Development of matching composition supermartensitic stainless steel welding consumables

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The development of matching composition supermartensitic welding consumables is presented. It is shown that the newly developed supermartensitic metal-cored wires OK Tubrod 15.53 and OK Tubrod 15.55 produce high-quality welds with properties which match requirements when used with realistic fabrication welding procedures.

Introduction

Duplex ferritic-austenitic stainless steels have been used for some years to combat corrosion problems in the oil and gas industry. New weldable supermartensitic stainless steels are, however, finding increasing application as an economical option, offering corrosion performance between that of carbon steel and duplex stainless steel (refs. 1-5). These steels offer sufficient corrosion resistance for sweet and mildly sour environments in combination with high strength and good low-temperature toughness and are specifically designed for field welding where the use of long-term post-weld heat treatment (PWHT) is impracticable (ref. 6). The carbon content is reduced to extra low levels in order to obtain the necessary properties in the as-welded condition and elements such as Mo and Cu are added for improved corrosion resistance.

The choice of filler material and welding procedure is largely governed by the need

1 to match parent material strength,
2 to achieve sufficient toughness,
3 to keep hardness at an acceptable level,
4 to match corrosion resistance and
5 to avoid PWHT.

Although good results have been obtained with soft martensitic 13%Cr 4%Ni + Mo alloys and duplex or superduplex consumables (refs. 2-4), supermartensitic consumables offer a number of advantages. Not only are the weld metal strength, hardness and corrosion resistance similar to those of the parent material. The weld metal and parent material also respond similarly to PWHT and thereby eliminate the risk of weld metal embrittlement which can occur in the case of superduplex weld metals. A further advantage is the decreased risk of distortion thanks to the lower thermal expansion coefficient of supermartensitic weld metals as compared to duplex weld metals. Complications related to the dilution of filler metal with parent material are also avoided if supermartensitic consumables are used.

The aim of the present study is to show that "matching" composition supermartensitic consumables can be formulated and can produce largely martensitic weld metals. It is also demonstrated that supermartensitic consumables can be used with realistic fabrication welding procedures to produce high-quality welds with satisfactory properties.

Chemical composition, microstructure and mechanical properties

Experimental welds

In the very early stages of development, it became evident that the weld metal chemical composition strongly influenced the microstructure and mechanical properties. As a first step, chemical compositions and mechanical properties for a large number of experimental weld metals were therefore determined and correlated to microstructure, transformation characteristics and welding procedure (see also refs. 7 and 8).

An evaluation showed that the very low C and N content (<0.01%), essential to obtain good toughness and low hardness, could be obtained most reliably with metal-cored wires. Furthermore, metal-cored wires are ideal for submerged arc (SAW), tungsten inert gas (TIG) and metal inert/active gas welding (MIG/MAG), thereby offering flexibility and high productivity.

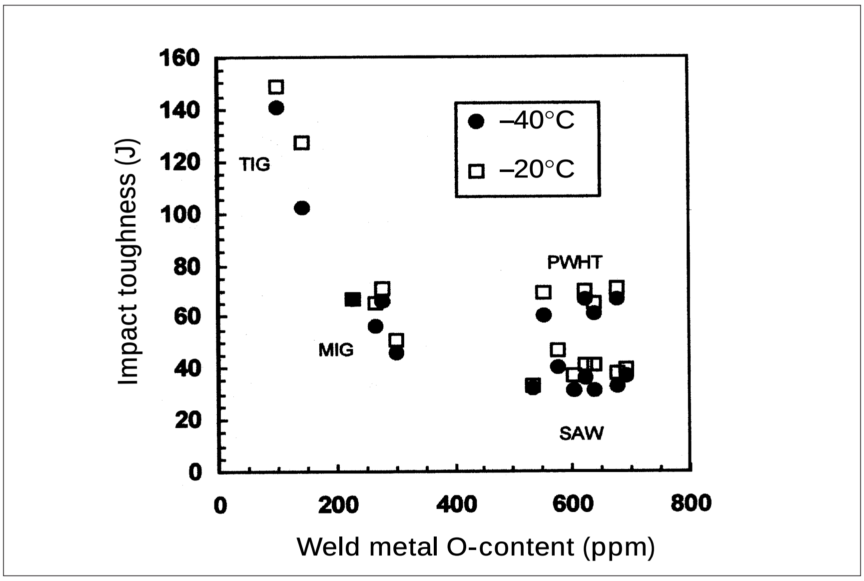

Figure 1.Influence of oxygen content on Charpy-V impact toughness at –20°C and –40° C in Mo-alloyed supermartensitic weld metals.

