New alloying concepts for high strength steel weld metals

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ABSTRACT

Innovative alloying contents in high strength weld metals were investigated with the primary aim of increasing strength while maintaining toughness. Abandoning the traditional low alloying levels, shielded metal arc weld metals with 7 wt. % nickel and up to 0.34 wt. % carbon were tried. Impact toughness greater than 70 J at -40ºC along with yield strength greater than 900 MPa was achieved through a combination of 0.11 wt. % carbon and 7 wt. % nickel. At higher carbon levels both yield strength and impact toughness were found to be reduced. Microstructural investigations were carried out using the relatively new technique of field emission gun scanning electron microscopy. The microstructure in these novel weld metals was found to be complex mixtures of martensite, upper, lower and the recently discovered coalesced bainite. Mechanical behaviour of the weld metals is explained through correlations with the weld metal microstructures. A well-balanced mixture of martensite, lower and coalesced bainite was found to give optimum strength and impact toughness.

KEYWORDS

High Strength Steel, Weld Metal, Martensite, Upper Bainite, Lower Bainite, Coalesced Bainite, FEGSEM, Impact Toughness, Carbon, Nickel

INTRODUCTION

High strength steels are increasingly employed in many applications due to the advantages they offer such as size and weight reduction along with greater load bearing capabilities [1]. However, as strength increases above the region of 690 MPa (100 ksi), the joining of such steel must often be carried out with caution, with particular emphasis placed on welding parameters, if toughness criteria are to be met. This is particularly the case when welding with the more adaptable and productive methods of shielded metal arc welding (SMAW), submerged arc welding (SAW) and flux cored arc welding (FCAW). The search for compositions offering both strength and toughness at low temperatures has been ongoing for these latter weld methods since the 1960's. Then, it became possible to meet requirements using gas tungsten arc welding (GTAW) [2]. Typical toughness requirements are 47 J at –20°C for shipbuilding, or 40 J at –40°C for offshore construction [3] with temperature requirements set at least 30°C below the expected service temperature. The present work is a continuation of a larger study [4 - 6] into the development and understanding of experimental high strength steel weld metals for the SMAW method.

Neural network modelling, which is further described elsewhere [7-9], was engaged to model the effect of changing chemical composition and welding parameters on mechanical properties. It was predicted and later confirmed that an experimental weld metal with a manganese level of 0.5 wt. % in combination with nickel at 7 wt. % and carbon at 0.024 wt. % gives both good impact toughness (113 J at – 40 °C) and yield strength (721 MPa) [10]. The microstructure in this weld metal was found to be mainly upper bainite [11]. The recorded mechanical results were in line with work on

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similar compositions elsewhere [12-13]. Using this latter combination of manganese, and nickel (0.5 and 7 wt. % respectively) in the base input composition, further neural network modelling suggested that the yield strength could be greatly increased at moderate expense to toughness though carbon additions (Fig. 1) [14]. Based on these predictions it was decided to make three additional weld metals with carbon levels of 0.11, 0.18 and 0.34 wt. %.

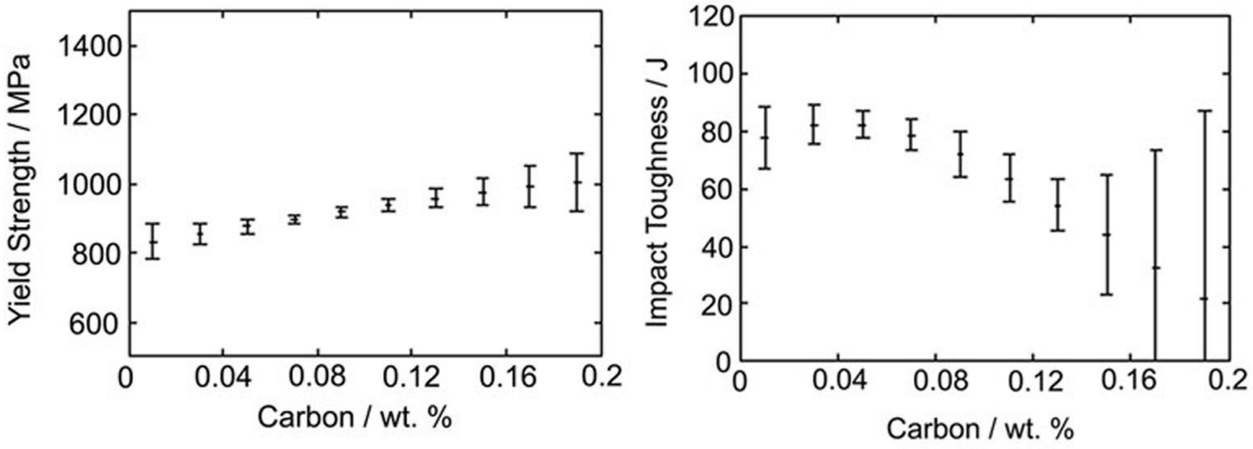

Fig. 1. Neural network model predictions of yield strength (MPa) and impact toughness (J) at –60°C as a function of carbon content in wt. % [14].

