Welding practice for the Sandvik duplex stainless steels SAF 2304, SAF 2205 and SAF 2507

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by
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Abstract

The weldability of the Sandvik duplex stainless grades SAF 2304, SAF 2205 and SAF 2507 is discussed. Suitable welding methods, joint preparation, welding technique, filler metals and proper shielding and root gases are recommended. Properties of all weld metal and welded joints are presented. Parameters for heat treatment of welds and post-weld cleaning are suggested.

Expansion of tubes and tube-to-tube-sheet welding is brought up, and the lecture is concluded with a discussion about duplex stainless steels and hydrogen embrittlement.

Introduction

The first duplex stainless steel (DSS) structure was described by Bain and Griffiths 1927. It was the starting point for the development of a group of steels, which about 40 years later would have a rapid growth and solve a lot of corrosion problems for the oil and gas industry. But also other areas like the pulp and paper industry and the chemical industry have discovered the potential of these steels to solve many of their corrosion problems. Above all it is the good resistance to pitting corrosion and chloride induced stress corrosion cracking that makes them so useful for these industries. To this should be added the good mechanical properties, which permit the use of lighter constructions with a corrosion resistance comparable with that of much more highly alloyed austenitic stainless steels, see figure 1.

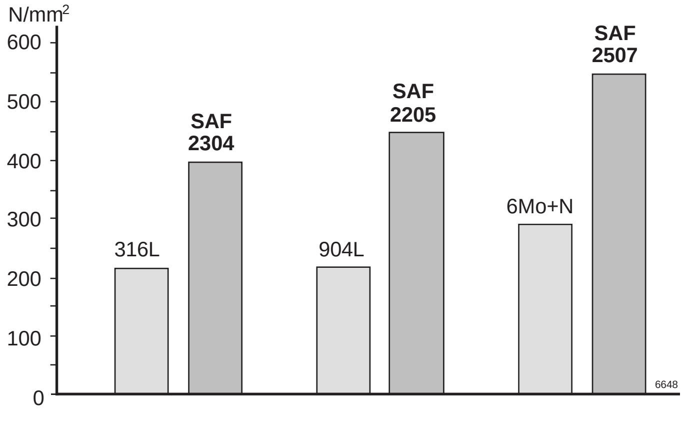


Figure 1. Comparison of minimum yield strength 0.2% offset of duplex steels and austenitic steels of corresponding corrosion resistance.

From a welding point of view, the first DSS's available had poor weldability, mainly because of the lack of understanding of the metallurgical process that takes place in the heat affected zone (HAZ).

The early DSS's did not have an optimized ratio between ferrite (α) and austenite (γ). In most cases the ferrite content was too high (~70%) causing the HAZ to be almost fully ferritic. These ferritic zones had inferior mechanical and corrosion properties, and it is fully understandable why these steels were not too popular in the beginning. Still today, there is a certain scepticism against the duplex stainless steels and their weldability. This could be one of the reasons why they have been the subject of so many studies and research activities during the last two decades.

The modern DSS's have an optimized ferrite-austenite ratio (~50% α; 50% γ) in order to get a good austenite reformation in the HAZ and thereby good mechanical and corrosion properties of the welded joint. In recent years the role of nitrogen has been discovered. Nitrogen is a very potent austenite stabilizer and optimizing of the α/γ ratio and alloying with nitrogen have made the weldability of the DSS's of today equal to that of the austenitic stainless steels.

The ferrite in the DSS's results in a lower coefficient of expansion than that of the austenitic steels, an advantage giving less distortions in welded constructions.

	Austenitic Stainless Steels	Duplex Stainless Steels
Coefficient of expansion, (x10^{-6})°C^{-1}	~17	~13

The Sandvik ferritic-austenitic stainless steels

Sandvik has mainly three grades covering most of the DSS needs on the market.

SAF 2304, which in general has a corrosion resistance comparable to that of AISI 316L.

SAF 2205, which can be compared to AISI 904L regarding corrosion, and

SAF 2507, which from a corrosion point of view is comparable to the 6Mo + N austenitic stainless steels. Regarding stress corrosion cracking the duplex stainless steels are superior to the austenitic stainless steels. The chemical composition and the mechanical properties of the steels are presented in tables 1 and 2.

Table 1. Nominal chemical compositions of the duplex stainless steels (wt-%)

Sandvik	UNS	C max.	Si	Mn	P max.	S max.	Cr	Ni	Mo	N
SAF 2304	S32304	0.03	0.5	1.4	0.040	0.04	23	4	–	0.1
SAF 2205	S31803	0.03	<1.0	<1.0	0.030	0.02	22	5.5	3.1	0.18
SAF 2507	S32750	0.03	<0.8	<1.2	0.035	0.02	25	7	4	0.3

Table 2. Mechanical properties of the duplex stainless steels. Minimum values for up to 20 mm (0.79") wall thickness of tubes. Considerably higher values are obtained for thinner wall thicknesses.

Sandvik	UNS	Proof strength				Tensile strength		Elong.	Hardness
		$R_{p0.2}$		$R_{p1.0}$		R_m		A	Vickers
		MPa min.	ksi min.	MPa min.	ksi min.	MPa min.	ksi min.	% min.	approx.
SAF 2304	UNS S32304	400	58	450	65	600–820	87–119	25	230
SAF 2205	UNS S31803	450	65	500	73	680–880	99–128	25	260
SAF 2507	UNS S32750	550	80	640	93	800–1000	116–145	25	290

Filler metals for the welding of the DSS's

Fusion welding always means a local heat treatment of the welded joint and the parent metal close to the joint. As the heating cycle is very rapid, the weld metal will not be in equilibrium from a thermodynamic point of view. A filler metal with the same chemical composition as the parent metal would give a weld with excess of ferrite and poor mechanical and corrosion properties. Therefore, the filler metal contains more Ni in order to give a higher portion of austenite in the weld, see table 3.

The molybdenum-free filler metals 23.7.L and 23.8.LR are not stock items. They are mainly used in oxidizing NO_3^- environments when Mo is not desired. In all other applications 22.8.3.L and 22.9.3.LR are recommended for the welding of SAF 2304.

