Welding duplex stainless steel – Industry Guide -

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Abstract. In 1992, the first issue of "Welding Duplex and Super duplex Stainless Steel – A Guide for Industry" by L.van Nassau et al [1] was published. Since the introduction, new processes, materials and classifications have been accepted. Nowadays, duplex stainless steel is a well recognized steel grade. For applications with specific corrosion requirements, super-duplex stainless steel is the preferred grade. A move from duplex stainless steel to lean duplex [2, 3]or stainless steel is made in applications where this grade has adequate corrosion properties and a cost saving can be achieved. For more severe requirements, hyper duplex stainless steel grades [4] have been introduced. In this paper, an up-to-date overview of welding consumables and processes with their relevant mechanical and corrosion properties is given, in relation to applications and requirements. For instance flux cored wires were at that time not general accepted, where today super duplex grades are standard commercially available. The paper will discuss base materials, code & specification requirements, welding consumables, procedural guidelines, joint properties, achieving code requirements and writing realistic specifications.

1 Introduction

Due to fabrication issues and practical experience in application and welding, the history of duplex stainless steels is relatively short. Early seventies, stainless steels with a duplex structure, like AISI 329 (25Cr, 4.5Ni, 1.5Mo), were mainly available in the US in the petrochemical industry. The first "duplex" type of stainless steel in the Netherlands was a grade with 18Cr, 4.5Ni, and 2.7Mo. At that time, there was no welding consumable available, and the closest match was 21Cr, 9.5Ni, 2.2Mo. The explanation was that the higher Cr would compensate the lower Mo, which was not too bad of a thought at time. The first real duplex was 1.4462, which caused some problems in fabrication and after welding. When welded in an X-joint with stick electrodes (matching chemistry), welding of the first side was okay. First pass of second side however, cracked. The explanation afterwards was simple based on microstructure deposited. It was Hoffmeister [5] who published on solidification behavior of relatively high Cr / low Ni, and indicated the path to follow to avoid 100% ferrite solidification, and create sufficient ductile austenite after cooling in welding conditions. Adding up to 9% Ni in the welding consumable, appeared to be the solution to create sufficient austenite to withstand contraction in the welded construction.

Early nineties, Welding in the World published the "Guide for Industry". Material engineers in the petrochemical industry and chemical tanker shipbuilding became convinced that the combination of higher strength and increased corrosion properties, compared to common austenitic stainless steel grades, offer a real advantage. The use of both duplex and super duplex stainless steels increased significantly. Worldwide consumption was estimated between 100.000 and 150.000 tons. Grade UNS S31803 reached the third place in stainless steel consumption. Initially, oil companies limited the allowable design temperature to -20°C and a material thickness of 25mm. Later on, impact toughness at -46°C, and CTOD at -40°C was referred to. Today many variants of duplex stainless steel, from "lean" to "hyper" grades, are commercially available, achieving a wide range of strength level, corrosion resistance and cost efficient solutions. Duplex stainless steels have found their way in applications in the chemical, oil and gas industries, petrochemical process plants, the pulp & paper industry, pollution control equipment, transportation and for general engineering.

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2 Base Materials

Duplex stainless steels are a mixture of bcc ferrite and fcc austenite crystal structures. Although the percentage of each phase is dependent on the composition and heat treatment, most duplex stainless steels are intended to contain around equal amounts of ferrite and austenite phases in the annealed condition (Fig. 1). The chemical composition, based on high contents of Cr and Mo, improves intergranular and pitting corrosion resistance, respectively. Additions of nitrogen, promote structural hardening by interstitial solid solution mechanism, which raises the yield strength and ultimate strength values. Compared to austenitic stainless steels, duplex alloys have greater tensile and yield strengths, typically twice as strong, but poorer toughness. The two-phase microstructure guarantees higher resistance to pitting and stress corrosion cracking in comparison with conventional stainless steels. The two phase mixture reduces the risk of intergranular attack and makes duplex stainless steel not prone to solidification cracking during welding. Duplex stainless steels, because of their high Cr concentration, are susceptible to 475°C embrittlement, so their application is frequently confined to temperatures below about 300°C.

Duplex stainless steels comprise a family of grades with a range in corrosion performance depending on their alloy content. Modern duplex stainless steels are often addressed in 5 groups:

1. Lean duplex like S32101 or S32304, which contain little or no Mo;
2. Standard 22% Cr duplex like S32205 or S31803, accounting majority of duplex use;
3. Super duplex with 25% Cr like S32550 or S31260;
4. Super duplex with 25% and increased Mo and N like S32750;
5. Hyper duplex like S32707 with increased Cr, Mo and N

In Table 1 and 2, an overview of the most common grades is listed, with its chemical composition and PRE_N (%Cr+3,3Mo+16N) or PRE_W {%Cr+3,3(Mo+0.5W)+16N)} and mechanical properties. Many of the grades have become commonly known by a number that reflects their composition, e.g., 2205 has 22% Cr and 5% Ni. In Fig. 2, a comparison of minimum proof strengths is shown.

