Welding duplex stainless steels – A review of current recommendations

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Abstract - A steel will not become widely accepted and used unless it can be successfully welded without too many limitations. Contemporary duplex stainless steel grades fulfil these requirements with some grade dependent differences. The duplex stainless steel family has during the last decade been extended with new lean grades and recently also highly alloyed hyperduplex grades. Most welding recommendations are very similar to those of the 1990's. However, the introduction of new grades and the increased use of newer welding methods has somewhat changed the perception of what is possible.

This paper discusses the state-of-the-art and trends in welding of duplex stainless steels. It is based on input from the world-wide welding community, including users and producers of steel and welding consumables as well as literature. In most cases there is consensus on recommendations but variations reflecting differences in practices exist in particular for newer steel grades where limits in e.g. allowable energy inputs are less well documented.

1 Background

Duplex stainless steels play an essential role since many years in industrial sectors such as gas and oil, process industry and fabrication of chemical tankers. They have also found their way into more general transportation and construction applications. There is nowadays a wide range of grades all offering an attractive combination of high strength and good corrosion resistance thanks to their two-phase microstructure consisting of approximately 50% ferrite and 50% austenite. Having grown to a large family, the duplex stainless steels range from the lean grades to the highly alloyed superduplex grades and recently also hyperduplex grades for more demanding applications [1-3].

In retrospect the duplex conference in Beaune in 1991 [4] marks a step change in the image of duplex stainless steels. Earlier often seen as exotic, rarely used and difficult to weld materials they since then have become modern steels considered by many end users as realistic and interesting alternatives to more established stainless steels. At this conference new grades with increased nitrogen additions and optimised compositions were presented. As a consequence many grades gained in structure stability, weldability and corrosion resistance. Not only the 2205 grades became better defined but also superduplex steels were promoted and redesigned for better corrosion resistance, weldability and phase stability [5,6].

The practical application of any steel on a larger scale is critically dependent on the use of welding for fabrication. Productivity is a key issue in manufacturing and with increased use of duplex stainless steels, this aspect has become more important. Compared to at the time of the duplex stainless steel conference in 1991 most welding recommendations are still valid [4,7]. However, the use of newer welding methods and the accompanying extension of possible heat input ranges both upwards and downwards has changed the welding engineer's toolbox. Examples include methods such as laser and laser-hybrid techniques as well as lower energy input variants of MIG/MAG welding and welding with or without addition of filler material. Welding recommendations therefore need to be critically reviewed and summarised for well established as well as newer grades.

This paper discusses experiences as well as recent trends in welding of duplex stainless steels based on input from the world-wide welding community, including users and producers of steel and welding consumables as well as literature. It is intended to assist in designing proper welding procedures and avoiding problems by summarising important aspects of the state-of-the-art of how to weld duplex stainless steels. Largely there is consensus on recommendations but variations in recommendation reflecting differences in practices will be highlighted.

A welding operation can have significant effects on mechanical properties and corrosion performance. For example excessively high weld metal or heat affected zone ferrite contents impair properties. It is also well established that the presence of small amounts of secondary phases can have significant deleterious effects [8-11]. Some typical problems are therefore identified and discussed in relation to welding recommendations.

The document does not promote specific grades of steels, specific grades or brands of welding consumables or the views of a particular company.

2 Duplex stainless steel grades

Duplex (austenitic /ferritic) stainless steels comprise a large family ranging from the lower alloyed lean grades, via the widely used 22%Cr grades to the highly alloyed superduplex and hyperduplex grades (Table 1). During recent years a number of so called lean duplex stainless steels have attracted a lot of interest as cost efficient alternatives to standard austenitic grades such as 304L (1.4307) and 316L (1.4401). Some of the Ni in these steels is often replaced by a combination of Mn and N in order to keep the alloying cost at a minimum whilst maintaining strength, corrosion resistance and a suitable phase balance. Lean duplex grades typically have a pitting corrosion resistance better or on par with standard austenitic grades [1,2].

The classification in Table 1 is inevitably somewhat arbitrary, as there is no standardised or generally agreed method of grouping duplex steels. The intention was however to group steels in a manner reflecting composition and properties, indicating which grades can be seen as contemporary and using the common definition of superduplex as steels with a minimum Pitting Resistance Equivalent (PRE_N or PRE_W) of 40. The very recent 24%Cr LDX 2404 grade was grouped together with the standard 22%Cr grades based on its PRE_N value.

For the less alloyed grades "lean" is primarily used for almost Mo-free grades with a low Ni-content [1]. However, also grades with intermediate Mo-contents or with significant Cu-additions are here classified as "lean" as they have significantly lower PRE_N than the standard 22%Cr grades. For the very highly alloyed grades there is a similar problem in defining the borderline between superduplex and hyperduplex. In the present paper the grades are considered hyperduplex when PRE_N or PRE_W are close to or above 50.

Table 1. Typical* chemical composition (wt. %) and Pitting Resistance Equivalents (PRE_N **and PRE_W***) of common wrought duplex stainless steels.