The fully basic electrodes 22.9.3.LB and 25.10.4.LB are not stock items either because of the small amounts demanded. They are mainly used in projects where for some reason a higher impact strength is needed.

25.10.4.L is designed for TIG welding. MIG welding with this filler is possible but somewhat difficult and we recommend contact with the Sandvik Welding Department before welding.

Typical values for the mechanical properties of all weld metal are shown in table 4.

Table 3. Filler metals for the welding of DSS's.

Parent metal Sandvik	Welding process	Filler metal Sandvik	Chemical composition, typical									
			C max.	Si	Mn	P max.	S max.	Cr	Ni	Mo	N	Ferrite All weld metal, %
SAF 2304	TIG, MIG, SAW	23.7.L	0.020	0.4	1.5	0.020	0.015	23	7	–	0.14	30-40
	MMA	23.8.LR	0.030	<0.9	0.5	0.030	0.025	25	9	–	0.12	30-40
SAF 2304 and SAF 2205	TIG, MIG, SAW	22.8.3.L	0.020	0.5	1.6	0.020	0.015	22.5	8	3	0.14	30-40
	MMA	22.9.3.LR	0.030	<1.0	0.8	0.030	0.025	22.5	9	3	0.12	30-40
		22.9.3.LB	0.04	<0.5	0.8	0.030	0.025	22	9	3	0.15	30-40
	FCAW	22.9.3.LT	0.030	<1.0	1.5	0.030	0.025	22.5	9	3	0.15	30-40
SAF 2507	TIG, (MIG),SAW	25.10.4.L	0.020	0.3	0.4	0.020	0.020	25	10	4	0.25	30-40
	MMA	25.10.4.LR	0.030	0.5	0.7	0.030	0.025	25	10	4	0.25	30-40
		25.10.4.LB	0.040	0.4	0.9	0.030	0.025	25.5	9.5	4	0.25	30-40

Table 4. Mechanical properties of all weld metal. Typical values.

Filler metal	Welding	$R_{p0.2}$	$R_{p1.0}$	R_m	A	Z	Impact strength, J	
Sandvik	process	MPa	MPa	MPa	%	%	RT	-40°C
23.7.L	TIG	525	595	708	34	58	171	156
23.7.L	SAW[1)]	503		671	34		101	72
23.8.LR	MMA	627	681	773	26	46	62	46
22.8.3.LR	TIG	610		760	28		207	160
22.8.3.L	SAW[1)]	578	664	775	33	53	139	84
22.9.3.LR	MMA	512		734	33		52	44
22.9.3.LT	FCAW	620	–	816	30	44	56	43
25.10.4.L	TIG	672		851	28	64	150	116
25.10.4.L	SAW[1)]	687	757	878	27	47	91	64
25.10.4.LR	MMA	645		850	28		46	33

[1)] Using Sandvik 15W flux.

Physical metallurgy

As already mentioned, an arc welding operation always means a more or less undesired heat treatment of the area close to the weld. This area, the heat affected zone (HAZ) or more accurately the high-temperature heat affected zone, is brought to a temperature, where the material is almost fully ferritic. At cooling a reformation of austenite starts in the grain boundaries and then continues in the ferrite grains forming a Widmanstätten type structure, see figures 2 and 3.

When welding the DSS's the heat input and the cooling rate are important parameters. At too rapid cooling chromium nitrides are formed owing to the fact that at high temperatures the solubility of nitrogen in the ferrite is increased and at rapid cooling, when the solubility drops, chromium nitrides are formed. A limited amount of chromium nitrides does not have any effect on the properties of the weld unless they are located to the grains close to the surface. In that case, the corrosion resistance will be decreased because of the depletion of chromium. Thus, welding of heavy wall thicknesses with too low heat input must be avoided.

Figure 2. Typical weld in SAF 2507. Clean structure and good austenite reformation.

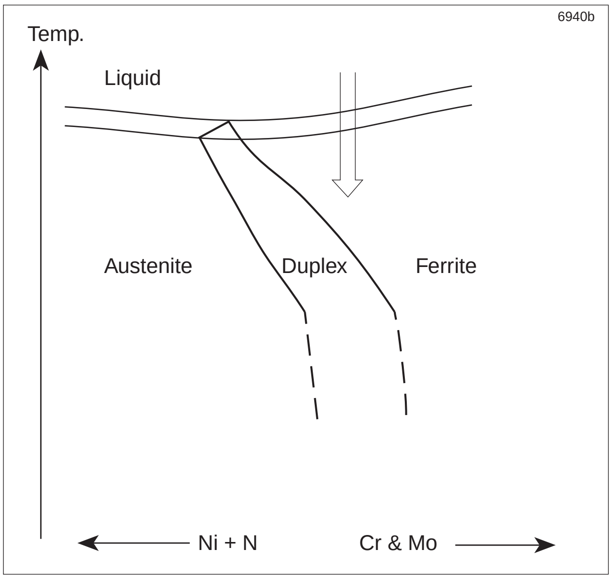


Figure 3. Schematic pseudo-binary diagram showing the solidification mechanism of the duplex stainless steels.

Figure 4. HAZ with chromium nitrides.

If on the other hand the heat input is too high, precipitation of intermetallic phases can occur. It is mainly the ferrite that is prone to form intermetallic phases, above all σ-phase, but also other intermetallics like χ-phase, π-phase, λ-phase, R-phase, Laves phase and carbides have been observed. The proneness to precipitation is directly proportional to the alloy content. This is illustrated in figure 5.

One precipitate that can be as detrimental as chromium nitrides if it occurs in ferrite grains at the surface is secondary austenite, figure 6. This phase forms at 800–950°C and can sometimes be seen in the upper parts of a root pass when the temperature conditions have been beneficial for this phase to form. As the secondary austenite is low in among others Cr, Mo and N, it means that its resistance to pitting corrosion is inferior to the surrounding matrix.

