Development of High Strength Steel Weld Metals –

Potential of novel high-Ni compositions

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Abstract

Neural network modelling has been applied to search for novel high strength steel weld metal compositions, potentially offering improved tolerance to variations in the weld thermal cycle. An experimental 7 wt% Ni manual metal arc electrode, formulated on these predictions, was used to produce all-weld metals and welds in high strength steel. Mechanical properties were correlated to weld metal microstructure and compared with those of a conventional 3 wt% Ni weld metal for different welding conditions. Light optical and transmission electron microscopy proved the 7 wt% Ni weld metal microstructure to be predominantly bainitic with some martensite. Also the 3 wt% Ni weld metals were bainitic/martensitic but with relative fractions being strongly cooling rate dependent. Similar strength and toughness were measured for both types of weld metals at intermediate cooling rates ($\Delta t_{8/5} \approx 10$ s). However, the properties of the 7 wt% Ni weld metal varied significantly less with welding conditions and this composition clearly offers an advantage in terms of tolerance to variations in the weld thermal cycle.

Introduction

Steels with minimum yield strength in excess of 690 MPa have been welded on a limited scale, although with many precautions, after matching strength weld metals became available in the 1960s. In recent years, a greater demand has arisen for strong steels in applications such as offshore structures, cranes and pipelines. Such applications require a wider range of welding processes, offering flexibility and higher productivity, to be competitive. There is therefore a growing need for high strength steel welding consumables whilst at the same time maintaining toughness and ease of use. Reasonable insensitivity of the weld metal properties to variations in welding procedure parameters, such as heat input and interpass temperature, is therefore desirable, especially during manual welding.

Current high strength steel welding consumables typically have compositions in the range 0.04-0.08C, 1-2Mn, 0.2-0.5Si, 1-3Ni wt% along with some additions of Cr, Mo and sometimes Cu [1-3]. As alloying content and strength increase, bainite and martensite gradually become the dominant microstructural components rather than the softer phases associated with strength levels less than 690 MPa. Although well-balanced mixed martensitic/bainitic/ferritic microstructures can offer attractive combinations of properties, the microstructure, and hence the properties, tend to become sensitive to the cooling rate [3, 4].

Greater tolerance to variations in the weld thermal cycle may require higher alloy content [3] and perhaps a radical departure from established alloying practices. Neural network modelling was therefore applied to search for promising compositional domains to investigate [5, 6]. This paper describes how the potential of a novel high strength steel weld metal with 7 wt% Ni has been explored and a comparison is made with a conventional 3 wt% Ni high strength weld metal. Microstructures were characterised and correlated to the mechanical properties of all-weld metals and welds in high strength steel for a range of welding parameters.

Neural Network Modelling

A neural network model was created with the task of exploring new compositions which might be suitable for high strength steel weld metals as described in [5, 6]. Figure 1 shows toughness simulations at -40°C as a function of the Mn- and Ni-concentrations at 0.03 wt% C. Based on these predictions and preliminary tests, it was decided to investigate in more detail a weld metal composition of 0.06C, 7Ni, 0.5Mn wt%.

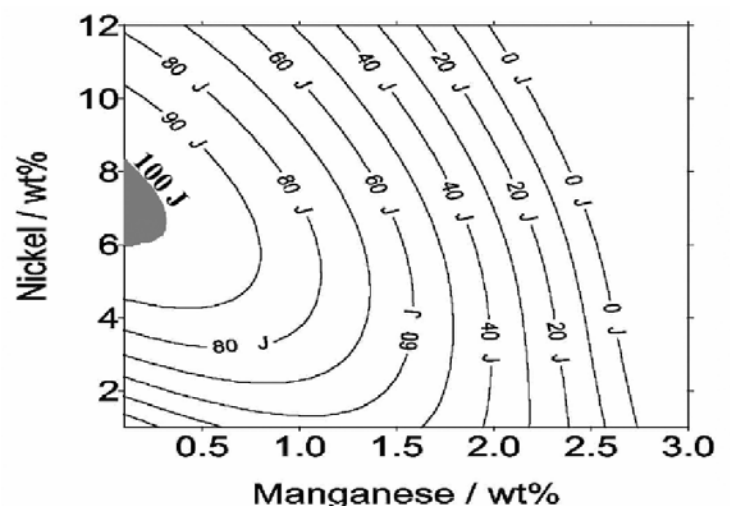


Figure 1 Contour plot showing the predicted behaviour of weld impact toughness at -40°C as a function of Mn- and Ni- concentrations at 0.03 wt% C.

