPS and PQR so that welders may duplicate the original during production welding. If the appropriate precautions and controls are not recognized during the WPS and PQR development stage, production welds can be plagued with problems. In addition to the requirements set forth in ASME, Section IX, or the appropriate design code for the weldment, there are a handful of additional tests and controls that should be applied to the WPS and PQR development to ensure that the welds produced are mechanically sound, corrosion resistant, and repeatable under shop or field conditions.
The requirements of ASME Section IX should be addressed in the development of WPS and PQR as well as the tests listed in Table 4.

Base Material Selection

Base materials should be delivered in an acceptable condition since

corrosion resistance and mechanical properties of duplex alloys rely so heavily on the phase balance and absence of deleterious microstructures. Generally, DSS are produced from the mills with a good $\alpha \rightarrow \gamma$ balance that is very close to 50:50; however, it is recommended that testing be conducted to verify the absence of harmful intermetallic compounds or precipitates. ASTM A923 is designed to detect the presence of intermetallic phases in the mill product of DSS to the extent that toughness or corrosion resistance is affected significantly[6]. It should be noted that the test methods will not necessarily detect losses of toughness or corrosion resistance attributable to other causes[6]. Good practice is to verify %ferrite of the base metal prior to welding.

Dissimilar metal welds (DMW) between DSS and other materials must be evaluated case by case. Generally, it is possible to weld all grades of DSS to DSS, carbon steel (CS), alloy steel, and austenitic SS[1]. In some cases it is necessary to use buttering techniques to avoid PWHT of the final weld.

Weld Preparation

Proper cleaning prior to welding is a foundation for successful DSS welds. Prior to any welding, all weld bevels should be examined using liquid penetrant testing for edge defects and laminations for all thicknesses greater than 6 mm (0.24 in), and visually inspected for nicks, dents, general damage or other surface irregularities. It is also important to clean the surrounding weld area, usually 2 inches back from the bevel, with grinding pads, then wiped with an approved solvent. Grinding pads, soft packs, wire brushes and others tools used in austenitic SS fabrication are acceptable for use on DSS. The base metal should also be cleaned of rust blooms and embedded iron.

Additional precautions for DSS should always be in place to minimize iron contamination. Some DSS are susceptible to iron contamination by free iron, whether it be impregnated or on the surface. The contamination mechanism is a galvanic reaction when an electrolyte is present. Fabricators should have an inspection procedure in place to prevent iron contamination in accordance with ASTM A380[7].

Measures to protect cleaned surfaces should be taken as soon as the final cleaning is completed and should be maintained during all subsequent fabrication, shipping, inspection, storage, and installation. Finished, cleaned materials should not be stored on the ground or floor, and should not be permitted to come in contact with asphalt, galvanized carbon steel, mercury, zinc, lead, brass, low melting point metals, or alloys that have been in contact with such materials[7]. Store DSS material and equipment on wood skids, pallets or metal surfaces, that are protected and prevent direct contact with the DSS surface. Keep openings of pipes, tubes, valves, tanks, pumps, and pressure vessels, etc., capped or sealed at all times except when in use.

Joint Preparation

Joint preparations for DSS are typically common to austenitic SS; however, deviations exceeding 20% of the PQR parameters may have significant detrimental effects on weld consistency. Experience shows that DSS can be cut using the plasma-arc process, a machine cutter, or grinding disc dedicated solely for the use on DSS. If plasma-arc cutting is used, the inside surface must be thoroughly cleaned of all spatter. Sufficient metal should be removed in the bevelling process to eliminate any HAZ that occurred as a result of the plasma-arc cutting. Carbon-arc should not be used for cutting or back gouging.

When DSS welds are to be completed from one side, a slightly wider gap and a more open angle is preferable since duplex filler metals do not penetrate as deeply as austenitic SS filler metals. To achieve a maximum of 50% dilution in the root pass, a wider gap is needed to allow additional filler to be deposited.

The final surface preparation and configuration should be obtained by machining or grinding. During machining operations, only a cutting fluid compatible with SS should be used. Any small burrs, nicks, or other irregularities on the weld bevel should be repaired, if possible, by light grinding. Follow necessary cleaning procedures.