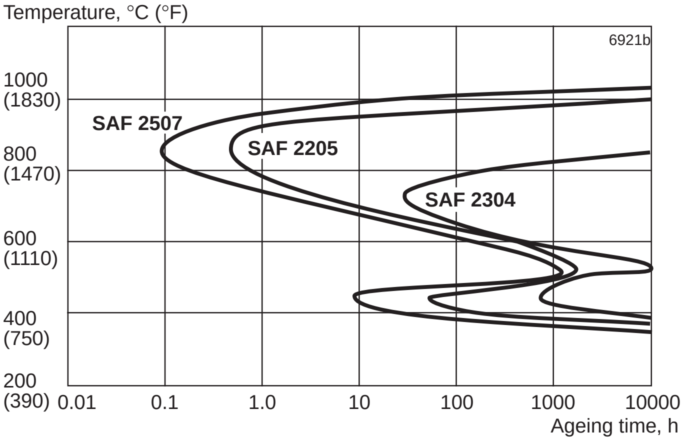


Figure 5. Embrittling of SAF 2304, SAF 2205 and SAF 2507 after ageing. To the left of the curves the impact strength is 27J or more.

Figure 6. Secondary austenite in weld metal.

In order to get optimum results the following welding data are recommended:

Table 5.

Sandvik	Heat input kJ/mm	Interpass temperature °C
SAF 2304	0.5–2.5	<250
SAF 2205	0.5–2.5	<250
SAF 2507	0.2–1.5	<150

The heat input is chosen to suit the thickness of the material and the welding process, e.g. for thin-wall tubes (t = 1.5 mm) <0.5 kJ/mm is optimum, and for heavier wall thicknesses a heat input closer to maximum is preferred. In any case the interpass temperature should be kept. Attention must be paid to super duplex steels in wall thicknesses ≥25 mm. As the interpass temperature is measured on the surface of the weld or on the base metal close to the weld, the actual temperature will be higher deeper inside the weld metal. This can cause embrittlement and low impact values in the root region.

Welding methods

The welding parameters used in different welding processes are in general the same for DSS's as for austenitic stainless steels.

Manual metal arc welding (MMA) is mainly used for filler passes. Owing to its low sensitivity to strong winds, MMA is very suitable for welding on site. Repair welding is often done with this method because of its flexibility.

Tungsten inert gas welding (TIG) is used for root passes and for the welding of thin-wall materials. The method gives a very pure weld deposit of high quality.

Plasma arc welding (PAW) is also a suitable method for DSS's. It is mainly used by manufacturers of e.g. welded tubes and tube parts. If annealing cannot be made after welding, addition of nitrogen to the shielding or plasma gas is recommended, about 5% N_2 in the plasma gas or 10% N_2 in the shielding gas.

Submerged arc welding (SAW). The method is mainly used for thick sections of sheet metal. It is a common method for the production of welded tubes. A suitable flux is Sandvik 15W.

Metal inert gas welding (MIG) is used in fabrication when a high productivity is desired. Sandvik filler metal 22.8.3.L gives acceptable performance, while our wire 25.l0.4.L is mainly designed for TIG-welding and therefore has less good MIG welding characteristics. To get good results we suggest contact with the Sandvik Welding Department.

Flux cored arc welding (FCAW) is like MIG welding a method which is used when a high productivity is desired. Filler metal is available for SAF 2304 and SAF 2205.

Laser and electron beam (EB) welding. These processes are used without the addition of filler metal and are not very suitable for the welding of duplex stainless steels as the welds will be very high in ferrite. Such a weld must be quench-annealed in order to get the correct structure.

Friction welding of SAF 2205 type materials has successfully been made at TWI (The Welding Institute, UK).

Spot and Seam welding

These methods are being used on DSS's. In order to improve the austenite reformation in spot welding, the electrodes can be kept in position after welding for a short-time resistance heating.

Autogeneous welding

As with laser and EB welding, autogeneous welding (welding without addition of filler metal) can be made as long as the whole construction can be quench-annealed after welding. In general, autogeneous welding is not recommended. If for some reason it has to be done, it must be followed by a full annealing cycle. If annealing is impossible, nitrogen addition to the shielding gas is strongly recommended, table 6.

Table 6. Quench-annealing of duplex steel welds.

Sandvik	Holding temperature °C	Quenching media
SAF 2304	930–1050	Water
SAF 2205	1020–1100	Water
SAF 2507	1080–1120	Water

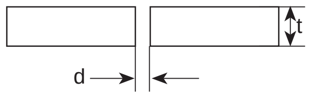
Joint prepartion

A proper joint preparation is important. For the duplex stainless steels, the same joint preparations can be used as those common for austenitic stainless steels.

Before welding, the joint surfaces shall be degreased and free from any form of contamination.

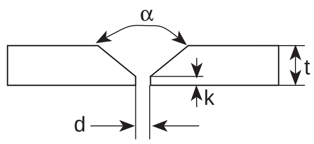
Square groove

	t mm	d mm
MMA	≤3	1–2
TIG	≤3	1–2
MIG	≤3	1–2



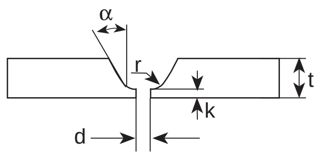
V-groove

	t mm	d mm	k mm	α
MMA	3–15	2–3	1–2	50–60°
TIG	2.5–8	2–3	1–2	60–70°
MIG	3–12	2–3	1–2	60–70°
SAW*	4–12	2–3	1–2	60–70°



U-groove

	t mm	d mm	k mm	r mm	α
MMA	>12	1–2	2–3	6	15°
TIG	>6	1–2	1–2	6–8	15°
MIG	>12	1–2	2–3	6	15°
SAW*	>10	1–2	1–3	6–8	15°

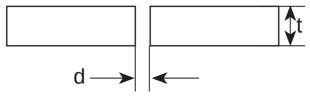


*Root pass with TIG, MIG or MMA. SAF 2507: Contact Sandvik for advice.

Figure 7. Joint preparation for one-sided butt welding.