Table 1. Chemical composition common grades of duplex

W. Nr.	Grade	UNS	Cr	Ni	Mo	N	Cu	Other	PRE
1.4482	19D	S32001	19.5-21.5	1.0-3.0	<0.60	0.05-0.17	< 1.00	Mn: 4-6	23
1.4162	2101	S32101	21.0-22.0	1.35-1.70	0.1-0.8	0.20-0.25	0.1-0.8	Mn: 4-6	24
1.4362	2304	S32304	21.5-24.5	3.0-5.5	0.05-0.6	0.05-0.20	0.05-0.60	-	25
1.4460	44LN	S31200	24.0-26.0	5.5-6.5	1.2-2.0	0.14-0.20	-	-	32
1.4460	329	S32900	23.0-28.0	2.5-5.0	1.0-2.0	-	-	-	34
1.4462	2205	S31803	21.0-23.0	4.5-6.5	2.5-3.5	0.08-0.20	-	-	35
1.4462	2205	S32205	22.0-23.0	4.5-6.5	3.0-3.5	0.14-0.20	-	-	36
-	DP3	S31260	24.0-26.0	5.5-7.5	2.5-3.5	0.10-0.30	0.20-0.80	W: 0.1-0.5	38
1.4507	255	S32550	24.0-27.0	4.5-6.5	2.9-3.9	0.10-0.25	1.5-2.5	-	42
1.4507	(2507)	S32520	24.0-26.0	5.5-8.0	3.0-4.0	0.20-0.35	0.50-2.00	-	42
1.4501	(2507)	S32760	24.0-26.0	6.0-8.0	3.0-4.0	0.20-0.30	0.50-1.00	W: 0.5-1.0	44
1.4410	2507	S32750	24.0-26.0	6.0-8.0	3.0-5.0	0.24-0.32	< 0.50	-	46
-	2707	S32707	26.0-29.0	5.5-9.5	4.0-5.0	0.30-0.50	< 1.0	Co: <2.0	50

Table 2. Mechanical properties common grades of duplex

W. Nr.	Classification	UNS	$Rp_{0.2\%}$ (MPa)	Rm (MPa)	Elongation (%) >	CPT (°C)	Hardness HB	CVN (J) -50°C
1.4162	X3 CrNiN 21 1	S32101	450	650-800	30	15	225	> 80
1.4362	X2 CrNiN 23 4	S32304	400	600-830	25	15	260	> 80
1.4460	X3 CrNiMoN 27 5 2	S32900	400	600-800	25	20	260	> 80
1.4462	X2 CrNiMoN 22 5 3	S32205	450	650-880	25	30	270	> 80
1.4507	X2 CrNiMoCuN 25 6 3	S32550	500	700-900	25	60	270	> 80
1.4410	X2 CrNiMoN 25 7 4	S32750	550	730-1000	25	70	290	> 80
1.4501	X2 CrNiMoCuWN 25 7 4	S32760	530	730-1000	25	80	290	> 80
-	*X2 CrNiMoCuCoN 27 7 5*	S32707	700	920-1000	25	95	300	> 80

Lean duplex:
S32101 and S2304 are lean duplex stainless steels containing low molybdenum and a low nickel content. It are high strength, low cost alternatives to standard austenitic grades such as 304L and 316L.

Standard duplex:
S32205 is a medium alloy duplex stainless steel with high corrosion resistance. The most widely used of the current duplex materials, continuous development over many years has led to further improvements in weldability and corrosion resistance through increased nitrogen and molybdenum contents.

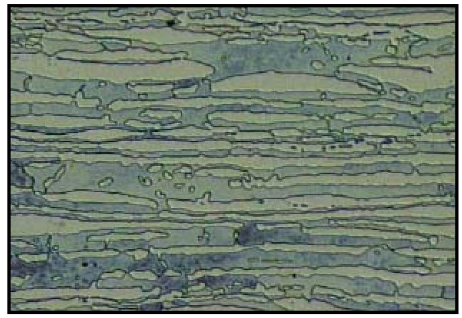

Fig 1. Microstructure S32205. (Mag. 250X)

Super duplex:
S32750 is a high alloy super-duplex steel for service in extremely corrosive conditions. Developed mainly for applications exposed to high stresses in chloride containing environments like seawater, it contains high amounts of chromium, molybdenum and nitrogen.

Hyper duplex:
S32707 is a high alloy, hyper-duplex stainless steel developed to provide high chloride corrosion resistance, combined with improved mechanical properties. It is particularly suitable for use in aggressive, acidic, chloride-containing environments.

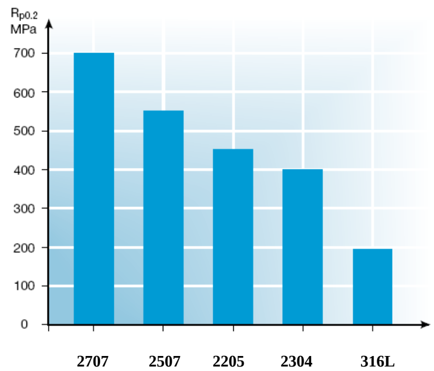

Fig 2. Comparison of minimum proof strength

3 Welding Consumables

3.1 Applicable Welding Methods

In the early 80's, second-generation (nitrogen-alloyed) duplex stainless steels saw rapid development. With only limited understanding of the formation of intermetallic phases, early views of welding duplex grades focused on limiting heat input, possibly because this approach is what is typically applied to special austenitic grades. With such severe limitations on heat input, many of the more economical welding methods with high deposition rates, such as submerged arc welding, were thought to be inappropriate for the duplex stainless steels. However, the final properties of the duplex stainless steels are of such interest that much effort was directed to learning how to use the more economical processes. Now virtually all welding processes, except for oxyacetylene with its associated carbon contamination of the weld, are applied to duplex stainless steels. Today arc welding processes like, GTAW, GMAW, SMAW, FCAW, and SAW have all seen practical application.