EXPERIMENTAL DETAILS

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. Chemical analysis was carried out using optical emission spectroscopy and Leco combustion equipment. It was decided to call the weld metals Low C, Medium (Med.) C, High C and Extra (Ex.) High C depending on the carbon contents that were 0.024, 0.11, 0.18 and 0.34 wt. %.

For Charpy testing, 10×10×55 mm transverse specimens were machined and notched perpendicular to the welding direction in the weld metal centre. 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.

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 field emission gun scanning electron microscopy (FEGSEM).

RESULTS

Mechanical Properties

Tensile properties are presented in Table 2 and the results of Charpy impact measurements are plotted in Fig. 2. Comparing the Med. C to the Low C weld metal it is found that the yield strength

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increased from 777 to 912 MPa and tensile strength from 831 to 971 MPa as a result of the carbon increase. There is a drop in impact toughness for the Med. C weld metal (Fig. 2), but it still recorded 78 J at –40 °C and 63 J at –100 °C despite having such good strength. Increasing carbon further (High C) gave a decrease in yield strength to 865 MPa while on the contrary tensile strength increased to 1086 MPa. A drop in impact toughness was experienced at all test temperature with 50 J recorded at – 40 °C. The Ex. High C weld metal showed a drop in both yield and tensile strength (798 and 963 MPa respectively) while impact toughness was also low with just 24 J recorded at -40°C.

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 [15]. Composition is in wt. % unless otherwise stated and '*' indicate elements analysed using Leco Combustion equipment. "n.a." stands for not analysed.

Weld Metal	Low C	Med. C	High C	Ex. High C
E / $kJmm^{-1}$	1.3	1.3	1.3	1.3
IPT / °C	200	200	200	200
$t_{8/5}$ / s	10	10	10	10
C *	0.03	0.11	0.18	0.34
Mn	0.60	0.53	0.57	0.56
Ni	6.10	7.04	6.90	6.90
Cr	0.16	0.14	0.14	0.14
Si	0.40	0.38	0.39	0.44
P	0.010	0.008	0.010	0.009
Mo	0.38	0.40	0.40	0.40
Cu	0.02	n.a.	0.04	0.04
S*	0.009	0.007	0.008	0.006
O / ppm*	340	260	n.a.	n.a.
N / ppm*	150	100	n.a.	n.a.

Table 2. Tensile properties.

Weld Metal	Low C	Med. C	High C	Ex. High C
Y.S. / MPa	777	912	865	798
U.T.S. / MPa	831	971	1086	963

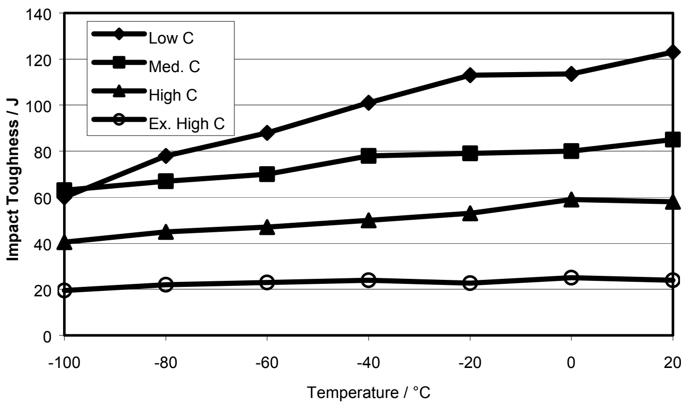

Fig. 2. Charpy Impact Toughness as a function of temperature.