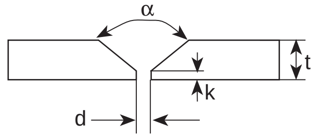
Square groove

	t mm	d mm
MMA	3–4	1.5–3
TIG	3–5	1.5–3
MIG	3–6	1.5–3



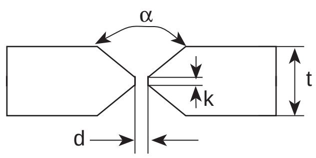
V-groove

	t mm	d mm	k mm	α
MMA	4–15	1–3	1–2	50–60°
TIG	2.5–8	1–3	1–2	60–70°
MIG	5–12	1–3	1–2	60–70°



Double V-groove

mm	t mm	d mm	k	α
MMA	>10	1.5–3	1–3	50–60°
MIG	>10	1.5–3	1–3	60–70°
SAW	>10	0	3–5	90°



Double U-groove

	t mm	d mm	k mm	r mm	α
MMA	>25	1–3	1–3	6–8	10–15°
SAW	>25	0	3–5	6–8	10–15°

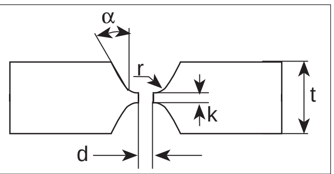


Figure 8. Joint design for butt welding from both sides.

Welding technique

There is no major difference in technique between welding austenitic steels and duplex stainless steels when it comes to welding parameters for different processes. Joint preparations are basically the same. However, at one-sided butt welding a slightly wider gap and a more open angle are preferable.

Shielding gases

At TIG shielding and root gases may differ depending on the demands regarding corrosion resistance of the welded joint. In most cases pure argon will be satisfactory and give a corrosion resistance with enough margin. As the duplex stainless steels are nitrogen alloyed, a loss of nitrogen is inevitable in the surface area of the weld and in the parent metal area 0.2–0.5 mm from the weld if pure argon is used as shielding or root gas, figure 9.

Figure 9. Ferritic area in SAF 2507 weld owing to the loss of nitrogen.

The most common way to prevent loss of nitrogen on the top side is to use a shielding gas containing nitrogen. Additions of 1-2% N_2 to the argon are optimum. Higher additions should be avoided as they affect the tungsten electrode and destabilize the arc causing spatter. An increased risk for porosity is also noted.

Nitrogen in the shielding gas will cause a nitrogen pick-up in the weld deposit. This will give a higher portion of austenite in the weld and a much lower risk for nitride precipitations in ferrite grains close to the surface of the weld. Figure 10 shows the difference in microstructure of the weld deposit as a result of 5% N_2 in the shielding gas.

Tables 7 and 8 below show how nitrogen additions affect the ferrite content in the welds and the amount of nitrogen pick-up. The filler metal contained 0.25% N. The low pick-up from the root gas should be noticed.

a) b)

Figure 10. Different structures of the weld because of nitrogen additions in the shielding gas. a) Ar, b) Ar + 5% N_2.

Table 7. Ferrite content in TIG-welds, SAF 2507.

Filler metal Sandvik	Shielding gas	Root gas	Ferrite content vol-% ± error with 95% confidence interval
25.10.4.L	Ar	Ar	55 ± 4.5
25.10.4.L	Ar	90% N_2 + 10% H_2	59 ± 4.0
25.10.4.L	Ar + 5% N_2	90% N_2 + 10% H_2	33 ± 4.0

Table 8. Nitrogen content in TIG welds of SAF 2507 and filler metal, 25.10.4.L, at increasing nitrogen content in the shielding gas. N = 0.25% in the filler metal.

Filler metal Sandvik	Shielding gas	Root gas	weight-% N in deposit
25.10.4.L	Ar	90% N_2 + 10% H_2	0.23
25.10.4.L	Ar + 3% N_2	90% N_2 + 10% H_2	0.27
25.10.4.L	Ar + 6% N_2	90% N_2 + 10% H_2	0.33

Other shielding gases can occur in TIG and PAW. In TIG welding 5% hydrogen is sometimes added to the shielding gas in order to increase the efficiency of the arc. This is not recommended as the weld deposit will pick up a substantial amount of hydrogen, which may cause cold cracking if at the same time the ferrite content is high (>70–75%). This subject will be further discussed under "Hydrogen embrittlement" below.

MIG welding of DSS's is used more and more but there are only a few MIG wires on the market today with good welding properties. For instance, for SAF 2304 or SAF 2205 Sandvik 22.8.3.L filler metal and mixed gases like AGA 301 (60% Ar + 39% He + 1% O_2) are recommended. In most cases the pulsed MIG process improves the result.

The Sandvik 22.8.3.L gives an acceptable result in MIG welding while the Sandvik 25.10.4.L wire in the first place is designed for TIG welding and has less good MIG welding characteristics. If MIG welding is done, fully inert shielding gases like pure Ar or Ar/He mixes shall be used. Before MIG welding with 25.10.4.L we suggest to contact the Sandvik Welding Department.

For FCAW the shielding gas 80% Ar + 20% CO_2 gives the best result.

Root gases

Generally pure argon is used for root protection, and for most applications this is satisfactory. However, as mentioned above, Ar leads to the loss of nitrogen at the surface of the root bead and at the parent metal 0–1 mm from the fusion line. Therefore, these areas will have inferior corrosion resistance. In order to keep a high pitting resistance a nitrogen bearing root gas can be used. Ar with 2–3% N_2 is not enough. At least 5% is needed. The best choice is 90% N_2 + 10% H_2 or pure nitrogen. As nitrogen is an excellent austenite stabilizer, a thin "skin" of austenite, about 20µm thick, will form at the surface of the root bead and at the fusion line enhancing the corrosion resistance, figure 11.

Studies at Sandvik and also in Germany by Alfward Farwer and Robert Killing have shown that the pick-up from the root gas will be limited to the very surface area contrary to the case with shielding gas. This is obvious in tables 7 and 8. For instance, table 8 shows that nitrogen is lost in the weld deposit, although the root gas contains 90% N_2 + 10% H_2 (pure Ar as shielding gas). Thus, 10% hydrogen will not cause any risk for hydrogen embrittlement.

Figure 11. "Skin" of austenite formed by use of a nitrogen bearing root gas.

