New Developments with C–Mn–Ni in High Strength Steel Weld Metals — Part B. Mechanical Properties

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Abstract

Microstructure and properties have been studied for high strength steel weld metals with variations in carbon, manganese and nickel. Based on neural network modelling, experimental welds were made using shielded metal arc welding with manganese at 0.5 or 2.0 wt. % and nickel at 7 or 9 wt. %. Additional welds were made where carbon was varied between 0.03 and 0.11 wt. %. Generally there was very good agreement between the recorded mechanical properties and the neural network predictions. A combination of high nickel and manganese was positive for strength but very negative for impact toughness while manganese reductions lead to large impact toughness increases. Carbon additions up to 0.11 wt. % were found to increase yield strength to 912 MPa while still maintaining toughness at over 60 J at –100 °C. Increasing contents of manganese and nickel resulted in a significant lowering of Ac_1 thereby contributing to less good impact toughness as a consequence of less tempering in reheated regions. Mechanical properties of the weld metals could be rationalised in terms of their relative amounts of the different microstructural constituents. Martensite provided the highest strength and reasonable toughness. Upper and lower bainite contributed to very good toughness and high strength. The least beneficial properties were found in the high manganese variants due to a combination of primarily coarse grained coalesced bainite and martensite. This combination of microstructural constituents resulted in poor toughness, relatively high yield strength and the highest tensile strength. The optimal combination of strength and impact toughness were found at 0.5 manganese and 7 nickel with intermediate carbon levels resulting in an easily tempered, fine scale mixture of upper and lower bainite together with some martensite.

Introduction

There has been ongoing development in high strength steel weld metals with the aim of increasing strength while maintaining acceptable toughness since the 1960's. Studies have mainly focused on welding processes which offer flexibility such as shielded metal arc welding (SMAW). Research has been carried out based on fundamental understanding of the effects of alloying on phase transformations and microstructure to develop new improved compositions. Ultimately the aim has been to achieve weld metal properties that surpass long-standing weld metals and show less sensitivity to welding parameters [1].

In the majority of high strength steel weld metals investigated, the typical compositions have been, C less than 0.2 wt. %, Ni less than 4 wt. % and Mn less than 4 wt. % [2–18]. These compositions have been used with a variety of welding processes and generated yield strengths ranging from below 500 MPa to above 1000 MPa with good impact toughness mostly achieved at lower yield strengths. Focusing on positive results with SMAW, Lord [10] found that nickel additions from 3 to 4 wt. % at decreasing Mn levels between 1.1 and 0.8 wt. % were good for toughness with minor losses of strength. It was found that toughness increased from 63 to 74 J at –60 ºC while yield strength decreased from 837 to 809 MPa [10].

This paper is the second of a two part report on an investigation of high strength steel weld metals with variations in nickel, manganese and carbon. In Part A, with Lord's results as a starting point [10], neural network modelling [19–21] was employed to allow the effect of a wide variety of parameters to be investigated quickly [19]. Based on simulations, experimental weld metals were produced with nickel at 7 or 9 wt. %, manganese at 0.5 or 2 wt. % and carbon was varied between 0.03 and 0.11 wt. %. The exact compositions and welding parameters are presented in Table 1. The weld metals were named according to their alloying content and interpass temperature. 7 or 9 is the nickel content in wt. %, 0.5 or 2 is the manganese content in wt. %, L, M, H are the carbon contents of 0.03, 0.06 or 0.11 in wt. % and 200 or 250 is the interpass temperature in °C. Using high resolution microstructural characterisation techniques, it was found that at 7 and 9 wt. % Ni along with 2 wt. % Mn the microstructure was a mixture of upper and coalesced bainite at dendrite core regions while martensite was found at interdendritic regions. Reducing Mn content to 0.5 wt. % promoted more upper and lower bainite, while increasing C from 0.03 to 0.11 wt. % was found to promote martensite [22–26].

This article (Part B) focuses on the mechanical properties and comparisons are made to the neural network predictions. In addition the recorded mechanical properties are explained in terms of the microstructures previously characterised in Part A [22] and elsewhere [23–26].

Experimental Procedures

The welded joints were made according to ISO 2560 using 20 mm plates with a backing plate. The joints were buttered prior to the deposition of the experimental weld metals that took place in 33 cm runs with two or three runs per layer.