UNS No.	EN No.	Common designation	Main alloying elements							PRE_N	PRE_W
			Cr	Ni	Mo	N	Cu	W	Other		
Early grades											
S32900	1.4460	329	25	5.5	1.7	0.09				32.0	32.0
S31500	1.4424	3RE60	18.5	4.5	2.6	0.07				28.2	28.2
S32404		UR50	21	6.5	2.5	0.07	1.5			30.4	30.4
Contemporary grades											
Lean duplex, $PRE_{N/W}$ ~ 20-30											
S32001	1.4482	19D	20	1.6		0.13	0.3		5 Mn	22.1	22.1
S32101	1.4162	LDX 2101	21.5	1.5	0.3	0.22	0.3		5 Mn	26.0	26.0
S32202	1.4062	UR2202	22	2	0.3	0.2	0.2			26.2	26.2
S82011		ATI 2102	21.5	1.5	0.3	0.22			2.5 Mn	26.0	26.0
S32304	1.4362	2304	22.5	4.8	0.3	0.1				25.1	25.1
	1.4655	-	23	4.5	0.3	0.1	2			25.6	25.6
S32003		ATI 2003	21.5	3.5	1.8	0.18				30.3	30.3
Standard 22%Cr duplex, $PRE_{N/W}$ ~ 35											
S82441	1.4462	LDX 2404	24	3.6	1.6	0.27			3 Mn	34.0	34.0
S31803	1.4462	2205	22	5.3	2.8	0.16				34.0	34.0
S32205	1.4462	2205	22.3	5.7	3.2	0.18				35.7	35.7
25%Cr duplex, $PRE_{N/W}$ ~ 35-40											
S31200		44LN	25	5	2	0.15				34.0	34.0
S31260		DP3	25.2	7.2	3.2	0.14	0.5	0.3		38.0	38.5
S32506		SD40	25	6.5	3.3	0.17				38.6	38.6
S32550	1.4507	255	26	5.5	3	0.17	1.7			38.6	38.6
S32950		7Mo Plus	26.5	4.5	1.5	0.25				35.5	35.5
Superduplex, $PRE_{N/W}$ ~ 40-50											
S32520	1.4507	2507Cu	25	7	3.5	0.25	1.5			40.6	40.6
S32750	1.4410	2507	25	7	4	0.27				42.5	42.5
S32760	1.4501	Zeron 100	25.4	6.9	3.8	0.27	0.7	0.7		42.3	43.4
S32808		DP28W	27.5	7.7	1	0.35		2		36.4	39.7
S32906	1.4477	SAF 2906 ®	29	7	2.3	0.35				42.2	42.2
S39274		DP3W	25	7	3.2	0.26	0.5	2		39.7	43.0
S39277		AF918	25.5	7.3	3.8	0.26	1.7	0.9		42.2	43.7
Hyperduplex, $PRE_{N/W}$ ~ >50											
S32707		SAF 2707 HD ®	27	6.5	4.8	0.4			1 Co	49.2	49.2
S33207		SAF 3207 HD ®	32	7	3.5	0.5				51.6	51.6

*Average of steel producers' data when available. Otherwise based on standards and specifications.
** $PRE_N = Cr + 3.3\times Mo + 16\times N$
*** $PRE_W = Cr + 3.3\times(Mo + 0.5\times W) + 16\times N$

3 Welding recommendations

The overall aim of welding recommendations is to assist welding engineers in designing welding procedures. These procedures should reliably and with desired productivity result in weldments fulfilling requirements on mechanical properties and corrosion resistance.

Although it should be made clear that microstructural features are not to be confused with properties it is important to be aware that they will govern the performance of the weldment. Welding therefore has to be performed in such a way that a suitable ferrite content (Fig. 1) and freedom from deleterious phases, such as nitrides or intermetallics, is ensured in the weld metal and the heat affected zone [7,12,13].

Generally speaking too rapid cooling may result in excessive amounts of ferrite and nitride formation in all duplex stainless steels although austenite formation is faster in grades with higher nitrogen contents. Slow cooling, or repeated heating to temperatures in the range of approximately 600-1000ºC, will on the other hand result in formation of intermetallic phases in particular in the more highly alloyed grades [11]. In practice intermetallic formation will rarely be a problem in welding of standard or lean grades whereas strict control of welding procedures is required for highly alloyed superduplex and hyperduplex grades. Whenever unwanted phases form or the ferrite content is excessively high toughness and corrosion resistance will suffer. Carbide formation is not discussed here, as modern duplex stainless steels are very low in carbon and chromium carbide formation therefore not a practical problem.

