

## Effective Welding of Duplex & Superduplex Stainless Steels

Graham Holloway BSc, CEng, SenMWeldI  
Metrode Products Limited, UK

### 1. Introduction

Duplex and superduplex stainless steels have become firmly established for a number of applications in the offshore sector because of their excellent combination of strength and corrosion resistance, Figure 1 on the right. The most commonly used alloys, giving typical properties, are shown in Table 1, along with 316L for comparison. This paper will firstly look at typical code/specification requirements and then examine the properties which can be realistically achieved with the various processes. It will then cover the key objectives which need to be achieved when welding duplex and superduplex stainless steels, and how to go about meeting these requirements.



**Table 1: Typical duplex alloys**

Grade	UNS	Cr	Ni	Mo	Cu	W	N	PRE <sub>N</sub>	PRE <sub>w</sub>	CPT °C	Min Proof MPa
<b>316L</b>	S31603	17	12	2.5	-	-	-	23	23	15	170
<b>Utility duplex</b>	S32304	23	4	0.10	-	-	0.1	25	25	15	400
<b>Standard duplex</b>	S31803	22	5	2.8	-	-	0.14	34	34	30	450
	S32205	23	5	3.2	-	-	0.18	36	36		470
<b>Super-duplex</b>	S32750	25	7	3.8	-	-	0.26	42	42	60	550
	S32760	25	7	3.5	0.7	0.7	0.26	41	42		
	S32550	25	5.5	3.5	1.8	-	0.22	40	40		
	S32974	25	7	3	0.3	2	0.26	40	42		

### 2. Processes & consumables

All of the common arc welding processes are suitable for joining duplex and superduplex stainless steels. For the root GTAW, plasma and pulsed MIG are most suitable although GTAW is most widely used; for the filling and capping runs, the aim is to fill the joint as quickly as possible whilst maintaining the procedural controls necessary to obtain the required properties. The filling runs can be deposited using GTAW, SMAW, pulsed MIG, flux cored wires or sub-arc; all of these processes except sub-arc are suitable for positional welding.

The weld metal compositions are similar to the base material compositions given in Table 1, with the exception of nickel which is typically about 3% higher. The relevant specifications for the consumables are given in Table 2. For manual GTAW, wire is supplied in cut lengths of 1.6mm,

2.4mm and 3.2mm diameters. The most commonly used size is 2.4mm, the 1.6mm is only used for thin wall tube, and the largest diameter is used to increase productivity when filling thicker joints. For GMAW, and mechanised GTAW, spooled wires are used in 0.8mm, 1.0mm and 1.2mm diameters. The most adaptable process, SMAW, is widely used for welding duplex stainless steels with electrodes of 2.5–5.0mm diameter. Basic coated electrodes (15 type coatings in AWS terminology) are utilised for positional welding and for optimum toughness; for optimum operability in less critical applications, rutile electrodes can be used (16 or 17 types in AWS). Flux cored wires are used almost exclusively in 1.2mm diameter either as downhand only wires with excellent slag release and bead profile, or all-positional wires. Both types of flux cored wire utilise a rutile flux system and argon-20% CO<sub>2</sub> shielding gas. Submerged arc welding makes use of the same wire as TIG and MIG with the wire diameter normally restricted to 2.4mm maximum in order to control heat input. A fully basic agglomerated flux is used in combination with the wire when submerged arc welding to get the best combination of properties and operability.

**Table 2: Consumable specifications.**

Alloy	Process	AWS Specification	BS EN Specification	Metrode
Duplex	GTAW	ER2209	W 22 9 3 N L	ER329N
	GMAW	ER2209	G 22 9 3 N L	ER329N
	SMAW	E2209-15/16/17	E 22 9 3 N L B/R	2205XKS/Ultramet 2205
	FCAW	E2209T0-1/4, E2209T1-1/4	T 22 9 3 N L R/P	Supercore 2205/2205P
	SAW	ER2209 + flux	S 22 9 3 N L + flux	ER329N + SSB
Super-duplex	GTAW	-	W 25 9 4 N L	Zeron 100X
	GMAW	-	G 25 9 4 N L	Zeron 100X
	SMAW	-	E 25 9 4 N L B/R	Zeron 100XKS, 2507XKS, Ultramet 2507
	FCAW	-	-	Supercore Z100ZP/2507P/2507
	SAW	-	S 25 9 4 N L + flux	Zeron 100X + SSB/LA491