Fig 3. Austenite formed in ferritic matrix (FN35) weld

The welding characteristics of duplex stainless steels are much more sensitive to minor within-grade variations in chemistry or processing than austenitic stainless steels. For example, the importance of having sufficient nitrogen in the duplex stainless steel base metal has been repeatedly emphasized. Air cooling of a plate, even when rapid, through the 705 to 980°C range, will limit the applicability. The metallurgical condition of the material used in actual fabrication should be the same quality with regard to composition and production practice, as the material used to qualify the welding procedure.

3.1 Consumables grades / standards

For consumables, the applicable standards are ISO3581/AWS A5.4 for covered electrodes, ISO 17633/AWSA5.22 for Tubular Cored wires, and ISO 14343/AWSA5.9 for solid wires. In Table 3 and 4, an overview per process is listed to meet both ISO/EN and AWS requirements.

Table 3. Expected chemical composition duplex consumables

Process	ISO	AWS	Cr	Ni	Mo	N	Cu	W
SMAW	*(E23 7 NL)*	*(E2307)*	22.5-25.5	8.0-10.0	0.1-0.8	0.08-0.20	-	-
	E22 9 3 NL	E2209	21.5-23.5	8.5-10.5	2.5-3.5	0.08-0.20	< 0.75	-
	E25 7 2 NL	-	24.0-28.0	6.0- 8.0	1.0-3.0	< 0.20	< 0.75	-
	-	E2553	24.0-27.0	6.5- 8.5	2.9-3.9	0.10-0.25	1.5-2.5	-
	E25 9 3 Cu NL	E2593	24.0-27.0	8.5-10.5	2.9-3.9	0.10-0.25	1.5-3.5	-
	(E25 9 4 NL)	E2594	24.0-27.0	8.0-10.5	3.5-4.5	0.20-0.30	< 0.75	-
	E25 9 4 NL	E2595	24.0-27.0	8.0-10.5	2.5-4.5	0.20-0.30	0.4-1.5	0.4-1.0
FCAW	*(T23 7 NL)*	*(E2307T)*	22.5-25.5	8.0-10.0	0.1-0.8	0.08-0.20	-	-
	T22 9 3 NL	E2209T	21.0-24.0	7.5-10.0	2.5-4.0	0.08-0.20	< 0.5	
	(T25 9 4 NL)	E2553T	24.0-27.0	8.5-10.5	2.9-3.9	0.10-0.20	1.5-2.5	
GMAW GTAW (SAW)	*(ER23 7 NL)*	*(ER2307T)*	22.5-25.5	8.0-10.0	0.1-0.8	0.08-0.20	-	-
	ER22 9 3 NL	*(ER2209)*	21.0-24.0	7.0-10.0	2.5-4.0	0.10-0.20	< 0.3	-
	(ER22 9 3 NL)	ER2209	21.5-23.5	7.5-9.5	2.5-3.5	0.08-0.20	< 0.75	-
	ER25 7 2 L	-	24.0-27.0	6.0-8.0	1.5-2.5	-	< 0.3	-
	ER25 9 3 CuNL	*(ER2553)*	24.0-27.0	8.0-11.0	2.5-4.0	0.10-0.20	1.5-2.5	-
	(ER25 9 3 CuNL)	ER2553	24.0-27.0	4.5-6.5	2.9-3.9	0.10-0.25	1.2-1.5	-
	ER25 9 4 NL	ER2594	24.0-27.0	8.0-10.5	2.5-4.5	0.20-0.30	< 1.5	< 1.0
	(ER27 9 5 NL)	*(ER2707)*	26.0-28.0	8.0-10.0	4.0-5.0	0.25-0.35	-	-

