Duplex stainless steel welding. Best practices

(Part 1)

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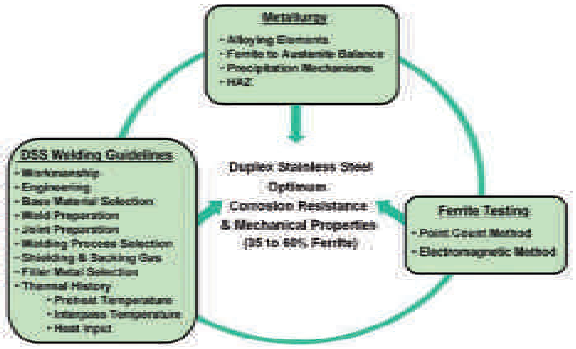


Figure 1 Overview - General Duplex Welding Guidelines

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 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 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-C1 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 nar-

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

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

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.

row 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. 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 phases3.

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 environments 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.

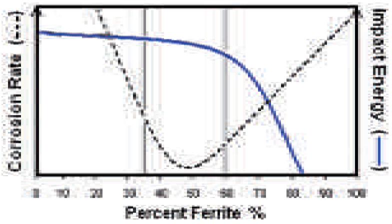


Figure 2 Corrosion rate and impact energy vs. percent ferrite of DSS.

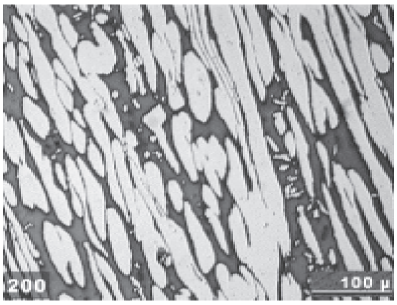


Figure 3: DSS micrograph (200X)[4]

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 reaction4. 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

	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.

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).

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).

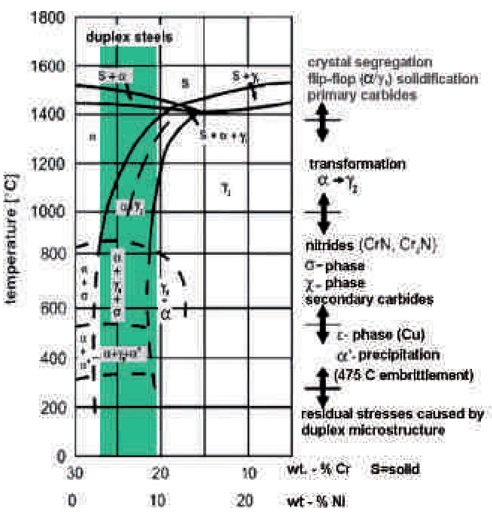


Figure 4 Pseudo-binary Fe-Cr-Ni phase at 70% Fe section illustrating areas of detrimental phase formation5.

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.

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

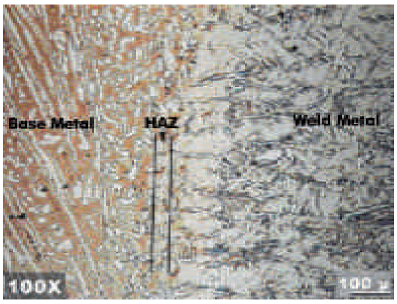


Figure 4: Light optical micrograph of a 50mm 2205 DSS material.

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.

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.

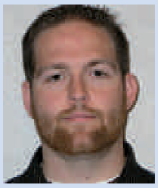
Table 4: Additional details to ASME Section IX in the development of a WPS and PQR.

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.

About the authors



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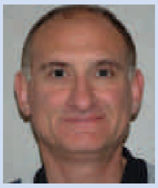

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