The effect of grain size on crack propagation in a ferritic steel

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Abstract

Polycrystalline ferritic steels show ductile fracture at higher temperatures and brittle fracture at relatively lower temperatures. The brittle fracture can be either transgranular cleavage or intergranular. The crack initiation and propagation in a polycrystalline ferritic steel, EN1, thermo-mechanically treated to produce material with a defined combination of grain size has been studied. This treatment produced a layered microstructure comprising grains of ~20 μm in one layer and ~40 μm in the other. Small three point bend specimens with a dimension of 2.7 mm×5 mm×20 mm have been tested at a constant displacement rate at a temperature of -196°C using a Zwick tensometer equipped with an environmental chamber. The influence of grain size on crack initiation and propagation has been studied with attention given to brittle cracks propagating from the coarser to finer grain structure and vice versa. The results are discussed with particular reference to changes in fracture morphology.

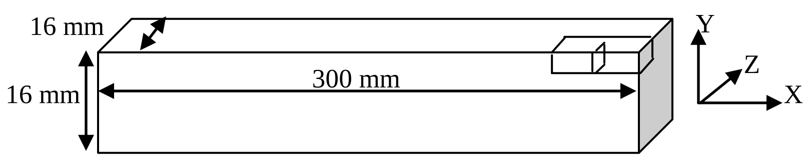
Introduction

The fracture of a solid arises from the formation of new surfaces in a body created by a thermomechanically irreversible process. Where a body is subjected to an external force an imperfection or flaw may grow into a sizeable fracture surface which leads to complete separation. As a consequence various approaches have been invoked to provide a description of the initiation and growth of cracks in single and polycrystalline materials [1,2]. The interaction between microstructure and brittle fracture in mild and low carbon steels has received much attention over the years and identified brittle cleavage and intergranular fracture [3]. Early cleavage fracture models assumed cracking of carbide precipitates at the ferrite grain boundary as an initiation mechanism [4]. Many researchers accepted this model where dislocations pile-up at grain boundary carbide precipitates to produce cracks and the final fracture is governed by the size of this precipitate crack [5,6]. In contrast, grain size is described as a controlling microstructural feature that determines the cleavage fracture stress [7,8]. Tweed and Knott were the first to report that non-metallic inclusions strongly influence the cleavage fracture stress and micro-mechanisms in steels [9]. Moreover both TiN particles and the grain size have been shown to affect the cleavage fracture processes in some steels [10].

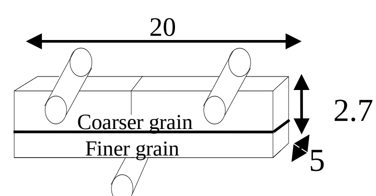
Overall there is a balance between crack propagation and resistance. Microstructural features such as grain boundaries can provide resistance to cleavage fracture because accommodation is required to compensate for the mismatch between the orientation of the cleavage planes on either side of the interface [11]. In the extreme such microstructural features can lead to crack arrest. Crack arrest has been observed in a range of materials. However in metals and alloys some variations in microstructure can lead to the arrest of a propagating crack. In this study we consider the role of grain size on the potential to arrest cleavage crack propagation on {001} planes in an EN1 ferritic steel thermo-mechanically treated to produce a defined combination of different grain sizes.

Experimental

A section of a 16 mm square EN1A ferritic steel bar was heat treated at a temperature of 920°C for 1 hour and air cooled to room temperature. The chemical composition of the material is given in Table 1. These, specimens were compressed in the Z direction, Figure 1a, using a Zwick tensometer to a strain level of 2.2% and annealed at 690°C for 3 hours. As a result of greater near surface strains, this heat treatment resulted in layered grain size microstructure which is used to propagate cracks from coarser to finer grains and vice-versa. The coarser mean grain size is ~40 μm and finer grain size is ~20 μm (mean linear intercept). A millimetre-scale three point bend geometry test has been developed to study the crack propagation in this ferritic steel. Specimens with dimensions of 20 mm × 5 mm × 2.7 mm were extracted from the EN1 steel bar by electric discharge machining (EDM) after the heat treatment with an orientation with respect to the original rolling direction as shown in Figure 1a. The notches were cut to a depth of ~ one third the width (a/w = 1/3) by electric discharge machining with a wire of diameter 0.1 mm. Details of the specimen is given in Figure 1b.