Table 4. Expected mechanical properties duplex consumables

Process	EN/ISO	AWS	Rp0.2% (MPa)	Rm (MPa)	Elongation (%)	CVN (J)	CPT (°C)
SMAW	*(E23 7 NL)*	*(E2307)*	675	800	28	40J @ -40°C	15
	E22 9 3 NL	E2209	675	800	28	50J @ -40°C	25
	E25 7 2 NL	-	590	750	25	50J @ -50°C	40
	-	E2553	-	760	25	50J @ -50°C	>40
	E25 9 3 Cu NL	E2593	700	875	25	50J @ -50°C	>40
	(E25 9 4 NL)	E2594	700	875	25	50J @ -50°C	40
	E25 9 4 NL	E2595	700	875	25	50J @ -50°C	>40
FCAW	*(ER23 7 NL)*	*(ER2307T)*	650	800	30	50J @ -40°C	15
	T22 9 3 NL	E2209T	650	800	30	>40J @ -50°C	25
	T25 9 4 NL	E2553T	675	850	30	>40J @ -50°C	40
GMAW GTAW (SAW)	*(ER23 7 NL)*	*(ER2307T)*	675	800	30	150J @ -20°C	17
	(ER22 9 3 NL)	ER2209	625	810	30	60J @ -50°C	25
	ER22 9 3 NL	*(ER2209)*	625	810	30	60J @ -50°C	25
	ER25 7 2 L	-	725	850	30	60J @ -50°C	40
	ER25 9 3 CuNL	*(ER2553)*	725	850	30	60J @ -50°C	>40
	(ER25 9 3 CuNL)	ER2553	725	850	30	60J @ -50°C	>40
	ER25 9 4 NL	ER2594	650	850	25	60J @ -50°C	40
	(ER27 9 5 NL)	*(ER2707)*	800	950	30	100J @ -50°C	55

In addition to ambient strength requirements, there has been projects were strength at elevated temperatures for super duplex have been specified. An example is shown in Fig. 4. For coated electrodes, impact toughness and chemistry might differ substantially between manufacturers as well as classification (basic or rutile). Rutile basic electrodes have been in use traditionally, but fully basic electrodes gain preference due to low defect rate, good weld pool control and better mechanical properties. For cored wires [6], the available range both in down hand and positional grades, has extended form lean 2304 grades to super-duplex grades with Cu and W. (See Figure 5)

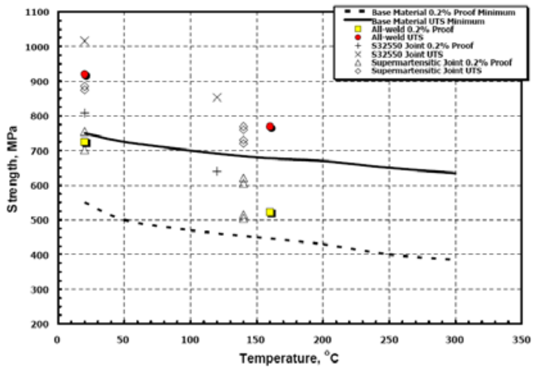

Fig. 4. 150°C Tensile ER25 9 4 CuWNL weld metal

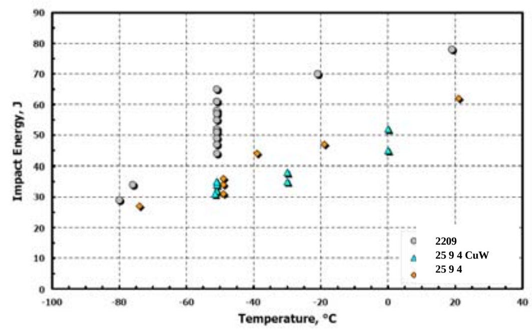

Fig. 5. Transition curve all weld FCW deposits

3.2 Phase Balance in the Weld

Modern duplex stainless steel mill products are balanced to have about 40-50% ferrite with the balance being austenite. It is generally agreed that the characteristic benefits of duplex stainless steels (strength, toughness, corrosion resistance, resistance to stress corrosion cracking) are achieved when there is at least 25% ferrite with the balance austenite. The ferrite in the weld metal (Fig. 3) is typically in the range of 25 to 70%, or in measurable terms: 35-100FN. Ferrite Number according to ISO 8249 [7]. Today, there are increasing requests for over 40% ferrite in the weld metal, which is unrealistic. In some welding methods, particularly those relying upon flux shielding, the phase balance of the filler has been adjusted toward more austenite to provide improved toughness, offsetting the loss of toughness associated with oxygen pickup from the flux. There are no problems associated with the ferrite contents at the lower end of this range, typically seen in SMAW or SAW welds. Rapidly quenched autogenous welds, e.g., arc strikes, repair of arc strikes, small GTA repair welds, etc., tend to have high ferrite, greater than 60%. Such welds can have low toughness and reduced corrosion resistance. There is little that can be done to affect the ferrite content of the weld joint (weld metal and HAZ) once the welding consumable has been selected, but weld procedure can have a secondary effect. The procedural factors which can influence ferrite content are those which affect cooling rate, like heat input, interpass temperature, preheat, and joint thickness (heat sink). The faster the cooling rate, the higher the ferrite content (Fig. 6)

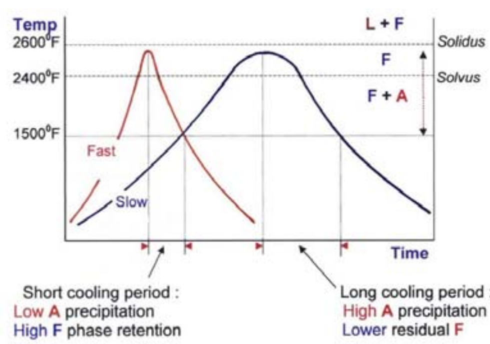

Fig. 6. Effect of cooling rate on ferrite content

3.3 Hardness requirements

Maximum allowable hardness may vary, depending on application, duplex grade, code requirements or customer specifications. Typical limits are 310H_V ($28H_{RC}$) for duplex and 330H_V ($32H_{RC}$) for super duplex grades used in sour service. Again here, no unrealistic limits should be specified.