Experimental

Manual metal arc (MMA) welding electrodes of nominal compositions 0.06C, 2Mn, 3Ni wt% and 0.06C, 0.5Mn, 7Ni wt% were used to deposit all-weld metals in 20 mm mild steel plates according to ISO 2560. Joint faces were buttered to avoid dilution with parent material and a range of heat inputs and interpass temperatures were used to vary the cooling time between 800˚C and 500˚C ($\Delta t_{8/5}$) (Table 1).

Table 1 Interpass temperatures, nominal heat inputs and calculated cooling times ($\Delta t_{8/5}$ calculated according to EN 1102, Annex D)

Weld No.	**3Ni**								**7Ni**						
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Interpass temperature (ºC)	125	150	200	200	200	125	200	250	150	100	150	200	200	200	150
Nominal heat input (kJ/mm)	1.4	1.3	1.1	1.3	1.3	1.8	1.7	1.7	0.6	1.5	1.4	1.3	1.3	1.4	2.7
$\Delta \mathbf{t_{8/5}}$ (s)	7.7	7.8	8.0	9.4	9.5	10	12	19	3.6	7.6	8.4	9.4	9.5	10	25

For comparison purposes and to study effects of dilution with plate material it was also decided to produce half-V butt welds in 20 mm high strength steel with nominal heat inputs of 1.4 and 2.8 kJ/mm. Weldox 700 plate material with actual yield strength of 827 MPa, actual tensile strength of 862 MPa and a chemical composition of 0.13C, 0.31Si, 0.99Mn, 0.24Cr and 0.17Mo wt% was selected as representative of steels with a minimum specified yield strength of 700 MPa.

Samples of weld metal were chemically analysed using optical emission spectrometry and Leco combustion equipment. Standard 10 by 10 mm Charpy-V impact toughness testing and tensile testing of longitudinal 10 mm diameter specimens were performed. Specimens from the weld metal cross section, perpendicular to the welding direction were mounted in bakelite for analysis with light optical microscopy (LOM). For transmission electron microscopy (TEM) studies, 3 mm disc shape specimens perpendicular to the welding direction were prepared from the last bead and from central regions reheated by subsequent weld passes.

Results

All-weld metals

Compositional ranges of the tested all-weld metals are presented in Table 2. The chemical composition varied within a very narrow range for the 7 wt% Ni weld metals whereas larger variations were found for the 3 wt% Ni variant. These welds are henceforth referred to as 7Ni and 3Ni respectively. The larger compositional variations for the leaner weld metals are most likely caused by the consumables being from several experimental batches whereas the 7 wt% Ni electrodes were from two different batches.

Table 2 Weld metal chemical compositions (wt%).

Element	**C**	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**O** (ppm)	**N** (ppm)
Welds 3Ni: 1-8	0.047-0.079*	0.19-0.30	2.07-2.16	0.27-0.44	2.56-3.16	0.60-0.66	280-410	90-160
Welds 7Ni: 1-7	0.059-0.061	0.32-0.34	0.54-0.56	0.14-0.15	6.60-6.84	0.35-0.39	310-350	80-160

*3Ni-4: 0.079, 3Ni-5: 0.047

The yield strength was typically around 850 MPa for both types of weld metals at $\Delta t_{8/5}$ of about 10 s (Table 3). However, the span between the highest and the lowest value was almost 250 MPa for the 3Ni weld metals compared to 100 MPa for the 7Ni type. Tensile strength was somewhat higher for the 3Ni than for the 7Ni weld metals at comparable cooling rates and varied somewhat more with cooling rate. Room temperature Charpy-V impact toughness was similar for both Ni-levels but varied less with cooling rate and test temperature for the more highly alloyed consumable.