### 3. Code & specification requirements

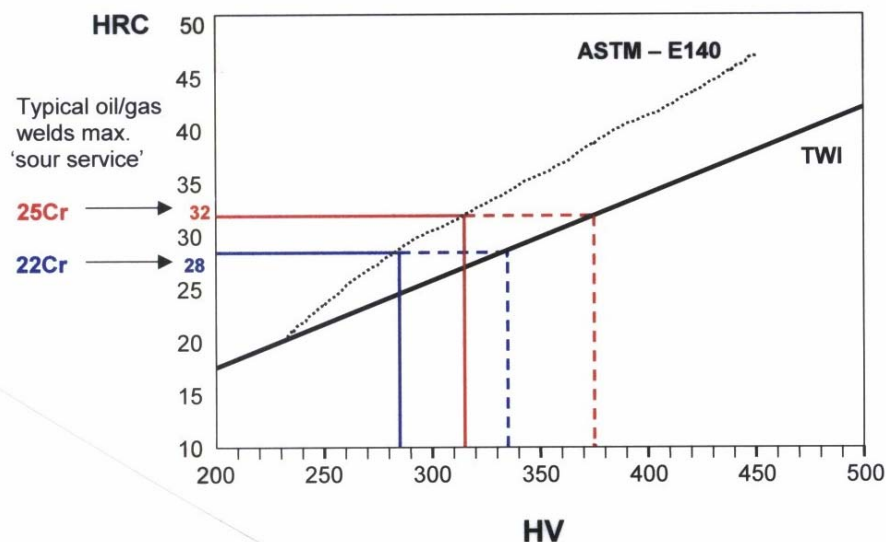
Most offshore projects which make use of duplex and superduplex stainless steels specify requirements for a similar range of properties:

- Strength.
- Hardness.
- Toughness (Charpy test).
- Ferrite and microstructure.
- Corrosion (ASTM G48A test).
- Other common weld procedure requirements, eg NDT, bend tests.

A number of these are common to all weld procedures and some are specific to duplex, but from Metrode's experience with various offshore projects, the aspects which cause the most problems are hardness, toughness, ferrite and corrosion. These are the four areas which will be covered in more detail.

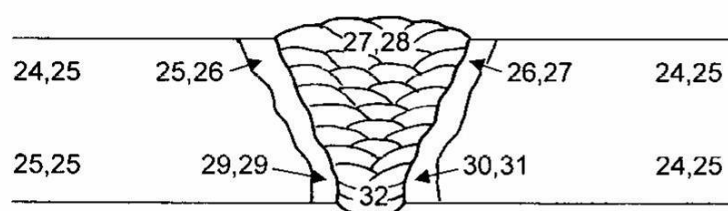
### 3.1 Hardness

Many operators impose their own hardness limit (eg. 28HRC for duplex and 32HRC for superduplex), but most limits originate from NACE MR0175. The maximum allowable hardness in NACE MR0175 for duplex and superduplex stainless steels depends on the alloy grade, product type and service environment. The 2003 edition of NACE MR0175 has changed compared to earlier versions; solution annealed duplex and superduplex base material no longer has a hardness restriction but for cold worked tubular products the limit is 36HRC for both duplex and superduplex (the latest edition of NACE MR0175 should be referred to for further information). The NACE standard, and therefore some project specifications, use the Rockwell C (HRC) hardness scale; other project specifications use the Vickers (HV) scale or a conversion from HRC to HV. The HV measurement is more convenient for weld joints because the smaller indenter makes it easier to test the HAZ. Caution should be used if converting HV to HRC because the ASTM E140 conversion developed for CMn steels which is commonly used is not accurate for duplex stainless steels. A hardness conversion based on work carried out by TWI is more accurate for duplex stainless steels:  $HRC = 0.091HV - 2.4$ . This is shown graphically in Figure 2. If HRC measurements cannot be carried out and it is necessary to convert HV measurements to HRC, it is recommended that the TWI conversion is used.



**Figure 2: Weld hardness conversion.**

If problems are encountered with high hardness during weld procedures, then it is normally in the root region of the joint, see example in figure 3. This is primarily a problem in multipass welds in thick material (above about 20mm). The higher hardness in the root is the result of strain hardening caused by the thermal cycle of subsequent passes. The only means that have been found to reduce the hardening effect in the root is to reduce the number of runs deposited and therefore the number of strain hardening events. It has also been reported that preheating (to approximately 100°C) can slightly reduce the hardness. If either of these methods is used to minimise hardening, then other procedural controls need to be maintained, eg maximum heat input and maximum interpass temperature.



**Figure 3: 18mm thick GTAW weld in Zeron 100 showing high hardness in the root.**

### 3.2 Toughness

Toughness requirements vary from one project to another but 40J minimum average and 30J minimum individual at -40/-50°C are typical offshore requirements seen in the North Sea. Duplex stainless steels do not have a pronounced ductile-brittle transition characteristic of CMn and low alloy steels, they exhibit a gentle sloping transition with good consistency within any set of Charpy specimens. Impact properties correlate very closely with weld metal oxygen content, and hence inclusion content of the weld metal. The GTAW process with ~150ppm oxygen achieves typically 150J at -50°C, whereas rutile coated SMAW electrode deposits containing ~1000ppm oxygen only achieve about 30/35J, see Table 3.