(a)



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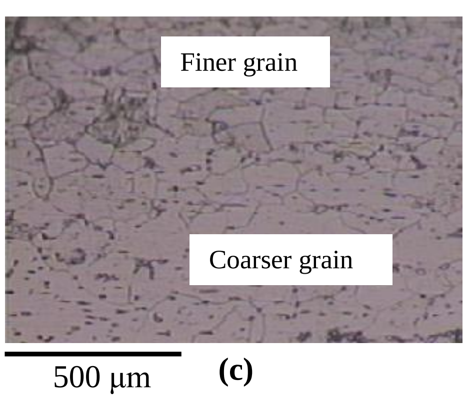

(c)

Figure 1. The EN1 steel thermo-mechanically treated to produce coarser and finer grain size layers (a) selection of the three point bend specimens (b) detail of the notched three point bend specimen (dimension in mm) (c) optical micrograph showing the finer and coarser ferrite layers

At a temperature of -196°C, the specimens were loaded with a load rate of $3Ns^{-1}$ and three repeated tests were undertaken. Load - displacement was acquired using the embedded software in the system. Fracture surfaces of the test specimens were examined using scanning electron microscope in the secondary electron mode at an accelerating voltage of 25 kV (Hitachi). The chemical micro-analysis was carried out using an energy dispersive X-ray analysis (EDX) spectrometer attached to the instrument.

Table 1 Chemical composition (wt%)

C	Si	Mn	P	S	Cr	Mo	Ni	Al	As	Ti	V	N	O	Fe
0.06	0.30	0.78	0.015	0.05	0.05	<0.01	0.02	0.03	<0.01	<0.01	<0.01	<0.007	<0.007	Bal

Results and Discussion

The population of inclusions were identified within the EN1 steel, Figure 1c, by X-ray microanalysis to be predominantly MnS with a mean size of ~1.4 µm. In addition both inter- and intra- granular carbide precipitates were present. The load-displacement curves obtained from the three point bend tests undertaken with the pre-notch positioned in the finer and coarser material respectively are shown in Figures 2a and b. The former gave load-displacement curves where the cracks propagated across the interface between the finer and coarser grain size, Figure 2a. In this case the curve was continuous to the peak load where fast fracture occurred, leading to final separation of the specimen.

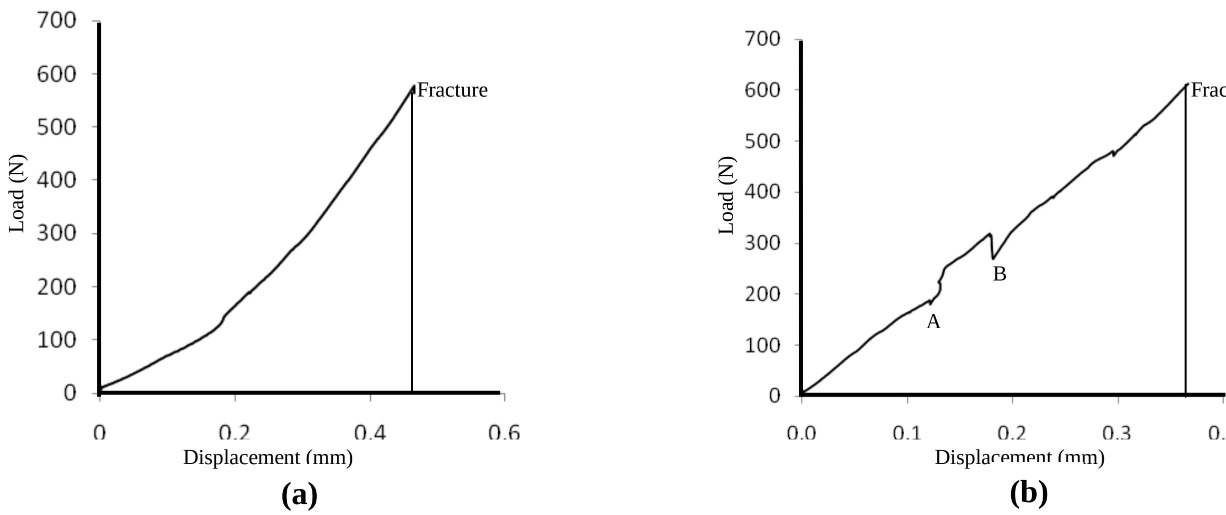

Figure 2. The load-displacement curves for the crack growing from (a) finer to coarser grains (b) the coarser to finer grains. The latter shows distinct positions A and B where crack arrest occurs.

