DUPLEX & SUPERDUPLEX

PROPERTIES & TEST REQUIREMENTS

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Welding Consumables for
Duplex & Superduplex Alloys

Stainless Steels

Duplex & Superduplex Stainless Steels

Properties & Weld Procedure Tests

CONTENTS

Duplex & Superduplex Stainless Steels

Properties & Weld Procedure Tests

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. The most commonly used alloys, giving typical properties, are shown in Table 1, along with 316L for comparison. Standard duplex is 22%Cr (eg. UNS S31803 and S32205) and superduplex is 25%Cr with a pitting resistance equivalent number (PRE_N) ≥40 (eg. UNS S32750, S32760 and S32550). This leaflet will look at typical code and specification requirements and examine the properties that can be realistically achieved with the various processes; identifying some of the unrealistic requirements imposed by specifications.

Metrode have a full range of consumables and data sheets for all products are included at the end. Detailed welding procedure guidelines are not covered but a separate leaflet is available from Metrode on request.

Table 1 Typical duplex alloys

Grade	UNS	Cr	Ni	Mo	Cu	W	N	PRE_N	PRE_W	CPT °C	Min Proof MPa
316L	S31603	17	12	2.5	-	-	-	23	23	15	170
Utility duplex	S32304	23	4	0.10	-	-	0.1	25	25	15	400
Standard duplex	S31803	22	5	2.8	-	-	0.14	34	34	30	450
	S32205	23	5	3.2	-	-	0.18	36	36		470
Super-duplex	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		

PRE_N = Cr + 3.3Mo + N. PRE_W = Cr + 3.3Mo + 1.65W + 16N.

2. Processes & consumables

All of the common arc welding processes are suitable for joining duplex and superduplex stainless steels. For the root TIG/GTAW, plasma and pulsed MIG/GMAW are most suitable although TIG 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 TIG, MMA/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 TIG, 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 MIG, and mechanised TIG, spooled wires are used in 0.8mm, 1.0mm and 1.2mm diameters. The most adaptable process, MMA, 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_2 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	TIG	ER2209	W 22 9 3 N L	ER329N
	MIG	ER2209	G 22 9 3 N L	ER329N
	MMA	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	TIG	-	W 25 9 4 N L	Zeron 100X
	MIG	-	G 25 9 4 N L	Zeron 100X
	MMA	-	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, plus additional information on tensile properties.

4. Strength

4.1 Requirements

The strength requirement for the weld metal is essentially the same as for the base materials: minimum 0.2% proof stress of 450MPa for duplex (480MPa for some materials) and 550MPa for superduplex.

4.2 Ambient tensile properties

In the as-welded condition duplex/superduplex weld metals comfortably exceed the strength requirements of the respective base materials, typical tensile properties are given in Table 3.

Table 3 Typical all-weld metal tensile properties.

Alloy	*Process*	*Consumable*	*Rp0.2% MPa*	*Rm MPa*	*A4 %*	*A5 %*	*Z %*
Duplex	TIG	ER329N	660	820	32	29	-
	MIG	ER329N	590	815	31	30	-
	MMA	2205XKS	665	810	28	26	45
		Ultramet 2205	675	850	27	25	40
		Supermet 2205	865	750	25	-	35
	FCAW	Supercore 2205/P	630	800	32	29	45
	SAW	ER329N + SSB	590	815	31	30	-
Superduplex	TIG	Zeron 100X	725	920	25	24	40
	MIG	Zeron 100X	725	920	25	24	40
	MMA	Zeron 100XKS	700	875	25	23	45
		2507XKS	700	900	28	25	45
		Ultramet 2507	750	890	26	24	35
	FCAW	Supercore Z100XP	690	880	27	25	33
		Supercore 2507/P	660	870	30	29	38
	SAW	Zeron 100X + SSB	725	920	25	24	40

The 22%Cr duplex weld metals are normally strong enough to meet the strength requirement of the superduplex base material and there have been examples of duplex weld metals being used for the filling runs on superduplex. The root and capping runs would still be deposited using superduplex to ensure adequate corrosion resistance, but filling runs could be deposited with duplex consumables. The main technical advantage in using duplex consumables is that it allows higher toughness to be achieved.

4.3 'Warm' tensile properties

There have been examples of projects where minimum 'warm' tensile strengths have been specified. The test temperature specified is normally in the range 125-160°C. The requirement is normally imposed on superduplex weld metals and it may be either for welding superduplex or supermartensitic base materials. An example of the strength of superduplex weld metals in comparison to the base material is shown in Figure 1.