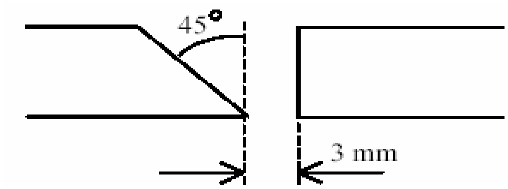
Table 3 Mechanical properties of experimental 3Ni and 7Ni weld metals.

Weld No.	**3Ni**								**7Ni**						
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Tensile properties															
$\mathbf{R_{p0.2}}$ (MPa)	978	885	922	885	844	939	858	734	882	889	871	865	848	858	789
$\mathbf{R_m}$ (MPa)	994	942	953	929	938	972	931	924	947	939	926	904	911	895	893
$\mathbf{A_5}$ (%)	18	20	19	22	20	18	19	18	16	14	18	18	18	18	22
Charpy-V impact toughness															
+20ºC (J)	86	101	94	105	104	84	87	78	86	87	100	99	93	109	91
-40ºC (J)	74	87	77	64	78	77	74	50	68	72	86	92	87	90	78

Butt welds in 20 mm plates

Weld metal chemical composition and mechanical properties of butt weld in 20 mm Weldox 700 plate material are presented in Table 4. Dilution with fused parent material was most clearly seen in the higher C- and lower Ni-contents compared to all-weld metal analyses in Table 2. Strength and toughness of butt welds were on similar but slightly lower levels compared to all-weld metals for comparable cooling rates.

Table 4 Effect of heat input on mechanical properties of a weld in a high strength steel produced with 7Ni experimental MMA electrodes.

Joint configuration		
Plate quality	Weldox 700, t = 20 mm	
Interpass temperature (ºC)	175-200	
No. of beads	14	8
Nominal heat input (kJ/mm)	1.4	2.8
$\Delta t_{8/5}$ (s)	10	36
Weld metal chemical composition (wt%)		
C	0.068	0.067
Si	0.37	0.31
Mn	0.58	0.55
P	0.010	0.010
S	0.012	0.011
Cr	0.18	0.17
Ni	5.9	5.8
Mo	0.36	0.36
Longitudinal all-weld metal tensile test		
$R_{p0.2}$ (MPa)	839	741
R_m (MPa)	895	852
A_5 (%)	21	19
Charpy-V impact toughness (3 mm into weld metal from fusion line)		
+20ºC (J)	80	85
-40ºC (J)	86	79

7Ni all-weld metal microstructure

A light optical micrograph from the last bead of a 7Ni weld metal representative of all cooling rates studied shows a microstructure with plate-like features (Fig. 2). Thin foil observations using TEM revealed a fine microstructure consisting mainly of bainitic ferrite plates with carbides and films of retained austenite. Limited amounts of martensitic regions were also found in agreement with studies of similar weld metals with 0.03 wt% C [5]. TEM micrographs from a weld centre reheated by subsequent weld passes, show a tempered bainitic/martensitic microstructure with carbide precipitation at lath boundaries (Fig. 3). Previous studies of 3Ni weld metals produced with consumables of the same formulations concluded these to be martensitic/ bainitic with the relative fractions being strongly dependent on the cooling rate [4].