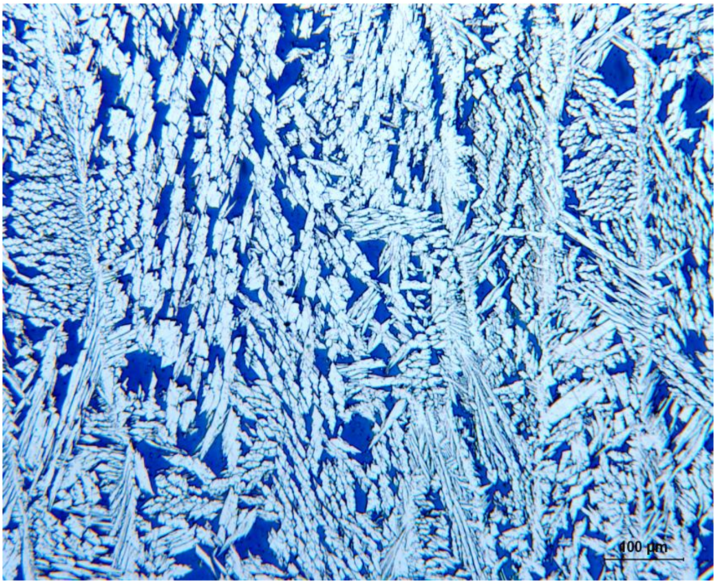

Fig. 1. Example of desired duplex weld metal microstructure, free from intermetallic phases and nitrides and with suitable ferrite/austenite balance.
Ferrite is coloured blue and austenite is white.

Recommendations aiming at controlling the microstructure can broadly speaking be divided into two categories:

1. Methods of controlling the cooling rate including preheat and interpass temperature and arc energy (heat input).
2. Composition of the fused weld metal that is governed by choice of steel grade, filler material, shielding gas and dilution.

3.1 Cooling rate

Recommended maximum interpass temperature and arc energy ranges are presented in Table 2. There is sometimes some confusion regarding recommendations as the heat input is often incorrectly used synonymously with arc energy (or energy input). In this paper recommendations are therefore presented as arc energy (alternatively energy input) regardless of the terminology used in the source. Arc energy does not consider the efficiency of individual welding methods and is therefore a somewhat blunt tool but on the other hand practical for general recommendations. The arc energy ranges should obviously be used as indications (see e.g. example in Fig. 2), as they consider neither the efficiency of the welding method nor the thickness of the material.

Fig. 2. Microstructure of 22%Cr duplex cladding layer (right) on mild steel. The cladding was deposited with electroslag strip cladding (left) in one layer using a 60 mm wide strip consumables with a linear energy input of approximately 11 kJ/mm. An appropriate ferrite/austenite balance was achieved and the weld metal was free from intermetallics.

Tables 2 and 3 present a summary of feedback received on a request for information circulated to a number of highly regarded experts within the world-wide welding community, including users and producers of steel and welding consumables. The replies reflect the opinion as of today. Lack of data on some steel grades appearing in Table 1 indicates less interest and experience of these grades within the group who replied but does not suggest that these steels are less suitable or less weldable than comparable grades. Fortunately replies were received for grades within each of the groups in Table 1 permitting an overview and comparison of welding characteristics as presented in Tables 2 and 3.

Recommendations are grade dependent but vary little within each group with some exceptions. Two major observation are 1)the lower maximum arc energy permitted for the more highly alloyed grades and 2)the lower minimum arc energy applicable for grades higher in nitrogen. It can also be noted that there is less agreement on recommendations for newer grades compared to older better established. The very recent 24%Cr LDX 2404 grade was not launched when the questionnaire was distributed and is consequently not listed in Tables 2 and 3. Producers' data suggest similar weldability as for other high nitrogen grades with low or medium alloy content and the use of 2209-type consumables.

Where recommendations differ between sources upper and lower values have been included. Specific comments on grades have been included where suitable. Higher interpass temperatures and arc energies than indicated in Table 2 are sometimes used in applications where post-weld solution annealing is applied.

Table 2. Recommended maximum interpass temperature and arc energy (energy input) intervals for a selection of duplex stainless steel grades.

UNS No.	EN No.	Common designation	Max. Interpass (ºC)	Arc energy* (kJ/mm) Min.	Arc energy* (kJ/mm) Max.	Comments
Early grades						
S31500	1.4424	3RE60	250	0.5	2.5	
Contemporary grades						
Lean duplex, $PRE_{N/W}$ ~ 20-30						
S32101	1.4162	LDX 2101	150/250	0.1/0.5	1.5/2.5	< 1.0 with SAW
S32202	1.4062	UR2202	150	0.5	2	
S82011		ATI 2102	150/250	0.5/1	3	
S32304	1.4362	2304	150/250	0.5	2.5	>1.5 kJ/mm for SAW, t=16 mm, < 0.5 kJ/mm if t<2 mm
S32003		ATI 2003	150/250	0.5/1.0	2/2.5	
Standard 22%Cr duplex, $PRE_{N/W}$ ~ 35						
S31803	1.4462	2205	150/250	0.5	2/2.5	>1kJ/mm for SAW, t=16 mm, < 0.5 kJ/mm if t<2 mm
S32205	1.4462	2205	150/250	0.4/0.5	2.5/3.5	< 0.5 kJ/mm if t<2 mm
25%Cr duplex, $PRE_{N/W}$ ~ 35-40						
S32550	1.4507	255	120/150	0.5	1.5/1.8	
Superduplex, $PRE_{N/W}$ ~ 40-50						
S32520	1.4507	2507Cu	120/150	0.5	1.5/1.8	
S32750	1.4410	2507	100/150	0.2/0.3	1/1.5	>0.5 kJ/mm for SAW, t=16 mm, <2.5 kJ/mm for SAW, t>12mm
S32760	1.4501	Zeron 100	100/150	0.3/0.5	1.5/1.8	
S32906	1.4477	SAF 2906®	100/150	0.2/0.5	1.5	<2.5 kJ/mm for SAW, t>12mm
Hyperduplex, $PRE_{N/W}$ ~ >50						
S32707		SAF 2707 HD®	100	0.2	1.5	<2 kJ/mm for SAW, t>15mm
S33207		SAF 3207 HD®	100	0.2	1.0	