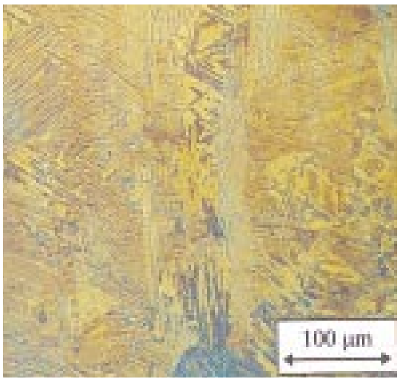

Figure 2. Fully martensitic microstructure of a 2.5% Mo supermartensitic weld metal deposited with the metal-cored wire OK Tubrod 15.55.

Mechanical properties

Weld metal yield and tensile strength were generally well above the typical values for supermartensitic parent materials (refs. 3, 4 and 6). The exception was weld metals with a large volume fraction of retained austenite (>25%) and with a yield strength below the minimum level of 550 MPa required for X80 grade steels. Both the yield and ultimate tensile strength were lower transverse to welds in supermartensitic plate material than along welds and fracture always occurred in the parent material. Elongation was typically in the range of 15-20%, regardless of composition and welding method.

Maximum hardness correlated well to the C content and PWHT (5 min/620°C) was effective in reducing hardness (cf. refs. 1, 3, 4 and 6, for example). A maximum as-welded hardness of approximately 350 HV10 could be obtained if the C content was kept below 0.013%C.

Significant amounts of ferrite were found to be detrimental to impact toughness and tended to result in an unacceptably high ductile to brittle transition temperature. However, the most significant effect on impact toughness was clearly the strong effect of weld metal oxygen content. By plotting impact toughness against oxygen content (Fig. 1), it can be seen that impact toughness increases rapidly for oxygen levels below approximately 300 ppm. For example, TIG welds with an oxygen content of about 100 ppm had a toughness of up to 150 J at –40° C, whereas SAW welds with about 600 ppm oxygen had the lowest toughness, typically 30–40 J at –40° C. However, a short PWHT could be used to improve the impact toughness of SAW welds significantly (Fig. 1).

Microstructure

Virtually fully martensitic weld metals could be obtained for an Mo content of up to 2.5% (Fig. 2). However, the compositional range for “fully“ martensitic weld metals was somewhat limited and became narrower as the alloying content was increased.

Ferrite (Fig. 3), with a morphology very similar to that of the ferrite found in duplex stainless steel weld metals, was present when the relative amount of ferrite stabilising elements was too high.. Another ferrite morphology, similar to that of common austenitic stainless steel weld metals, was found in weld metals solidifying as a mixture of ferrite and austenite (Fig. 4). One complication, which was dependent on

Weld	Consumables	Parent material	Joint/ position	Interpass temp. (°C)	Heat input (kJ/mm)	Comments
OK Tubrod 15.53: 1.5 % Mo, ∅ 1.6 mm metal cored wire:						
TIG/MIG-1.5Mo	Ar/ Ar + 0.5%CO_2	12Cr 4.5Ni 1.5Mo 0.5Cu/ 20 mm plate	60°V, PA	<100	1.0/1.5	TIG/pulsed MIG, 3+11 beads
OK Tubrod 15.55: 2.5 % Mo, ∅ 1.6 mm metal cored wire:						
TIG/MIG-2.5Mo	Ar/ Ar + 0.5%CO_2	12Cr 6.5Ni 2.5Mo 0.5Cu/ 20 mm plate	60°V, PA	<100	1.0/1.5	TIG/pulsed MIG, 3+11 beads
SAW-2.5Mo	OK Flux 10.93	2Cr 6.5Ni 2.5Mo 0.5Cu/ 20 mm plate	60°X, PA	<100	0.7	side 1: 11 beads side 2: 3 beads
TIG/MIG-2.5Mo-pipe	Ar/ Ar + 0.5%CO_2	12Cr 6.5Ni 2.5Mo 0Cu/ pipe ∅ 255 mm, t= 13 mm	60°V, PA	<100	1.5/ 2.8	TIG/pulsed MIG, 1+2 beads

Table 1. Welding conditions for pipe girth weld and plate butt welds in supermartensitic steels.