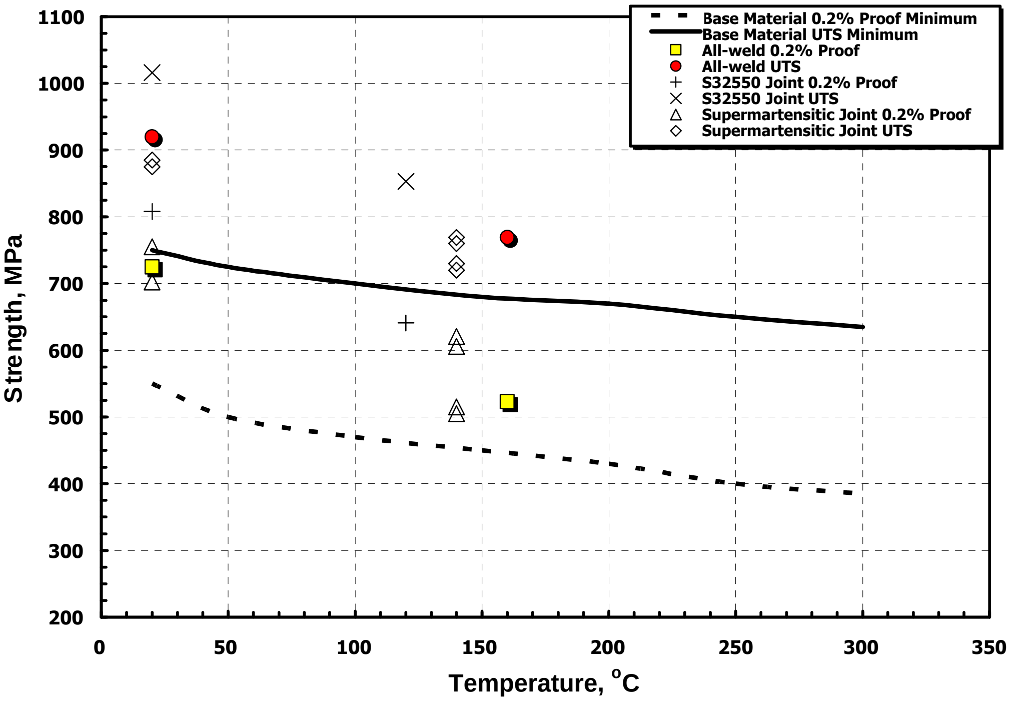

Figure 1 High temperature tensile properties of Zeron 100X TIG welds

5. Hardness

5.1 Hardness limits

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 originally depended 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 have 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). There are other codes that impose hardness restrictions eg. NORSOK M-601 350HV, or if for sour service 310HV (28HRC) for duplex and 330HV (32HRC) for superduplex.

When designers and specifiers write hardness restrictions they should not impose unrealistic limits. It should firstly be remembered that duplex and superduplex materials are both high strength alloys and this strength can only be produced with a certain level of hardness; secondly hardness limits are primarily placed to avoid stress corrosion cracking (SCC) and testing has shown both duplex and superduplex to be resistant to SCC to hardnesses up to 36HRC.

5.2 *Hardness conversion*

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 indentor 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.

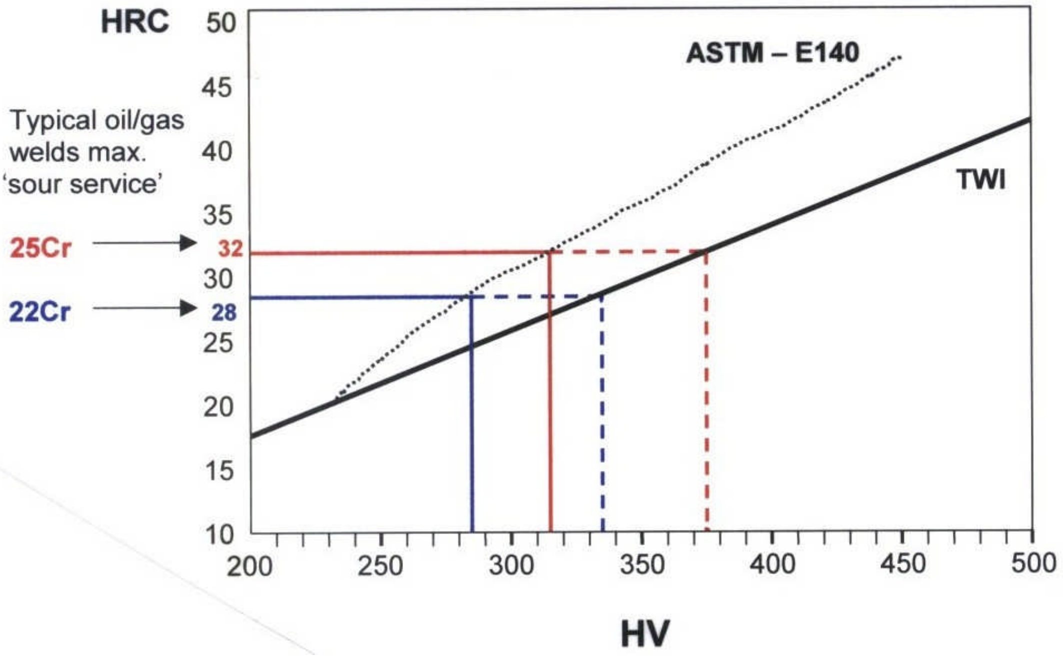

Figure 2 TWI's HV-HRC hardness correlation

5.3 *High hardness values*

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; this is very well demonstrated by the graph in Figure 4. 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.