A similar behaviour was observed for all the specimens tested. The load-displacement curves for coarser to finer microstructure showed three discrete regions before the final separation, Figure 2b. The curve is linear up to a load of ~180 N which corresponds with point A, in Figure 2b, where there is a load drop corresponding to the arrest of the crack at the coarser to finer grain interface. This is followed by a rise in load to ~290 N and a further decrease at point B, followed by a rise in load to final fracture of the specimen. Figure 3a shows a low magnification image of the fracture surface obtained at -196°C for coarser to finer region microstructure. The corresponding features across this fracture surface are given schematically in Figure 3b. From the notch root to a distance of ~0.2mm, in the coarser grain region cleavage fracture is observed, Figure 3c (region X in Figure 3b). This corresponds to point A in Figure 2b where the crack arrests at the coarser to finer grain interface. Following this initial load drop there is an increase in load to point B where there is a second load drop and the crack then propagates along an intergranular path, Figure 3d. The intergranular cracking extends over a distance of about 100 μm or five fine grains, region Y in Figure 3b. The load again recovers at point B, Figure 2b and final cleavage fracture, Figure 3e, within the finer grain size material occurs at peak load across the remaining section of the specimen, region Z in Figure 3b.

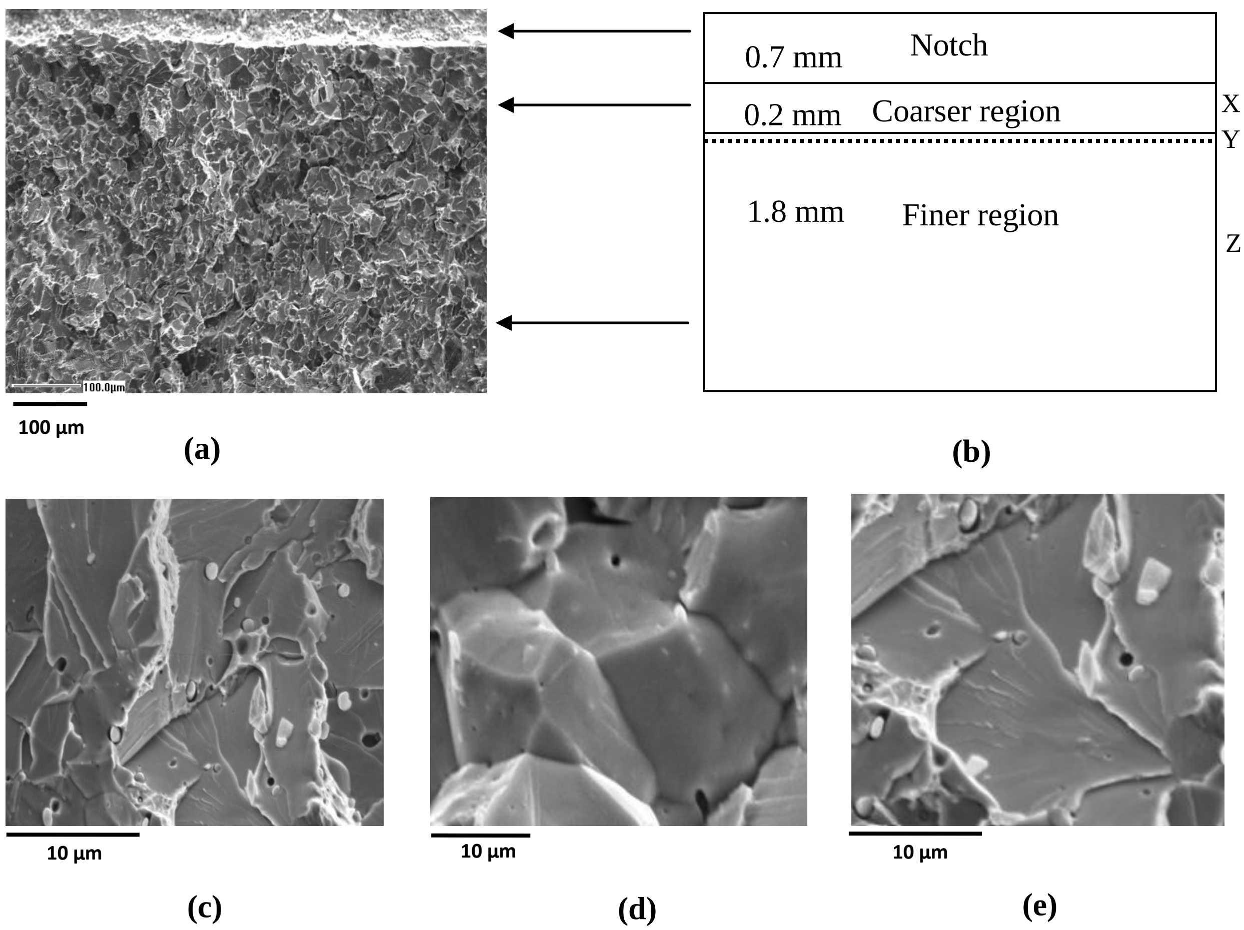

Figure 3. (a) Secondary electron image of the fracture surface across the section of the specimen (b) the corresponding schematic diagram showing the related dimensions (c) the coarser grain size region X (d) the localized region Y and (e) the finer grain size region Z