Post-weld treatment of welded joints und overlay welds

Preheating or post-weld heat treatment (PWHT) is not necessary or recommended for welding duplex stainless steels with the exception for autogeneous welds, which is already discussed above.

Stress relieving is sometimes specified in certain constructions. One example is overlay welds on tube sheets for heat exchangers, where a stress relieving has to be made at a temperature depending on the type of parent metal, see table 9.

Table 9. Stress relieving temperatures for different parent metals after overlay welding.

Parent metal	°C
Carbon steel	580
Carbon manganese steel	610
2 1/4 Cr 1 Mo steel	690

A duplex overlay weld will be embrittled at these temperatures. If allowed by the specification, this problem can be solved by stress relieving only after the first layer and not after the second.

Post-weld cleaning is important not only for the appearance but also for the corrosion resistance. Figure 12 shows the efficiency of different cleaning methods. The most efficient one is pickling followed by grinding. The finer the grains in the emery paper, the better the result. Wire brush or sandblasting will improve the corrosion resistance somewhat.

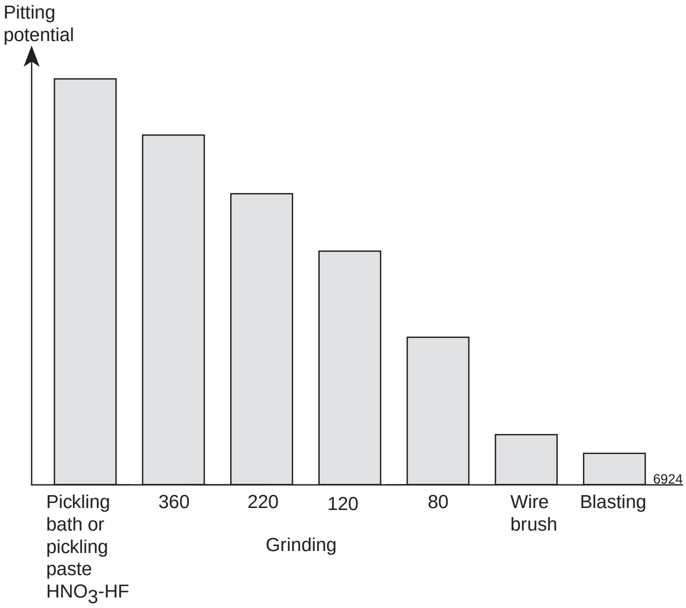


Figure 12. The efficiency of different post weld cleaning processes.

Mechanical properties of welded joints

In table 4 on page 3 the mechanical properties of all weld metal are presented. Tables 10 and 11 show the mechanical properties of welded joints

Table 10. Charpy-V impact strength of welded joints. Notch in the centre of the weld. Typical values.

Parent metal Sandvik	Filler metal Sandvik	Welding process	Impact strength, J	
			RT	-40°C
SAF 2304	23.7.L	TIG	213	74
	23.7.L	SAW1)	105	17
	23.8.LR	MMA	46	38
SAF 2205	22.8.3.L	TIG	282	133
	22.8.3.L	SAW1)	54	42
	22.8.3.LR	MMA	52	43
	22.9.3.LT	FCAW	55	44
SAF 2507	25.10.4.L	TIG	110	78
	25.10.4.L	SAW1)	100	58
	25.10.4.LR	MMA	58	39

1) Using Sandvik 15W flux

Table 11. Mechanical properties of welded joints. Cross-weld tensile test.

Parent metal Sandvik	Filler metal Sandvik	Welding process	$R_{p0.2}$, MPa		R_m, MPa		A, %
			min.	typical	min.	typical	typical
SAF 2304	23.7.L	TIG	400	446	600	650	30
	23.7.L	SAW1)	400	452	600	689	30
	23.8.L	MMA	400	462	600	647	30
SAF 2205	22.8.3.L	TIG	450	553	680	784	29
	22.8.3.L	SAW1)	450	588	680	757	26
	22.9.3.LR	MMA	450	588	680	757	28
	22.9.3.LT	FCAW	450	585	680	760	28
SAF 2507	25.10.4.L	TIG	550	645	800	848	32
	25.10.4.L	SAW1)	550	628	800	842	34
	25.10.4.LR	MMA	550	628	800	846	33

1) Using Sandvik 15W flux

Corrosion resistance – Pitting corrosion

The resistance to pitting corrosion is an important property of the duplex stainless steels and, of course, in a design it is important to make sure that the welds are not a limiting factor. The most common and convenient way to determine the critical pitting temperature (CPT) is by the ASTM G-48 A test, table 12.

The role of nitrogen

In a duplex stainless steel, nitrogen plays two important roles. The first one is to contribute to the resistance to pitting corrosion. The well-known PRE formula illustrates this

PRE = Cr % + 3.3 Mo% + 16 N%

The second one is to give the welds as fast and as complete austenite reformation as possible.

Low solubility of N in the weld pool accounts for the loss of N in the weld surface. As already mentioned, this is the case especially with the TIG method and when pure Ar is used as shielding gas. On an average, when pure Ar is used, the loss is in the magnitude of 0.03–0.05%. The loss of nitrogen also depends on the welding technique. As an example, when welding a butt joint in 6G position (fixed position 45° angle), some welders can have a higher loss in the 3 to 9 o'clock positions than in the horisontal position. This is illustrated by table 13, page 10.

Consequently, when maximum resistance to pitting corrosion is required, nitrogen bearing shielding and root gases should be used to compensate for the loss of nitrogen.

Dissimilar joints

In the fabrication of equipment in duplex stainless steels, there is often a need of welded joints between the duplex stainless steel and other steels, e.g. carbon steel, austenitic steel, etc. For dissimilar joints the duplex filler metal can be used in most cases, with the exception for joints between SAF 2507 and high alloyed austenitic grades, table 14, page 10.

In dissimilar joints, where Sanicro 60 is used as filler metal, the heat input shall be low and a low dilution by the parent metals is desired.

Table 12. Typical CPT values from G-48A tests for parent metals and welded joints using different welding processes and shielding media.

