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The role of deformation twins in brittle crack propagation in iron–silicon steel

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Abstract

Crack initiation and propagation in polycrystalline metals and alloys can be characterized by the crack driving force and the resistance to fracture. Interfaces such as grain, sub-grain and interphase boundaries are microstructural features that can resist crack propagation. For iron–silicon polycrystalline steels, brittle fracture occurs predominately by transgranular cleavage but intergranular fracture is enhanced by embrittling heat-treatments. In this paper, we consider the role of deformation twin boundaries on the brittle crack propagation and fracture resistance of poly and single crystals of Fe–3 wt.% Si steel. Three-point bend, impact and miniaturized disc tests have been undertaken at temperatures in the range of 77–273 K. The fractographic features have been characterized with attention being given to (i) the role of the {1 1 2} deformation twins on the propagation of the {0 0 1} cleavage cracks and (ii) the process-zone of the propagating cleavage cracks. The results are discussed with reference to three-dimensional model predictions.

Keywords: Cleavage fracture; Iron–silicon steel; Three-dimensional geometrical models; Focused ion beam; Deformation twins

1. Introduction

In polycrystalline ferritic steels, crack initiation and growth mechanisms change with temperature. This results in the well-established variation of Charpy impact energy and fracture toughness with test temperature. These changes arise as brittle fracture at low temperatures is gradually replaced by ductile fracture as the temperature is increased [1]. Certainly, there have been advances in the ability to model fracture in polycrystalline materials, including three-dimensional (3-D) models describing brittle fracture at the microscale [1,2]. For ferritic steels at low temperatures, transgranular cleavage on {0 0 1} planes predominates. However, at grain and sub-grain boundaries (e.g. twins), it has been demonstrated that significant accommodation is required to compensate for the mismatch between the orientation of cleavage planes on either side of the interface [2]. Indeed, the importance of grain boundary orientation on the propagation of cracks, and in particular brittle cracks, has been recognized by various workers [3,4]. This is because cracks in adjacent grains do not meet each other in a line at the common boundary, except in special circumstances. Therefore, if the polycrystal is to separate into two parts, some accommodation is required at the grain boundary. Such accommodation can take the form of boundary failure by either a brittle or ductile mechanism, multiple cleavage or a mixture of these processes [1]. In addition to grain boundaries, metals and alloys may contain a range of other boundaries and interfaces that can affect the propagation of brittle cracks, particularly transgranular cleavage cracks [5,6]. Examples of such interfaces are twins observed in body-centred cubic (bcc) and hexagonal close-packed (hcp) metals, martensite and bainite plates or laths encountered in ferritic steels, and, more generally, interphase boundaries.

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The activation of {1 1 2} deformation twins can be an alternative to slip [7] and may contribute to the strengthening of brittle materials by work-hardening [8]. Proof of the formation of mechanical twins is typically given by instabilities or serrations in the stress–strain curves [9] or by metallographic [10] and fractographic examination [11,12]. It is noteworthy that in polycrystals and single crystals of materials, such as α-iron and Fe–3 wt.% Si steel, the role of deformation twins on the initiation of {0 0 1} cleavage cracks has been considered extensively. However, less attention has been given to the contribution of such {1 1 2} deformation twins on crack propagation. Tensile and bend-loading tests have shown that some twins may form prior to the onset of brittle fracture, thus resulting in an increase in plasticity and fracture resistance of metals and alloys [11,12]. Although the load–displacement curves usually indicate that twinning is confined to the lower shelf of the ductile-to-brittle transition (DBT) curve, tensile tests and fractographic examination of coarse-grain α-iron has revealed that twins can form at temperatures up to those approaching the onset of the brittle-to-ductile transition [11].