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Microstructure – The Last Bead

To understand the complex changes in mechanical properties it was necessary to carry out microstructural investigations. Fig. 3 shows four low magnification FEGSEM micrographs that allow an overview of the microstructure in the last bead in each of the four experimental weld metals. Interpretations of the individual microstructural constituents are made from investigations at higher magnifications. Micrographs showing each microstructural constituent at high magnification are shown in Fig. 4. Comparing the micrographs in Fig. 3 it is clearly observed that the microstructure has a very different morphology in each weld metal. With the Low C weld metal, the microstructure was found to be mainly upper bainite. A micrograph showing upper bainite at high magnification in the Low C weld metal is presented in Fig. 4. In the Med. C weld metal (Fig. 3) the microstructure was characterised to be a mixture of lower bainite, martensite and coalesced bainite. Coalesced bainite is a novel variant of bainite, which leads to a large grain size, and forms when the martensite and bainite start temperatures are close to each other [16]. It was first characterised using FEGSEM and transmission electron microscopy (TEM) in a variant of the Low C weld metal with 2 wt. % Mn [17]. High magnification images of lower bainite, coalesced bainite and martensite are shown in Fig. 4. It was found that as carbon was increased (High C and Ex. High C), martensite became the more dominant microstructural constituent (Fig.3).

