Understanding Mechanical Properties of Novel High Strength Steel Weld Metals Through High-Resolution Microstructural Investigations

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Abstract

Shielded metal arc welding and submerged arc welding were used to prepare experimental weld metals with variations in nickel, manganese and carbon contents. The weld metals contained Ni between 6.6 and 10.5 wt. %, Mn between 0.5 and 2.0 wt. % while carbon was varied between 0.03 and 0.11 wt. %. Mechanical properties were found to be sensitive to alloying content. However once the optimum level of Mn, Ni and C are chosen, impact toughness greater than 60 J at -100°C, was possible to achieve in combination with a yield strength over 900 MPa. Utilizing the recently developed possibilities of high-resolution field emission gun scanning electron microscopy, correlations could be made between the microstructure and mechanical properties. Large amounts of coarse grained coalesced bainite was associated with moderate strength and toughness while a combination of upper and lower bainite led to high impact toughness with relatively high strength. A fine distribution of martensite and coalesced bainite gave high strength and toughness. Finally it was also confirmed for a range of Ni, Mn and C levels, that coalesced bainite forms at compositions where the martensite and bainite-start temperature are narrowly separated.

Introduction

High strength steel can be exploited in many applications, for example to reduce size and weight. However such steels must be joined with care with particular attention placed on welding parameters, if both strength and toughness are to be achieved [1-3]. The achievement of both strength and toughness becomes problematic at strength levels above the region of 690 MPa (100 ksi) for shielded metal arc welding (SMAW). Given the flexibility offered with SMAW, research in the pursuit of a weld metal that combines strength, toughness and insensitivity to the welding conditions has been ongoing for some time [1-3].

Present commercial compositions found to produce the best combination of properties are usually in the range 0.04–0.08C, 1–2Mn, 0.2–0.5Si, 1–3Ni wt. % along with minor additions of Cr, Mo and sometimes Cu [3-5]. Metallurgists have tried to address the challenges of increasing strength and toughness using primarily grain refinement, precipitation hardening and solid solution hardening. Most research has been carried out by varying the chemical composition or changing the welding parameters, however only limited success has been achieved.

In previous work, neural network modelling was employed to allow the influence of a wide variety of parameters to be perceived [6-7]. It was predicted that the impact toughness could be drastically increased at a moderate expense to yield strength when Mn was reduced from 2.0 to 0.5 wt. % at a nickel content of 7 wt %. [8]. Additionally, it was suggested that once the optimum manganese and nickel contents were chosen yield strength could be greatly increased at minor expense to toughness due to carbon additions [9]. Based on these predictions and literature, experimental weld metals were produced with variations of nickel, manganese and carbon. In addition, for the purpose of a microstructural comparison a submerged arc welding (SAW) with a compatible experimental composition was also investigated.

Experimental procedures

Welded joints were made according to ISO 2560 using 20 mm plates along with a backing plate. The joints were first buttered to limit dilution before the deposition of the experimental weld metals which took place in 33 cm runs with two runs per layer and three on the top layer. The welding parameters and chemical compositions are presented in Table

1. It was decided to call the experimental weld metals 7-2L250, 7-0.5L250, 7-0.5H200, 10-0.5M200 and 8-1.2SAW. Here 7, 8 or 10 is the Ni content in wt. %, 2, 0.5 or 1.2 the Mn content in wt. %, L, M or H indicates low, medium or high carbon and 250 or 200 the interpass temperature in °C. SAW stands for submerged arc welding and is used to indicate that 8-1.2SAW used a different welding method to deposit the weld metal.

For Charpy testing, 10_10_55 mm transverse specimens were machined and notched perpendicular to the welding direction in the weld metal center. Two or three specimens were tested at each temperature. Tensile specimens were machined longitudinally from the weld deposits with a specimen diameter of 10 mm and a gauge length of 70 mm. Charpy impact testing and tensile testing were performed in compliance with standard EN 10045–1.