Charpy impact testing and tensile testing were performed in compliance with standard EN 10045–1. For Charpy testing, transverse specimens were machined having dimensions 55×10×10 mm. These were then notched perpendicular to the welding direction in the weld metal cen-

	7-2L250	9-2L250	7-0.5L250	7-0.5L200	9-0.5L200	7-0.5M200	7-0.5H200
E / kJ mm^{-1}	1.2	1.2	1.0	1.3	0.7	1.4	1.3
IPT / °C	250	250	250	200	200	200	200
$t_{8/5}$ / s	12	11	10	10	5	11	10
C *	0.032	0.031	0.024	0.030	0.026	0.061	0.110
Mn	2.02	2.11	0.64	0.61	0.37	0.56	0.53
Ni	7.23	9.23	6.6	6.11	8.67	6.84	7.04
Cr	0.47	0.48	0.21	0.16	0.2	0.15	0.14
Si	0.25	0.27	0.35	0.4	0.34	0.34	0.38
S*	0.008	0.008	0.008	0.009	0.008	0.006	0.007
P	0.011	0.011	0.012	0.010	0.007	0.011	0.008
Mo	0.63	0.64	0.4	0.38	0.41	0.35	0.40
V	n.a.	n.a.	n.a.	0.018	n.a	0.014	0.016
Cu	0.03	0.03	0.03	0.02	0.01	0.01	n.a
O / ppm *	380	340	400	340	367	350	260
N / ppm *	250	260	197	150	130	160	100

Table 1 Welding parameters and chemical composition. Welding parameters presented are energy input (E), interpass temperature (IPT) and the estimated cooling time between 800 and 500 °C ($t_{8/5}$) calculated from WeldCalc [27]. Composition is in wt. % unless otherwise stated '*' indicate elements analysed using Leco Combustion equipment and "n.a." are elements not analysed.

tre and 2 or 3 specimens were tested at each temperature. Tensile specimens were machined longitudinally from the centre of the weld deposits with a specimen diameter of 10 mm and a gauge length of 70 mm. Hardness measurements were carried out in cross sections of the joint perpendicular to the welding direction using Vickers method with a 10 kg load (HV10), starting in the last bead and then proceeding into the joint centre, with 1 mm in distance between the indentations.

Results

Strength and Impact Toughness

The results of Charpy impact toughness test are plotted in Figures 1–3. Figure 1 shows the results from the first three alloys welded with an interpass temperature of 250 ºC. Comparing 7-2L250 and 9-2L250, the lowering of impact toughness by increasing Ni from 7 to 9 wt. % at a Mn level of 2.0 wt. % is observed. Comparing 7-0.5L250 with 7-2L250, a large increase in impact toughness was measured at all test temperatures as a result of reducing Mn content. An average increase of over 80 J was recorded at each test temperature down to –60 ºC. The tensile properties for these weld metals are presented in Table 2. It is seen that 7-2L250 and 9-2L250 which had poor impact toughness recorded relatively high yield strength (YS), 795 and 848 MPa respectively, and ultimate tensile strength (UTS) over 1000 MPa. Weld metal 7-0.5L250, which showed the higher impact toughness, recorded a relatively low strength with UTS at 823 MPa and YS at 721 MPa. Weld metal 7-0.5L250 also recorded good elongation with a value of 21 %.

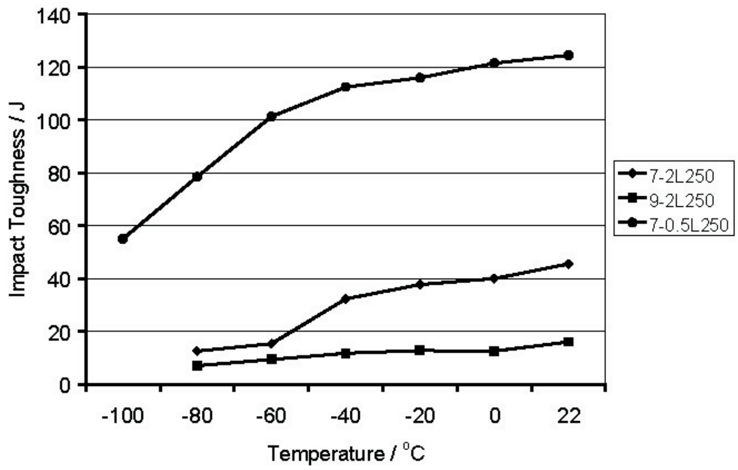


Figure 1 Charpy impact toughness plots showing the effect of increasing Ni from 7 to 9 wt. % and the effect of reducing Mn from 2 to 0.5 wt. %.

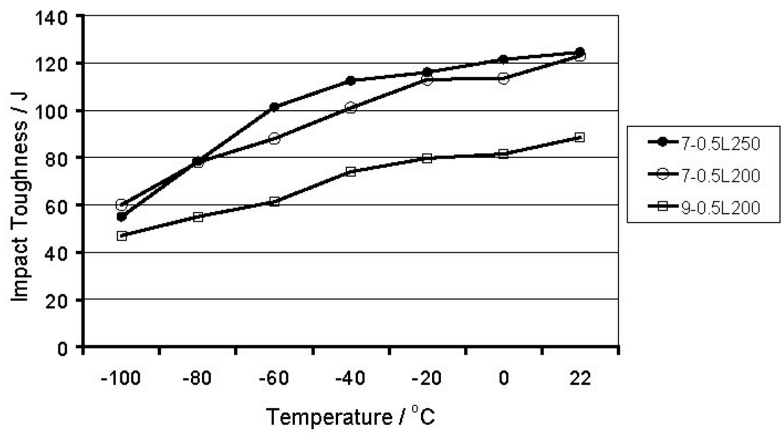


Figure 2 Impact toughness plots illustrating the effect of increasing Ni from 7 to 9 wt. % with Mn level at 0.5 wt. %. Also shown is the effect of increasing interpass temperature for the 7 Ni weld metals.