Welding Process Selection

Process selection is usually dictated more by the availability of consumables, economics, and logistic considerations than by end desired properties. As well, it is commonly mistaken that DSS can be welded similarly to austenitic SS. For DSS, the narrow welding parameters and specific filler metals defined in the PQR must be closely monitored to maintain a balanced microstructure. If the balance is significantly altered and the two phases are no longer in similar proportions, then loss of material properties can be significant. Where exceptional low-temperature toughness is required, gas-shielded processes may be specified to produce higher weld metal toughness properties than flux-shielded processes[2].

Gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), submerged arc welding (SAW), flux cored arc welding (FCAW), gas metal arc welding (GMAW) and plasma arc welding (PAW) are commonly used with success for most DSS grades. Although all of the common arc welding processes are suitable for welding DSS, generally a welding process is selected based on suitability for the welding environment (whether it is field or shop welding), size, type, orientation of joints, and the required balance between speed and quality. Once the process has been selected, it can be optimized for the specific grade of DSS being joined.

Autogenous welding, such as electron-beam welding and laser-beam welding, is not very suitable for the welding of DSS since this process creates welds with very high ferrite content. In these cases, a solution-anneal PWHT can restore an acceptable weld and HAZ phase balance and remove undesirable precipitates provided ideal cooling rates are followed.

Shielding and Backing Gas

Pure argon (Ar) shielding and backing gases can create weldments with sufficient corrosion resistance.

Table 5 Shielding gas general recommendations.

Welding Process	Gas Types
GTAW	99.996%Ar, Ar+2%N_2, Ar+5%N_2
GMAW	Ar+1%O_2, Ar+30%He+1%O_2, Ar+2%CO_2, Ar+15%He+2%CO_2
FCAW	Ar+1% O_2, Ar+20%CO_2, Ar+2%CO_2
PAW	99.996%Ar

Table 6 DSS and SDSS consumable specifications.

Alloy	Process	AWS Specification	BS EN Specification
DSS	GTAW	ER 2209	W 22 9 3 N L
	GMAW	ER 2209	G 22 9 3 N L
	SMAW	E 2209-15/16/17	E 22 9 3 N L B/R
	FCAW	E 2209 t0-1/4, E 2209 t1-1/4	T 22 9 3 N L R/P
	SAW	ER2209+flux	S 22 9 3 N L R/P
SDSS	GTAW	-	W 25 9 4 N L
	GMAW	-	G 25 9 4 N L
	SMAW	-	E 25 9 4 N L B/R
	FCAW	-	-
	SAW	-	S 25 9 4 N L + flux

However, N loss is not uncommon to a depth of 0.5 mm from the surface of the weld. To correct the phase balance and improve corrosion resistance of the weld, it is beneficial to have additions of 1-2% N in the Ar shielding and 90% N and 10% hydrogen (H) in the backing gas. Nitrogen contents above 2% in the shielding gas can cause degradation of the tungsten electrode for GTAW processes. The addition of H to the shielding gas is not recommended as it may cause H absorption in the weld.

Back purging should be maintained on the joint until at least 6 mm of weld metal thickness has been deposited. The oxygen content of the back purged volume should not exceed 0.25% (2500 ppm)[1].

Since DSS have relatively high chromium contents and relatively low thermal expansion, an oxide scale appearing as an oxide tint is produced during welding that is typically thin and difficult to remove. The appearance and amount of heat-tint produced during welding can be minimized with low levels of oxygen (below 0.25%) in the shielding and backing gases, with minimal moisture in the backing gas, and with limiting contaminants on the surface prior to welding. Hydrogen in the Ar backing gas can adversely affect the appearance of heat tint, and the base metal's surface finish. Shielding gases suitable for the various gas shielded processes are listed in Table 5.

Filler Metal Selection

Welding consumables for DSS are similar in composition to that of the base material, but the consumables do require nitrogen and higher levels of nickel to ensure an appropriate phase balance in the deposited weld metal. A nitrogen addition in filler metals, 0.14-0.20% N, helps to prevent the formation of σ phases. Increased addition of Ni promotes a change in crystal structure from ferrite to austenite and also delays the formations of intermetallic phases. A weld metal microstructure from a filler composition exactly matching that of the base metal would yield high ferrite content, off balancing the optimal $\alpha \rightarrow \gamma$ required. It is important that the Cr-content of the deposited filler metal selected provides a close match of the base metal. DSS and SDSS may be welded with a DSS filler metal that is alloyed with higher amounts of Ni or, alternatively, they could be welded with a fully austenitized Ni-alloy filler metal. Welding DSS-2205 with ER 2209 filler metal is an effective method of achieving optimal $\alpha \rightarrow \gamma$ phase balance. The ER 2209 filler metal has equal quantities of Cr-content as well as 7 to 9% nickel compared to the 5.5% nickel of the base metal. Table 6 lists consumable specifications for DSS and SDSS according American Welding Society (AWS) and British Standard (BS).