Table 1: Welding parameters and chemical composition. Welding parameters presented are energy input (E), maximum interpass temperature (IPT) and the estimated cooling time between 800 and 500 °C ($t_{8/5}$) calculated from WeldCalc [10]. Composition is in wt. % unless otherwise stated and '' indicate elements analyzed using Leco Combustion equipment.*

Weld Metal	7-2L250	7-0.5L250	7-0.5H200	10-0.5M200	8-1.2SAW
Method	SMAW	SMAW	SMAW	SMAW	SAW
E / $kJmm^{-1}$	1.2	1.0	1.3	1.2	1.5
IPT / °C	250	250	200	200	200
$t_{8/5}$ / s	12	10	10	9	16
C *	0.032	0.024	0.110	0.08	0.061
Mn	2.02	0.60	0.53	0.56	1.21
Ni	7.23	6.60	7.04	10.51	8.60
Cr	0.47	0.21	0.14	1.13	0.46
Si	0.25	0.35	0.38	0.23	0.22
P	0.011	0.01	0.008	0.015	0.017
Mo	0.63	0.40	0.40	0.29	0.41
Cu	0.03	0.02	n.a.	0.30	0.19
S*	0.008	0.008	0.007	0.007	0.007
O / ppm*	380	400	260	380	270
N / ppm*	250	197	100	110	80

Specimens for metallographic analysis from the weld metal cross section, perpendicular to the welding direction, were mounted in bakelite, wet ground and polished to 1 µm diamond grain size. They were then etched using 2 % nital and studied using both light optical microscopy (LOM) and field emission gun scanning electron microscopy (FEGSEM).

Results

Microstructure

Light optical microscopy was used to get an overview of the different welded joints. Figure 1 is a typical LOM micrograph of the microstructure in the last bead of weld metal 10-0.5M200. The former dendrite boundaries are clearly seen and it is observed that the microstructure is fine scale, typical of martensite or bainite. In addition large grains not typically found in high strength steel weld metals can be observed. The large grains were also observed within the microstructure of weld metals 7-2L250 and 8-1.2SAW. In previous work on 7-2L250 these large grains were characterized using FEGSEM and transmission electron microscopy (TEM) to be a novel variant of bainite, coalesced bainite, that forms when the martensite and bainite start temperatures are close to each other [11].

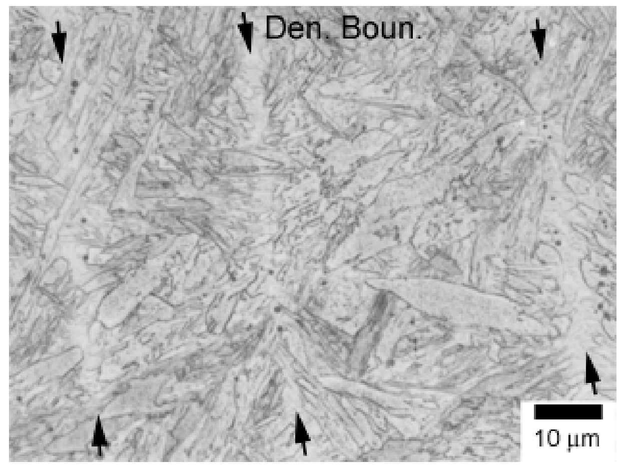

Figure 1: The last bead of 10-0.5M200 shown using LOM. The black arrows show the former dendrite boundaries

Figure 2 allows a comparison between the five experimental weld metals using FEGSEM. Interpretations of the microstructural constituents are made from investigations at higher magnifications. A high resolution FEGSEM micrograph showing lower and coalesced bainite in the last bead of weld metal 10-0.5M200 is also presented in Figure 2. It is possible to see precipitates within the bainitic ferrite grains and films at the grain boundaries. Comparing the overview micrographs of 7-2L250 with 7-0.5L250 that has reduced manganese, it was found that greater amounts of coalesced bainite were formed with 7-2L250. Generally in these weld metals, martensite occurs mainly at interdendritic regions while upper, lower and coalesced bainite were found in dendrite core regions. The microstructure in the high carbon weld metal (7-0.5H200) contained a well mixed dispersion of martensite and coalesced bainite and the former dendrite boundaries were not as pronounced. In weld metals 10-0.5M200 and 8-1.2SAW substantial amounts of lower and coalesced bainite formed along with some martensite.