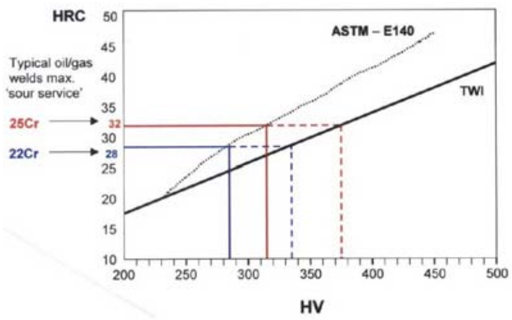

Fig. 7. Correlation hardness H_V vs. H_{RC}

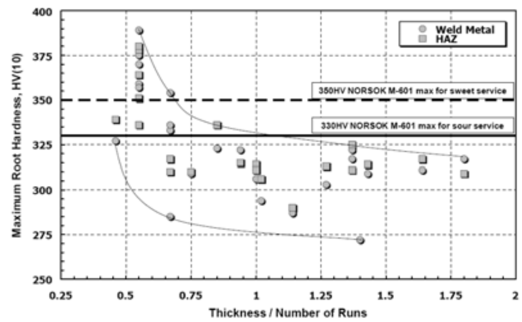

Fig. 8. Effect of "joint thickness/runs" on hardness

Duplex grades are high strength alloys, which can only be produced with a certain level of hardness. Hardness limits are primarily placed to avoid stress corrosion cracking (SCC) and testing has shown (super) duplex to be resistant to SCC to hardness up to $36H_{RC}$. A correlation is shown in Figure 7. In Figure 8, the effect of joint thickness / runs ratio on hardness is illustrated.

4 Welding Practice, Process and Procedures

4.1 Joint design

Duplex stainless steels require good joint preparation (Fig. 9). For duplex stainless steels, a weld joint design must facilitate full penetration and avoid autogenous regions in the weld solidification. It is best to machine rather than grind the weld edge preparation to provide uniformity of the land thickness or gap. When grinding must be done, special attention should be given to uniformity of the weld preparation and the fit-up. Any grinding burr should be removed to maintain complete fusion and penetration. For an austenitic stainless steel, a skilled welder can overcome some deficiencies in joint preparation by manipulation of the torch. For a duplex stainless steel, these techniques can cause a longer than expected exposure in the harmful temperature range, leading to results outside of the qualified procedure.

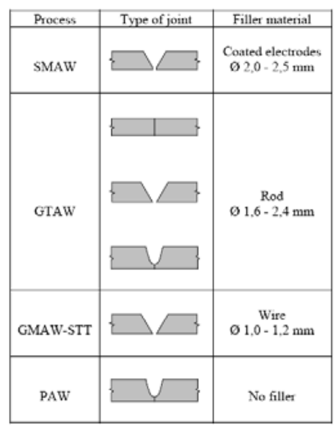

Fig. 9. Joint preparation

4.2 Preheating

As a general rule, preheating of duplex stainless steel is not recommended because it slows the cooling of the heat-affected zone. Preheating should not be a part of a procedure unless there is a specific justification. Preheating may be beneficial when used to eliminate moisture from the steel as may occur in cold ambient conditions or from overnight condensation. When preheating to remove moisture, the steel should be heated to about 95°C uniformly and only after the weld preparation has been cleaned. Preheating may also be beneficial in those exceptional cases where there is a risk for forming a highly ferritic HAZ because of very rapid quenching. Like welding a thin sheet to a plate, as with a liner to a vessel or a tube to a tube sheet, or any very low heat input weld where there is exceedingly rapid cooling.

4.3 Heat Input and Interpass Temperature

Although compared to austenitic stainless steels, duplex stainless steels can tolerate relatively high heat inputs, heat input needs to be kept within specified limits (0.5-2.5kJ/mm for duplex and 0.5-2.0kJ/mm for super-duplex) to ensure optimum properties. Most codes restrict the maximum to 1.75 or 2.0kJ.mm for duplex and 1.5 or 1.75kJ/mm for the super-duplex grades. The duplex solidification structure of the weld metal is resistant to hot cracking, much more so than that of highly austenitic weld metals. Duplex stainless steels, with higher thermal conductivity and lower coefficient of thermal expansion, do not create the same high intensity of local thermal stresses at the welds of austenitic stainless steels. While it is prudent to avoid severe restraint, hot cracking is seldom a problem. To avoid problems in the HAZ, the weld procedure should allow rapid (but not extreme) cooling of this region. The temperature of the work piece is important because the plate itself provides the most effective cooling of the HAZ. Typically, the maximum interpass temperature is limited to 150°C. That limitation should be imposed when qualifying a weld procedure, and production welding should be monitored to assure that the interpass temperature is no higher than that used in the qualification. The size of the test piece used in qualifying a weld procedure may affect the cooling rate and the interpass temperature. Higher interpass temperature slows the cooling and increases the time at temperature for the HAZ in actual practice.

