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Effect of microstructure and grain size on the fracture toughness of a micro-alloyed steel

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ABSTRACT

It has been reported that the high temperature austenitisation heat treatments have resulted in improving the fracture toughness of several structural steels. This is contrary to the conventional understanding of the relationship between larger prior austenite grain sizes, associated with high austenitising temperature, and fracture toughness. This anomalous increase in fracture toughness has some important practical significance to welded joints where the material adjacent to fusion zone experiences high austenitising temperatures resulting in a coarse grain zone. This investigation has been undertaken to verify the effects of microstructure and grain size on fracture toughness in a typical pressure vessel steel that is extensively welded during fabrications. A range of simulated weld heat affected zone microstructures were produced by austenitising the specimens at various temperatures followed by quenching at three different cooling rates. The trends of variations in properties, such as, fracture toughness are explained in terms of grain size, and microstructural analyses. It was observed that the specimens provided with low temperature austenitisation followed by air-quench possess a better fracture toughness than the base metal.

1. Introduction

Conventional structural engineering alloys undergo significant alterations in prior austenite grain sizes and the phase constituents during heat treatment and result in different mechanical properties. The conventional understanding is that the larger grain sizes, associated with higher austenitising temperature, would generally result in a lower toughness. Further, the fracture toughness is also expected to vary in a manner similar to that of impact toughness. However, anomalous increase in the plane strain fracture toughness, K_{IC}, of a typical high strength low alloy steel (HSLA) was observed by Zackay et al. [1] at higher austenitising temperatures than the conventional heat treatment temperatures. Similar results have been reported by several investigators [2–18] which confirm that, in case of certain HSLA steels, C–Mn micro-alloyed steels and C–Mn steels, the high temperature (HT) austenitising heat treatment results in an improvement in the plain strain fracture toughness in spite of a decrease in impact toughness, which is contrary to the conventional knowledge of the relation between grain size and toughness. Various mechanisms, such as, presence of inter-lath retained austenite film [2,3,5,9], elimination of twinned martensite plates [2,5,10], changes in the morphology of inclusion and second phase particles [5–7,11,12,16–18], difference in the stress triaxiality that exists at a notch tip as compared to a sharp crack tip [13–15] have been attributed to explain this anomalous behaviour. It is also reported [13,14] that with an increase in the prior austenite grain size the characteristic fracture process zone size, usually of the order of the grain size to cause cleavage and intergranular fracture, also increases leading to an increase in the fracture toughness.

A recent study [18] on C–Mn–B micro-alloyed steel subjected to a range of austenitising treatments (950–1350 °C) showed negligible effect of grain size on the fracture toughness. The fracture toughness remained more or less unaltered irrespective of the austenitising temperature. Thus, the published literature is ambiguous with respect to the effect of prior austenite grain size on the fracture behaviour.

Conventionally, thermo-mechanical treatments are carried out at about Ac3 temperature and most of the studies on the effect of austenitising temperature on the material behaviour thus centred around this temperature. There is also a great deal of interest in understanding the effect of high temperature austenitisation and

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Table 1
Chemical composition and mechanical properties of the base material.

(i) Chemical analysis (wt.%)								
C	Mn	Si	S	P	Nb	N	O	Carbon equi-valent, CE_{IIW}
0.19	1.48	0.032	0.025	0.033	0.012	0.0087	0.0085	0.43

(ii) Mechanical properties				
Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)	Impact toughness (J)	CTOD, δ_c (mm)
400 (min)	600 (min)	22 (min)	84	0.188

cooling rates on the fracture toughness and this has very important practical significance and the subject material is a typical structural steel that is extensively welded during fabrication. During the process of welding, material adjacent to the fusion zone also experiences high austenitising temperatures resulting in a coarse grain zone. A thorough understanding of the effects of high temperature austenitisation on fracture properties could avoid a number of weld related failures that are often attributed to low toughness in the heat affected zone (HAZ). The present investigation is an attempt to explain the effect of higher austenitising temperature, on the toughness behaviour of a structural steel, in terms of microstructure and grain size.