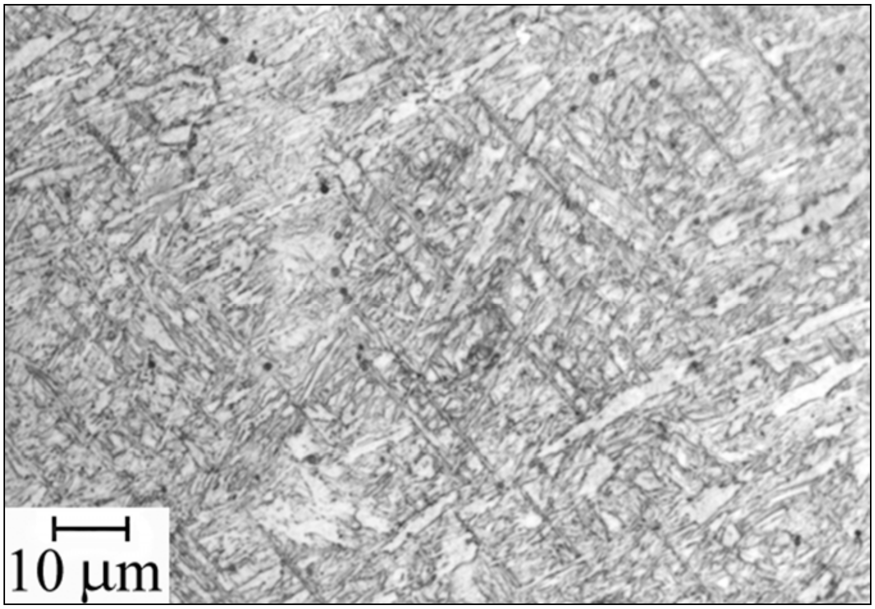


Figure 2 Light optical micrograph from the last bead of a 7Ni weld metal showing a fine bainitic/martensitic microstructure.

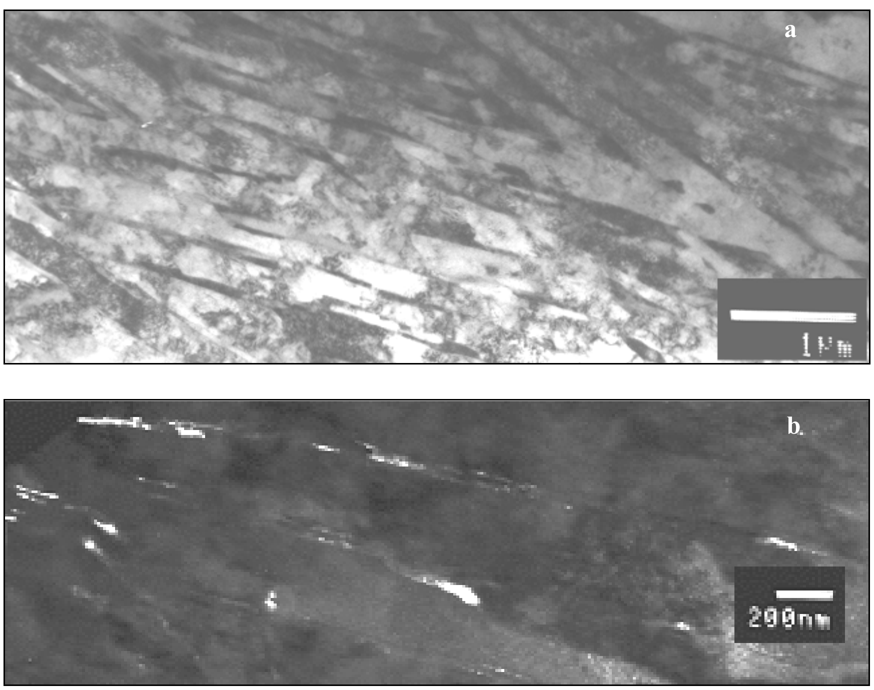


Figure 3 Transmission electron micrographs from a reheated region at the centre of a multipass 7Ni weld metal.
a) Bright field image of tempered bainitic/martensitic microstructure.
b) Dark field micrograph of carbide precipitation at lath boundaries.

Discussion

Mechanical properties

There is no fundamental reason to expect a linear relation between strength or impact toughness and cooling rate. Nevertheless linear regression analysis was used to evaluate the cooling rate dependence since the number and distribution of experimental points didn't motivate a more elaborate approach. Analysis of yield and tensile strength of the 3Ni and 7Ni experimental weld metal compositions clearly revealed a much stronger cooling time dependence of the leaner weld metal (Figs. 4a and 4b). In particular the slope of the yield strength curve was much steeper for the 3Ni composition.

Data published for 0.06C, 1.8Mn, 2.6Ni, 0.6Mo, 0.2Cr, 0.2Cu wt% weld metals deposited with a solid wire [2] and for 0.05C, 1.3Mn, 2.3Ni, 0.5Mo, 0.8Cu wt% MMA weld metals [1] were analysed in the same way. Information was available only for a narrow cooling time range for the solid wire ($\Delta t_{8/5}$ 3.8 to 5.6 s) but suggested a pronounced dependence of strength on cooling conditions (Fig. 4c). Also the MMA weld metal properties were significantly more cooling time dependent than the 7Ni alloy when $\Delta t_{8/5}$ varied between 6 and 17 s (Fig. 4d).