4.4 Post Weld Heat Treatment

Post weld stress relief is not necessary or useful for duplex stainless steels. Unlike the low carbon austenitic stainless steels, the duplex stainless steels are sensitive to even relatively short exposures to temperatures in the 300 to 1000°C range. Thermal stress relief in the 300 to 700°C range may cause precipitation of alpha prime phase (475°C embrittlement), causing a loss of toughness and corrosion resistance. Stress relief in the range of 700 to 1000°C leads to rapid precipitation of intermetallic phases with moderate to severe loss of toughness and corrosion resistance. Any heat treatment of a duplex stainless steel, should be a full solution anneal, followed by water quenching. As an example, for 2205 that minimum temperature is 1040°C.

For some duplex stainless applications, a full anneal is required (like the forming of large heads or the fabrication of some valve and pipe assemblies). When there is a full solution anneal and quench subsequent to welding, that heat treatment is a part of the welding procedure. Annealing can restore the equilibrium phase balance and eliminate the problems associated with excessive ferrite and intermetallic phases. When common duplex filler metals are used, typically over-alloyed with nickel, phase balance in the fully annealed weld may shift toward austenite. Water quenching is essential after the final anneal, but air cooling from intermediate thermal exposures, such as in hot forming, have been found to be practical and economical.

4.5 Arc Welding Processes

Over the years, developments in arc welding processes continued. These developments are in control of welding characteristics, metal transfer and wave form design. New power sources, with a programmed full control of the wave form, may provide high productivity in all position welding. What was introduced in the 90's as the GMAW-STT process, a wave form controlled process that monitors arc current and voltage. The process today is fully accepted for root runs in pipes, and allows for increased welding speeds with low heat input.

4.6 Dissimilar Metal Welds

Duplex stainless steels can be welded to other duplex stainless steels, to austenitic stainless steels, and to carbon and low alloy steels. Duplex stainless steel filler metals are most frequently used to weld duplex stainless steels to other duplex grades. When welding duplex stainless steels to austenitic grades, the austenitic filler metals with low carbon and a molybdenum content intermediate between the two steels are typically used. AWS E309LMo/ER309LMo is frequently used for these joints. The same filler metal or AWS E309L/ER309L is commonly used to join duplex stainless steels to carbon and low alloy steels. Because austenitic stainless steels have lower strength than duplex grades, welded joints made with austenitic filler metals may not be as strong as the duplex base metal. In Figure 10, the actual strength of duplex weld metals in comparison to lean duplex base material requirements is stated. When welding the highly alloyed austenitic stainless steels, nickel-base fillers are used. The nickel-base filler metals are not normally used for duplex stainless steels, but if they are, they should be free of niobium. It has been suggested that the ENiCrMo-3 filler (625) has been less than satisfactory, possibly because of interaction of the niobium from the filler with the nitrogen from the duplex base metal. Table 5 summarizes filler metals that may be used to weld duplex stainless steels to dissimilar metals. These examples show the bare wire designation (ER), but depending on the process, joint geometry and other considerations, coated electrodes, and flux-cored wire may be considered.

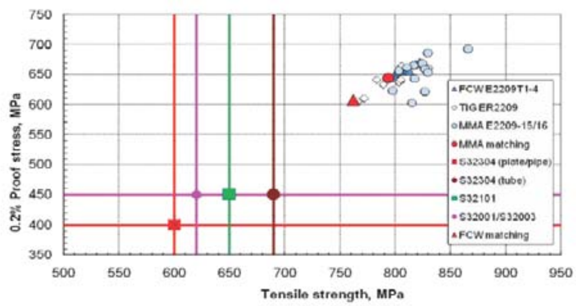

Fig. 10. Actual strength duplex weld metals compared to lean duplex base material requirements

Table 5. Consumables for welding duplex stainless steel to dissimilar metals

	S32101	S32304	S32205	S32750/32760	S32707
S32101	ER23 7NL	ER23 7NL	ER22 9 3 NL	ER22 9 3 NL	ER27 9 5 NL
S32304	ER23 7NL	ER22 9 3 NL	ER22 9 3 NL	ER22 9 3 NL	ER27 9 5 NL
S32205	ER22 9 3 NL	ER22 9 3 NL	ER22 9 3 NL	ER25 9 4 NL	ER27 9 5 NL
S32750	ER22 9 3 NL	ER22 9 3 NL	ER25 9 4 NL	ER25 9 4 NL	ER27 9 5 NL
S32707	ER27 9 5 NL	ER27 9 5 NL	ER27 9 5 NL	ER27 9 5 NL	ER27 9 5 NL
304	ER22 9 3 NL	ER22 9 3 NL	ER22 9 3 NL	ER22 9 3 NL	ER27 9 5 NL
316	ER22 9 3 NL	ER22 9 3 NL	ER22 9 3 NL	ER22 9 3 NL	ER27 9 5 NL
C-steel	ER23 12 L	ER23 12 L	ER23 12 L	ER23 12 L	ER27 9 5 NL

5 Corrosion Resistance

Each of the duplex grades, brings particular benefits to the wide range of applications in industry. The duplex stainless steel resistance to general corrosion is an important factor in prolonging the service life of process equipment. In today's duplex stainless steels the chemical composition is balanced in such a manner that the reformation of austenite in the heat-affected zone of the weld takes place quickly. This results in a microstructure that gives corrosion properties and toughness roughly equal to that of the parent metal. Welded joints in duplex steels easily pass the intergranular corrosion test according to ASTM A262 Practice E (Strauss' test). They are a superior alternative to standard austenitic grades such as 304L and 316L.