Sandvik	Filler metal	Welding process	Shielding gas	Root gas	CPT °C
SAF 2304					~15
All weld metal	23.7.L	TIG	Ar	–	<15
Joint	23.7.L	TIG	Ar	Ar	<15
Joint	23.7.L	SAW[1]	–	–	<15
Joint	23.8.LR	MMA	–	–	<15
SAF 2205					30
All weld metal	22.8.3.L	TIG	Ar	–	20–23
Joint	22.8.3.L	TIG	Ar	Ar	20–23
Joint	22.8.3.L	TIG	Ar + 2% N_2	90 N_2+10 H_2 (or pure N_2)	23–25
All weld metal	22.8.3.L	SAW[1]	–	–	25–30
Joint	22.8.3.L	SAW[1]	–	–	25–30
All weld metal	22.9.3.LR	MMA	–	–	25–30
Joint	22.9.3.LR	MMA	–	–	25–30
SAF 2507					80
	Autogeneous TIG-welding				40
All weld metal	25.10.4.L	TIG	Ar	–	45–50
Joint	25.10.4.L	TIG	Ar	Ar	45–50
Joint	25.10.4.L	TIG	Ar	90 N_2+10 H_2 (or pure N_2)	50–55
Joint	25.10.4.L	TIG	Ar + 2% N_2	90 N_2 +10 H_2 (or pure N_2)	55–60
All weld metal	25.10.4.L	SAW[1]	–	–	50–55
Joint	25.10.4.L	SAW[1]	–	–	50–55
All weld metal	25.10.4.LR	MMA	–	–	50–55
Joint	25.10.4.LR	MMA	–	–	50–55

[1] Using Sandvik 15W flux

Table 13. Nitrogen analysis from the top of the TIG weld. SAF 2507 parent metal and 25.10.4.L filler metal. Pure Ar as shielding and root gas. Welding performed in 6G position.

	%Nitrogen in position (o'clock)						Analysis at
	3	5	6	7	11	12	
Welder No. 1	0.17	0.18	0.15	0.16	0.19	0.19	Top side
Welder No. 2	0.18	–	0.19		0.19	–	Top side
	0.20	–	0.21		0.20	–	Root side
Welder No. 3	0.22	–	0.21		0.20	–	Top side
	0.21	–	0.21		0.20	–	Root side

In all cases the filler metal had a nitrogen content of 0.25%.

Table 14. Recommended filler metals for dissimilar joints.

SAF	Carbon steel	AISI 200 and 300-series	AISI 904L, Sanicro 28, 254 SMO, etc.
2304	22.8.3.L 22.9.3.LR 22.9.3.LT	22.8.3.L 22.9.3.LR 22.9.3.LT	22.8.3.L 22.9.3.LR 22.9.3.LT
2205	22.8.3.L 2.9.3.LR 22.9.3.LT	22.8.3.L 22.9.3.LR 22.9.3.LT	22.8.3.L 22.9.3.LR 22.9.3.LT
2507	25.10.4.L 25.10.4.LR	25.10.4.L 25.10.4.LR	1)Sanicro 60 Sanicro 60

1)Chemical composition of Sanicro 60 wire

C	Si	Mn	P	S	Cr	Ni
≤0.04	0.2	0.2	<0.015	0.010	22	≥60
Mo	Nb	Ti	Fe			
9	3.5	0.2	≤4			

Sanicro 60 covered electrode

C	Si	Mn	P	S	Cr	Ni
≤0.05	0.3	0.1	<0.020	<0.015	21	≥60
Mo	Nb	Fe				
9	3.5	≤6.0				

"Shop discipline"

From a corrosion point of view, the welded joint is always the weakest point in a stainless steel construction. In practice the final level of corrosion resistance is set by the welder. There are some simple, basic rules, which can be followed in order to get as good results as possible:

1. If possible, stainless steel and carbon steel fabrication should be separated .
2. Avoid at all times contamination of the stainless steel with carbon steel or other impurities. E.g. use nylon slings instead of chains for lifting. Be careful when using fork lifts, etc.
3. Do not mix hand tools, grinding wheels, etc. between stainless steel and carbon steel manufacturing.
4. Always follow the welding recommendations given by the material supplier regarding suitable filler metals, minimum or maximum heat input, maximum interpass temperature, etc.

Tube-to-tube sheet welding and expansion of tubes

Tube-to-tube sheet welding (T/TS) is performed with duplex stainless steels in the same way as with austenitic stainless steels. The most common types of joint preparation used for duplex stainless steel T/TS welds are shown in figure 13.

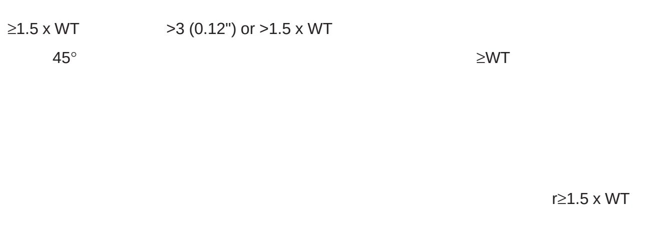


Figure 13. Joint preparations for T/TS welding of duplex stainless steels.

One problem with T/TS welding of DSS's is the rapid cooling through the tube sheet, which causes the weld deposit to solidify too fast. This often gives welds high in ferrite, and nitrides are often seen in the top grains of the bead, figure 14.

This situation is still more accentuated if a joint preparation for autogeneous welding is used, and, therefore, such joints are not recommended. Internal bore welding (joint d) must sometimes be used when there is a risk for crevice corrosion but then the reduced corrosion resistance must be taken into consideration.

In orbital TIG welding the weakest spot has turned out to be the "slope-down" area where a very low-energy weld is produced, right before the arc is extinguished. In order to improve the quality of the weld and make it less ferritic, Ar + 2% N_2 as shielding gas is strongly recommended.

When duplex stainless steel tubes are expanded into a tube sheet, the same procedures and rules as for austenitic stainless steel tubes can be followed. The only exception is that a higher expansion force must be applied owing to the higher mechanical strength of the duplex stainless steel.

Figure 14. Structure of T/TS weld.