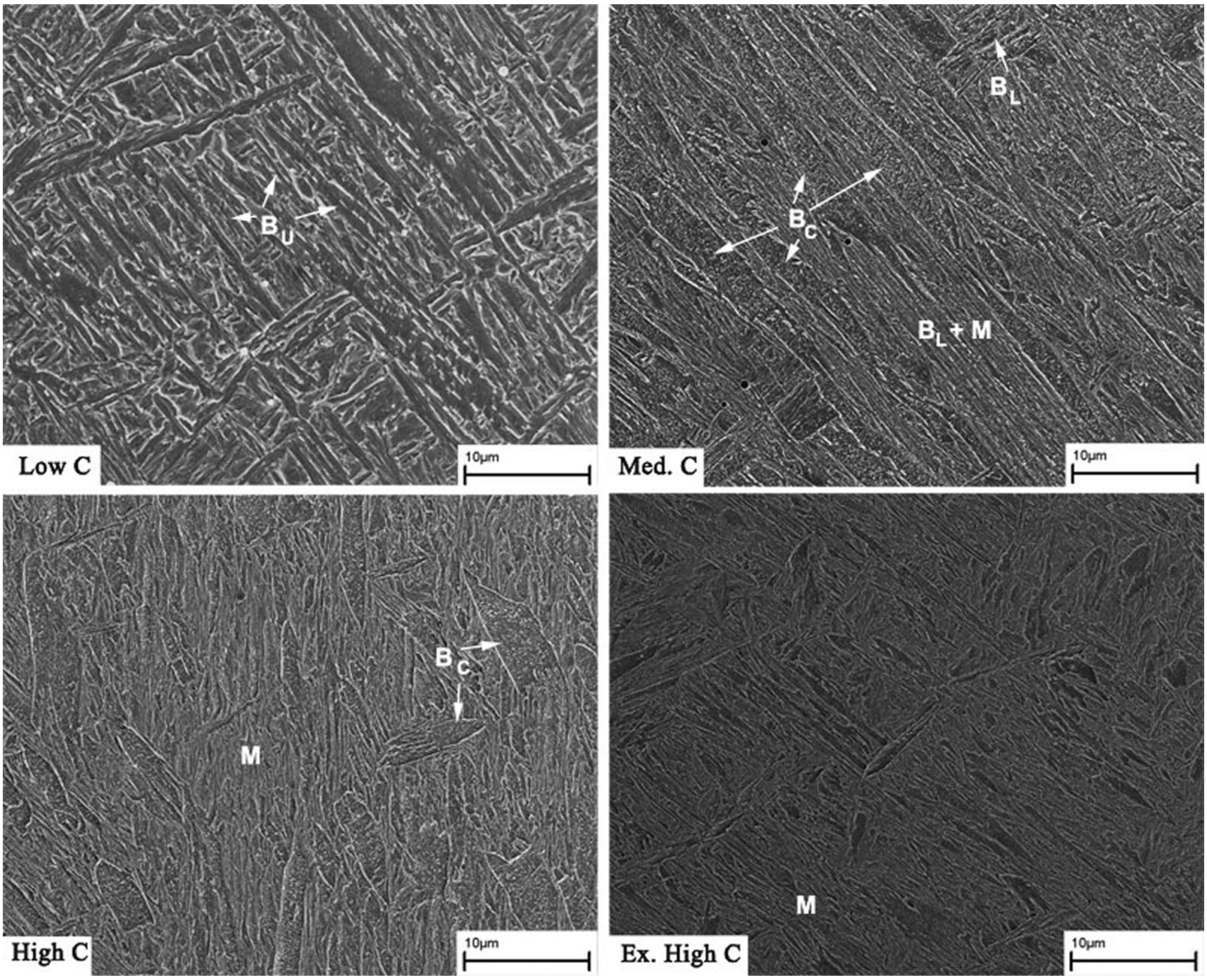

Fig. 3. Low magnification FEGSEM micrographs presenting an overview of the microstructure in the last bead of each weld metal. Interpretations of the microstructural constituents are made from investigations at higher magnifications. B_U is upper bainite, B_L is lower bainite, B_C is coalesced bainite, and M is martensite.

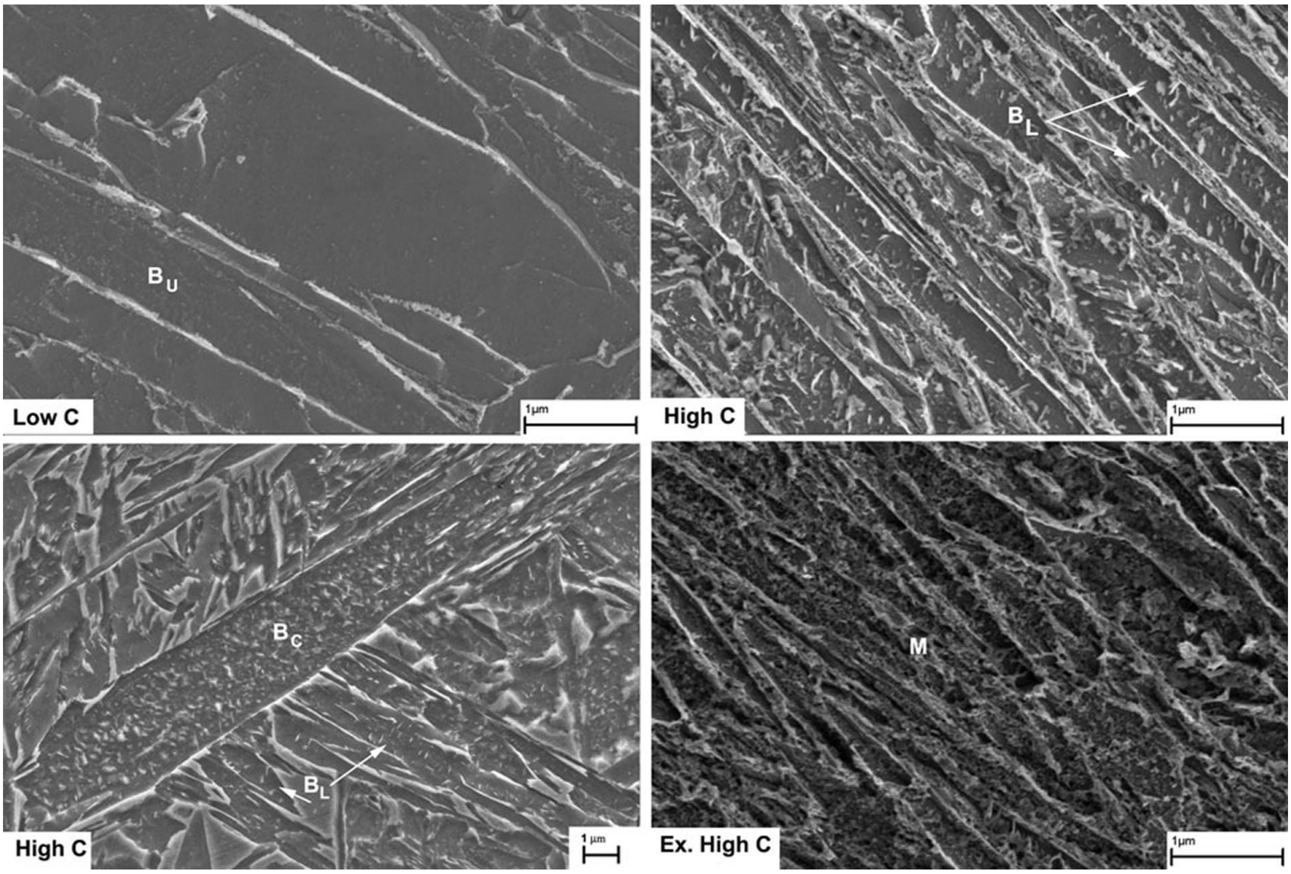

Fig. 4 FEGSEM micrographs presenting the morphology at high magnification of the different microstructural constituents as found in as deposited weld metal. B_U is upper bainite, B_L is lower bainite, B_C is coalesced bainite, and M is martensite.