The brittle crack nucleation and growth in ferritic steels at low temperature takes place on {100} planes [12] with the initiation at microstructural features such as carbide precipitates and inclusions [5]. Knott has reported that for cleavage fracture in low carbon ferritic weld metals, fracture is promoted by the presence of coarser inclusions and coarser ferrite grain grains [13]. The load-displacement data, Figures 2a and b combined with the observed crack morphologies demonstrated that brittle crack propagation across the mixed grain sized structure in the EN1 ferritic steel at -196°C is complex. In the case of cracks which initiate within the finer grain size material and then propagate from this region to the coarser grain region the process is continuous cleavage frature on {100} ferrite planes [14]. This leads to final separation of the three point bend geometry specimens. Once initiated at an inclusion or carbide precipitate in the finer grain ferrite the transition across the finer to coarser interface reduces the resistive path for crack propagation. Hence as shown in Figure 2a there is a single load at which failure of the specimen occurs. In the case of the cleavage crack propagating from the coarser grain size ferrite to the finer the process is complex with the observation of discrete crack arrest points A and B in the load-displacement curve, Figure 2b. The sequence of crack propagation is summarised schematically in Figure 4.

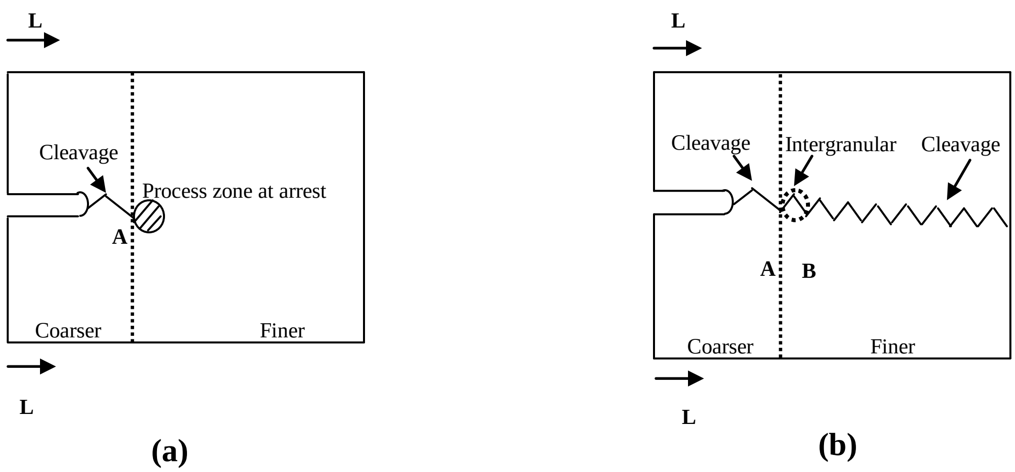

Figure 4. A schematic diagram summarizing the crack propagation sequence from the notch root (a) cleavage fracture in the coarser grains up to the coarser to finer interface (b) extension through the process zone and then to final specimen separation