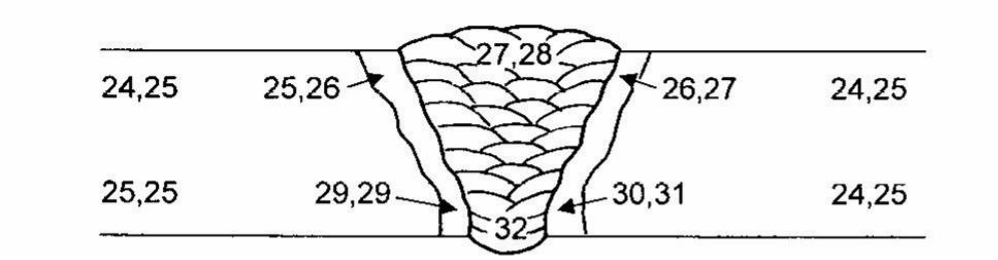

Figure 3 ***18mm thick GTAW weld in Zeron 100 showing high hardness in the root.***

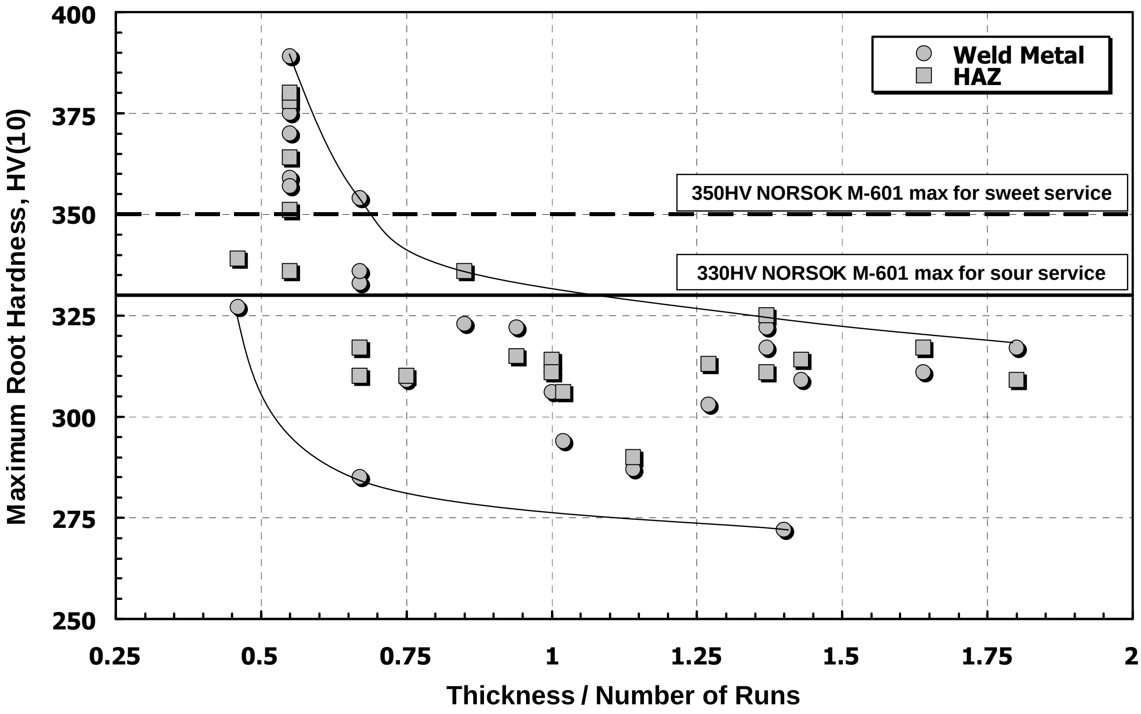

Figure 4 ***The effect of the number of runs deposited in a superduplex (S32750 / S32760) joint on root hardness. The 'thickness/number of runs' ratio is simply the joint thickness divided by the number of runs deposited.***

6. Toughness

6.1 Requirements

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. The NORSOK M-601 specification has a requirement of 27J minimum (or 0.38mm lateral expansion) at -46°C (or the minimum design temperature).

6.2 Typical all-weld toughness of Metrode's consumables

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. The typical impact properties to be expected at -50°C for the Metrode range of duplex and superduplex consumables is summarised in Table 4. More detailed transition curves for the TIG, MMA, FCW and SAW processes are given in Figures 6-9.

Table 4 Typical all-weld metal impact properties.

Alloy	*Process*	*Consumable*	*Temperature, °C*	*Charpy energy, J*	*Lateral expansion, mm*
Duplex	TIG	ER329N	-50°C	>120	1.75
	MIG	ER329N	-50°C	>60	0.75
	MMA	2205XKS	-50°C	>60	0.75
		Ultramet 2205	-20°C	45	0.70
			-50°C	35	0.45
		Supermet 2205	-20°C	45	0.45
			-50°C	35	0.35
	FCAW	Supercore 2205	-20°C	40	0.60
			-50°C	30	0.45
		Supercore 2205P	-20°C	65	0.85
			-50°C	55	0.70
	SAW	ER329N + SSB	-50°C	>35	0.50
Superduplex	TIG	Zeron 100X	-50°C	>100	1.25
	MIG	Zeron 100X	-50°C	60	0.50
	MMA	Zeron 100XKS	-20°C	65	0.75
			-50°C	50	0.65
		2507XKS	-50°C	55	0.70
		Ultramet 2507	-20°C	35	0.50
			-50°C	>27	0.35
	FCAW	Supercore Z100XP	-20°C	40	0.45
			-50°C	30	0.40
		Supercore 2507	-20°C	35	0.35
			-50°C	30	0.30
		Supercore 2507P	-20°C	45	0.55
			-50°C	35	0.45
	SAW	Zeron 100X + SSB	-50°C	40	0.45

6.3 *Effect of oxygen on toughness*

Impact properties correlate very closely with weld metal oxygen content, and hence inclusion content of the weld metal. The effect of oxygen content on weld metal impact properties is shown in Figure 5; and Table 5 summarises the typical deposit oxygen content that will be produced with the different welding processes.

Table 5 Approximate oxygen content of the various arc welding processes.