Microstructural investigations were also carried out on reheated beads within the welded joints. It was found that the microstructure in reheated beads consisted of the same constituents except that tempering had taken place. Figure 3 shows an example of the microstructure in a reheated bead of 10-0.5M200. Within the micrograph a former dendrite boundary region is very pronounced. In this region mainly tempered martensite was found. In dendrite core regions tempered lower and coalesced bainite was found.

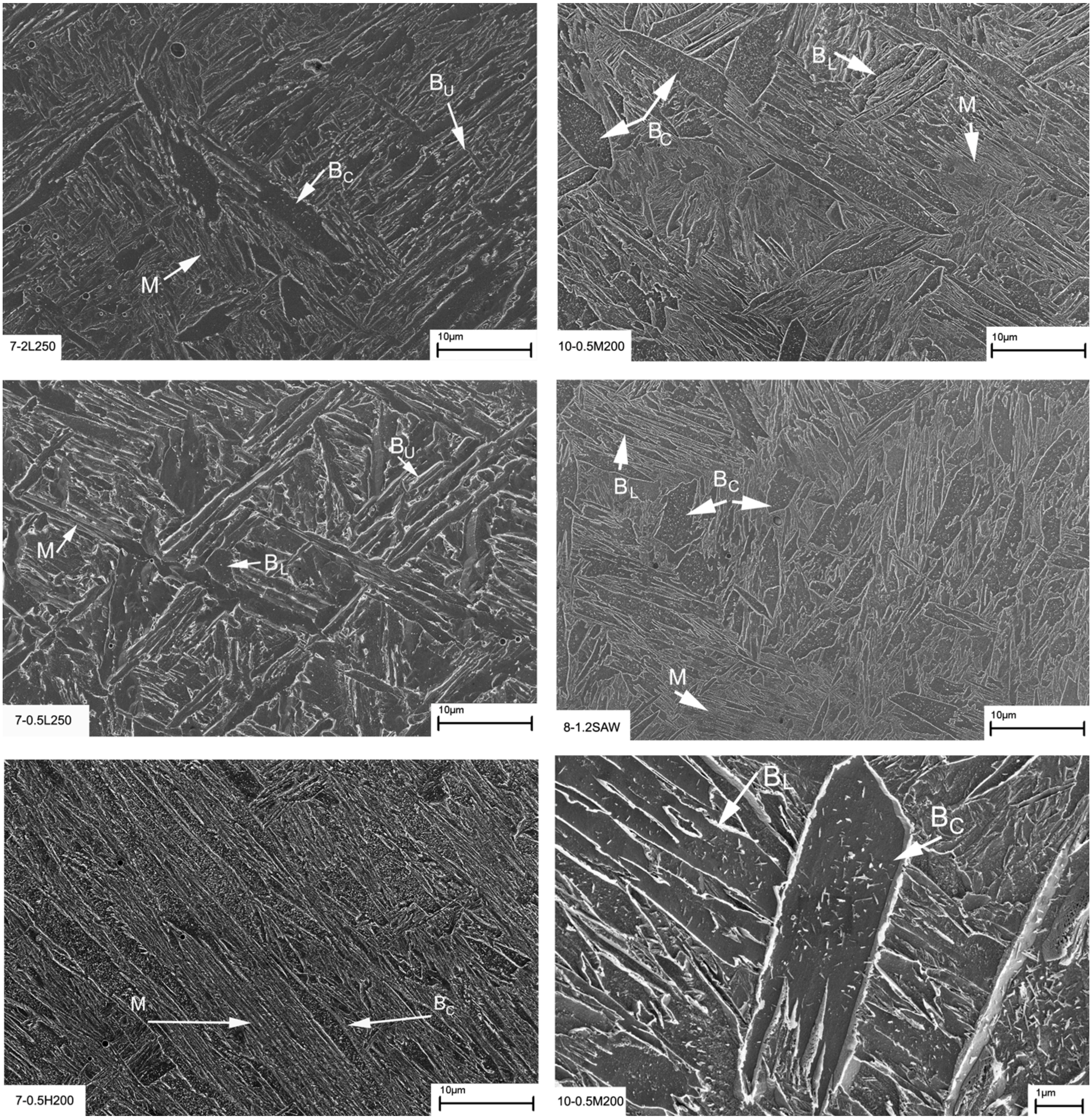

Figure 2: FEGSEM micrographs showing the last bead of the five experimental weld metals at a similar magnification. Also shown is a FEGSEM micrograph presenting lower and coalesced bainite at higher magnification in weld metal10.5M200. Martensite is M, lower bainite is B_L, upper bainite is B_U and coalesced bainite is B_C.