TEMA (Tubular Exchanger Manufacturers Association) has issued tables for tube holes and tolerances, table 16. In this table the column for "Special Close Fit" tolerances shall be followed for the DSS's.

Table 16. Tube hole diameters and tolerances according to TEMA Class "C" Heat Exchangers.

Nominal Tube O.D.	Nominal tube hole diameter and minus tolerance				Plus tolerance (96% of tube holes must meet value in column (c). Remainder may not exceed value in column (d).	
	Standard Fit (a)		Special Close Fit (b)			
	Nominal diameter	Minus tolerance	Nominal diameter	Minus tolerance	(c)	(d)
Dimensions in inches						
1/4	0.259	0.004	0.257	0.002	0.002	0.007
3/8	0.384	0.004	0.382	0.002	0.002	0.007
1/2	0.510	0.004	0.508	0.002	0.002	0.008
5/8	0.635	0.004	0.633	0.002	0.002	0.010
3/4	0.760	0.004	0.758	0.002	0.002	0.010
1	1.012	0.004	0.010	0.002	0.002	0.010
1 1/4	1.264	0.006	1.261	0.003	0.003	0.010
1 1/2	1.518	0.007	1.514	0.003	0.003	0.010
2	2.022	0.007	2.018	0.003	0.003	0.010
Dimensions in millimetres						
6.35	6.58	0.10	6.53	0.05	0.05	0.18
9.53	9.75	0.10	9.70	0.05	0.05	0.18
12.70	12.95	0.10	12.90	0.05	0.05	0.20
15.88	16.13	0.10	16.08	0.05	0.05	0.25
19.05	19.30	0.10	19.25	0.05	0.05	0.25
25.40	25.71	0.10	25.65	0.05	0.05	0.25
31.75	32.11	0.15	32.03	0.08	0.08	0.25
38.10	38.56	0.18	38.45	0.08	0.08	0.25
50.80	51.36	0.18	51.26	0.08	0.08	0.25

Retubing of heat exchangers originally equipped with austenitic stainless steels has been made successfully. If the tube sheet material has equal or higher strength than the tubes, expanding can be made with normal reduction of the wall thickness (7–10%). If the tube sheet has lower strength than the tube a lower degree of expansion is recommended (3–5%) combined with welding. In order to avoid damage on the tubes, only a length of the tube that is 85% of the tube sheet thickness shall be expanded.

Expansion after welding should not be closer than 10 mm from the weld.

The degree of expansion is calculated as reduction of wall thickness according to the formula

$$R = \frac{(d_1 - d_0) - (H - D)}{D - d_0} \cdot 100\ (\%)$$

d_1 = inside diameter of tube after expansion
d_0 = inside diameter of tube before expansion
H = diameter of the hole
D = outside diameter of the tube before expansion

The width of the roll should be max 85-95% of the tube sheet thickness and the recommended speed of the shaft is 150 rpm at a mandrel pitch of 1:20. It is important to use a suitable high-pressure lubricant to cope with the high surface pressures. The lubricant must, however, be handled carefully to prevent it from penetrating into the crevice between the tube and tube-sheet. It is important to practise expansion on test pieces to establish parameters before starting the expanding operation on the heat exchangers.

Mechanized welding

When welding the same type of joint in large series, mechanized welding is often used in order to get a good productivity and a good reproducibility from joint to joint.

The duplex stainless steels are very suitable for mechanized welding and one good example is the butt-welding of tubes used in so-called umbilicals for the offshore industry. Umbilicals have different designs depending on what purpose they are intended for.

A quite common component is hydraulic tubing in wall thicknesses between 1.5–2.0 mm. Special attention must be paid to the heat input when welding these tubes in order to get an optimum structure. The use of filler metal and a heat input of 0.2–0.4 kJ/mm is recommended. As post-weld cleaning, wire brushing with a stainless steel brush is often chosen as there is a limited amount of time between welding and coiling of the tube.

Hydrogen embrittlement

How sensitive are the DSS's for hydrogen embrittlement and under what circumstances can it occur? Generally they are not, but cold cracking caused by hydrogen may occur under certain circumstances.

Basically there are three conditions to be fulfilled for hydrogen cracking to occur, and all of them may sometimes be fulfilled in welding.

1. Presence of hydrogen.
2. Sensitive phase in the steel.
3. High tensile stress.

For the DSS's, it is the ferrite that is the "sensitive" phase. At a balanced 50/50 ferrite/austenite ratio, there are no signs of embrittlement, but as the amount of ferrite increases, the risk for hydrogen embrittlement will increase. There are different opinions about the ferrite level where the risk starts. Walker and Gooch at TWI have set the limit at 72%, and somewhere between 70-75% the risk definitely increases. Of course, in order to get cold cracking also tensile stresses and hydrogen must be present.

In MMA welding the hydrogen source could be moisture in the covering. The moisture can be present in two ways, either as crystal water in the minerals or as moisture pick-up from the air. The most efficient hydrogen source is moisture present as crystal water. Absorbed moisture from the air is more loosely bonded and most of it disappears during welding from the resistance heating of the core wire.

Figure 15 below from our investigation shows that there are small differences between dried electrodes and electrodes where the covering has picked up 1.4% of water. The hydrogen pick-up is in the magnitude of 5–6 ml/100 g and too low to cause embrittlement. The hydrogen content was measured in a Stroehlein H-mat 251 equipment where the hydrogen was extracted at 950°C, brought by argon to a thermistor cell (TCD) and determined by thermal conductivity. This method is more reliable than the mercury method which is quite sensitive to the sample surface.

In SAW there is a more pronounced difference in hydrogen pick-up between dried flux and moist flux. When compared with covered electrodes, the moist flux, which had a moisture content of 0.16%, gave a hydrogen content in the weld deposit that was about 3 times higher. The flux shall always be dried at 350°C for 4 hours before welding, figure 16.

In TIG welding the hydrogen content can be controlled in a more precise way than in the processes described above. To get hydrogen in a TIG weld deposit hydrogen must be added to the shielding gas. Moisture in e.g. pure Ar gives a small contribution but is in reality of no interest.

