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EVALUATION OF TOUGHNESS OF HIGH STRENGTH LOW ALLOY (HSLA) STEELS AS A FUNCTION OF CARBON CONTENT

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Abstract - The influence of carbon content on the microstructure and toughness of HSLA steel at room temperature was investigated based on experimental work and literature. It was revealed that increasing the carbon content in from 0.06 to 0.14 wt-% is detrimental to toughness, giving higher impact transition temperature. The deterioration of toughness was correlated to undesired changes in the microstructure, which showed an increase in pearlite volume fraction at the expense of ferrite. At high carbon content, cementite of pearlite was found to grow more rapidly to form continuous plates which act as preferred sites for crack nucleation and propagation. In addition, the lamellar spacing of the pearlite increased as a function of carbon content, which in turn gave worse toughness. The presence of high carbon content and carbide forming elements in the chemical composition was more detrimental to toughness due to the formation of thick carbides around the grain boundaries. These carbides act as a path for crack propagation, which makes it easy for cracks to cohere, leading to intergranular fracture.

Keywords - HSLA steel, Carbon, Brittleness, Toughness, Impact Transition Temperature (ITT).

I. INTRODUCTION

In recent years, much attention has been paid to the development of steel having superior properties such as high strength, good fracture toughness at low temperature [1] and low impact transition temperature (ITT) [2]; the temperature at which the steel fracture transits from ductile to brittle condition. Steels for various high-technology applications, such as aerospace and automotive, need to have ultrahigh strength combined with good toughness to meet the essential requirements of minimum weight and maximum reliability [3].

HSLA steel offers a favourable strength-to-weight ratio while maintaining a good level of toughness at low cost in comparison with conventional steels [4]. Therefore, the production rate of HSLA steels has increased considerably in the last decade and it is gradually increasing [5]. However, higher strength-to-weight ratios are becoming in demand, particularly for the automobile industry in order to increase fuel efficiency and minimise CO_2 emissions.
It is well established that strength can be enhanced considerably by the addition of high amount of carbon but generally carbon is not a favoured element when considering toughness [6]. Deterioration of toughness was found to be associated with alteration of microstructural features, such as the phases present in the microstructure and the formation of embrittling compounds [6].

The current work aims to investigate the effect of carbon content on the toughness of HSLA steel in order to deeply understand the relationship between microstructural features and toughness based on the current experimental work and literature.

II. EXPERIMENTAL

The steel was laboratory vacuum 22kg melt. The ingot was soaked at 1200°C and hot rolled to a thickness of 15mm, finish rolling at 950°C. The plate was air cooled from 950°C to room temperature; the cooling rate through the transformation being 33°C min^{-1}.
In the current work, the carbon content is kept low at ~0.06 wt-% so as to minimise the likehood of formation of lower temperature products. The current work will compare the toughness of low carbon containing steel used in this work with previous work [7] which used higher carbon addition ~0.14wt-%.
The toughness was evaluated using Charpy V-notch impact testing at various temperatures to establish the impact transition curve. Standard Charpy V-notch impact samples were machined from the rolled plates in the rolling direction. The samples were prepared for the Charpy impact V-notch test at various temperatures based on ISO 148-1 standard. Controlling the temperature of each sample was achieved by immersing the specimen into constant temperature baths of liquid nitrogen and isopentane for 30 minutes. This process was repeated for each sample over a range of temperatures to assess the toughness behaviour against temperature.

III. RESULTS

Figure 1 shows the impact behaviour at various temperatures of high carbon bearing steel (0.14wt-%) from previous work [7] and impact behaviour of low carbon bearing steel (0.06wt-%) examined in the current work. The results show that as the temperature drops the toughness deteriorates and the steel becomes more brittle for both steels. However, reducing carbon content in the chemical composition is shown to improve the toughness considerably. The higher carbon bearing steel (0.14wt-%) has an ITT of -30°C while lowering the carbon content to 0.06wt-% lowered the ITT considerably to -80°C. The fracture behaviour of the low carbon bearing steel showed a drop in toughness as the temperature drops from -20 to -100°C (Figure 2).

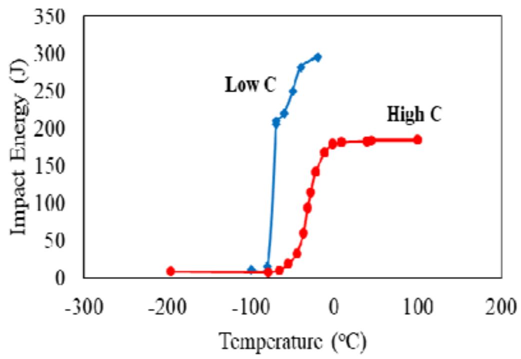

Figure 1. Impact transition curves of HSLA steels at high carbon content (0.14wt-%) from previous work [7] and at low carbon content (0.06wt-%) examined in the current work.

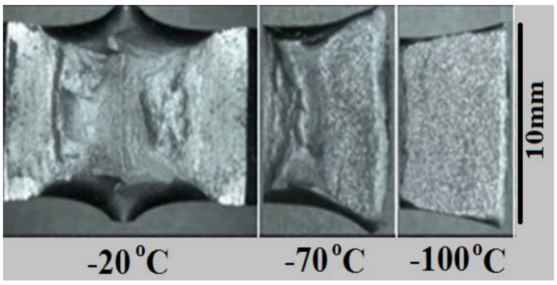

Figure 2. Fracture behaviour of HSLA steel at the low carbon content (0.06wt-%) at various temperatures in the current work.