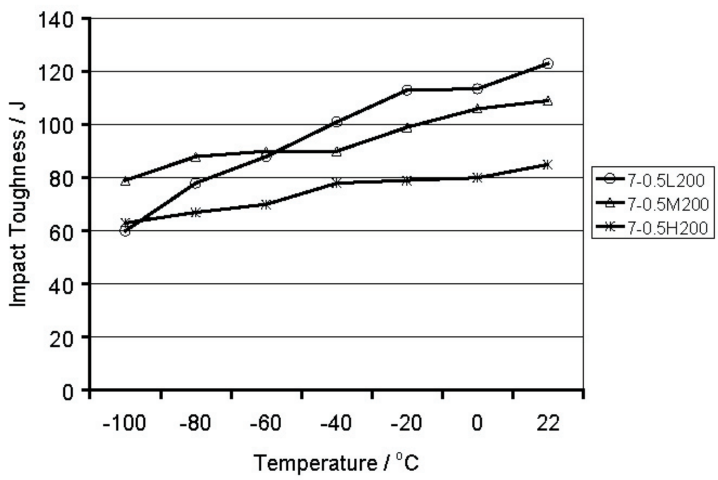


Figure 3 Impact toughness plots that show the effect of increasing carbon from 0.03 to 0.11 wt % at 7Ni and 0.5 Mn.

	7-2L250	9-2L250	7-0.5L250	7-0.5L200	9-0.5L200	7-0.5M200	7-0.5H200
YS / MPa	795	848	721	777	827	858	912
UTS / MPa	1006	1051	823	831	895	895	971
A5 / %	14.8	13.1	21.3	22	18.3	18	18

Table 2 Tensile properties of the different weld metals.

With a view to increasing strength it was decided to lower interpass temperature to 200 ºC in order to promote faster cooling. Comparing 7-0.5L250 with 7-0.5L200 that have similar compositions, yield strength increased from 721 MPa to 777 MPa. However this trend was limited with UTS which only increased from 823 MPa to 831 MPa. The impact toughness, plotted in Figure 2, was maintained very well with over 100 J recorded at –40 ºC. Increasing nickel from 7 to 9 wt % in combination with low manganese and 200 ºC interpass increased YS by 50 MPa and UTS by 64 MPa, where 895 MPa was recorded for UTS (Table 2). These changes were accompanied by a decrease in impact toughness, but only to 75 J at –40 ºC (Figure 2). A common feature of the low Mn weld metals was that good impact toughness was maintained down to at least –100 ºC.

Given the results of the modelling and the recorded mechanical properties with the first six alloys, it was decided to set Mn at 0.5 wt. %, Ni at 7.0 wt % and use an interpass temperature of 200 ºC. The effect of carbon additions on mechanical properties were then examined with the deposition of 7-0.5M200 and 7-0.5H200. From Table 2, it is seen that carbon additions were positive to YS and UTS. 7-0.5H200 recorded the best YS of all alloys studied with 912 MPa achieved at a carbon level of 0.11 wt. %. Given the strength, high impact toughness was also recorded with over 60 J at –100 ºC (Figure 3). Surprising was that although the higher carbon weld metals showed lower impact toughness than 7-0.5L200 at room temperature, they maintained impact toughness to lower temperatures and both actually surpassed 7-0.5L200 at –100 ºC.

Hardness

Hardness measurements for all weld metals are presented in Figures 4–6. The measurements were made starting at the top of the last bead and then proceeding down through the centre of the welded joint. Looking at 7-2L250 and 9-2L250 shown in Figure 4, minor fluctuations are seen in the recorded values but generally hardness levels are high and fairly constant throughout the welded joint. In contrast 7-0.5L250 that was the softer of the three alloys lost hardness very much in the centre of the welded joint. This latter weld alloy also had the better impact toughness of the three. The effect on hardness of decreasing interpass temperature can be studied by comparing 7-0.5L250 and 7-0.5L200 shown in Figure 5. It is found that decreasing interpass temperature give an increase in hardness. Comparing 9-0.5L200 with 7-0.5L200, it is seen

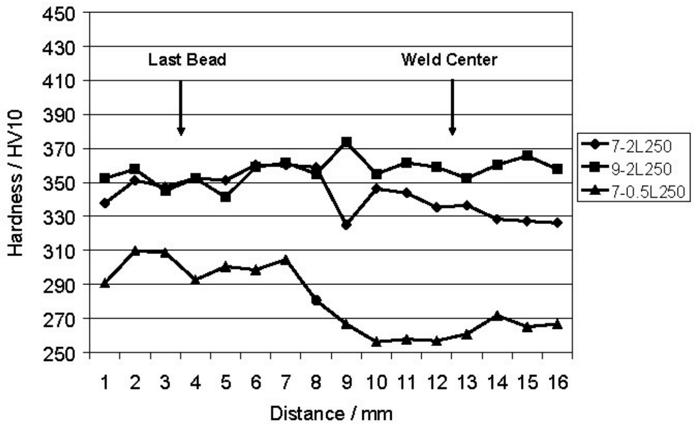


Figure 4 A comparison of hardness measurements that show the effect of increasing Ni from 7 to 9 wt. % and the effect of reducing Mn from 2 to 0.5 wt. % at 7 wt. % Ni.