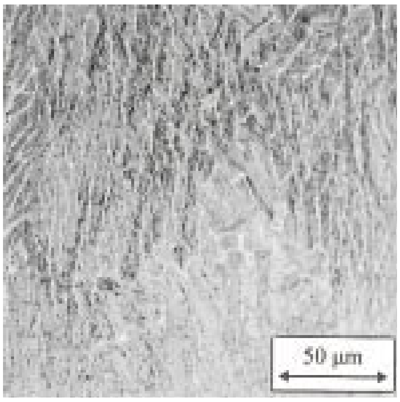

Figure 3. Ferrite (white phase) in a mainly martensitic 1.5% Mo weld metal solidifying as ferrite.

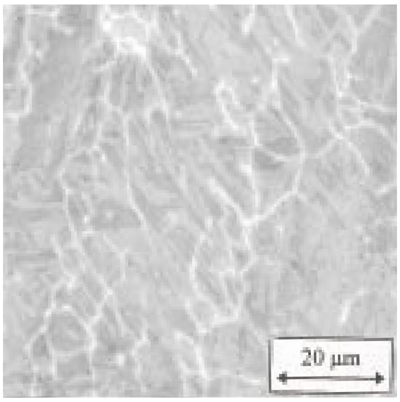

Figure 4. Ferrite (white phase) formed during ferritic/austenitic solidification of a mainly martensitic 2.5%Mo weld metal.

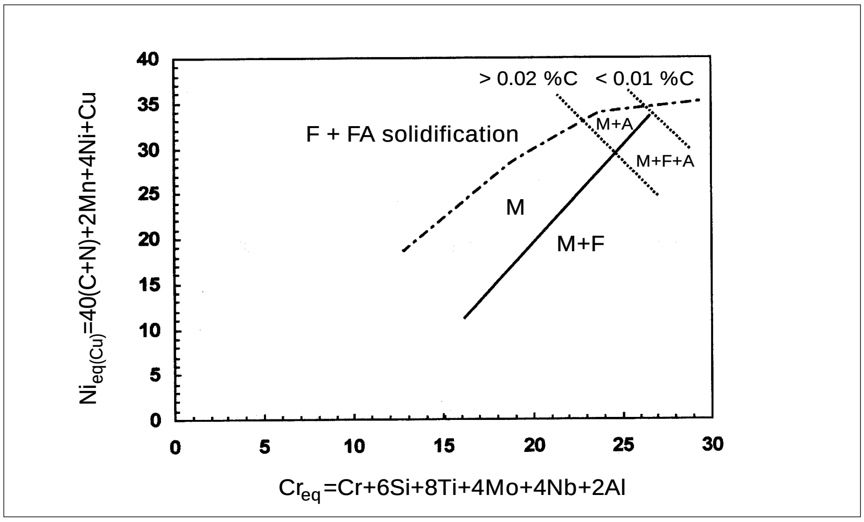

Figure 5. Constitution diagram for supermartensitic weld metals. Information is provided about the solidification mode and microstructural constituents, including the presence of significant amounts of retained austenite at two different C levels.

the C content, was the sometimes unacceptably high amount of retained austenite in some of the most highly-alloyed experimental grades.

Supermartensitic weld metal constitution diagram

The need for a tool capable of predicting weld metal microstructure from chemical composition was recognised at an early stage of consumable development. The negative effects of ferrite, austenitic solidification and excessive residual austenite content have to be avoided to obtain the optimum properties. However, no diagram or equation covering the range of compositions studied in the present investigation could be found in the literature. A new constitutional diagram for supermartensitic weld metals therefore had to be constructed.