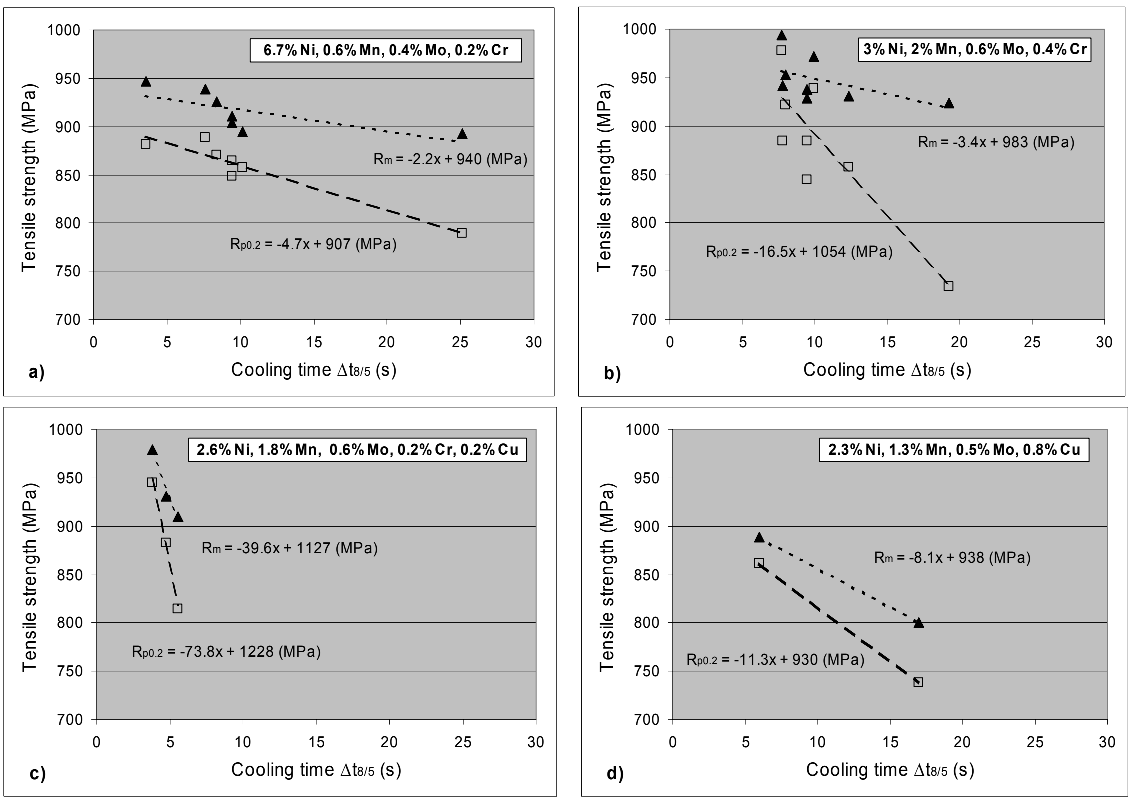


Figure 4 Strength as a function of cooling time ($\Delta t_{8/5}$) for weld metals with Ni contents in the range 2.3 - 6.7 wt%.

Room temperature impact toughness data for the four weld metal compositions are presented in Figure 5. All except the 7Ni weld metal show a more or less pronounced variation of toughness with cooling time. Although some scatter is inevitably present in weld metal impact toughness testing it is interesting to note that the linear regression analysis suggests a constant toughness independent of cooling time in the range $\Delta t_{8/5}$ 3.6 to 25 s for the 7Ni composition. A comparison of Figures 4 and 5 also shows the unexpected feature of the 3Ni weld metal of increasing toughness with increasing strength. However, literature data for the 2.3Ni and 2.6Ni weld metals suggest the more commonly observed decrease of toughness with increasing strength.