Microstructure – Reheated Bead

The microstructure of reheated beads was also examined using FEGSEM. Fig. 5 shows six micrographs, three at low magnification and three at high magnification. As expected from investigations in the last bead, the microstructure was found to change from bainitic to martensitic with the grain size getting finer as a result of increasing carbon content. Fig. 5 A and B show the Low C weld metal at low and high magnification after reheating. The last bead was characterised to be mainly upper bainite (Fig. 3 and 4) and in reheated regions it is found that the cementite has coarsened at the grain boundaries and that very small precipitates have developed within the bainitic ferrite grains (Fig. 5B). These precipitates were confirmed to be cementite using transmission electron microscopy and electron diffraction with the results presented in previous work [11]. The Med. C weld metal was found to consist of tempered lower bainite, tempered coalesced bainite and tempered martensite (Fig. 5C). Fig. 5 D presents the typical morphology of tempered lower bainite in the Med. C weld metal where the cementite precipitates have coarsened. Fig. 5 E and F show the morphology of tempered martensite both at low magnification and at high magnification in the Ex. High C weld metal.

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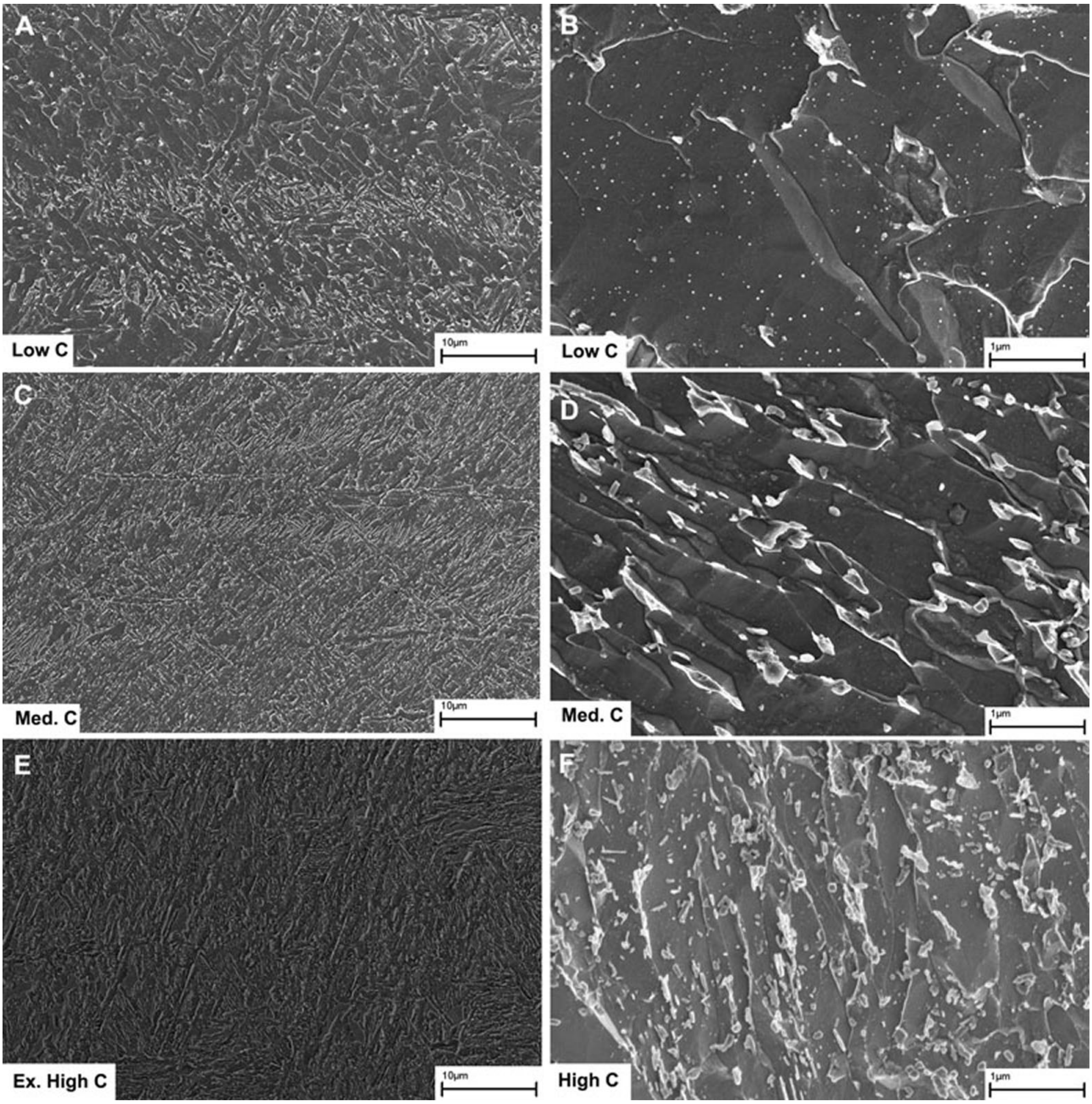