It is noteworthy that fine surface features, generally described as tongues, have been observed by Crussard et al. and associated with cleavage fracture [13]. Indeed, Berry suggested that they could represent fracture along {1 1 2} twins in ferritic steels [14]. More recently several workers, using atomistic modelling, have proposed that deformation twins may form ahead of a growing cleavage crack in bcc materials. For example, Bošanský and Šmida suggested that, as the local stress intensity increases, microcracks form at the interface of one of these twins and join the main cleavage crack [15]. These speculations are consistent with the atomistic models reviewed and studied by Machová and Ackland [16] and Farkas [17]. In particular, Machová and Ackland have examined the growth of sharp cracks in an atomistic model of α-iron using a 2-D plane strain approximation and an N-body potential. They found that the dominant process accompanying crack propagation is transient twin formation on the {1 1 2} planes. According to Machová and Ackland, twin nucleation is a reversible process so that twins may shrink and disappear as the cracks grow. Gao et al. [18] drew similar conclusions using different empirical potential functions for bcc materials. Therefore, it is important to understand the role of deformation twins during the propagation of {0 0 1} cleavage cracks in ferritic metals and alloys.

Various techniques are available to examine the details of these local crack-boundary interactions, ranging from simple optical microscopy to high-resolution scanning electron microscopy and in some cases, scanning probe techniques. More recently Hughes et al. have demonstrated that focused ion beam (FIB) systems can be used to study the interaction between cleavage cracks and grain boundaries [2]. The FIB provides a tool with which both to image and manipulate specimen surfaces at high resolutions. Through the use of an ion beam, material is sputtered from the surface as the beam rasters and secondary electrons can be collected to image the surface, in a manner similar to that of a scanning electron microscope. The use of ion-induced, secondary-electron imaging in the FIB lends itself to fractography through material and crystallographic channelling contrast effects. The ion beam can be used to mill and polish areas that create cross-sections, thus revealing subsurface information in combination with the fracture surface.

In this paper, for both polycrystals and single crystals of iron–silicon steel we consider the interaction of cleavage cracks with {1 1 2} deformation twins that form during the early stages of deformation and, therefore, prior to the onset of brittle fracture. In addition, {1 1 2} deformation twins that form during the propagation of {0 0 1} cleavage cracks are investigated. In Section 2, we describe a 3-D geometric model used to predict the interaction of cleavage cracks with deformation twins. Sections 3 and 4 describe the experimental procedures and the results. These results are discussed with respect to predictions of the 3-D model for cleavage crack interaction with pre-existing {1 1 2} twins and the mechanism of cleavage crack propagation. Conclusions are presented in Section 5.

2. 3-D geometric model

A 3-D geometric model of the type described by Crocker et al. [1] and Smith et al. [19] has been used to study the interaction between {0 0 1} cleavage cracks and {1 1 2} twins in a bcc crystal. A model consisting of a spherical grain was adopted to investigate the way in which a cleavage crack can propagate either across a twin or along a twin boundary. The crystallographic orientation of this bcc grain was selected randomly and the stress axis was fixed in space. A single twin boundary was introduced passing through the centre of the grain to generate the parent P and twin T as shown in Fig. 1. Hemisphere P has the original grain orientation and T is the mirror image of this

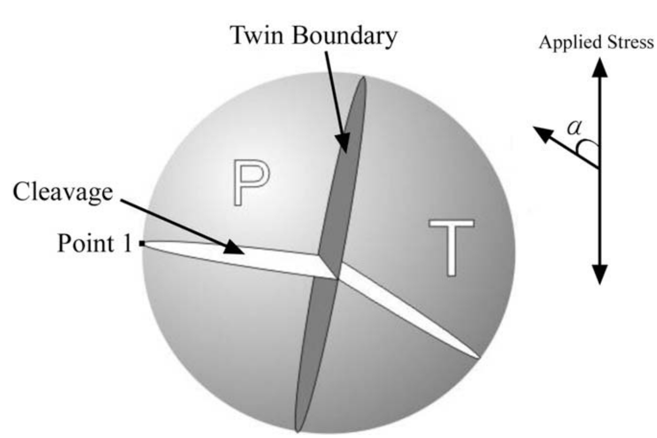

Fig. 1. The spherical model grain. The {1 1 2} twin boundary is a diametral plane which separates the parent grain (P) and the twin (T). The direction of the applied stress defines the specific {0 0 1} plane where cleavage fracture occurs.