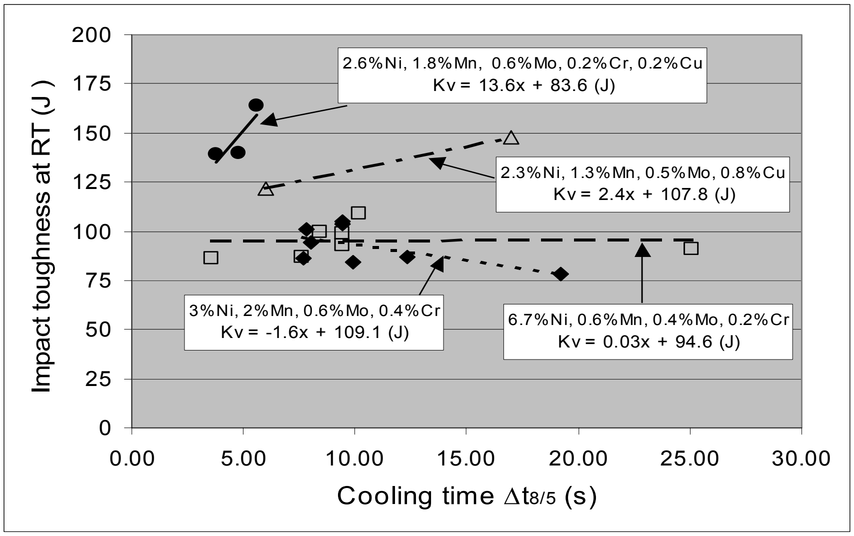


Figure 5 Charpy-V room temperature impact toughness as a function of cooling time ($\Delta t_{8/5}$) for weld metals with Ni contents in the range 2.3 - 6.7 wt%.

The regression equations for the 7Ni weld metal presented in Figures 4 and 5 predicted the butt weld properties surprisingly well considering effects of dilution and the very slow cooling of the 2.8 kJ/mm heat input weld. At a $\Delta t_{8/5}$ of 10 s the actual yield strength was 21 MPa lower than the predicted value, the tensile strength 23 MPa lower and the Charpy –V impact toughness 15 J lower. For $\Delta t_{8/5}$ of 36 s the corresponding differences were even smaller: +3 MPa, -9 MPa and –11 J, respectively. In conclusion, the robust mechanical properties of the 7Ni all-weld metals, showing little dependence on cooling rate, were maintained also in the diluted weld metal of butt welds over a large cooling time interval.

Microstructure

The fine microstructures of 2-3Ni high strength weld metals are inherently difficult to characterise and quantify with their martensitic, bainitic and ferritic components. However, the 3Ni weld metal has previously been described as bainitic/martensitic, the solid wire 2.6Ni weld metals as largely bainitic/martensitic with some acicular ferrite and the 2.3Ni MMA weld metal as consisting of predominantly acicular ferrite with some granular bainite. Properties of all three 2.3-3.2Ni weld metals rely on formation of optimal proportions of stronger, less tough, and softer, less strong, components forming as the weld metal cools. Hence, it is not surprising that the cooling rate will have a strong influence on microstructure and thereby properties.

Attempts have earlier been made, with limited success, to design weld metals with more robust mechanical properties based on leaner compositions producing either an “ultra-low carbon bainite” microstructure or quite different compositions, claimed to give martensitic structures [3]. The more highly alloyed 7Ni weld metal represents a different approach producing a microstructure consisting mainly of bainite with a limited effect of cooling time on martensite content. Although further studies are needed, the 7Ni composition seems to offer an interesting combination of strength and toughness for a wide range of cooling rates.

Conclusions

The potential of a novel high strength steel weld metal with 7Ni has been explored and mechanical properties are compared with those of conventional 2-3Ni high strength weld metals. Optical and transmission electron microscopy revealed the microstructure to be predominantly bainitic with some martensite, irrespective of cooling rate. An interesting combination of strength and toughness was found for a wide range of cooling rates. These properties were largely maintained even in diluted weld metal of butt welds in 20 mm high strength plate material. The cooling rate had a much more pronounced effect on mechanical properties of the conventional 2-3Ni high strength weld metals. The 7Ni weld metal composition is clearly promising in terms of tolerance to variations in the weld thermal cycle and with respect to dilution with parent material.

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