Like earlier diagrams proposed by Balmforth and Lippold (refs. 9 and 10), the new diagram was based on the Kaltenhauser Cr and Ni equivalents (ref. 11), but the compositional range was extended and Nb and Cu were included in the compositional factors. Limiting boundaries between different microstructural regions (Fig. 5) were defined from microstructural information for a large number of experimental welds, plotted on the diagram. The new diagram was found to be very useful in defining the optimum consumable compositions suitable for steels with a varying Mo content.

Representative micrographs for weld metals belonging to the martensite (M), the martensite and ferrite (M+F) and the mixed solidification microstructural regions of the constitution diagram (Fig. 5) are shown in Figures 2, 3 and 4 respectively.

Simulated production welds

Welding conditions

Consumables producing the desired weld metal microstructure were selected for welding trials in pipe and plate material using simulated production welding procedures. Metal-cored wires with 1.5%Mo (OK Tubrod 15.53) and 2.5%Mo (OK Tubrod 15.55) were used for the butt welding of 20

Weld/steel	C	N (ppm)	Si	Mn	Cr	Ni	Mo	Cu	O (ppm)
Steel:									
Plate: 12Cr 4.5Ni 1.5Mo 0.5Cu	0.023	112	0.19	1.96	11.5	4.5	1.3	0.48	51
Pipe: 12Cr 6.5Ni 2.5Mo 0Cu	0.010	87	0.17	0.50	12.3	6.6	2.5	0.02	63
Plate: 12Cr 6.5Ni 2.5Mo 0.5Cu	0.020	130	0.10	1.76	12.4	6.5	2.3	0.49	110
Weld:									
MIG/TIG-1.5Mo	0.017	80	0.63	1.32	12.4	6.7	1.5	0.55	230
TIG/MIG-2.5Mo	0.012	90	0.33	1.97	12.5	7.0	2.3	0.50	270
SAW-2.5Mo	0.008	220	0.35	1.78	12.6	6.9	2.4	0.50	670
TIG/MIG-2.5Mo-pipe	0.009	135	0.31	2.0	12.5	7.0	2.2	0.44	284

Table 2. Chemical composition (wt.%) of steels and weld metals.

mm 1.5%Mo and 2.5%Mo supermartensitic plates and for the girth welding of a 2.5%Mo pipe with an outer diameter of 255 mm and a wall thickness of 13 mm. As shown in Table 1, TIG was used for root passes in MIG welds, whereas the SAW welding of plate material was performed from both sides in an asymmetrical X joint. The pipe girth weld was completed in only three passes, one TIG root pass and two MIG passes (Fig. 6), with a heat input of approximately 2.8 kJ/mm.

Microstructure and chemical composition

All the plate and pipe welds were defect free and had a largely martensitic microstructure. The chemical compositions of weld metals and parent materials of simulated production welds are presented in Table 2. It can be seen that TIG/MIG welds in a high-C parent material have a C content of above 0.010%, whereas the SAW and the TIG/MIG welds in the low-C pipe material have 0.008%C and 0.009%C respectively.

Mechanical properties

The mechanical properties of the simulated production welds were in good agreement with the experience acquired from the experimental welds. The strength was clearly overmatched, as is evidenced by cross-weld tensile test fractures appearing in the parent material, and the ductility was sufficient to pass bending tests (Tables 3 and 4). The maximum hardness was approximately 350 HV10 or below and, as expected, the impact toughness was strongly dependent on the oxygen content (Table 2). However, a comparison of the impact toughness of the TIG/MIG-2.5Mo pipe weld and the TIG/MIG-2.5Mo plate butt weld produced the somewhat unexpected result that a higher heat input and larger weld beads were beneficial (Tables 3 and 4). This result is contrary to what has been seen for experimental welds and further studies are clearly needed to establish the effect of heat input on impact toughness. It is encouraging, however, that high productivity welding procedures could also offer advantages in terms of improved toughness.

Corrosion resistance

The preliminary results from SSC testing in formation water (20°C, 20 bar pCO_2, 100,000 ppm Cl^-, 4 mbar or 40 mbar pH_2S, 4.5<pH<5) show that welds produced with supermartensitic consumables have a corrosion resistance comparable to that of the parent material. The tests were performed on specimens machined from welds in the as-welded condition. In this particular environment, a PWHT, decreasing hardness and lowering residual stresses, does not therefore appear to be necessary to ensure sufficient corrosion resistance.