Fig. 5. FEGSEM micrographs presenting an overview of the microstructural morphology in reheated beads (left column) and high magnification micrographs (right column) showing the morphology of tempered bainite (B and D) and martensite (F).

DISCUSSION

As carbon increased, the microstructure changed from mainly upper bainite (Low C weld metal) to lower bainite, coalesced bainite with martensite (Med. C weld metal) and then became mainly martensitic at the highest carbon levels (High C and Ex. High C weld metals). From a basic understanding of these microstructural constituents, it is clear that carbon additions are increasing the stability of austenite to lower transformation temperatures on cooling. This trend was measured and reported in previous work for the Low C and Med. C weld metals using dilatometry. It was found that the austenite transformation temperature was reduced from 490°C to 355°C when carbon was increased from 0.03 to 0.11 wt. % [18].

Initial additions of carbon increased both yield and tensile strength as was expected from neural network model predictions (Fig. 1). However, as relatively high carbon levels were reached (0.18 and 0.34 wt. %), both yield and tensile strength began to decrease due to carbon additions (Table 2). The initial gain of strength may be accounted for by the microstructure changing from mainly upper bainite to that of lower bainite and martensite. The fact that strength drops at high carbon levels is more difficult to explain. One theory is that retained austenite has become more prominent within the microstructure as a result of reducing the austenite transformation temperature. Although this has not been identified and is almost impossible to do so with FEGSEM, it is expected that increasing carbon will promote greater amounts of retained austenite within the microstructure. Measurement of the retained austenite content is planned for further work using X-ray diffraction.

Coalesced bainite is a recently discovered constituent in high strength steel weld metals [17] and is expected to have a negative effect on toughness. It 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 [16]. It was also reported that segregation, which develops during cooling is important in determining the local austenite transformation temperature [14]. In addition to segregation effects, in these weld metals as carbon is increased and transformation takes place at lower temperatures, kinetics will also play a more important role in determining which constituent forms [19].

Toughness was found to decrease with every increase in carbon (Fig. 2), which was expected and predicted by the neural network modelling (Fig. 1). Toughness loss can be attributed first to the presence of greater amounts of coalesced bainite at intermediate carbon levels and then martensite at high carbon levels. The presence of coalesced bainite leads to a large grain size and is expected to offer little resistance to a propagating crack. It was observed that as carbon increases, martensite becomes the dominant microstructural constituent. On reheating due to the multiple weld passes, the martensite tempers and a lot of precipitation is taking place in the underlying beads (Fig. 5). The number and size of these precipitates is also believed to contribute to a reduction in toughness.

CONCLUSIONS

Four experimental weld metals were produced using SMAW with increasing carbon content from 0.03 to 0.34 wt. % in combination with 7 and 0.5 wt % Ni and Mn, respectively. These were then mechanically tested and their microstructure characterized using FEGSEM.

Carbon additions from 0.03 to 0.11 wt. % increased yield strength to 912 MPa while impact toughness recorded 63 J at –100 °C. Above 0.11 wt. % carbon, both yield strength and impact toughness were reduced as a result of carbon additions.

Mechanical properties of the weld metals were explained in terms of their microstructural content. At 0.03 wt. % carbon, upper and lower bainite was found to provide good strength and excellent impact toughness. A microstructure with a well-interspersed distribution of martensite, lower and coalesced bainite was found to give the best combination of strength and toughness at 0.11 wt. % carbon. At higher carbon levels strength loss is attributed to the expected presence of retained austenite within a mainly martensitic microstructure while decreasing toughness is accounted for by the larger and more numerous precipitates that form when high carbon martensite is tempered.

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