Process	*Approximate deposit oxygen, ppm*	*Notes*
GTAW	50-150	--
GMAW	150-450	The higher the oxidising potential of the shielding gas the higher the deposit O_2. To get the lowest level requires an inert gas which may not be practical for the best operability.
SAW	500-650	Dependent on the flux.
SMAW (basic)	550-800	--
FCAW	~1100	This is assuming a rutile flux system.
SMAW (rutile)	1000-1500	--

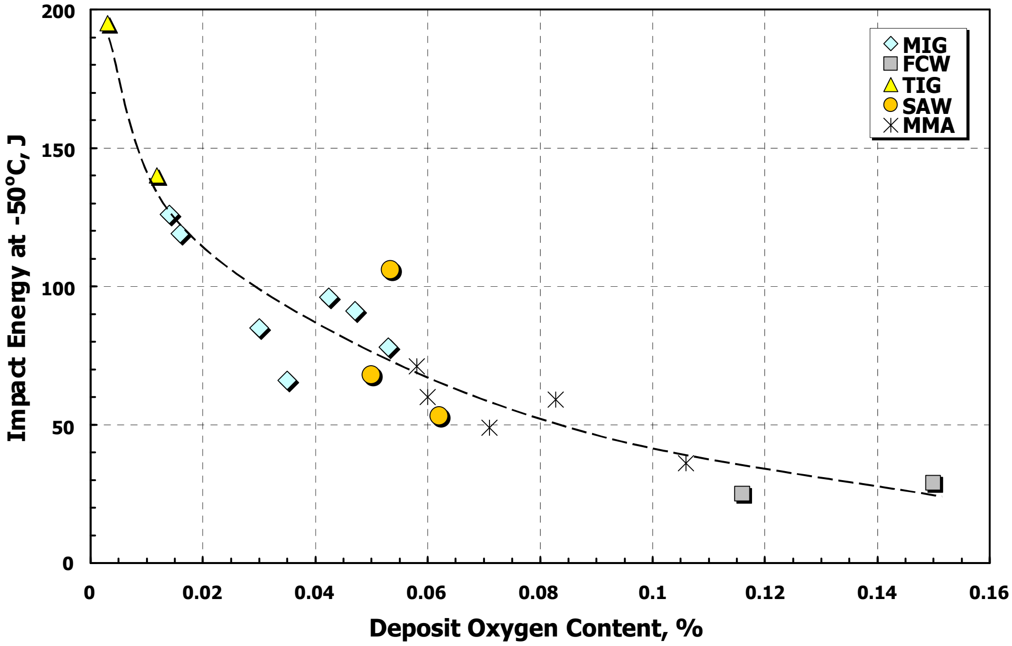

Figure 5 The effect of weld metal oxygen on toughness at -50°C.

6.4 *Sub-size Charpy specimens*

Not all material is thick enough to take full size Charpy specimens from so there are occasions when sub-size specimens need to be used. An example of the same Zeron 100X TIG weld being tested at -50°C using different specimen sizes is shown in Table 6. It can be seen that when corrected to J/cm^2 the results are similar for all of the specimen sizes, but what provides an even more consistent indication of toughness irrespective of the specimen size is the lateral expansion. Except for the smallest Charpy specimen (10x3.3) all of the specimen sizes gave an average lateral expansion of 0.89±0.05mm.

Table 6 Sub-size impact specimens.

Specimen size, mm	*Impact values, J*	*Lateral expansion, mm*	*Average impact, J*	*Average lateral expansion, mm*	*J/cm^2*
10x10	84, 99, 103	0.72, 0.90, 1.101	95	0.88	119
10x7.5	53, 50, 66	0.81, 0.84, 1.03	56	0.89	93
10x6.6	55, 64, 53	0.93, 1.01, 0.87	57	0.94	108
10x5	37, 39, 47	0.80, 0.79, 0.92	41	0.84	103
10x3.3	26, 28	0.74, 0.72	27	0.73	102