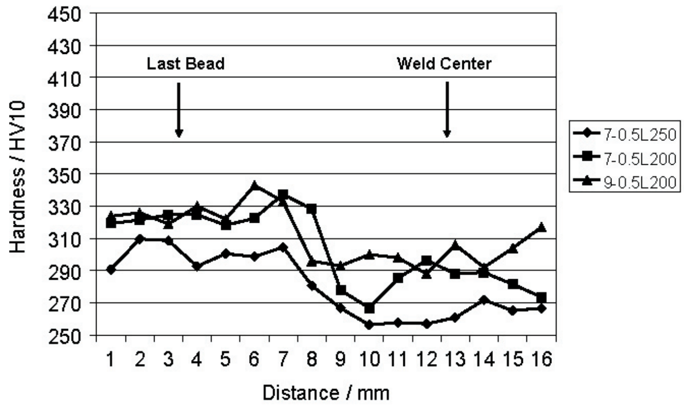


Figure 5 Hardness plots showing the effect of increasing Ni from 7 to 9 wt. % with Mn levels 0.5 wt. %. Also shown is the effect of reducing interpass temperature at a Mn content of 0.5 wt.%.

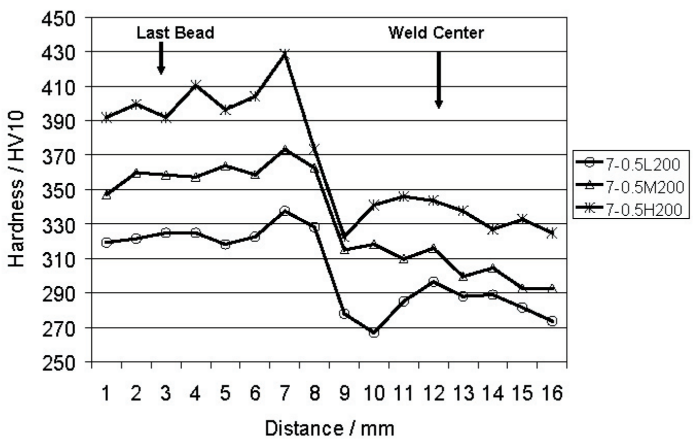


Figure 6 The effect on hardness of increasing C from 0.03 to 0.11 wt %

that nickel additions at 0.5 wt. % Mn produce a marginally harder weld metal. In Figure 6, as carbon increases from 0.03 to 0.11 wt. %, hardness levels increase as expected. 7-0.5H200 had the highest hardness levels in the last bead but it also lost the most hardness of all alloys as the central regions of the welded joint were encountered.

Discussion

Modelling

A comparison between the recorded mechanical properties, the neural network predictions and the characterised microstructural constituents are presented in Figures 7 and 8. Generally, good agreement was found between the experimental data and the predicted values. The contour plot of impact toughness as a function of Mn and Ni content was more or less proven correct. It was found that impact toughness was underestimated with 7 wt. % Ni combined with 0.5 wt. % Mn. For weld metal 9-0.5L200 there was a slight overestimation between predicted and the recorded toughness but this is to be expected since the predictions are for an interpass temperature of 250 ºC. Yield strength as a function of carbon content was found to be slightly overestimated but recorded results where mostly within the error limits. Impact toughness as a function of carbon content was found to be marginally underestimated. Overall, it can be concluded that the models were reliable in predicting the mechanical properties for the studied weld metal compositions and as expected most accurate within compositional regions where input data were available.

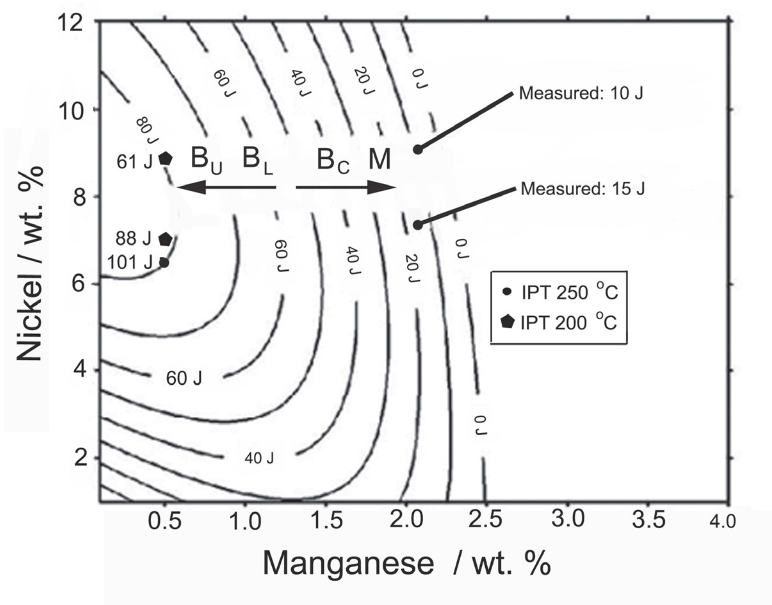


Figure 7 Comparison between recorded and predicted impact toughness at –60 ºC as a function of manganese and nickel content. See Part A [22] for details of the modelling. Upper bainite is B_U, lower bainite is B_L, coalesced bainite is B_C and martensite is M. These were the observed microstructures from microstructural investigations.