*Arc energy (Energy input): E = (Voltage × Current) / Welding speed (travel speed)

Preheating is usually not recommended. However, if welding is performed at lower than room temperatures it is advisable to preheat to 50-80ºC to ensure moisture free joint surfaces. In rare cases preheating to maximum 150ºC is used to minimise the risk of cracking when welding thick and/or heavily restrained work pieces with low arc energy.

3.2 Welding methods

The choice of welding method is governed by several factors but generally the aim is to produce a weld with desired properties with the highest possible productivity. High productivity in welding is usually synonymous with one or more of the following: high arc energy, high welding speed and narrow joint configuration. As pointed out above welding of duplex stainless steels has to be performed in such a way that a suitable ferrite content and freedom from deleterious phases is ensured. This therefore imposes some restrictions in the use of welding methods, which to some extent is dependent on joint configuration, steel grade and thickness.

To generalise, all welding methods commonly used for stainless steels are usually well suited for duplex stainless steels. However, welding with low energy input methods should be used with caution and welding without filler material is generally not recommended unless full solution heat treatment is to be performed [12]. As always there are no rules without exceptions as illustrated in Table 3 below. It can be noted that grades higher in nitrogen generally seem better suited for low arc energy/high dilution welding methods. Recommendations given within brackets in Table 3 indicate that caution has to be applied, opinions vary or that suitability depends on thickness. The fact that a certain welding method is not recommended is either due to lack of information or because it can result in a weldment with unsuitable microstructure and thereby less good properties. Readers are referred to steel producers for further details for specific grades.

Some comments received (slightly edited) regarding choice of welding method are listed below.
TIG: Nitrogen additions are beneficial to compensate for losses.
MIG/MAG: Synergic pulse machines recommended for best results.
Autogenous welding: Only recommended for small thicknesses with special welding procedures requiring solution annealing or welding with nitrogen containing shielding gas. Maximum 1.5mm plate thickness is recommended for S32101/1.4162.
High power density welding processes: Risk of nitrogen loss.
Laser: CO_2 laser welding permits formation of more austenite contents compared to welding with high-brightness lasers such as fiber- and disc-lasers. PWHT is preferred.
Resistance welding: A double pulse technique reheating the weld is beneficial for improved austenite formation.

3.3 Welding consumables

The choice of welding consumables is largely governed by the need to match base material strength, achieve sufficient toughness and ensure that corrosion properties match requirements. Although welds often have very good corrosion resistance it is hardly realistic to require matching properties unless a full solution treatment is performed after welding.
In terms of guaranteeing good corrosion resistance, the choice of filler material and shielding/backing gas boils down to making sure the weld metal will have similar or higher contents of critical alloying elements such as Cr, Mo + W, N and for some applications Cu. In addition they need to be higher in elements promoting austenite formation, usually Ni, to avoid excessively high weld metal ferrite contents [12]. Filler materials for duplex stainless steels are therefore different in composition compared to the corresponding steel grade.

Table 3. Recommended welding methods for a selection of duplex stainless steel grades.