Welding SDSS-2507 using ER 2209 filler metal is not advised due to under-matching chemistry. Some fabricators use AWS ER 2553 for welding SDSS-2507; however this practice is not recommended due to under-matching Ni-content and unacceptably high addition of copper (Cu). Increased Cr-content and low Ni-content of the filler metal will produce welds and HAZ with excess ferrite upon welding. The increased Cu additions will produce detrimental Cu precipitates (ε-phase) as Cu has a low solubility in ferrite (<0.2%).

Welding SDSS-2507 with a 25Cr-9Ni-4Mo filler metal according to EN specification (Table 6), or choosing a Ni-alloy filler metal in replacement of DSS filler metal is suggested. Fully austenitic Ni-alloy filler metals provide improved pitting corrosion resistance as well as immunity from SCC to the weldment. Successful welding has been reported with various Ni-alloy filler metals such as E/ER NiCrMo-14, E/ER NiCrMo-10, and E/ER NiCrMo-3. It is important to note that caution is needed while welding DSS with Ni-alloy filler metals that contain niobium (Nb). For example, E/ER NiCrMo-3, as the weldment is more susceptible to stress cracking when welded with high heat inputs, forming Nb-nitride and Nb-carbonitride precipitates. A low heat input is recommended in this case.

Dissimilar metal weld (DMW) filler selection should preserve the low carbon content of DSS to achieve a phase balance that is mechanically tough and strength and corrosion resistance superior to at least one of the dissimilar metals[1]. DSS filler is generally used for DMW joints between DSS and CS or austenitic SS[1]; however, a case-by-case review is necessary for process conditions and design parameters. For further analysis, refer to NACE Corrosion Paper No. 07568 "Selection of Dissimilar Metal Welds in Severe Environments for Today's Petrochemical Plants."

Thermal History

Preheat and Interpass Temperatures

DSS should be free of moisture prior to welding. Preheating to a maximum of 95°C (203°F) may be applied to remove moisture; however, weldments should be allowed to cool to room temperature prior to welding. Generally, preheating is not recommended immediately prior to weld-

ing as it may negatively affect cooling rates required to achieve optimal phase balance. There may be instances, for example thick-wall to thin-wall, where weldments may require a small degree of preheating to prevent too rapid a cooling rate. These instances should be reviewed by a welding engineer on a case by case basis.
The maximum recommended interpass temperature should not exceed 200°C (392°F) for DSS alloys and 150°C (302°F) for SDSS alloys throughout welding operations[2]. Excessive interpass temperatures can cause embrittlement and low impact values in the root region. Take temperature readings on the base metal surface, directly adjacent to the weld groove[1]. Note that wall thicknesses greater than 25 mm will have higher temperatures deep in the weld than the temperature measured on the surface. In these situations, harmful phases could form over prolonged time.

Heat Input

Heat input significantly affects the cooling rate that results in the final microstructure. Too low a heat input will often result in a weld that is predominantly ferritic and will not have the same characteristics as the base metal. Often a moderately low preheat (below 75°C (167°F)) combined with low heat input can achieve optimum phase balance without the formation of excessive ferrite.
Conversely, high a heat input results in slow cooling rates that increase the risk of the formation of intermetallic compounds or precipitates in the weld and HAZ. Choose a heat input with an appropriate intermediate cooling rate that favors austenite re-formation at high temperatures and retards sigma formation at lower temperature[1]. For DSS, a relatively low heat input, in the range of 0.5-2.5 kJ/mm and for SDSS, 0.2-1.5 KJ/mm has been successfully used.