The critical pitting temperature (CPT) an critical crevice corrosion temperature (CCT) can be predicted by the pitting resistance equivalent (PRE), but preferably be determined by a standardized method like ASTM G48A/G48B, where the sample is exposed to a $FeCl_3$ solution at increasing temperatures, to determine the temperature where pitting starts. In practice, these temperatures depend on welding process and procedure. Typically, they are approximately 15-20°C for lean duplex, 25-30°C for duplex, 40-45°C for super duplex and 55-65°C for hyper duplex stainless steel weld metal. Increasingly, these limits pushed up in purchase specifications. Although one might achieve in individual procedures higher CPT's, one should maintain realistic specifications.

The standard austenitic steels of the 304L and 316L types are prone to stress corrosion cracking (SCC) in chloride-bearing solutions at temperatures above 60°C. Duplex stainless steels are far less prone to this type of corrosion. Practical experience and laboratory tests have shown their good resistance to stress corrosion cracking.

Briefly, the following applies:

- Lean-duplex offers in general a similar corrosion resistance as 316L, but has advantages in oxidizing media such as nitric acid solutions due to its low molybdenum content.
- Duplex has better resistance to general corrosion than the standard austenitic stainless steel 316L in most media. It is suitable for use in many different industrial environments.
- Super-duplex, being higher alloyed than the medium alloyed and lean duplex grades, have a very high corrosion resistance in chloride containing media, including seawater. They are typically also well suited for use in organic acids and other environments where the general corrosion resistance for lower alloyed grades is insufficient.
- Hyper-duplex is a further development of super-duplex, improving the performance in aggressive, acidic, chloride-containing environments. They can be a very competitive alternative to highly alloyed austenitic stainless steels and Ni-based alloys in the most demanding applications, such as hot tropical seawater.

6 Applications

Oil and gas applications

Duplex stainless steels are being used extensively in the onshore and offshore sectors of the oil and gas industry over the years, during which an extensive project reference has been established. Duplex grades have been utilized primarily for two reasons: their corrosive resistance to the various corrosive media found in onshore/offshore environments, e.g. CO_2, H_2S, chlorides, low pH etcetera and secondly their increased strength levels. Typical applications are production tubing, subsea manifolds and flow lines, subsea pipeline systems and topside process systems.

Chemical process industry

The chemical process industry requires duplex stainless steels in a wide spectrum of corrosive conditions. In particular corrosion problems in processes with elevated temperatures and chloride conditions can be solved by the application of duplex. Typical examples are PVC stripper columns and heat exchangers, pressure vessel for organic products, reactors for the oxo alcohol production, sulphuric acid applications and phosphoric acid production. The use of duplex stainless steels in the chemical process industry has expanded over the past years. They are now used not only in chloride environments, where they are more resistant to SCC than austenitic stainless steels, but also in a wide variety of other demanding applications. A new trend is going towards “hyper duplex”, due to lower life cycle costs of equipment, and increasing demand on materials, where super duplex grades are insufficient

Pulp and paper industry

The obvious reason for increased use of duplex in the pulp and paper industry is economics. The use of duplex stainless steels can often be justified on cost since wall thickness reduction of 50% on carbon steel and 35% on clad steel can be achieved. Duplex stainless steels have been successfully used for decades and a lot of service experience has become available. Applications include the preparation of the chips, chemical pulping, bleaching, chemi-thermomechanical pulping, liquor tanks, paper machines and the recovery and steam plants. The development of the second generation duplex stainless steels has opened a wide range of applications, including batch and continuous pulp digesters, oxygen delignification units and pulp bleaching systems. In the digester application, soon to be the largest application of duplex stainless steel in this industry, 2205 duplex stainless steel is replacing steel construction for both safety and operational conditions.

Shipbuilding

Another important area of duplex stainless steel applications is shipbuilding. Most of the chemical tankers are designed for the transportation of a variety of chemicals. More and more aggressive chemicals and hazardous or toxic materials have to be shipped imposing ever higher demands on materials selection. In many cases duplex has replaced the use of austenitic stainless steels due to its better performance with regard to pitting and crevice corrosion resistance in chloride containing media. Moreover duplex grades have much higher mechanical properties compared to austenitic stainless steels. As a consequence operators can achieve substantial cost saving because of weight reduction of the carrier up to 10% in total.

A Welding procedure Approval Record for a duplex SAW weld is shown in Figure 11, as an example.

7 Future

Demand for duplex grades is likely to remain high, because several industries that require it are growing. The increasing scarcity of easily extractable oil and gas is driving the trend towards exploration and development in ever deeper water, often remote from land and in inhospitable regions.

Drinking water is another commodity in short supply in some areas in the world. This will increase the demand for desalination facilities. For instance, Dubai, is planning to build several desalination plants in the next years.

