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Effect of inclusion density on ductile fracture toughness and roughness

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ABSTRACT

Three dimensional calculations of ductile fracture under mode I plane strain, small scale yielding conditions are carried out using an elastic-viscoplastic constitutive relation for a progressively cavitating solid with two populations of void nucleating second phase particles. Larger inclusions that result in void nucleation at an early stage are modeled discretely while smaller particles that require large strains to nucleate voids are homogeneously distributed. Full field solutions are obtained for eight volume fractions, ranging from 1% to 19%, of randomly distributed larger inclusions. For each volume fraction calculations are carried out for seven random distributions of inclusion centers. Crack growth resistance curves and fracture surface roughness statistics are calculated using standard procedures. The crack growth resistance is characterized in terms of both J_{IC} and the tearing modulus T_R. For all volume fractions considered, the computed fracture surfaces are self-affine over a size range of nearly two orders of magnitude with a microstructure independent roughness exponent of 0.53 with a standard error of 0.0023. The cut-off length of the scale invariant regime is found to depend on the inclusion volume fraction. Consideration of the full statistics of the fracture surface roughness revealed other parameters that vary with inclusion volume fraction. For smaller values of the discretely modeled inclusion volume fraction ($\leq 7\%$), there is a linear correlation between several measures of fracture surface roughness and both J_{IC} and T_R. In this regime crack growth is dominated by a void-by-void process. For greater values of the discretely modeled inclusion volume fraction, crack growth mainly involves multiple void interactions and no such correlation is found.

1. Introduction

Two fundamental questions in the mechanics and physics of fracture are:

1. What is the relation between observable features of a material's microstructure and its resistance to crack growth?
2. What is the relation between observable features of a material's microstructure and the roughness of the fracture surface?

An obvious corollary question is: What is the relation, if any, between a material's crack growth resistance and the roughness of the corresponding fracture surface?

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Here, we report on calculations of ductile crack growth aimed at addressing these questions. At room temperature, ductile fracture of structural metals generally occurs by the nucleation, growth and coalescence of micron scale voids. The voids nucleate either by debonding or cracking of inclusions and/or second phase particles. This process was identified by Tippur (1949) and subsequently documented by Puttick (1959), Rogers (1960) and Gurland and Plateau (1963). Micromechanical modeling of this process of ductile fracture initiated with the work of McClintock (1968) and Rice and Tracey (1969). Reviews from a range of perspectives and with extensive references are available from Goods and Brown (1979), Garrison and Moody (1987), Tvergaard (1990) and Benzerga and Leblond (2010).

In a variety of structural alloys, the distribution of void nucleating particles can be idealized as involving two size scales; larger inclusions that nucleate voids at relatively small strains and smaller particles that nucleate voids at much larger strains. The size of the void nucleating particles is typically between 0.1 μm and 100 μm, with volume fractions of no more than a few percent. It is well appreciated that the distribution of void nucleating particles plays a major role in setting the crack growth resistance in such materials. We idealize such a microstructure by modeling the larger inclusions discretely (e.g. MnS inclusions in steels) to introduce a length scale, while the smaller particles (e.g. carbides in steels) are taken to be homogeneously distributed. This type of idealized microstructure has been used in a variety of 2D and 3D ductile fracture studies, e.g. Needleman and Tvergaard (1987), Mathur et al. (1996), Tvergaard and Needleman (2006). However, it is only recently that the computational capability has been available, e.g. Needleman et al. (2012), Tang et al. (2013), to compute ductile crack growth of sufficient extent and in sufficient detail to quantify fracture surface roughness as in Needleman et al. (2012), Ponson et al. (2013, submitted for publication).