UNS No.	EN No.	Common steel designation	Welding method											Comments/ Other methods
			MMA	MIG/MAG Solid wire	MIG/MAG Cored wire	TIG	SAW	PAW	Autogenous	Laser	Hybrid	Electron beam	Resistance weld.	
Early grades														
S31500	1.4424	3RE60	x	x		x								
Contemporary grades														
Lean duplex, $PRE_{N/W}$ ~ 20-30														
S32101	1.4162	LDX 2101	x	x	x	x	x	x	(x)	x	x	(x)	(x)	SAW not first choice
S32202	1.4062	UR2202	x	x	x	x	x	x	x	x	x	x	x	
S82011		ATI 2102	(x)	x	(x)	x	x	x	x	x	x	(x)		
S32304	1.4362	2304	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	ESW/SAW strip cladding
S32003		ATI 2003		x		x	x	x	x	x	x	(x)		
Standard 22%Cr duplex, $PRE_{N/W}$ ~ 35														
S31803	1.4462	2205	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	ESW/SAW strip cladding
S32205	1.4462	2205	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	ESW/SAW strip cladding
25%Cr duplex, $PRE_{N/W}$ ~ 35-40														
S32550	1.4507	255	x	x	x	x	x	x	x	x	x	x	x	
Superduplex, $PRE_{N/W}$ ~ 40-50														
S32520	1.4507	2507Cu	x	x	x	x	x	x	x	x	x	x	x	
S32750	1.4410	2507	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	FSW possible
S32760	1.4501	Zeron 100	x	x	x	x	x	x	(x)	(x)	(x)	(x)	(x)	
S32906	1.4477	SAF 2906®	x		x	x	x	(x)						ESW strip cladding
Hyperduplex, $PRE_{N/W}$ ~ >50														
S32707		SAF 2707 HD®				x	x							
S33207		SAF 3207 HD®				x								

"x" = recommended
"(x)" = caution has to be applied, opinions vary or recommendations depend on thickness
" " = not recommended or lack of information

3.3.1 Filler materials

The standard recommendation is usually to use a “matching consumable”. Matching should here be understood as matching in elements critical for corrosion resistance (Cr, Mo + W, N and sometimes Cu). The Ni-content is always higher compared to the steel except for consumables designed for applications where a solution heat treatment is to follow the welding operation. Matching consumables are available for most major steels grades.

Within each group of duplex stainless steels, as defined in Table 1, experience has shown that consumables for grades with similar $PRE_{N/W}$ values in practice are interchangeable although different opinions exist. The need for Cu-containing consumables for welding Cu alloyed steels is sometimes disputed. A rational approach seems to be to use Cu-alloyed consumables whenever steels are specifically selected for applications where Cu is desired. Cu-alloyed consumables can without any known deleterious effects be used also for Cu-free steels.

The need for W additions to fillers when welding W-alloyed steels is another issue. W is basically added for three reasons: to differentiate grades for patent and licensing reasons, to improve corrosion resistance in the same manner as Mo and it is also claimed that W slows down precipitation of intermetallics in steels. Studies of weld metals have however not conclusively shown any beneficial effect of W on precipitation behaviour in weld metals [14-17]. As the PRE_W formula suggests, consumables with or without W can therefore be used to weld W-containing or W-free steels as long as the total W+Mo-content is sufficient to provide the desired corrosion resistance. It should be noted however that it is sometimes claimed that joining different superduplex grades, e.g. where W contents differ, may increase the risk of intermetallic formation.

To summarise current practice without going into grades or specific fillers, typical recommendations are:

- *Early grades*: Matching consumables are used when required and available. The standard recommendation is however typically to use 22Cr9Ni3Mo+N type fillers.

- *Lean duplex stainless steels*: All lean duplex grades can with few exceptions be welded with fillers for 22%Cr providing excellent mechanical and corrosion properties. However, lean duplex fillers (typically 23Cr7Ni+N) are more cost efficient and metallurgically designed to give the weld properties similar to the base material. There are some applications where Mo has a negative effect on corrosion resistance making 22Cr9Ni3Mo+N type fillers less suitable. The Mo-alloyed lean grade S32003 is preferably welded with Mo-containg 22%Cr fillers to ensure matching corrosion resistance.

- *22%Cr standard duplex stainless steels (including LDX 2404):* These grades are welded with the well-established 22Cr9Ni3Mo+N type matching filler materials. Over-alloyed (superduplex) fillers are often recommended for root passes in single-side welds where corrosion resistance of the root is critical.

- *25%Cr duplex stainless steels:* Common recommendations are, depending on grade, 25Cr7Ni2Mo+N type consumables or superduplex 25Cr fillers with or without Cu.

- *Superduplex stainless steels:* Superduplex grades are commonly welded with matching consumables. A number of filler grades are available with or without Cu and W. As discussed above these are in most cases interchangeable depending on requirements and application. The S32906/1.4477 grade is due to its different alloying concept preferably welded with 29Cr8Ni2Mo+N fillers. Highly corrosion resistant Ni-base filler are sometimes used but Nb-alloyed grades should be used with care due the strong tendency of N and Nb to combine into unwanted precipitates (Fig. 3) [18-20]. Strength will also be undermatching compared to the steel. With the introduction of hyperduplex steels, and corresponding 27Cr9Ni5Mo+N fillers, these could be an alternative when overalloying is needed. However, there is little or no documented experience of this approach.