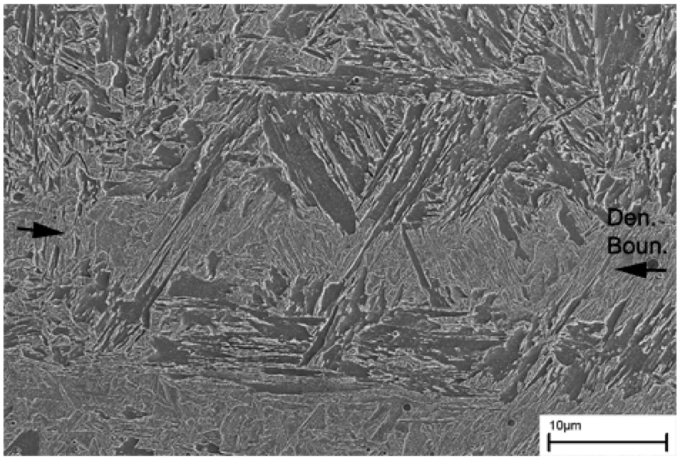

Figure 3: FEGSEM micrograph showing the microstructure within a reheated bead of 10-0.5M200.

Mechanical Properties

The results of tensile testing and Charpy impact toughness testing are presented in Table 2. Reducing manganese content from 2 (7-2L250) to 0.5 wt. % (7-0.5L250) leads to a moderate loss in yield strength and a substantial loss in ultimate tensile strength. However, at the reduced Mn level a large increase in impact toughness at both room temperature and at –40 ºC was recorded in agreement with model predictions. Increased carbon (0.11 wt. %) with manganese and nickel set at 0.5 and 7.0 wt. % (7-0.5H200), respectively, greatly enhanced tensile properties with 912 MPa recorded in yield strength and 971 MPa for ultimate tensile strength. Even though such high yield strength was recorded, impact toughness remained high with 78 J at –40 ºC and 63 J at –100 ºC recorded. Increasing nickel from 7 to 10.5 and reducing carbon to 0.8 wt. % was found to give a large increase in ultimate tensile strength, however, toughness was relatively low with 33 J recorded at room temperature. Comparing the mechanical properties of the SAW weld metal that had 1.2 wt. % Mn, 8.6 Ni and 0.06 C to the SMAW weld metals it was found that yield strength was relatively low while tensile strength was high. This weld metal also recorded low toughness.

Table 2 Recorded tensile properties (MPa) and impact toughness (J) at room temperature, –40 and –100 ºC. "n.m." is not measured.

	7-2L250	7-0.5L250	7-0.5H200	10-0.5M200	8-1.2SAW
Y.S.	795	721	912	904	674
U.T.S.	1006	823	971	1135	1110
22 ºC	45	124	85	33	37
-40 ºC	32	112	78	31	31
-100 ºC	n.m.	55	63	25	n.m

Discussion

The microstructure in these weld metals was characterized to be a complex mixture of different constituents. It is nevertheless possible to explain the mechanical properties once the characteristics of the individual microstructural constituents are understood.

Coalesced bainite is a recently discovered constituent in high strength steel weld metals. From microstructural studies it was found that coalesced bainite very often leads to a large grain size (up to and greater than 10 μm in length and a few microns in width). A proposed mechanism as to how it forms is presented in Figure 4 along with that of upper and lower bainite [11-12]. In short, it is suggested that many supersaturated bainitic ferrite plates begin to form and during growth these coalesce into one big grain. As the temperature drops, precipitation begins both within the grain and at the grain boundaries. Coalesced bainite has been observed to form primarily at compositions where the gap between the bainite-start ($B_{s)}$ and martensite-start (M_s) temperatures is narrow. It has been reported that the driving force for nucleation of bainitic ferrite is high when B_s and M_s are close to each other [13].

