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Micromechanics of cleavage fracture initiation in ferritic steels by carbide cracking

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Abstract

Cleavage fracture in ferritic steels is often initiated in brittle carbides randomly distributed in the material. The carbides break as a result of a fibre loading mechanism in which the stress levels in the carbides are raised, as the surrounding ferrite undergoes plastic deformation. The conditions in the vicinity of the nucleated micro-crack will then determine whether the crack will penetrate or be arrested by the ferrite. The ferrite is able to arrest nucleated cracks through the presence of mobile dislocations, which blunt and shield the microcrack and thus lowers the stresses at the crack tip. Hence, the macroscopic toughness of the material directly depends on the ability of the ferrite to arrest nucleated micro-cracks and in turn on the plastic rate sensitivity of the ferrite. The initiation of cleavage fracture is here modelled explicitly in the form of a micro-crack, which nucleates in a brittle carbide and propagates into the surrounding ferrite. The carbide is modelled as an elastic cylinder or in a few cases an elastic sphere and the ferrite as an elastic viscoplastic material. The crack growth is modelled using a cohesive surface, where the tractions are governed by a modified exponential cohesive law. It is shown that the critical stress, required to propagate a microcrack from a broken carbide, increases with decreasing plastic rate sensitivity of the ferrite. The results also show that a low stress triaxiality and a high aspect ratio of the carbide promote the initiation of cleavage fracture from a broken carbide.

Keywords: A. Cleavage nucleation; B. Elastic-viscoplastic material; Dynamic fracture; Ferritic steel; Fracture mechanisms

1. Introduction

Cleavage fracture in ferritic steels is often initiated in brittle second phase particles, e.g. carbides (McMahon and Cohen, 1965; Gurland, 1972; Lee et al., 2002; Hahn,

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1984). Carbides can be spherical as well as oblong, but as a result of a fibre loading mechanism oblong carbides experience very high stresses as the surrounding ferrite undergoes plastic deformation (Lindley et al., 1970; Echeverria and Rodriguez-Ibabe, 1999), which makes oblong carbides more critical as regards initiation of cleavage fracture. Furthermore, the fracture of a brittle particle presents the adjacent ferrite with a rapidly advancing microcrack, and if the arrest fracture toughness of the ferrite is too low the crack will penetrate into and cleave the neighbouring ferrite grains. The growing crack will encounter grain boundaries on its way which will force the crack to change its propagation direction due to the difference in lattice orientation and preferred cleavage planes in different grains. The grain boundaries are also important obstacles for continued crack growth and often cause crack arrest. However, if growth is sustained long enough the crack will cause macroscopic cleavage.

In the ductile to brittle transition region the fracture toughness of structural steels decreases drastically with decreasing temperature, as empirically described by the *master curve* (Wallin, 1991). Attempts to explain this decrease in toughness in terms of a subsequent increase in yield stress have proved insufficient. The common denominator in these steels is ferrite, and experiments show that the plastic rate sensitivity of ferrite changes substantially in the ductile to brittle transition temperature region (Campbell and Ferguson, 1970; Klopp et al., 1985). The role this change in plastic rate sensitivity of the ferrite plays for the change in fracture toughness in the transition region will be explored in this study. And, as will be shown quantitatively as well as qualitatively, the ability of the ferrite to blunt and shield micro-cracks that nucleate in the material will notably affect the macroscopic toughness in the transition temperature region.

The penetration of a rapidly advancing crack across an interface between an elastic and an elastic viscoplastic solid, which is the issue here, has also been studied by Siegmund et al. (1997) and Arata and Needleman (1998). Their work focus on the effect of plastic flow on whether the crack penetrates or deflects into the interface. Also related is the work by Freund and Hutchinson (1985) who study the energy release rate required to advance a crack tip at a high speed in an elastic viscoplastic solid under steady state conditions.

In this study the initiation of cleavage in a ferritic steel is studied in the form of a micro-crack nucleating in a brittle carbide embedded in ferrite. As the rapidly advancing crack enters the ferrite it will either be arrested or it will continue to propagate at an accelerating speed through the ferrite and possibly cause macroscopic failure. The carbide is modelled as an elastic cylinder (approximating an oblong brittle particle) and the surrounding ferrite as an elastic viscoplastic material. The crack growth is modelled using a cohesive surface governed by a modified exponential cohesive law. In addition to the plastic rate sensitivity of the ferrite some other important factors affecting the ability of the ferrite to arrest running cracks will be investigated, such as global stress level, stress triaxiality and aspect ratio of the carbide. The results will also be discussed in terms of a modified Griffith criterion, which relates the size of an interior micro-crack to the critical normal stress required to propagate the crack. In this context of a rapidly advancing crack, the surface energy in the Griffith criterion can be viewed as an arrest toughness. The problem will be analysed numerically using the finite element method (FEM) taking full account of dynamic effects.