2. Materials and methods

The chemical composition and the mechanical properties of the as-received steel are reported in Table 1. Fracture toughness test specimens and impact toughness test specimens (nominal dimensions: 12 mm × 22 mm × 105 mm and 12 mm × 12 mm × 60 mm, respectively) were fabricated and nickel plated, to avoid oxidation during austenitising process, for heat treatments. The specimen blanks were austenitised for 1 h at a temperature ranging between 825 °C and 1275 °C and then quenched, in air, oil and water to induce various cooling rates. For the purpose of this investigation the heat treatments at 825 °C and 975 °C were termed as low temperature-austenitised (LT) and those at 1125 °C and 1275 °C were denoted as high temperature-austenitised (HT). For both the LT and HT series, the letter A, O, or W that follows represents quenching in air, oil or water, respectively.

2.1. Metallography and mechanical property evaluation

The metallographic examination was conducted on small coupons that were cut from the impact-tested specimen ends. General microstructures were revealed by etching in a freshly prepared 2% nital solution and the prior austenite grain size was determined after etching in Vilella's reagent. An optical microscope (Leco DM 400) with image analysis software was employed for all the microstructural analyses.

Standard Charpy V notch (CVN) samples with a 2 mm notch were tested on a Wolpert pendulum impact testing machine, as per ASTM E 23 at room temperature (27 °C). For each of the heat treated specimen condition at least five specimens were tested.

A single edge notch bend (SENB) geometry was chosen for fracture toughness testing of heat treated specimens. The specimens were prepared, as per BS 7448-1:1991, with a 4 mm deep V notch across the thickness at the mid-length [19]. All the specimens were machined with the crack plane parallel to the rolling direction and the longitudinal axis of the specimen normal to the rolling direction of the plate. The heat treated specimens were surface ground to remove any decarburised layer and finished to 2 μm on the loading surfaces. These were fatigue pre-cracked to a crack length, a, of 10 mm ($a/W \cong 0.5$) and subsequently loaded in a three point bend fixture till complete failure or an appreciable load drop was detected on the load–displacement plot. A preliminary calculation revealed that, for the specimen size considered in these investigations, a valid plane strain fracture toughness, K_{IC}, could not be obtained. Hence, the crack tip opening displacement (CTOD, δ), at the onset of crack initiation, was chosen as the critical fracture toughness, δ_c, for comparing across specimens of various heat treated conditions. In softer conditions of the specimens, such as base material and LTA conditions, where a distinct crack initiation point could not be noticed on the load *vs.* displacement plots, the critical point was taken as the attainment of first load maxima. The measured crack mouth opening displacement, by a clip-on displacement gauge attached to the knife edges affixed to the front face on either side of the notch of the specimen, was converted to CTOD as per BS 7448-1:1991 [19] using the following equation:

$$\mathrm{CTOD} = \delta = \frac{K^2(1-\nu^2)}{2\sigma_{ys}E} + \frac{V_p}{1+\frac{a+z}{r(W-a)}} \quad (1)$$

where K is the stress intensity factor; ν is the Poisson's ratio; E is the Young's modulus; a is the crack length; W is the specimen width; z is the thickness of the knife edge; V_p is the plastic opening of the COD gauge and r is a rotational factor taken as 0.45 for deep cracked three point bend specimens. It may be noted that wherever fracture toughness has been mentioned in this text, it refers to CTOD in millimetres obtained from Eq. (1).

The fracture toughness tests were performed on an Instron closed loop servo hydraulic test machine with model 8501 digital controller. The tests were conducted under displacement control at a rate of 0.2 mm/min. All the tests were conducted on duplicate specimens and if the results were found to differ by more than 10% a third was tested and the average of the three specimens is reported.

2.2. Fractography

The fracture surfaces of the fracture toughness and the impact toughness test specimens were examined under a scanning electron microscope (Jeol, JSM 840A) to observe the fracture mode.

3. Results and discussion

The material under investigation is micro-alloyed steel with Nb as the micro-alloying element which showed an average prior austenite grain size of 42 μm. The microstructure of the as-received material is shown in Fig. 1. The as-received material showed typical ferrite pearlite structure. Austenitising treatment at various temperatures brought about major microstructural changes to the starting ferrite–pearlite microstructure.

3.1. Effect of heat treatment on microstructure

3.1.1. Prior austenite grain size

Fig. 2 shows the variation of prior austenite grain size with the austenitising temperature. The specimens austenitised at 825 °C and 975 °C, when compared with as-received material, resulted