Although the qualitative study of fracture surface morphology dates back to the sixteenth century, technological advancements (ASM Handbook, 1987) and advancements in the description of complex scale invariant geometries (Feder, 1988) in the twentieth century have made quantitative statistical fractography possible. In particular, Mandelbrot et al. (1984) were the first to quantitatively characterize the scale invariant properties of fracture surfaces and termed them fractal (Mandelbrot, 1983). Subsequently, the distinction between self-similar and self-affine objects was appreciated (Mandelbrot, 1985). A function $y = h(x)$ is said to exhibit self-similar (or fractal) properties if it remains statistically invariant under a uniform dilatation in the x and y directions, while a self-affine function is statistically invariant under the anisotropic scaling $h(\lambda x) = \lambda^H h(x)$. A self-affine function with Hurst exponent H is a fractal object with dimension $D = 2 - H$ (where D is the box or Minkowski–Bouligand dimension, see e.g. Moreira et al., 1994) when viewed at sufficiently small length scales but is an ordinary one dimensional object ($D = 1$) when viewed over a sufficiently large length scale, see for example Barabasi and Stanley (1995) or Feder (1988). Fracture surfaces have been shown to be self-affine, not self-similar. The self-affine nature of the roughness of fracture surfaces can be characterized by the Hurst exponent of the correlation function of the fracture surface profile, also referred to as the roughness exponent. The self-affine nature of the roughness of fracture surfaces has been observed over a range of size scales in a wide variety of materials (metals, ceramics, glasses, rocks) and under a wide variety of loading conditions (quasi-static, dynamic, fatigue), see for example Underwood and Banerji (1986), Dauskardt et al. (1990), Cherepanov et al. (1995), Bouchaud (1997), Charkaluk et al. (1998).

In Mandelbrot et al. (1984) a negative correlation was found between what they termed the fractal dimension of the fracture surface roughness and the corresponding impact energy (equivalent to a positive correlation with the roughness exponent). This gave rise to the hope that the fractal dimension of the fracture surface roughness could be related to the material's toughness. Subsequent studies have been inconclusive, with some studies reporting a positive correlation, Wang et al. (1988), Ray and Mandal (1992), others a negative correlation, Mu and Lung (1988), Su et al. (1991), Carney and Mecholsky (2013) reported a positive or negative correlation depending on the fracture mechanism, and still others reported no correlation, Pande et al. (1987), Richards and Dempsey (1988), Davidson (1989). Charkaluk et al. (1998) argued that the discrepancy between these results is related to the methods used to calculate the fractal dimension.

Bouchaud et al. (1990) proposed that the exponent characterizing the scale invariance of the fracture surface roughness is universal, i.e. independent of the material and its toughness as long as the fracture mechanism remains fixed. Alternatively, a multifractal characterization of fracture surface roughness has been suggested as discussed at length by Cherepanov et al. (1995). Dauskardt et al. (1990) suggested that the scaling properties of the fracture surface may depend on the fracture mechanism and/or the range of length scales considered. Ponson et al. (2006) characterized the roughness scaling in terms of two exponents, one for the roughness in the direction of crack propagation and the other for the roughness parallel to the crack front. Bonamy et al. (2006) (see also Bonamy and Bouchaud, 2011) argued that there are two roughness regimes, one pertaining to length scales smaller than the fracture process zone and the other to length scales larger than the fracture process zone, with each regime characterized by different values of scaling exponents. More recently, Bouchbinder et al. (2006), Vernède et al. (submitted for publication), Ponson et al. (2013) have stressed the importance, particularly for ductile fracture, of considering the full fracture surface statistics, not just the correlation function. The full roughness statistics of the calculated ductile fracture surfaces in Ponson et al. (2013) were found to vary with the fracture parameters.

A variety of models have been introduced aimed at understanding and simulating the scaling characteristics of fracture surfaces, e.g. Ramanathan et al. (1997), Dauskardt et al. (1990), Bouchbinder et al. (2004), Afek et al. (2005), but these have only focused on the value of the roughness exponent and do not provide a basis for calculating crack growth resistance as well as roughness. Here, as in Needleman et al. (2012), Ponson et al. (2013, submitted for publication), we report on 3D finite deformation calculations of ductile crack growth under small scale yielding conditions with imposed monotonically increasing mode I remote loading. The analyses are based on a constitutive framework for a progressively cavitating ductile