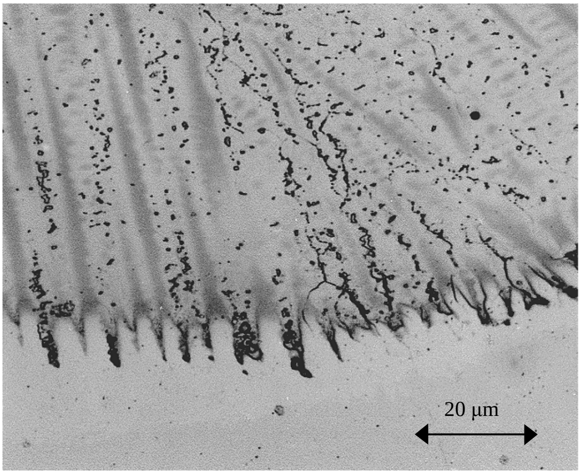

Fig. 3. Nb- and N-rich precipitates next to fusion boundary in superduplex steel TIG-welded with an Alloy 625 type Ni-base filler wire.

- *Hyperduplex stainless steels:* These should be welded with hyperduplex fillers of the 27Cr9Ni5Mo+N type. Highly alloyed Ni-base filler materials could in theory be used if lower strength is acceptable. The high N-content of the steels might however cause problems with porosity.

- *Dissimilar joining:* Joining duplex stainless to unalloyed, low alloyed or to other stainless steels is rarely a problem as long a post-weld heat treatment is not required. Usually the duplex consumable recommended for the particular duplex stainless steel grade is used. A standard 22Cr9Ni3Mo+N type or over-alloyed stainless fillers such as 23Cr12Ni or 23Cr12Ni+Mo are also common choices. Ni-base consumables are recommended for joining duplex to Ni-base alloys.

3.3.2 Shielding and backing gases

Two trends emerge when comparing typical recommendations today and at the time of the duplex conference in Beaune in 1991 [4]. Firstly nitrogen-containing gases are today commonly used for shielding and purging. Nitrogen additions are more or less standard practice in TIG-welding but also often used in MIG/MAG- and plasma-welding. The second trend is to use multicomponent gases with He-additions to improve weld pool fluidity and to permit higher welding speeds.

Recommendations vary somewhat between grades depending on the need to compensate for potential losses of nitrogen or improve austenite formation. The dividing line is therefore usually between newer high-nitrogen grades and older grades lower in nitrogen rather than between groups as presented in Table 1. Typical recommendations are consequently summarised in Table 4 based on welding methods rather than groups of steels. Brackets indicate second choice, that practices vary or that recommendation depend on steel grade.

Table 4. Recommended shielding gases.

Shielding gas	Welding method						Root shielding
	MIG/MAG		TIG	PAW	Laser[3]	Hybrid	
	Solid wire	Cored wire					
Ar			(x)	(x)[2]	x	(x)	x
He					x	x	(x)
CO_2		(x)					
N_2					x		x
Ar+1-2%O_2	x				(x)	(x)	
Ar+2-3%CO_2	x				(x)	(x)	
Ar+16-25%CO_2		x					
Ar+1-3%N_2	(x)[1]		x	x[2]	(x)		x
Ar+20-30%He				(x)[2]	x	x	(x)
Ar+30%He+1-3%CO_2	x				(x)		
Ar+30%He+2%N_2	(x)[1]		x	x[2]	(x)	x	(x)
Ar+30%He+1-2%N_2+1-2%CO_2	(x)[1]						

[1]Generally only recommended for high-N grades

[2]Typically the same gas is used as plasma and shielding gas

[3]Depends on type of laser and laser power

Root shielding with a purging gas is, as always in welding of stainless steels, critical for optimum corrosion resistance in particular for single sided welds. Ar, He or mixtures thereof can be used but He is seldom an option for cost reasons. Nitrogen containing purging gases are often recommended for best corrosion resistance but is sometimes claimed to give rise to a yellow discoloration that is not found with Ar. Addition of hydrogen to the purging gas is effective at reducing oxidation and 90%N_2 + 10%H_2 is therefore sometimes recommended. However, gases including hydrogen are often avoided due to the risk of hydrogen embrittlement.

3.4 General recommendations

In most respects duplex should be treated similar to any stainless steel when it comes to handling and preparation for welding. A few points not discussed above are listed below for completeness.

- *Joint design:* To achieve good penetration a slightly wider root gap, a smaller land and a joint angle about 10° larger than for standard stainless joints, should be used.
- *Joint preparation:* Standard joint preparation methods used for stainless steels are suitable also for duplex stainless steels. Oxides resulting from thermal cutting shall be removed before welding.
- *Tack welding:* Tacks shall be longer and they should have a shorter distance compared to tacks in austenitic stainless steel grades.
- *Cleaning:* Cleaning joints, before and after welding, follows standard stainless practice.

4 Welding related problems

Overall modern duplex stainless steels have good weldability and welding is generally seen as much less of a problem compared to at the time of the duplex conference in Beaune in 1991. Nevertheless welding has to be performed in such ways that weld imperfections are avoided. As most grades are high in nitrogen, porosity can occur and is most commonly observed with thick beads and high welding speeds. Welding duplex stainless steels also require understanding of the need to weld in such a way that a balanced microstructure free from deleterious phases is achieved. Problems therefore typically occur due to lack of knowledge and training or due to neglecting the need to follow recommendations. One such example is TIG re-melting to improve weld profiles, which inevitably leads to poor corrosion resistance.