IV. DISCUSSION

The deterioration of toughness in high carbon bearing HSLA steel will be discussed thoroughly based on changes of microstructural features. The discussion is based on previous studies found in literature in order to have a deep understanding of the role of carbon in controlling the microstructure and hence toughness.

4.1. Phases in the microstructure

The microstructure of HSLA consists mainly of ferrite and pearlite. Each of these phases has its own properties. Therefore, the volume fraction of each phase contributes significantly in altering the mechanical properties of the steel. Ferrite is soft in nature and hence increasing its content in the microstructure enhances toughness. Pearlite consists of a lamellar of ferrite and cementite which is rich in carbon and this makes it harder and more brittle at room temperature. Increasing the carbon content, raises the volume fraction of pearlite in the microstructure at the expense of ferrite. Initially, cracks initiate in cementite plates during deformation then extend through the pearlite colonies. Subsequently, cracks extend from the pearlite colonies into adjacent ferrite grains, leading to brittle fracture [8]. Therefore, the lower brittleness given by the lower carbon containing steel in this work can be mainly attributed to the lower volume fraction of the brittle pearlite phase present in the microstructure.

4.2. Characteristics of cementite

The morphology and volume fraction of cementite in pearlite has a major effect on toughness in low alloy steel [9]. In high carbon containing steels, cementite forms as thick and continuous plates but changes to dispersed, discontinuous and thinner ones upon reducing the carbon content. This is attributed to the lack of carbon in the pearlite colony leading to the formation of degenerate pearlite which enhances toughness. In addition, more space becomes available for the soft ferrite to form in the pearlite colony at the expense of the brittle cementite, giving better toughness, owing to the lower carbon content [9].

The size of the pearlite grains plays a dominant role in controlling the toughness of steel through the thickness of cementite [10]. Coarse pearlite size deforms inhomogeneously leading to strain concentration in narrow slip bands [11]. The thick cementite of coarse pearlite provides poor toughness under impact loading, leading to immediate fracture without prior deformation. This behaviour is ascribed to a shear cracking process which at a later stage develops into cleavage type cracks [12]. On the other hand, thin cementite in fine pearlite offers better level of toughness and necks down into fragments under impact loads, giving ductile fracture [13,14]. Other work [15] has reported that the refinement of the pearlite colony size enhances toughness due to higher area fraction of boundaries which act as obstacles to brittle crack propagation.

4.3. Prior austenite grain size and interlamellar spacing of the pearlite

Bae et al., [16] investigated the influence of microstructural features, such as prior austenite grain size and interlamellar spacing of the pearlite on the toughness of pearlitic steels at carbons in the range of 0.52 – 0.82wt-%. They observed that the size of prior austenite grain and interlamellar spacing increased considerably with increase in carbon content leading to worse toughness. Although interlamellar spacing is affected markedly by the carbon content, cooling rate was reported to have a stronger effect, in which increasing the cooling rate (100 – 1000°C min^{-1}) was found to reduce the interlamellar spacing considerably [15].

4.4. Grain boundary carbides

Grain boundary carbides act as preferred sites for cracks initiation, propagation and coalescence leading to poor toughness [17]. This behaviour was found to be associated with the presence of carbide forming elements, such as Nb which is a strong carbide forming element. The degree to which carbides influence toughness depends on their thickness on their thickness and volume fraction and they have a big in influence on impact performance and brittle fracture. Most of the thermomechanical processing techniques lack the capability of hindering the formation of grain boundary carbides. However, the characteristics of carbides, i.e. size and volume fraction, can be controlled through carbon content and processing parameters.

4.5. Reaction of carbon with manganese and silicon

Most steels are alloyed with various amounts of manganese and silicon. In the constitutional equilibrium Fe-C diagram, approx. 0.8%C is present at the eutectoid composition. Mn and Si reduce the carbon content, (the eutectoid is at 0.6%C when 1.4%Mn is present) and this increases the amount of proeutectoid cementite and reduces the volume fraction of ferrite in the microstructure [8]. The formation of an increased amount of pearlite, pearlite being deleterious to impact behaviour is more than compensated for by Mn giving additional grain refinement and in the case of Si by reducing the C that segregates to the boundaries and locks the dislocations. However, the addition of silicon to very high carbon steels (0.8wt-%C) is reported to retard the formation of the network of the continuous grain-boundary cementite film which is present when silicon is absent [18]. Therefore, steels at the hypereutectoid range have a better than expected combination of high strength and impact behaviour through the addition of silicon.

Low carbon containing steels are chosen for their good toughness, weldability and impact behaviour. However, the strength level in these steels is not sufficient to meet the growing demands for high strength steels in the rapidly developing industry. Therefore, alternative alloying elements are being explored to compensate for this poor strength.

V. CONCLUSIONS

The current work examined the effect of carbon content on the toughness of high strength low alloy (HSLA) steel. High addition of carbon in the alloying composition leads to poor toughness through altering the microstructural features by the following mechanisms:

- Carbon alters the microstructure by increasing the volume fraction of pearlite at the expense of ferrite.
- Carbon enhances the formation and growth of cementite in the pearlite colonies. The cementite plates are preferred sites for cracks formation and propagation under impact load.
- Carbon enlarges the interlamellar spacing of pearlite, which contributes in the deterioration of toughness.
- Carbon encourages the formation of lower transformation products, such as martensite and baintite, especially at the presence of aluminium. Both products are hard and undesirable when considering toughness.
- Combination of high carbon content and carbide forming elements enhances the formation and growth of carbides at the grain boundaries. Under impact load, cracks preferably initiate at these brittle carbides then propagate and interlink, leading to final fracture.

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