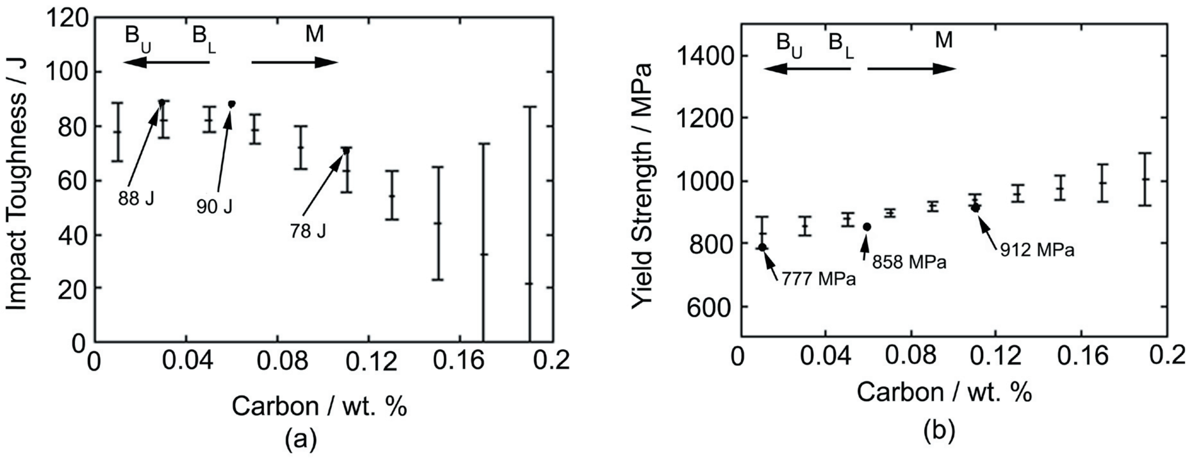


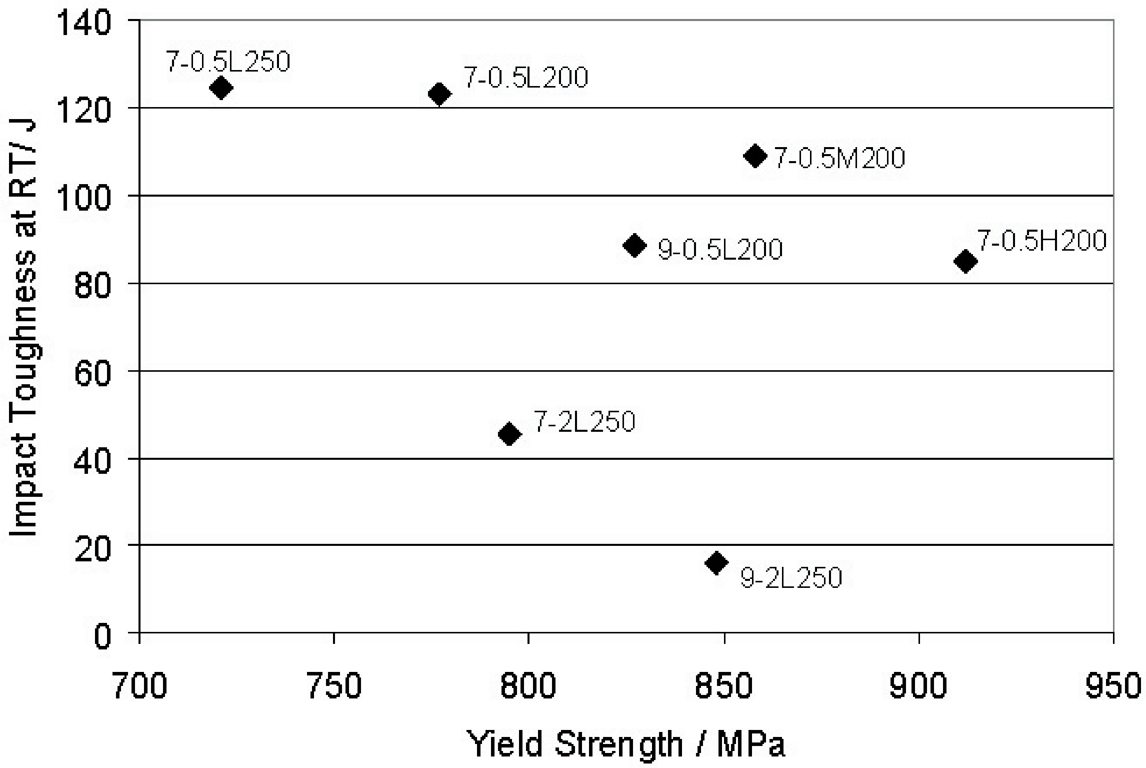
Figure 8 A comparison between the recorded impact toughness at –60 °C (a) along with yield strength (b) versus the neural network predictions as a function of carbon content for 7 wt. % Ni combined with 0.5 wt. % Mn. Also shown are the microstructural changes in relation to the increasing carbon content as was observed with microstructural investigations. B_U is upper bainite, B_L is lower bainite and M is martensite.