The process of cleavage crack propagation in the coarser grain ferrite is dynamic so that energy will be absorbed by the specimen on arrest of the crack, Figure 4a. The yield strength of the finer grain size ferrite will exceed that of the coarser. The concept of a process zone is a fundamental length parameter [15,16]. The characteristic length of the process zone at the tip of the cleavage crack at arrest point A in Figure 4a is determined to be ~114 μm [17]. However this value is derived from a static calculation based upon the size of the notch plus crack, but in reality the process zone formed at arrest is dynamic. Hence the arrest of the rapidly propagating cleavage crack creates a transient process zone. The associated additional energy can further extend the size of the process zone and/or promote energy absorbing deformation processes such as twin formation and enhanced slip. Certainly it is recognised that increasing strain rate promotes the formation of {112} twins in a ferritic steel [12]. The increased load in Figure 2b to point B where further arrest occurs is associated with intergranular brittle fracture, Figure 3d. Hence, it is proposed that the strength of the grain boundaries within the process zone is degraded relative to the cleavage fracture energy by the dynamic processes. The intergranular fracture, Figure 3d, extends over a region of about five grains, ~100µm, and is therefore consistent in spatial extent with the size of a process zone. Certainly examination of the intergranular fracture surfaces, Figure 5, provides evidence of both slip steps and twins.

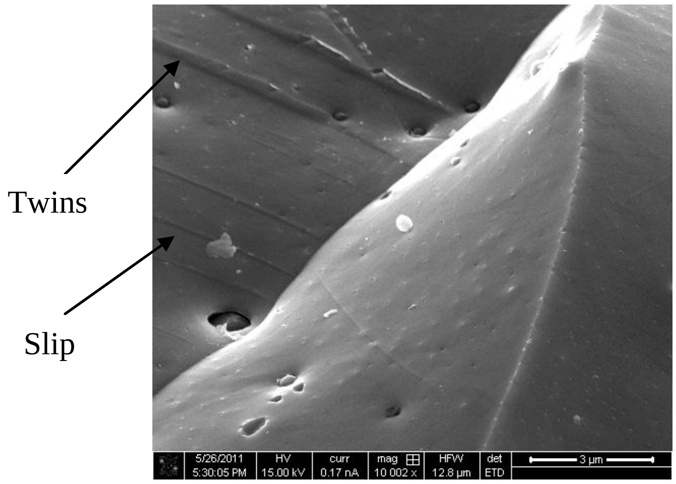

Figure 5. A scanning electron micrograph showing the residual damage at the interface between coarser and finer grain region

Interaction of twins and the pile-up of slip dislocations are recognised to promote localised voids at grain boundaries. This leads to small voids or decohesion of the interfaces between inclusions and/or carbide precipitates at the grain boundaries. It is this localised damage that is proposed to be sufficient to reduce the resistance to intergranular fracture to below that for cleavage. Following the intergranular crack extension to the spatial limit of the process zone, point B in Figure 2b, there is further arrest before the load is sufficient to effect cleavage failure across the remaining finer grain sized ferrite region, Figure 4b.

The present consideration provides a qualitative description of the fracture process which is summarised in Figure 4. However, a quantitative model to describe the arrest process observed as the brittle cracks propagate from the coarser to finer grain size material is being developed based upon a consideration of energy release under both static and dynamic conditions.

Conclusions

1. The initiation and propagation of brittle fracture in an EN1 ferritic steel with a bimodal grain size distribution tested at a temperature of -196°C has been considered.

2. Crack propagation from a finer to coarser grain region showed cleavage fracture.

3. The coarser to finer grain region showed crack arrest at the interface between coarser and finer grain region; initial cleavage fracture in the coarser grain ferrite and then intergranular fracture over a limited region in the finer grain material followed by final cleavage fracture.

4. The extra energy released on the arrest of the cracking accounted for residual damage within the process zone formed at the interface between the coarser and finer grain size

material. Damage within the process zone is proposed to give arise for the observed localised intergranular fracture.

Acknowledgement

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