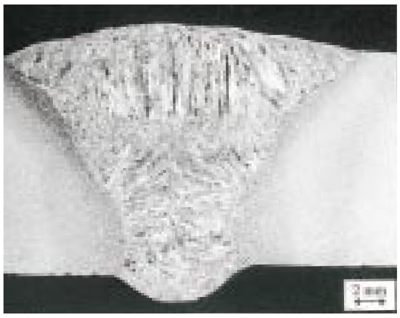

Figure 6. Cross-section of TIG/MIG-2.5 Mo pipe girth weld in 2.5% Mo pipe with a wall thickness of 13 mm. (Consumable: OK Tubrod 15.55)

Future supermartensitic welding consumables

Although the development of matching composition supermartensitic welding consumables is still progressing rapidly, it is al-

Impact toughness (J)				Cross weld tensile strength (MPa)	Maximum hardness (HV10)		Face bend	Side bend (t=10 mm)
–60°C	–40°C	–20°C	+20°C	R_m	Weld metal	HAZ	∅ 3 x t, 120°	∅ 4 x t, 180°
58	66	75	80	895*	323	326	OK	OK

* Fracture in parent material

Table 3. Mechanical properties of TIG/MIG-2.5Mo-pipe girth weld (consumable: OK Tubrod 15.55) in a 2.5 % Mo supermartensitic pipe (∅ 255 mm, t= 13 mm).

Weld	Impact toughness (J)				Cross weld tensile strength (MPa)	Maximum hardness (HV10)		Bend testing		
	Weld centre		Fusion line							
	–40°C	–20°C	–40°C	–20°C	R_m	Weld metal	HAZ	Face ∅ 3 x t, 120°	Root ∅ 3 x t, 120°	Side (t=10 mm) ∅ 4 x t, 180°
TIG/MIG-1.5Mo	63	64	184	175	898*	348	359	OK	Fissures	OK
TIG/MIG-2.5Mo	50	50	77	65	905*	351	363	OK	OK	OK
SAW-2.5Mo	38	40	66	76	–	–	–	–	–	–

Table 4. Mechanical properties of welds produced with OK Tubrod 15.53 and 15.55 metal-cored wires in 20 mm supermartensitic plate material.

ready obvious that this concept offers a number of advantages in terms of properties, productivity and the chance to perform a PWHT when desired.One further advantage that is often overlooked is the fact that a martensitic weld metal microstructure is expected for all levels of dilution with parent material when welding with a supermartensitic consumable. This is clearly an advantage compared with what happens when using duplex or superduplex consumables, as the resulting microstructure in this case is directly related to the degree of dilution.

In conclusion, although the further fine tuning of matching composition supermartensitic consumables is expected, it is now possible to predict the microstructure from the new supermartensitic weld metal constitution diagram and the relationship between microstructure, composition and properties is fairly well understood. It is therefore most probably only a matter of time before supermartensitic consumables replace duplex and superduplex in the welding of supermartensitic stainless steel.

Conclusions

Metal-cored wires have been developed for supermartensitic steels; OK Tubrod 15.53 with 1.5%Mo is suitable for steels with 0–1.5%Mo and OK Tubrod 15.55 with 2.5%Mo is intended for steels with an Mo content of up to 2.5%Mo. A very low C and N content (<0.01%) was consistently obtained in SAW, MIG/MAG and TIG welding.

A constitution diagram was designed for supermartensitic weld metals defining the compositional ranges that produce a martensitic microstructure and providing information on the solidification mode and retained austenite.

Weld metal strength overmatched parent material strength, apart from excessive weld metal residual austenite content. The maximum hardness was approximately 350 HV10 or lower at 0.010%C. The impact toughness was critically dependent on the weld metal oxygen content and was reduced by residual ferrite.

A short (5 min/620°C) PWHT increased impact toughness and reduced hardness.

SSC testing shows that welds produced with supermartensitic consumables have a corrosion resistance comparable to that of the parent material.

It is shown that supermartensitic consumables can be used with realistic fabrication welding procedures to produce high-quality welds with mechanical and corrosion properties that match requirements.

Acknowledgements

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About the authors

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