For safety critical pressure vessel applications CTOD fracture toughness for duplex alloys has been assessed by Charpy correlation and 40J average (27J individual) at the minimum design temperature has been calculated to be sufficient to avoid the risk of brittle fracture. A CTOD value of 0.1mm is considered appropriate to meet this requirement. CTOD requirements are not normally specified for offshore applications.

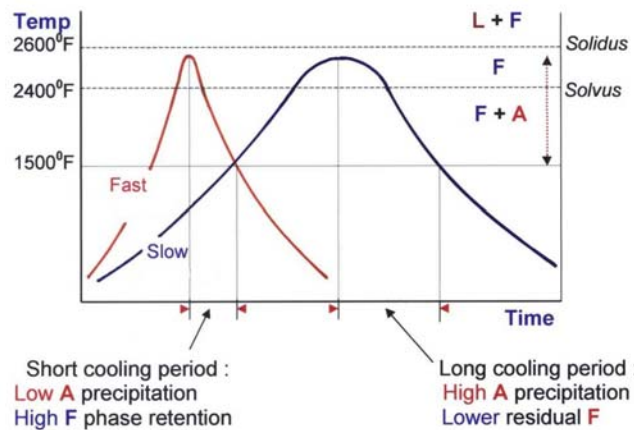
**Table 3: Approximate impact properties for duplex stainless steel weld metals at -50°C.**

Process	Duplex	Superduplex	Approximate oxygen, ppm
GTAW	150J	150J	150
GMAW	75J	60J	400
SAW	70J	50J	500
SMAW (basic)	65J	50J	600
FCAW	55J	30J	750
SMAW (rutile)	35J	30J	1000

### 3.3 Ferrite

Typical oil and gas requirements specify 30–60% ferrite in the weld metal, with some codes allowing down to 25% (eg NORSOK M601). These requirements are only called up in weld procedure qualifications, no national standards (eg AWS or EN) for welding consumables have a ferrite requirement. The requirements for weld procedure qualifications are normally based on point counting (eg ASTM E562), although some codes also have a requirement for production checks to be carried out using magnetic instruments.

The various techniques used for carrying out ferrite measurements are point counting, magnetic measurement and also predictions based on analysis. Point counting is the most widely specified technique for weld procedure approval, but for weld metal microstructures, the technique has been shown to produce significant lab-to-lab variations. If point counting has to be carried out, then the magnification which is used should be selected sensibly (for most weld metals this will be in the region of X400) and sufficient fields and areas should be measured to get a representative ferrite value. Magnetic measurement instruments (eg Ferritescope), when properly calibrated using secondary standards, have been shown to produce more accurate and reproducible results. The secondary weld metal standards used to calibrate instruments are normally certified in ferrite number (FN) rather than percent ferrite, but it is hoped that magnetic measurements will become more widely accepted. Analytical predictions are normally only used for estimation purposes but the WRC diagram has shown good correlation with Ferritescope measurements for weld metals.

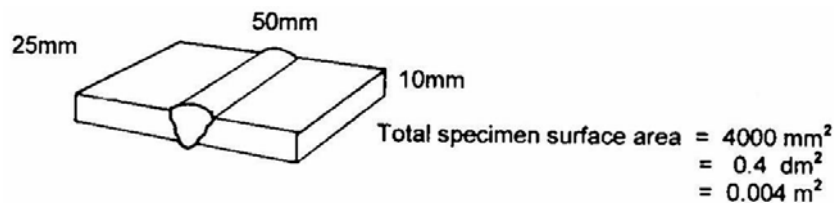


**Figure 4: Effect of cooling rate on ferrite content.**

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: heat input, interpass temperature, preheat, joint thickness (heat sink). The faster the cooling rate, the higher the ferrite content, Figure 4.

### 3.4 Corrosion

The corrosion resistance of duplex alloys is normally assessed using the ASTM G48A ferric chloride pitting test. The test is used, not because it is representative of the service environment, but because it provides an accelerated assessment of weld procedure control. The pass criteria, at the given test temperature, are normally no pitting and a maximum weight loss of either  $4\text{g/m}^2$  or of  $20\text{mg}$  on a standard size specimen, Figure 5.