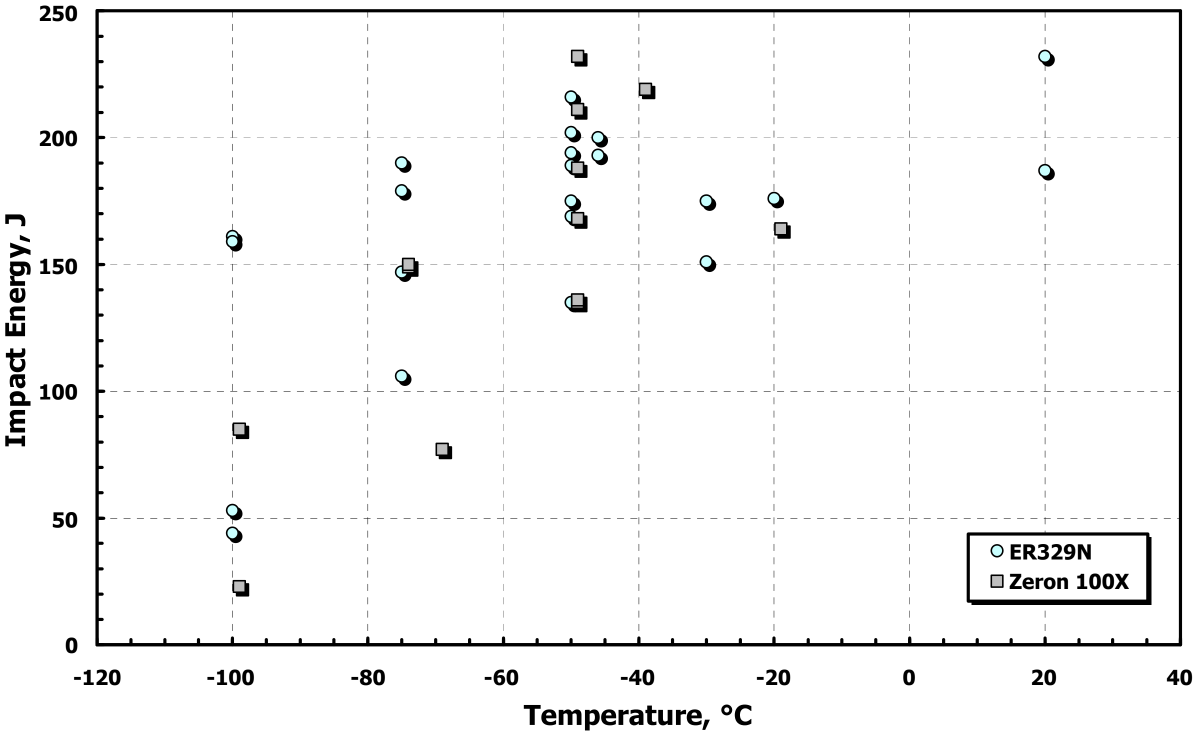

Figure 6 Transition curve for all-weld TIG duplex and superduplex deposits.

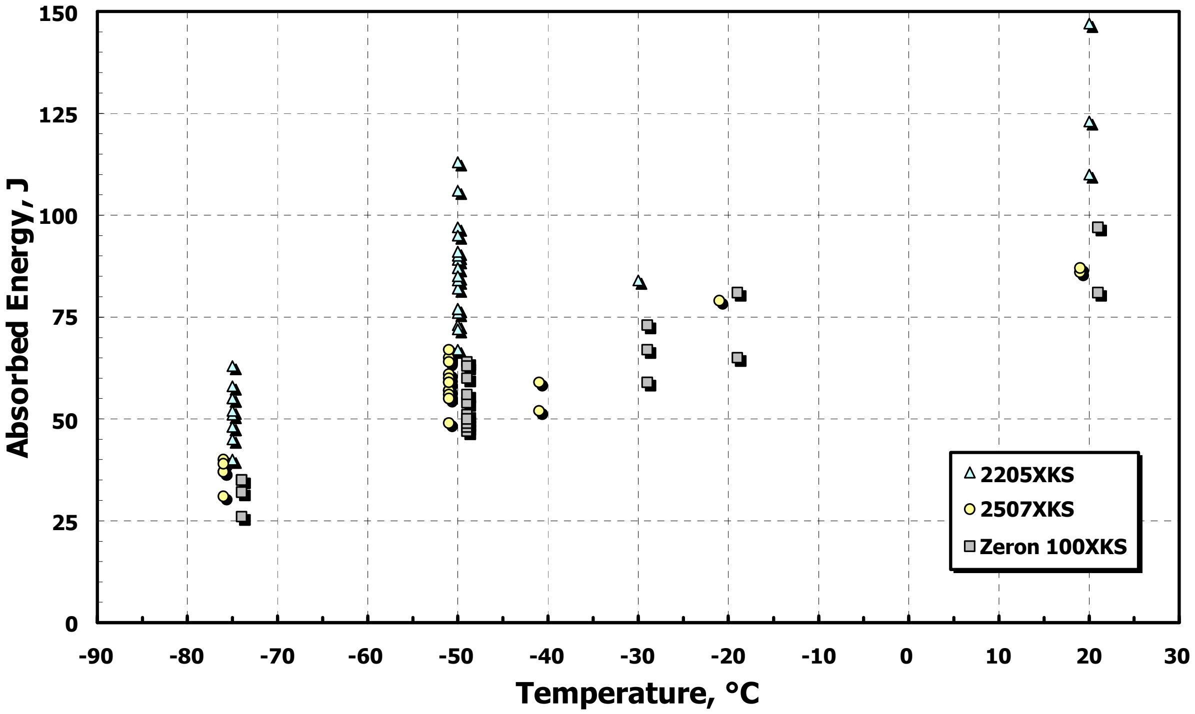

Figure 7 ***Transition curve for all-weld MMA duplex and superduplex deposits.***