Strength versus Impact Toughness

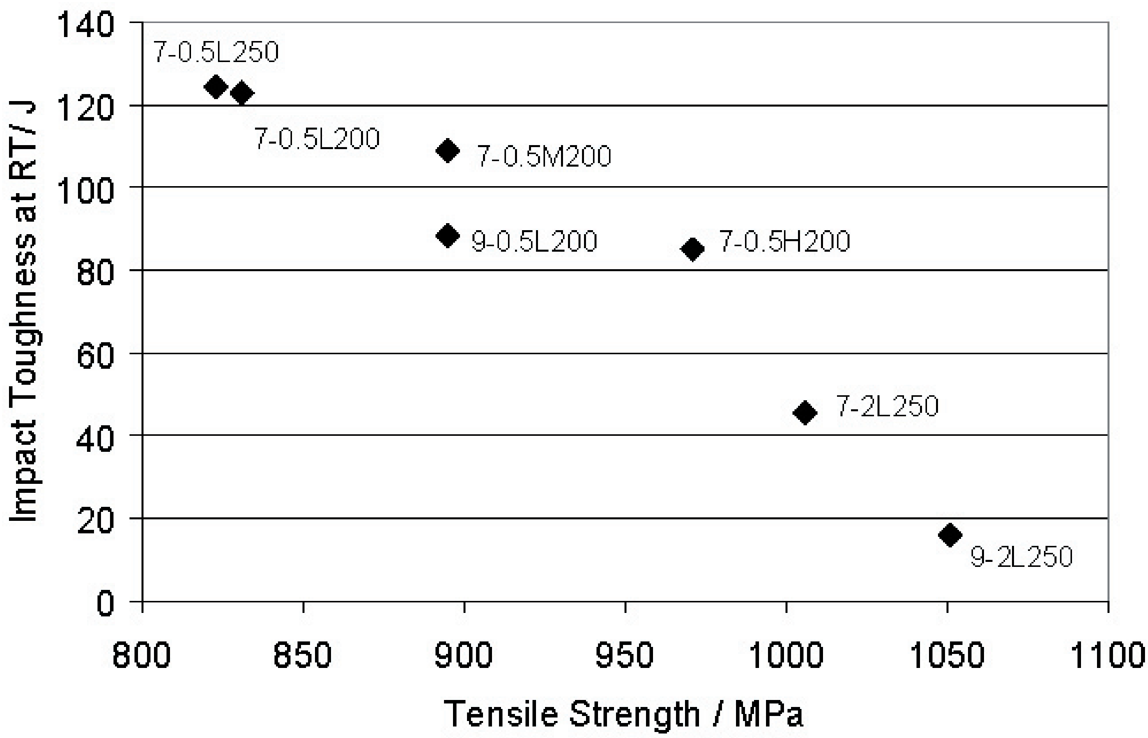
In Figure 9 yield strength and ultimate tensile strength are plotted versus impact toughness at room temperature. Normally it is found that there is a good correlation between tensile strength and impact toughness in that an increased tensile strength results in decreased impact toughness. This behaviour was indeed observed for the presently studied weld metals showing a nearly linear relationship between impact toughness and tensile strength (Figure 9). However, comparing weld metals 9-2L250, 7-2L250, 9-0.5L200 and 7-0.5M200 it can be seen that there is a large variation in toughness at similar yield strengths. It can be noted that the high Mn weld metals, having a wide gap between yield strength and tensile strength (Table 2), are those having the lowest impact toughness at a given yield strength level. The variation may be attributed to differences in the microstructure [22] as will be discussed in more detail in the following section.

Constitutional Diagram

Figure 10 presents a constitutional diagram (microstructure as a function of nickel and manganese content) which was introduced in Part A [22]. This was based on microstructural observations, dilatometry experiments, martensite start temperature (M_S) and bainite start temperature (B_S) predictions and literature. The martensite composition start line is plotted with values taken from literature [28]. Also shown is the line where B_S and M_S are equal as predicted from empirical equations [29–30]. With alloying contents around this line coalesced bainite was observed with 7 and 9 wt. % Ni in combination with 2 wt. % Mn. For compositions above the line martensite becomes the dominant constituent whereas upper and lower bainite becomes the main constituents below the line [22].