**Figure 5: Typical G48A specimen where  $20\text{mg}$  weight loss on the specimen =  $5\text{g/m}^2$ .**

The main reasons for failure of G48A tests are poor root welding procedure and nitrogen loss in the root, see section 4. There are other factors outside the scope of the weld procedure which can influence the G48A result, the main one is the test itself, and sample preparation in particular. All cut faces should be ground to a 1200 grit finish and corners should be rounded; many specifications now also allow specimens to be pickled, eg NORSOK M601 requires pickling of specimens (20% nitric acid + 5% hydrofluoric acid at  $60^\circ\text{C}$  for 5 minutes). Pickling reduces weight loss and test-to-test variability. The final factor is to ensure that the test temperature is realistic; for 22%Cr, this is  $25^\circ\text{C}$  as an absolute maximum and  $40^\circ\text{C}$  for 25%Cr.

Using good procedural control, 22%Cr duplex welds are capable of passing G48A tests in the as-welded condition at  $+22.5^\circ\text{C}$ ; to ensure a pass at  $+25^\circ\text{C}$  it is recommended that superduplex filler wire is used for the root run. For 25%Cr superduplex, it should be possible to pass G48A tests at  $+35^\circ\text{C}$ , but to ensure a pass at  $+40^\circ\text{C}$  it is recommended that an Ar-2%N<sub>2</sub> shielding gas is used for the root run. Fabricators have increasingly standardised on the precautionary approach of using superduplex 25%Cr root filler for 22%Cr duplex and Ar-2%N<sub>2</sub> torch gas for the root run on 25%Cr superduplex procedures.

## 4. Joint objectives and procedural guidelines

### 4.1 Basic procedural guidelines

The two most basic precautions imposed when welding duplex and superduplex stainless steels are heat input and interpass temperature. Satisfactory properties can generally be achieved with heat inputs in the range 0.5–2.5kJ/mm, but there are codes and client specifications which restrict the maximum heat input down to 1.75kJ/mm for 22%Cr duplex and 1.5kJ/mm for 25%Cr superduplex. Although codes tend to concentrate on restricting the maximum heat input, it is also detrimental to deposit an excessive number of runs in a joint at low heat inputs. By depositing a lot of low heat input runs, numerous reheating cycles will occur which can cause the formation of intermetallic phases. These heat input controls are far more critical for 25%Cr superduplex alloys than the standard 22%Cr duplex grades.

Interpass temperature is restricted to 150°C maximum to minimise the risk of third phase formation. The use of restrictive interpass temperatures can reduce productivity but forced air cooling of joints has been used without affecting joint properties.

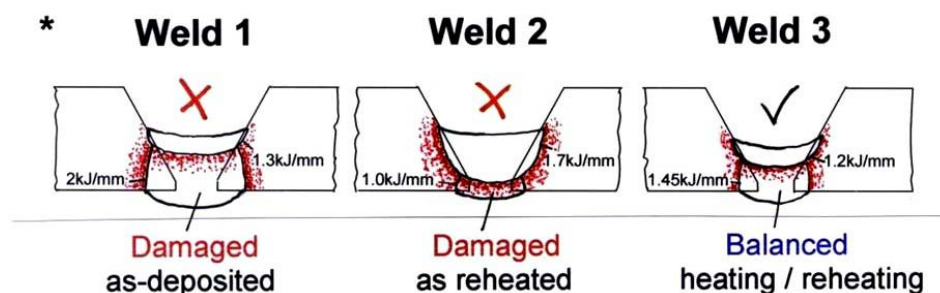
### 4.2 Joint objectives

In order to simplify the objectives of the joint, the weld can be considered in two parts: the root and the fill. The root is the most critical part of the joint with respect to corrosion resistance, whereas the filling runs provide the strength and toughness. By considering the joint in two parts, it is possible to select the consumables most suitable for each region.

The consumables in the root can be selected to meet the required corrosion properties, but the weld procedure will be just as influential. The simplest approach to producing a satisfactory root is by controlling a few basic factors:

- Joint preparation and fit-up.
- Gas purging.
- Interpass temperature.
- Arc energy balance between runs 1 and 2.

The last one of these, which will determine the microstructure of the root region weld metal and HAZ, is specific to duplex and particularly superduplex joints and is explained in Figure 6.



**Figure 6:** *Weld 1 – High heat input root, low heat input second run.  
 Weld 2 – Low heat input root, high heat input second run.  
 Weld 3 – Medium heat input root, second run ~75% of the heat input of the root.*

## 5. Conclusions

Duplex and superduplex stainless steels are readily weldable as long as a number of factors are remembered by fabricators, consumable manufacturers, code writers and other authorities. These factors can be summarised as follows:

- Good quality stainless steel fabrication practice is applied.
- Appropriate welding processes and consumables are available and should be selected to meet the code requirements.
- A weld procedure should be developed to meet the required properties.
- Welders need to be trained to weld superduplex stainless steels and guidance should be provided explaining why it is critical to accurately follow the weld procedure.
- Authorities should set realistic code requirements and avoid the trend for imposing more onerous requirements without any real technical or metallurgical justification.
- Once imposed, the tests and results should be properly and consistently carried out and assessed.

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