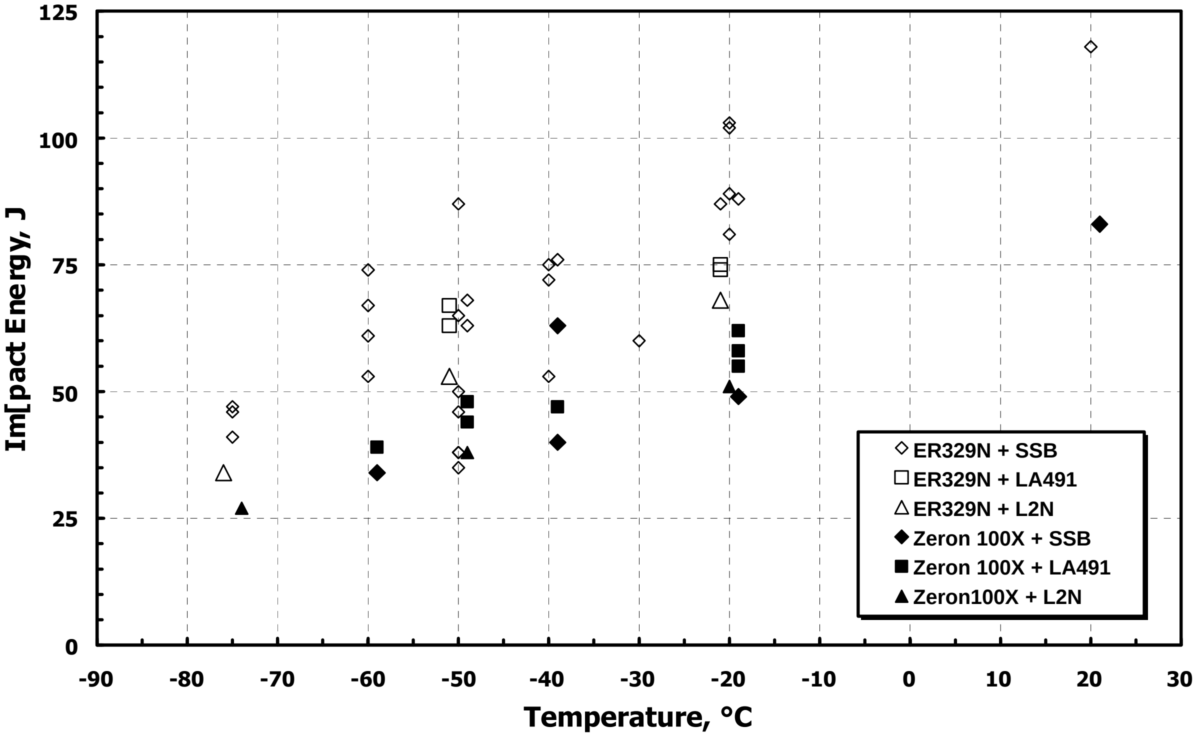

Figure 8 ***Transition curve for all-weld sub-arc duplex and superduplex deposits.***

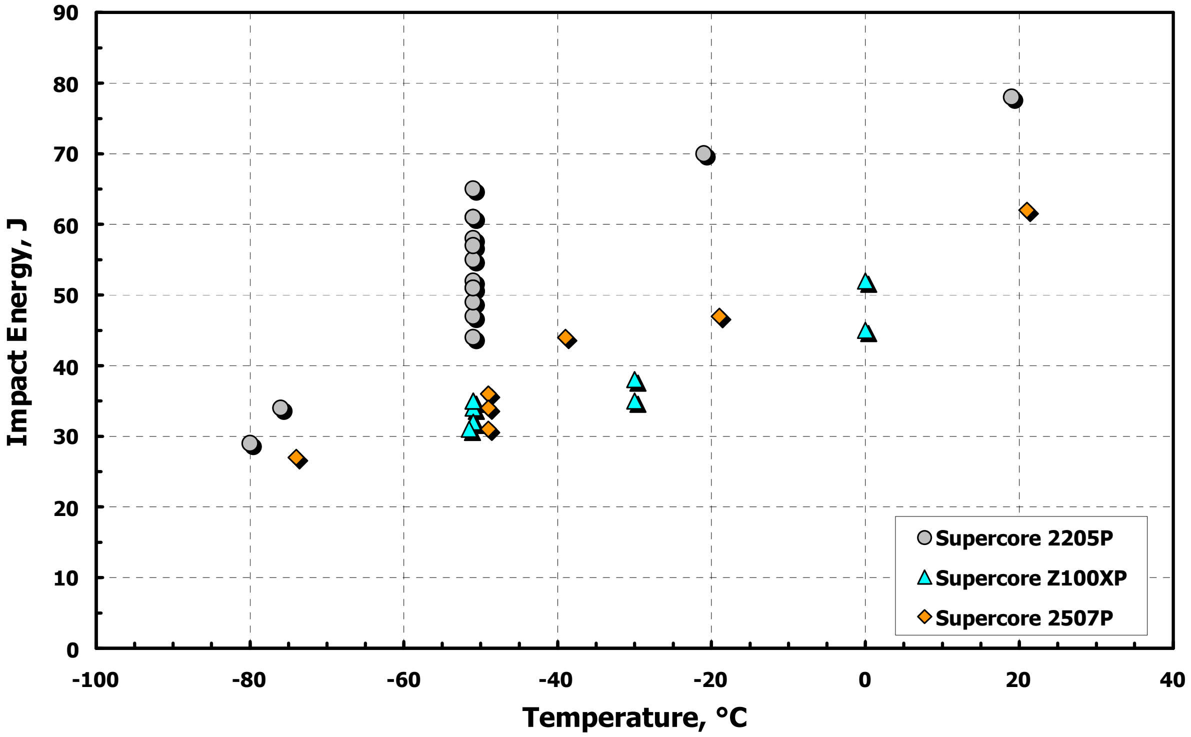

Figure 9 ***Transition curve for all-weld FCW duplex and superduplex deposits.***

6.5 CTOD data

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.

7. Ferrite

7.1 Ferrite requirements

Typical oil and gas requirements specify 30–60% ferrite in the weld metal. 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.

7.2 Measurement techniques

The various techniques used for carrying out ferrite measurements are point counting, magnetic measurement and also predictions based on analysis:

Point counting

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, example of a round-robin is shown in Table 7. If point counting has to be carried out, then the magnification which is used should be selected sensibly and sufficient fields and areas should be measured to get a representative ferrite value.