(a)



(b)

Figure 9 Impact toughness as a function of (a) yield strength and (b) ultimate tensile strength.

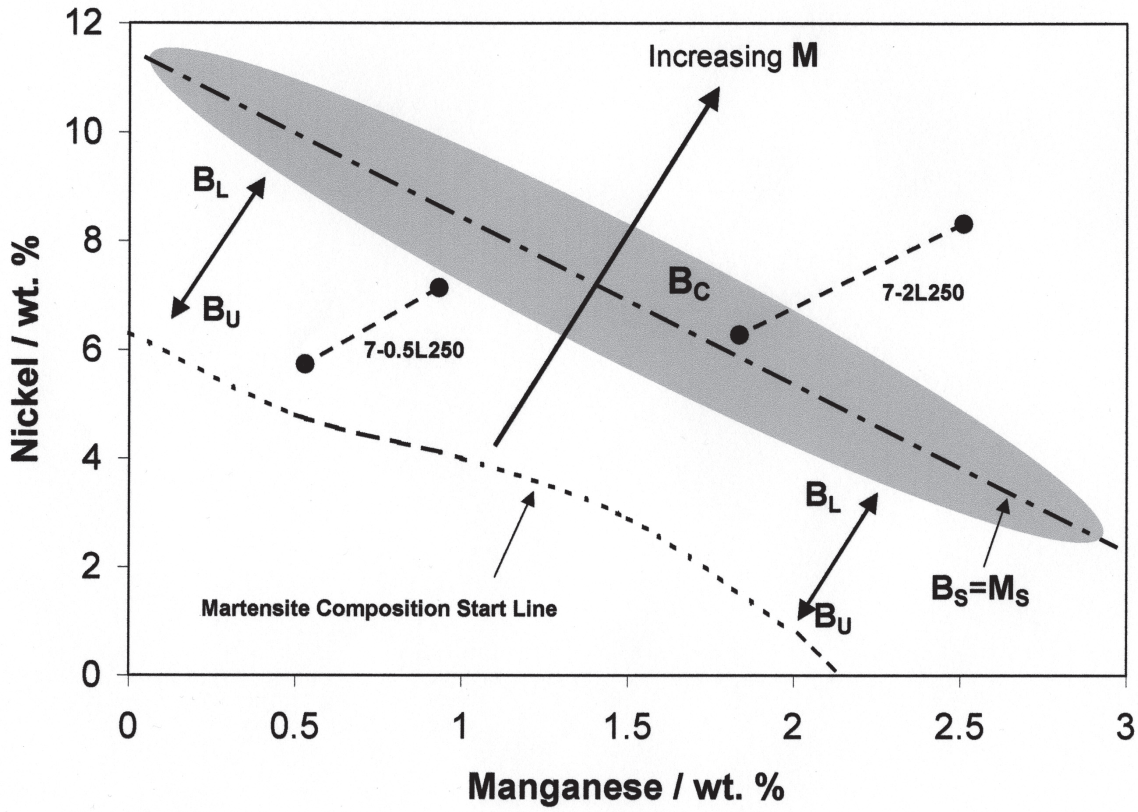


Figure 10 Constitutional diagram showing the weld metal microstructure as a function of Mn and Ni for a base composition of 0.034 C, 0.25 Si, 0.5 Cr and 0.62 Mo.The martensite start composition line from literature is presented [28] along with the line where B_S and M_S are equal according to standard empirical equations [29–30]. Around these compositions coalesced bainite (B_C) is expected. Above martensite (M) becomes the main constituent whereas the volume fraction of upper (B_U) and lower (B_L) bainite increases below this line as shown in Part A [22].

Correlating Properties to Microstructure

From the studies carried out, it is clear that the amount of C, Mn and Ni affects the microstructure that, in turn, determines the mechanical properties. A short summary of the results will be made and it will then be shown that strength, elongation and impact toughness can be rationalised in terms of the microstructural constituents.

A combination of 7 wt. % Ni and 2 wt. % Mn gave poor toughness but good strength. Nickel additions with this Mn content were found to increase strength slightly but decrease toughness even further. From microstructural examinations, a combination of upper bainite and coalesced bainite with a large grain size formed in dendrite core regions with martensite present at interdendritic regions. Significant amounts of coalesced bainite were only observed in these weld metals. Overall there was no major difference in the microstructure between 7-2L250 and 9-2L250. For these weld metals hardness was maintained at similar levels throughout the welded joint with only a slight decrease in reheated regions (Figure 4).

Impact toughness was most sensitive to Mn content with a dramatic increase obtained when Mn was reduced from 2 to 0.5 wt. % (Figure 7). It was found that weld metal 7-0.5L250 had the highest impact toughness but the lowest yield strength (721 MPa) and tensile strength (824 MPa) of the weld metals tested. There was also a large decrease in hardness compared to the high Mn weld metals, and a significant decrease in reheated regions (Figure 4). Microstructural studies revealed that reducing Mn content was found to promote austenite transformation at higher temperatures with more upper and lower bainite forming. Decreasing the interpass temperature to 200 ºC was found to increase hardness and reduce toughness marginally which was attributed to faster cooling and greater amounts of martensite.