Weld metals with a lot of coalesced bainite in dendrite core regions (7-2L250, 10-0.5M200 and 8-1.2SAW) showed a relatively large difference between yield and tensile strength while toughness was relatively poor (Table 2). Making a comparison between 7-2L250 and 7-0.5L250, reducing manganese from 2 to 0.5 wt. %, greater amounts of upper and lower bainite were present largely at the expense of coalesced bainite. Upper and lower bainite gave somewhat lower strength, the difference between yield and tensile strength was less and impact toughness was very good (Table 2). With Mn and Ni set at 0.5 and 7 wt. % respectively, carbon additions up to 0.11 wt. % gave a fine distribution of martensite and coalesced bainite. This latter microstructural combination gave high yield and tensile strength in combination with relatively good toughness.

The mechanical properties of these weld metals can be rationalized in terms of their microstructures. Once coalesced bainite develops with a large effective grain size it seems to offer little resistance to cleavage crack propagation. Coarse ferrite is also expected to have low yield strength explaining the lower yield strength of weld metals with significant amounts of coalesced bainite. For the purpose of having a high yield strength and good toughness it is therefore recommended to avoid forming coalesced bainite and instead aim for the classical constituents of martensite, upper and lower bainite. Given the complexity introduced as a result of segregation in these weld metals, this can be a challenging task. Also the effects that tempering introduces on the microstructure after multiple weld passes have been carried out needs be considered in order to achieve optimum mechanical properties.

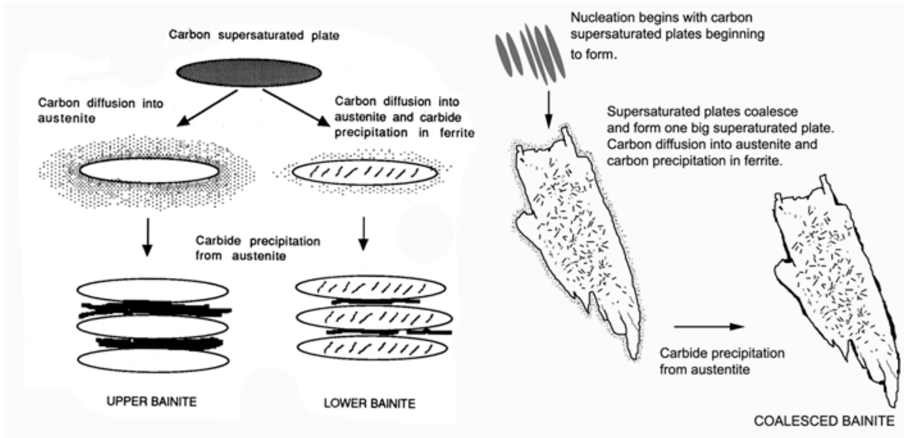

Figure 4: Schematic representation of the formation of upper and lower bainite [12] along with coalesced bainite [11].

Constitutional Diagram

Based on microstructural studies it was decided to construct a constitutional diagram (Figure 5) that shows the microstructural constituents as a function of manganese and nickel contents. The diagram was first constructed in previous work [9] and in this paper extra data have been added. The martensite composition start line as a function of Mn and Ni content has been taken from literature [14]. Increasing alloying content above the martensite composition start line is predicted to promote greater amounts of martensite at the expense of upper and lower bainite.

A shaded region is plotted around a line where M_s (Martensite start temperature) and B_s (Bainite start temperature) are predicted to be equal. The B_s=M_s line was calculated by varying the Ni and Mn content in the B_s and M_s empirical equations (B_s=830-270(%C)-90(%Mn)-37(%Ni)-70(%Cr)-83(%Mo)) and (M_s=539-423(%C)-30.4(%Mn)-17.7(%Ni)-12.1(%Cr)-7.5(%Mo)) [15-16] along with using the base input composition of 7-2L250. Compositions around the shaded region are predicted to give significant amounts of coalesced bainite.