Most commonly problems are seen when too low or excessively high heat input is used, when dilution is too high and when too much nitrogen is lost from the weld pool.

4.1 Loss of N and low energy input

In the authors experience the most frequent problem is poor corrosion resistance, typically in ASTM G48 testing of TIG welds. Examples of pitting attack in weld metal are shown in Fig. 4.

Fig. 4. Examples of pitting attack in TIG-welded 22%Cr duplex and superduplex stainless steels seen after ASTM G48 testing.

The common denominator of these problems is loss of nitrogen and/or too rapid cooling. As show in Fig. 5 this results in a highly ferritic as-deposited microstructure and copious amounts of secondary austenite in reheated regions, sometimes together with nitride formation. The secondary austenite is low in nitrogen and hence pitting corrosion resistance will be poor in these regions [9].

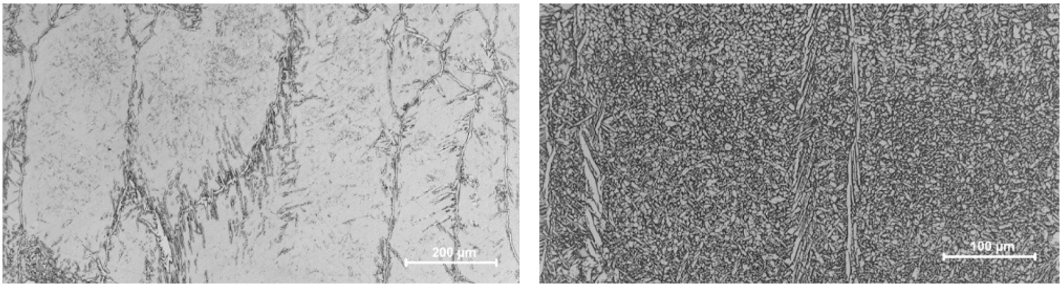

Fig. 5. Microstructure of last bead (left) and reheated beads (right) in 22%Cr duplex stainless steel TIG-welded with a 22Cr9Ni3Mo+N type filler. Massive formation of secondary austenite can be seen in the reheated bead.

The remedy is to use higher energy input often in combination with an N-containing shielding gas to enhance austenite formation. In 22%Cr steels, root passes are often welded with superduplex filler to further improve the root side corrosion resistance.

4.2 Intermetallic phase formation

In superduplex and hyperduplex grades intermetallic phase formation (Fig. 6) can occur if cooling is too slow or if a weld region is reheated repeatedly in the range of approximately 600-1000ºC [11]. Whenever intermetallic phases form toughness and corrosion resistance will suffer. A strict control of welding procedure is therefore required for highly alloyed grades. Not only must the upper recommended energy input and interpass temperature limits be adhered to. It is also important to plan the bead sequence to avoid unnecessary repeated reheating of preceding beads. A too small root bead followed by a larger “hot pass” should normally be avoided.

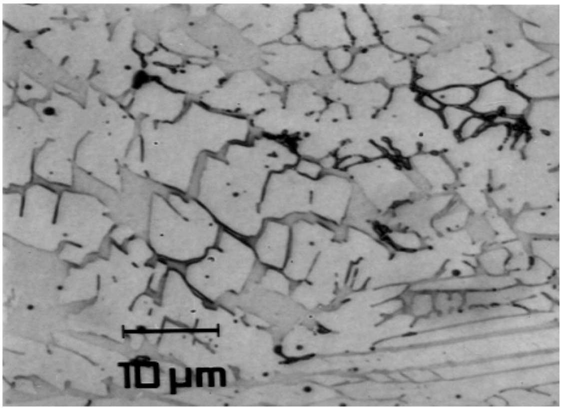

Fig. 6. Intermetallic phase (dark etching) formation in a repeatedly reheated region of a superduplex weld.

4.3 Solidification cracking

Solidification cracking is a minor problem in welding of duplex stainless steels. However, this is not to say it cannot occur under certain conditions. A high restraint in combination with deep and narrow beads is a classical condition when cracking can become a problem with conventional arc welding methods. This tendency is generally counteracted by modifying the bead profile and for thick material sometimes using a moderate preheat.

Two less well-known situations when hot cracking sometimes is observed is with very shallow beads or in highly ferritic welds. The first case is illustrated in Fig. 7 for a submerged arc weld in 22%Cr duplex material. Typically hot cracks appear under high restraint situation, with shallow beads forming “wings”. Cracking is either found in the “wing” region were stresses will act perpendicular to the vertical ferrite grains or in the transition region between the “wing” and the central penetrating portion of the weld. These cracks can be avoided by modifying welding parameters to avoid “wing” formation.