Table 7 Variation in point counting results between different laboratories (5 laboratories; 100 points in each area).

Area	*Percent ferrite average & range*
Parent	56±4
HAZ	54±18
Cap weld metal	61±8
Fill weld metal	36±11

Magnetic measurement methods (eg Ferritescope)

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. The reproducibility of measurements carried out using magnetic instruments has been shown to be better than point counting.

If magnetic measurements are to be carried out then the other factor to take into consideration is the surface finish that the measurements are being carried put on. On ground surfaces the variation in measurements is generally quite low but if measurements are carried out on the surface of a weld bead then there will tend to be more variation in the results.

Analytical prediction methods

Analytical predictions are normally only used for estimation purposes but the WRC diagram has shown good correlation with Ferritescope measurements for weld metals. Figure 10 shows the correlation between measured ferrite (Ferritescope) and ferrite calculated according to the WRC diagram.

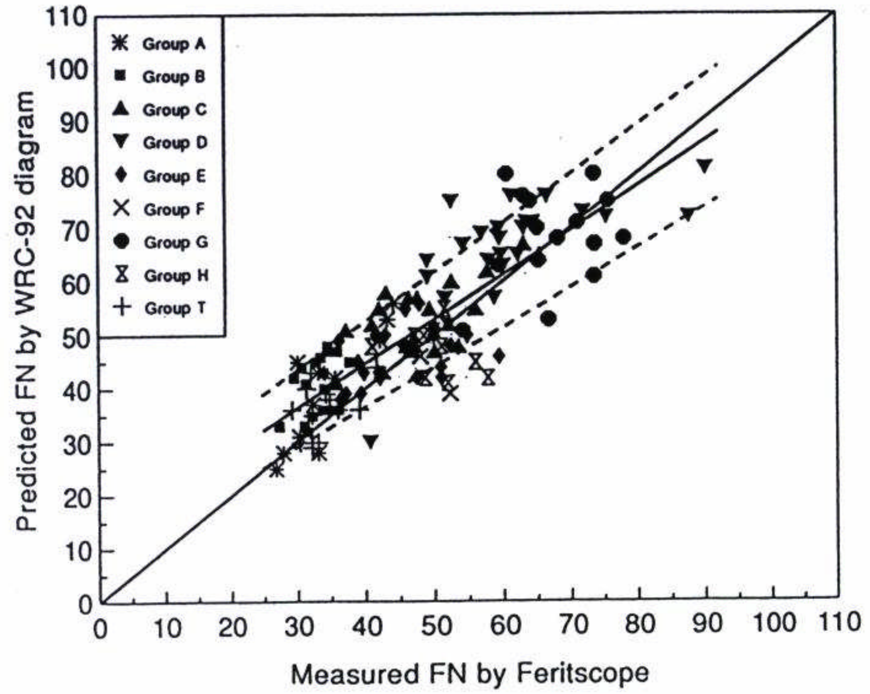

Figure 10 Correlation between measured (Ferritescope) and calculated ferrite (WRC). A=Ultramet 2205; B=2205XKS; C=Supermet 2205; D=Supermet 2506Cu; E=Zeron 100XKS; F=Ultramet 2507; G=Zeron 100XKSW; H=2507XKS; T=TIG Zeron 100X.

7.3 *Effect of measurement location on ferrite level*

The location of the ferrite measurements can also affect the results because the as-deposited weld metal will be higher in ferrite than reheated weld metal. This means that the ferrite level in the root and bulk weld metal will tend to be lower than the cap. The actual change in ferrite content on reheating varies considerably but will tend to be greater for superduplex weld metals than duplex, but the superduplex will start from a higher value.

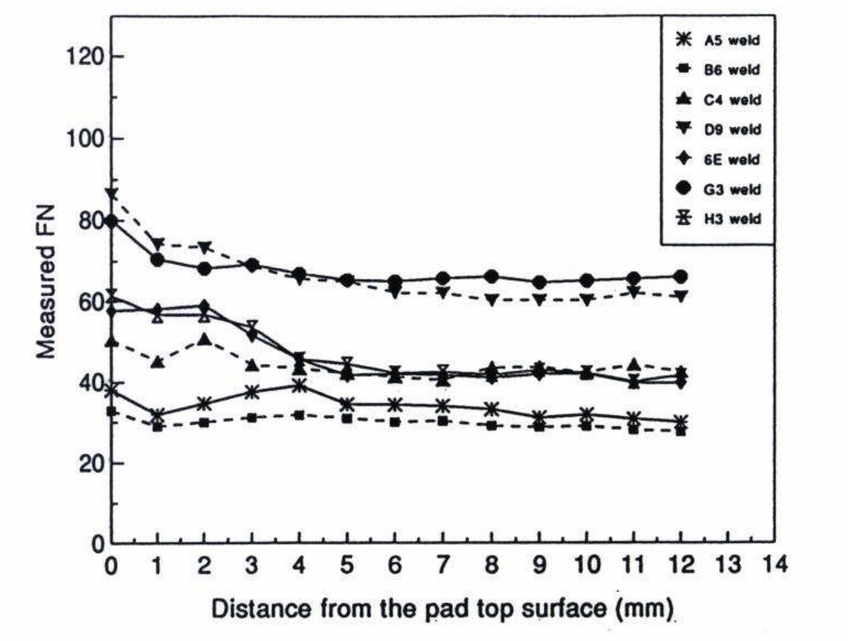

Figure 11 Variation of ferrite content with measurement location.