Increasing C to 0.11 wt. % caused yield and tensile strength to increase while impact toughness was maintained (Figure 8). Austenite was stabilised to lower transformation temperatures with an increasingly finer microstructure forming and martensite becoming the dominating constituent. As expected, hardness increased with the greater amounts of martensite. The decrease in hardness on reheating became more extreme with increasing C levels, which is typical of a martensitic microstructure.

The amount of tempering which is largely controlled by Ac_1 and Ac_3, also has an important effect on the mechanical properties in reheated regions of these weld metals. It was observed that significant softening takes place in reheated beads with weld metal 7-0.5H200 (which is mainly martensitic) and with 7-0.5L250 (which is primarily a mixture of upper and lower bainite). Both of these weld metals had relatively high Ac_1 and Ac_3 values [22]. However with weld metals 7-2L250 and 9-2L250 with lower Ac_1 and Ac_3 temperatures [22] hardness was maintained into reheated regions. This can be attributed to less tempering in regions reheated to below Ac_1 due to slower kinetics at lower temperatures and most likely to the formation of more fresh untempered microstructural constituents. Furthermore it is likely that the observed precipitation in the tempered coalesced bainite [22] contributes to the higher hardness of these weld metals.

Summarising the above results the effects of microstructure on the mechanical properties can be rationalised as follows:

- A mainly martensitic microstructure (e.g. 7-0.5H200) gave high yield strength and tensile strength with a small difference between the two. In addition acceptable impact toughness was recorded.

- A mixture of mainly upper and lower bainite (e.g. 7-0.5L200) gave lower yield and tensile strengths with a small difference between the two values. For this combination of microstructural constituents very good impact toughness was recorded.

- Coalesced bainite combined with upper bainite and significant amounts of martensite (7-2L250 and 9-2L250) gave relatively high yield strength and a very high tensile strength but poor elongation. Most significantly very poor impact toughness was recorded. This latter mixture of coalesced bainite combined with upper bainite and martensite is obviously unfavourable. It can be assumed that yield strength is determined by the relatively weaker coarse grained coalesced bainite and tensile strength by martensite. Poor elongation suggests that deformation takes place unevenly within the microstructure. The poor impact toughness can most likely be attributed to the combined effect of coalesced bainite and poor tempering characteristics.

In conclusion, designing high strength steel weld metals that have a combination of both high yield strength and good impact toughness is a complex task. In terms of microstructural constituents it is clear from this study and literature that interesting properties can be obtained with different proportions of upper and lower bainite and martensite. However, compositional regions where the bainite and martensite start temperatures are close, promoting coarse grained, relatively weak and brittle coalesced bainite should be avoided. It remains to be clarified whether the microstructural inhomogeneity (a banded microstructure) introduced by the higher alloying contents and austenitic solidification can be used to optimise properties. It is clear though from a parallel study on the 7Ni 0.5Mn weld metal [31] that the high alloying content resulted in a robust weld metal in the sense that large variations in welding parameters had little effect on strength and impact toughness. The identification of coalesced bainite and its effects on mechanical properties helped to clarify the relation between properties and microstructure. Nevertheless, further work exploring effects of also other alloying elements is clearly needed to make understanding more complete and facilitate development of further improved high strength steel weld metal compositions.

Conclusions

Based on neural network modelling, experimental welds were produced using SMAW with Mn at 0.5 or 2.0 wt. % and Ni at 7 or 9 wt. %. Additional welds were made where carbon was varied between 0.03 and 0.11 wt. % with Mn set at 0.5 wt % and Ni at 7 wt. %. Generally there was very good agreement between the recorded mechanical properties and the neural network predictions for these weld metal compositions.

A combination of high nickel and manganese was positive for strength but very negative for toughness. Poor toughness was attributed to the presence of coalesced bainite and relatively low Ac_1 and Ac_3 temperatures which give less tempering within the welded joint.

Mn reductions lead to large increases in toughness with a content of 7–9 wt. % Ni. Impact toughness of 113 J at –40 °C, and yield strength of 721 MPa was recorded for 0.6 wt. % Mn and 6.6 wt. % Ni. Impact toughness gain was explained by the replacement of coalesced bainite with upper and lower banite along with greater amounts of tempering due to higher Ac_1 and Ac_3 temperatures.

Carbon additions up to 0.11 wt. % increased yield strength to 912 MPa while still maintaining toughness at over 60 J at –100 °C. Carbon additions were found to promote a fine martensitic microstructure increasing strength with limited loss of toughness.

Mechanical properties of the weld metals were explainable in terms of their relative amounts of the different microstructural constituents. Martensite was found to provide high strength and reasonable toughness whereas upper and lower bainite contributed to very good toughness and somewhat lower strength. The coarse-grained coalesced bainite found for compositions with M_S and B_S close to each other was concluded to give relatively low strength and poor impact toughness.

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