The location of weld metals 7-2L250, 7-05L250, 10-0.5M200 and 8-1.2SAW are plotted in the diagram with a "filled box" based on their average Mn and Ni contents. In addition both 7-2L250 and 7-05L250 are plotted over an interval of Ni and Mn content based on EDX segregation measurements presented in previous work [9]. These confirmed enrichment of Mn and Ni at interdendritic regions and depletion in dendrite core regions.

Newly added to the diagram are weld metals 10-0.5M200 and 8-1.2SAW that have a slight deviation in alloying content from 7-2L250 and 7-0.5L250. However based on the microstructural characterization that showed a mixed microstructure of lower and coalesced bainite along with martensite these weld metals are in agreement with the diagram. Calculating the M_s and B_s temperatures for these weld metals, 10-0.5M200 has B_s of 266 °C and M_s of 286 °C while 8-1.2SAW has B_s of 320 °C and M_s of 316 °C. These calculated values are in agreement with the diagram that suggests coalesced bainite should form when B_s and M_s are close.

Given the wide range of Ni, Mn and C levels studied and from microstructural observations, it can be concluded coalesced bainite forms at compositions where M_s and B_s are close.

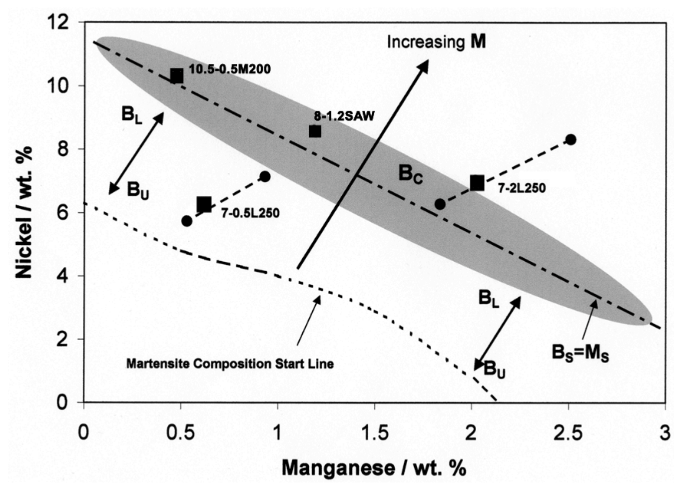

Figure 5: Constitutional diagram showing the dominant microstructural constituents as a function of Mn and Ni contents for the base composition of 0.034 C, 0.25 Si, 0.5 Cr and 0.62 Mo. The martensite composition start line was taken from literature [14]. The line where B_s and M_s are calculated to be equal along with compositions within the shaded area around the line are expected to be most prone to the formation of coalesced bainite. Martensite is M, lower bainite is B_L, upper bainite is B_U and coalesced bainite is B_C.

Although the constitutional diagram is in excellent agreement with the weld metals studied here, one must consider the effects of variation in cooling rate and changes in alloying content for additional elements other than Mn and Ni before applying the diagram.

Conclusions

Experimental weld metals were produced using SMAW and SAW with variations in Mn, Ni and C contents. These were then mechanically tested and their microstructure characterized using LOM and high resolution FEGSEM.

Reducing manganese from 2 to 0.5 wt. % in combination with nickel at 7 wt. % was found to promote impact toughness at moderate expense to strength. Increased impact toughness was attributed to greater amounts of upper and lower bainite instead of coalesced bainite.

Carbon additions up to 0.11 wt. % in combination with 7 and 0.5 wt % Ni and Mn, respectively, increased yield strength to 912 MPa while impact toughness recorded over 60 J at –100 °C. The high strength and toughness was attributed to the presence of a fine distribution of martensite and coalesced bainite.

Mechanical properties of the weld metals were explained in terms of their microstructural content. Upper and lower bainite was found to provide good strength and excellent impact toughness. Coalesced bainite was concluded to be negative for impact toughness and to give relatively low yield strength. A martensitic microstructure with a well interspersed distribution of coalesced bainite was found to give a good combination of strength and toughness.

Finally, it was confirmed that coalesced bainite forms at compositions where M_s and B_s are close to each other for a range of Ni, Mn and C levels.

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