Air pollution control is another possible growth area for (super) duplex grades. In flue gas desulphurization units and wet electrostatic precipitators the corrosion resistance of duplex UNS S32205 and super duplex UNS S32520 is often equal to or better than that of the traditional austenitic or super austenitic materials.

In the chemical process and chemical tanker industries too, duplex grades have been replacing 300 grades and nickel alloys.

Paper & pulp is another sector where one can expect to see increased use of (super) duplex grades. Global demand for paper and paper board is expected to rise at 2.5 per cent per year. Pulp mills are being built in South America and Russia, and paper and board machines in Asia, especially China, where paper consumption is rising sharply. Here too, duplex grades (especially 2205) are replacing stainless steel and nickel alloys, a trend that will no doubt continue.

Finally in architecture, duplex is increasingly seen as competitive with mild steel when life cycle is taken into account, and as offering cost reduction because of the weight saving.

8 References

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Welding Procedure Approval Record

Page 1 / 2
WPAR: P2000.01
Rev. : 1
Ref. WPQ: 95.023

Procedure Specification

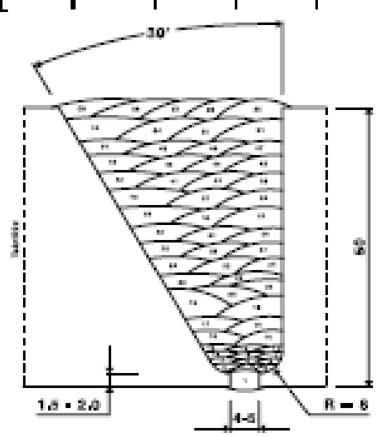
Base material	1.4462	
Welding processes	A: GTAW	B: SAW
Manual or machine	Manual and machine	
Welding position	1G (PA)	
Filler metal	**1: LNT 4462**	**2: LNS 4462**
Flux	P 2000, EN 760: A AF 2 63 DC	
Filler metal classific.	1: EN 12072: W 22 9 3 N L	
	2: EN 12072: S 22 9 3 N L	
Shielding gas [l/min]	Argon 4.0	Flow 10
Backing (gas) [l/min]	Argon	Flow 10
Gouge method	N.A.	
Current / polarity	GTAW = DC - ; SAW = DC +	
Preheat temp. [°C]	min. 100	
Interpass temp. [°C]	max. 150	
Postheat treatment	N.A.	
Welder's name	Tiny Boumans	

Remarks : P 2000, batch F3053
LNT 4462, batch 51469429
LNS 4462, batch 51467032
Welded under fully restraint conditions

Welding Procedure

Pass	Consumable		Welding Current		Speed	H.I.
No.	Index	Ø [mm]	Ampere	Volts	[mm/min]	[kJ/mm]
1	A1	2.0	85 - 90	12	36	1.8
2 - 4	A1	2.0	106	12	35	2.18
5 - 7	A1	2.0	115	12	43	1.93
8-13	A1	2.0	120	12	43	2.0
14-21	B2	3.2	350	32	50 - 52	1.32
22-23	B2	3.2	450	32	60	1.44
24-54	B2	3.2	450	32	55	1.57
55-59	B2	3.2	450	34	55	1.67

Joint Detail



Test Results

Radiographic-ultrasonic Examination: acceptable

Reduced-section tension test
Tensile strength [MPa] — Fracture location
Cap :
Root :

All-weld-metal tension test	St 1	St 2	St 3
Yield point [MPa] :	601	626	676
Tensile strength [MPa] :	775	773	806
Elongation, A5 [%] :	30	26	30
Reduction, Z [%] :	51	51	47

Side-bend tests — Former diameter:
Root
Face

Impact tests ISO - V [J] — Test temp. [°C]: RT
Size of specimen: 10 x 10 x 55mm

Level	CL			FL + 0-0.5			FL + 2-5		
1	100	104	102	294	298	293	173	182	148
2	92	100	90	136	120	121	98	96	90
3	106	108	106	131	87	136	98	135	101
4	138	132	134	256	224	243	154	119	122

Impact tests ISO - V [J] — Test temp. [°C]: - 40
Size of specimen: 10 x 10 x 55mm

Level	CL			FL + 0-0.5			FL + 2-5		
1	79	86	91	91	93	86	76	83	80
2	73	73	72	113	81	83	295	296	295
3	111	99	100	90	90	90	92	91	98
4	77	79	72	109	140	106	220	260	272

Ferrite Content (FN) see sketch

	BM	HAZ	WM	HAZ	BM
Face 1					
Mid					
Root					
Face 2					

Hardness see sketch
Test type : Vickers — Load : 10 kg

	WM	HAZ	BM
Face 1	243-258-258-251-254	270-264-270-264-258	236-236-236
Mid	264-258-258-274-264	258-264-258-263-268-264	228-232-232
Root	274-274-274-274	285-285-279-279-274	238-233-232

Sketch

We the undersigned, certify that the statements in this record are correct.
Manufacturer or Contractor — Lincoln Smitweld and MPS/DSM
Authorized by
Issued by
Date

Fig. 11. Welding procedure Approval Record for a duplex SAW weld