Post-Weld Heat Treatment (PWHT) and Cleaning

PWHT of DSS is generally not required but may be necessary when detrimental amounts of intermetallic phases have formed. Typically, a full solution anneal followed by a water quench should be considered. When correction heat treatments are not possible, cut out and replacement should be considered.
Post weld cleaning is required to maintain the corrosion resistance. Removal of any heat tint helps to achieve maximum heat resistance. Grinding to clean bright metal is effective. Blasting might be effective, but depending on the scale and the blasting medium it may not be as effective as grinding.

Testing for Optimum Properties

At present, experimental methods are not available that give absolute measurements of the ferrite content in weld metal, either destructively or non-destructively. This situation has led to the development and use, internationally, of the concept of a "ferrite number" (FN). The FN is a description of the ferrite content of a weld metal determined using a standardized procedure. FN is approximately equivalent to the weight percentage ferrite content, particularly at low FN values.
A number of methods exist to measure the ferrite of a given sample although, historically, there is a great deal of confusion over which method to apply and how to interpret the results. The most common methods to measure ferrite content of DSS are point count method (PCM) and an electromagnetic measuring device (EMD), both governed by ASTM E562. The PCM, a more time consuming but more accurate method, is best to verify the consistency of balanced $\alpha \rightarrow \gamma$ during WPS and PQR development because it is a destructive test.
The EMD is a preferred method for verifying the austenite to ferrite ratio of production welds. The ferrite content determined by these methods is arbitrary and is not necessarily the true or absolute ferrite content throughout the weldment thickness. The relative percent accuracy is based on unbiased statistical estimations described in ASTM E562.

Point Count Method (PCM)

The PCM is a systematic, manual counting procedure for statistically estimating the volume fraction of an identifiable constituent or phase. This method requires a mounted and polished planar cross section of the weld specimen, a method that cannot be applied to production welds, but can be applied to WPS and PQR. The PCM verifies $\alpha \rightarrow \gamma$ balance in the PQR test coupons to provide assurance that the WPS will yield optimum phase balance during production welding. Tests are recommended for the following locations:

- In the parent metal, one measurement on each side of the weld at mid thickness (total 2).
- In the HAZ on each side of the weld, in the region of the root pass (total 2). Sufficient micrographs may be required to ensure discontinuous ferrite along the narrow HAZ.
- In the weld metal, 3 measurements near to the vertical center line of the weld, one in the cap, one in the root, and one at mid thickness (total 3).

Electromagnetic Measuring Device (EMD)

An EMD provides fast and easy readings without any significant preparation or the requirement to section welds and verifies that ferrite values do not deviate significantly from values in the WPS and PQR. The Fischer Feritscope® MP30E is an example of an EMD that measures both ferrite numbers (FN) and percent ferrite according to the magnetic induction method. This device can measure from 0.1 to 110 FN and 0.1 to 80% ferrite[8]. Production ferrite tests should be performed at intervals of 3 tests every 5 feet of weld; one in each of the base metal and weld metal. All single point measurements from this method should be within the specified range. Surface preparation should follow the manufacturers recommendations. The ferrite content of the narrow HAZ cannot be accurately measured by this method.

Conclusions

Good corrosion resistance and mechanical properties of DSS are the result of well crafted WPS/PQR that define heat inputs and cooling rates to achieve weldments with optimum ferrite to austenite balance. The

presence of ferrite in DSS imparts the superior CSCC resistance and high strength. On the other hand, austenite in DSS provides the high aqueous corrosion resistance and low temperature impact toughness. The recommended phase balance of DSS and SDSS should contain 40-60% ferrite in the base metal and 35-60% ferrite in the weld metal. Special consideration must be given to the narrow-HAZ. It is essential to have a discontinuous fine grain microstructure of ferrite and austenite in the narrow region.

DSS shows rather complex precipitation behaviour due to the high amount of alloying elements. The formation of carbides, nitrides and intermetallic phases, which can be detrimental, will begin to form in short periods of time as cooling proceeds to lower temperatures in the range of 475-955°C (887-1750°F). For this reason DSS should not be used at temperatures above 300°C (570°F).

Optimum DSS welds depend on multiple factors such as engineering design, material selection, pre/post-weld cleaning, joint preparation and most importantly, choice of a suitable welding process. Guidelines supplement API 938C and provides recommendations for WPS and PQR development to achieve an optimum ferrite to austenite balance during welding.

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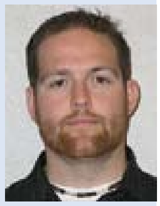

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