Sometimes argon-hydrogen mixtures are used as shielding gas in order to increase the efficiency of the process. As this is a very effective way to introduce hydrogen into the weld deposit, it is not recommended for the DSS's. If the ferrite content is below 70–75% nothing will happen, but at higher ferrite levels, cold cracking may occur, figure 17.

What will happen if a hydrogen bearing root gas is used? The simple answer to that question is, nothing! The pick-up of hydrogen from the root gas is negligible. This has been shown by our own studies and has also been confirmed by others.

Figure 18 shows a small contribution of approximately 2 ml/100 g.

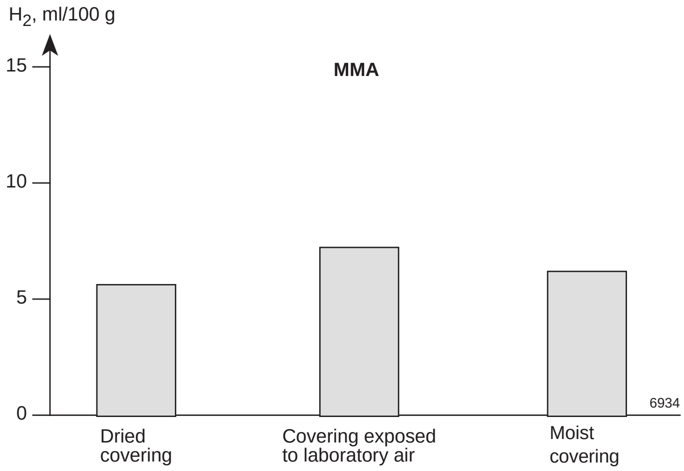


Figure 15. Hydrogen pick-up from covered electrodes - Sandvik 25.10.4.LR.

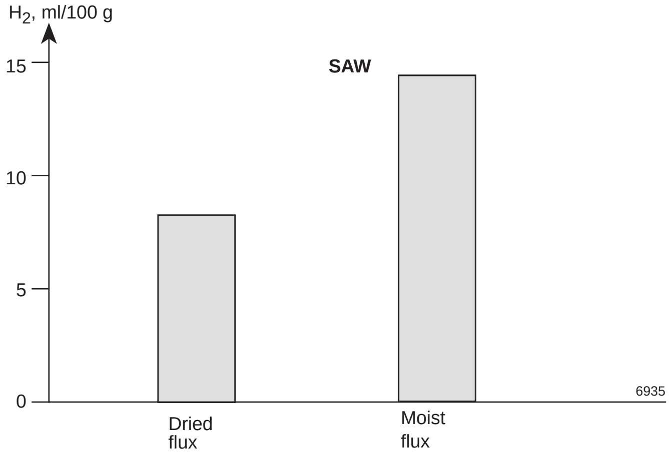


Figure 16. Hydrogen pick-up from SAW flux.

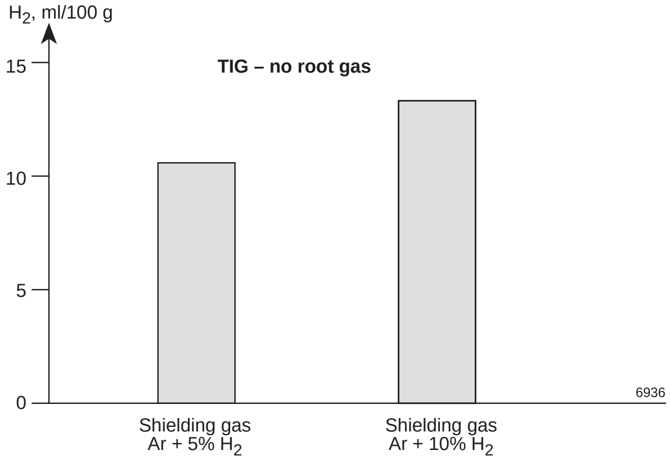


Figure 17. Hydrogen pick-up from shielding gas in TIG welding.

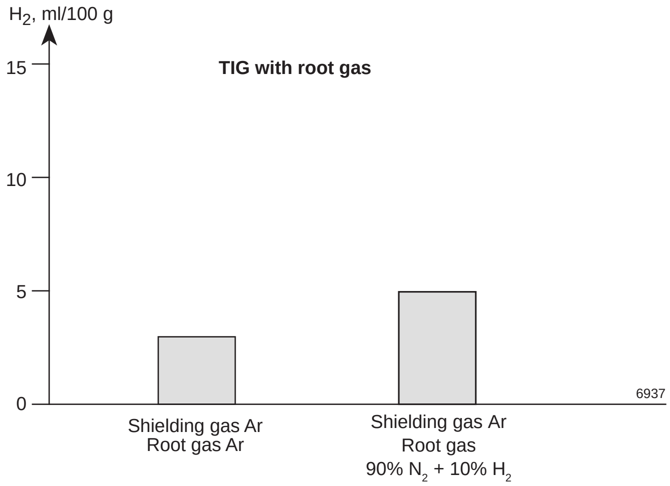


Figure 18. Hydrogen pick-up from shielding gas and root gas in TIG welding.

Conclusion

The modern duplex stainless steels have as good weldability as the austenitic stainless steels. The same type of joint preparations can be used for both, with the exception of one-sided butt welding where a slightly wider gap and a larger angle are preferred.

For the DSS's too low and too high heat inputs should both be avoided, as both extremes can lower the corrosion resistance of the welded joint. There is wide range between the extremes and optimum results will be achieved by following the recommendations given above.

Nitrogen additions to the shielding gas and the root gas can be used with advantage, when a higher corrosion resistance is desired in the weld, than normally can be obtained by pure argon. Especially in tube-to-tube sheet welding nitrogen is strongly recommended in order to make the weld less ferritic.

The duplex stainless steels are not sensitive to hydrogen embrittlement. However, there is a risk for cold cracking under extreme conditions, namely if a low-energy weld has caused high-ferrite zones in the bead and HAZ (>70–75% α) and if hydrogen is introduced by moisture in fluxes, electrode coverings or as hydrogen addition in the shielding gas.

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