Zero distance from top surface is as-deposited weld metal, below that the weld metal is reheated.

7.4 *Effect of procedure 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, and joint thickness (heat sink). The faster the cooling rate, the higher the ferrite content, Figure 12.

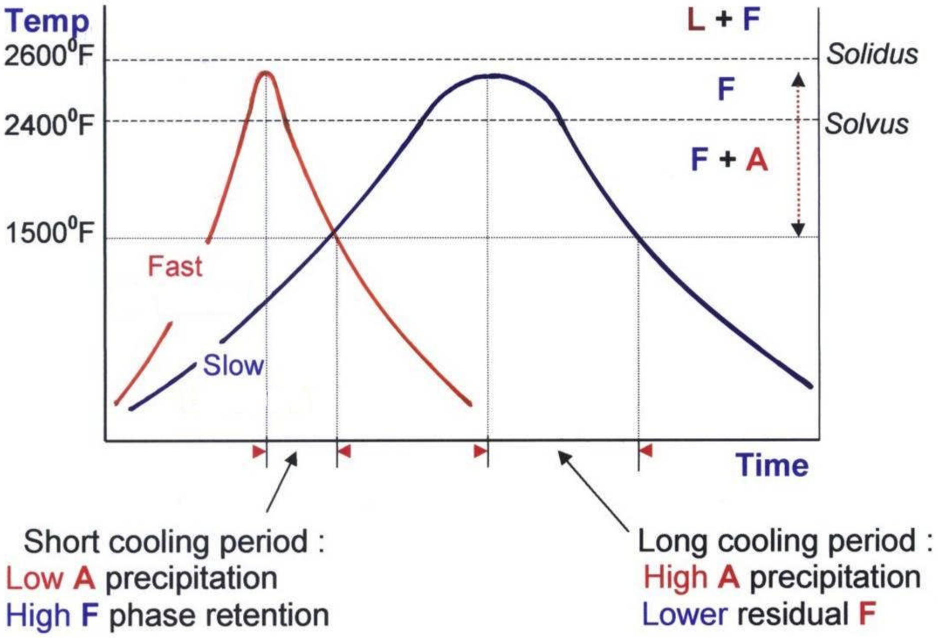

Figure 12 Effect of cooling rate on ferrite content.

7.5 Summary on ferrite

A number of organisations, including TWI and The International Institute of Welding (IIW), have made proposals to encourage duplex/superduplex weld procedures to be assessed on the mechanical and corrosion properties, with the ferrite content only being used for guidance. This view is expressed an IIW 'Position Statement'.

8. 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 4g/m^2 or of 20mg on a standard size specimen, Figure 13.

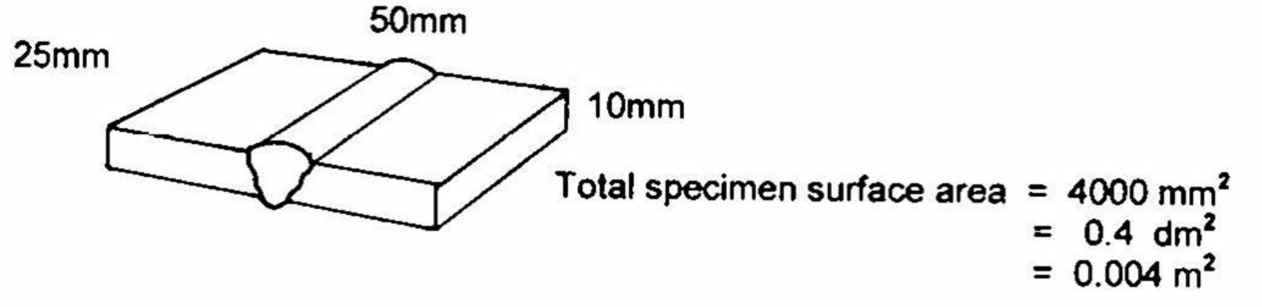

Figure 13 Typical G48A specimen where 20mg weight loss on the specimen = 5g/m^2.

The main reasons for failure of G48A tests are poor root welding procedure and nitrogen loss in the root. 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 M-601 requires pickling of specimens (20% nitric acid + 5% hydrofluoric acid at 60°C for 5 minutes). Pickling reduces weight loss and test-to-test variability, see Table 8. It also helps to ensure that the test temperature is controlled accurately; the ASTM G48A procedure only requires control to ±2°C. Significantly different results would be seen on a 22%Cr duplex weld when tested at 20°C compared to 24°C. It is recommended that the temperature be controlled as accurately as possible but certainly to within ±0.5°C.

The final factor is to ensure that the test temperature is realistic; for 22%Cr, this is 25°C as an absolute maximum and 40°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°C; to ensure a pass at +25°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°C, but to ensure a pass at +40°C it is recommended that an Ar-2%N_2 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_2 torch gas for the root run on 25%Cr superduplex procedures, see Table 8.

Table 8 Effect of shielding gas and pickling (20% nitric acid + 5% hydrofluoric acid at 60°C for 5 minutes) on G48A performance.

Gas	*Pickling*	*Test temperature, °C*	*Weight loss, g/m^2*	*Pitting*
Ar	No	+35	31.9	No
	Yes	+35	5.5	No
Ar+2%N_2	No	+35	3.1	No
	Yes	+35	0.1	No

9. 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.