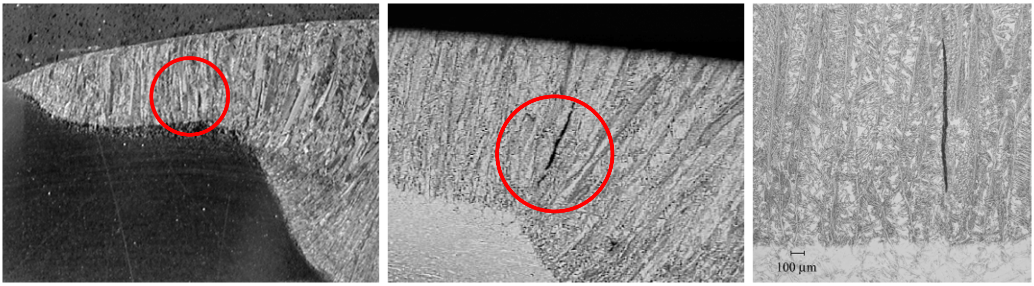

Fig. 7. Hot cracks in submerged arc welds in 22%Cr duplex stainless steel.
The red circles show regions with solidification cracks in the macrographs (left and centre).
A close-up of a crack is seen in the micrograph (right).

The second condition when hot cracks appear is most commonly seen with low energy input and high dilution welding situations. Two examples are shown in Fig. 8 for autogeneous laser welding and hybrid welding of 22%Cr duplex material. It is well known that hot cracking resistance decrease when going from austenitic weld metals with some ferrite towards fully ferritic compositions [21]. The solution is therefore commonly to modify the welding procedure to permit formation of more austenite by adding more austenite promoting elements through shielding gas and filler wire and by increasing the energy input.

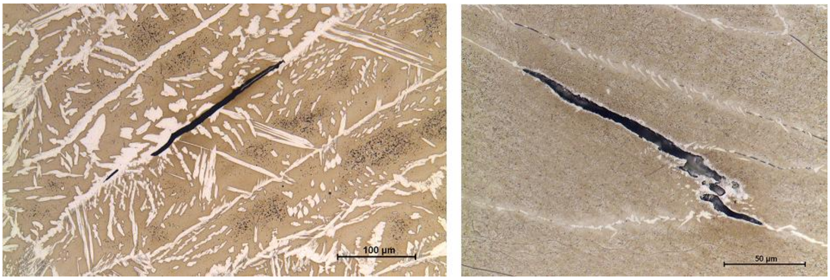

Fig. 8. Hot cracks in hybrid (left) and laser welds (right) in 22%Cr duplex stainless steel. The energy input was 0.6 kJ/mm and 0.1 kJ/mm for the hybrid weld and the laser weld, respectively.

5 Concluding remarks

There is a lot more to be said and discussed regarding welding of duplex stainless steels. Important aspects such as standardisation, suitability and reliability of various test methods, hydrogen effects, post weld straightening and cleaning, characterisation and prediction of microstructures and properties etc. have not or only briefly been touched on [22-25]. Many of these aspects were discussed in papers at the recent conference on duplex stainless in Beaune France in 2010 and the reader is referred to the proceedings for more detail [4].

Generally the knowledge about what can be done and what should be avoided is at a high level among experienced users and these consequently report very few welding related problems. Nevertheless duplex stainless steels do, as discussed above, require understanding of how welding will affect the microstructure and thereby properties. New users/fabricators therefore occasionally experience problems when cutting corners to save time.

Summarising some of the more important aspects discussed in the paper:

- The range of duplex grades has in recent years been extended both with lean less alloyed grades as well as highly alloyed hyperduplex grades.
- The newer as well as more established grades are welded with excellent result provided basic rules and recommendations are followed.
- Generally there is consensus on welding recommendations but variations reflecting differences in practices exist in particular for newer steel grades.
- Limits in allowable energy inputs are less well documented for some of the newer grades.
- Welding related problems are most commonly encountered when too low or excessively high heat input is used, when dilution is too high or when too much nitrogen is lost from the weld pool. In particular resistance to localised corrosion and impact toughness is affected.

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Additional literature

The interested reader is referred to the proceedings of duplex conferences for further details. These give an excellent overview of the development of steels, applications and welding experiences during the last four decades:

- Proc. Conf. *Duplex Stainless Steels'82*, St Louis, USA (Oct. 1982)
- Proc. Conf. *Duplex Stainless Steels'86*, The Hague, Netherlands (Oct. 1986)
- Proc. Conf. *Duplex Stainless Steels'91*, Beaune, France (Oct. 1991)
- Proc. Conf. *Duplex Stainless Steels'94*, Glasgow, Scotland (Nov. 1994)
- Proc. Conf. *Duplex Stainless Steels'97*, Maastricht, The Netherlands (Oct. 1997)
- Proc. Int. Conf. *Duplex 2000*, Venice, Italy (Oct. 2000)
- Proc. Int. Conf. *Duplex 2007*, Grado, Italy (June 2007)
- Proc. Int. Conf. *Duplex World 2010*, Beaune, France (Oct. 2010)