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The effect of loading rate on ductile fracture toughness and fracture surface roughness

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ABSTRACT

The variation of ductile crack growth resistance and fracture surface roughness with loading rate is modeled under mode I plane strain, small scale yielding conditions. Three-dimensional calculations 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 as discrete void nucleation sites while smaller particles that require large strains to nucleate voids are homogeneously distributed. The calculations are carried out for two values of density of the larger inclusions, 3.6% and 7.1%, and for prescribed loading rates $\dot{K}_I$ ranging from $1 \times 10^5\ \mathrm{MPa}\sqrt{\mathrm{m}}\ \mathrm{s}^{-1}$ to $5 \times 10^7\ \mathrm{MPa}\sqrt{\mathrm{m}}\ \mathrm{s}^{-1}$. The ductile fracture mode is found to undergo a transition from one that can be regarded as growth of a dominant main crack at the lower loading rates to one dominated by damage nucleation and micro-cracking ahead of the main crack at the higher loading rates. The values of J_{IC}, the tearing modulus, T_R, the total plastic dissipation and the plastic dissipation in the fracture process region are all found to increase with increasing loading rate. However, the ratio of plastic dissipation in the fracture process region to total plastic dissipation decreases with increasing prescribed loading rate. The fracture surfaces are found to display two self-affine regimes, with a Hurst exponent $\beta \approx 0.60$ at small length scales and with $\beta \approx 0.45$ at larger length scales. The multi-fractal spectra indicate multi-affine behavior in most cases but a range of loading rates and length scales exhibiting mono-affine behavior is also found. Parameters characterizing the fracture surface statistics, including the length scale at which a transition from a power law tail to an exponential tail occurs, are related to the mode of crack growth/damage accumulation. A linear relation is found between the values of J_{IC} and T_R and the saturation value of the correlation function of the surface roughness for $\dot{K}_I < 3 \times 10^7\ \mathrm{MPa}\sqrt{\mathrm{m}}\ \mathrm{s}^{-1}$.

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1. Introduction

The crack growth resistance of a material depends on the material's resistance to the creation of new free surface, on its deformation characteristics, particularly those related to dissipation, on its microstructure, and on the imposed loading conditions. In Srivastava et al. (2014), ductile fracture crack growth and the statistics of ductile fracture surface roughness were quantified and related for a model 3D microstructure under mode I loading at a fixed loading rate. Here, we analyze the same microstructure and loading mode as in Srivastava et al. (2014), but consider the effect of loading rate on crack growth resistance and fracture surface roughness. There is a large literature both on ductile fracture and on the modeling and characterization of fracture surface roughness. For background and references see Tvergaard (1990), Benzerga and Leblond (2010), Bouchaud (1997), Bonamy and Bouchaud (2011) as well as Srivastava et al. (2014).

The microstructure analyzed here is one where the ductile fracture mechanism involves two populations of void nucleating particles; larger inclusions that nucleate voids at relatively small strains and smaller particles that nucleate voids at much larger strains. The larger inclusions are modeled discretely while the smaller particles are taken to be homogeneously distributed. The mean spacing of the larger inclusions introduces a length scale into the formulation. The constitutive framework is a modified Gurson constitutive relation (Gurson, 1975; Tvergaard, 1990) for a progressively cavitating solid with material rate dependence. The initial/boundary value problem analyzed is a mode I small scale yielding problem with symmetry conditions used to give an overall plane strain constraint. However, the microstructure modeled is fully 3D.

Srivastava et al. (2014) reported results for eight volume fractions, ranging from 1% to 19%, of discretely modeled void nucleation sites referred to as the larger inclusions. For each inclusion volume fraction seven realizations were analyzed. In all cases, the inclusion size and material properties were the same. Two regimes of crack growth behavior were found: for sufficiently small inclusion volume fractions crack growth was dominated by a void-by-void process while for larger inclusion volume fractions, crack growth involved multiple void interactions. For small inclusion volume fractions (the void-by-void dominated crack growth regime), the values of J_{IC} and the tearing modulus T_R decreased rapidly with increasing inclusion volume fraction (decreasing mean spacing). For larger inclusion volume fractions (the multiple void interaction regime), the values of J_{IC} and the tearing modulus T_R showed little or no dependence on inclusion volume fraction. The computed fracture surfaces were found to be self-affine over a size range of nearly two orders of magnitude with the surface roughness correlation function exhibiting power law behavior with a Hurst exponent ≈ 0.53. Various parameters characterizing the fracture surface roughness were found to be linearly related to J_{IC} and the tearing modulus in the regime in which crack growth occurred by a void-by-void process. No such relation was found in the multiple void interaction regime.

Experimentally, for a variety of materials, the crack growth resistance is found to increase with increasing loading rate, see for example Ravi-Chandar and Knauss (1984), Owen et al. (1998), Kalthoff (1986), and Rittel and Maigre (1996). At least for metals this corresponds to circumstances, as modeled here, where a change in fracture mechanism from ductile void growth to brittle cleavage does not occur. Ravi-Chandar and Knauss (1984) noted that there are several quite general reasons for such an increase: (i) the size of the fracture process zone increases as the stress intensity factor increases; and (ii) as the fracture process zone grows in size, the number of potential micro cracks contributing to the fracture process zone increases which increases the plastic dissipation in the fracture process zone.

As noted by Broberg (1982) and Johnson (1993), at higher crack speeds damage (void nucleation and growth leading to the formation of micro cracks) occurs in a region that is no longer confined to the immediate vicinity of the main crack tip. The question then arises as to how this affects the correlation between toughness and roughness measures reported by Srivastava et al. (2014), since the damage region is then much larger than the length scale dictated by material's microstructure, making additional dissipation routes available.

Here, we focus attention on the effect of the loading rate on a ductile solid's crack growth resistance, as characterized by J_{IC} and the tearing modulus T_R (Paris et al., 1979), and on the associated fracture surface roughness. Previous calculations of the effect of loading rate on crack growth initiation have been carried out, see for example Siegmund and Needleman (1997) and Jacques et al. (2012). However, here as in Srivastava et al. (2014), J_{IC} is defined by simulating the procedure outlined in the ASTM E1820-11 (2011) standard and, in addition, we calculate T_R. Our calculations are carried out for two volume fractions of the discretely modeled void nucleation sites (the "larger inclusions"), 3.6% and 7.1%, and for prescribed loading rates ranging from $\dot{K}_I = 1 \times 10^5\ \mathrm{MPa}\sqrt{\mathrm{m}}\ \mathrm{s}^{-1}$ to $\dot{K}_I = 5 \times 10^7\ \mathrm{MPa}\sqrt{\mathrm{m}}\ \mathrm{s}^{-1}$. One random distribution of the larger inclusions is analyzed for each volume fraction. The quantities characterizing the ductile fracture toughness and fracture surface roughness statistics along the direction of crack growth are computed as in Srivastava et al. (2014). Possible connections between quantitative measures of crack growth resistance and quantitative measures of fracture surface roughness are explored. A linear relation between the saturation value of the height correlation function and the values of J_{IC} and the tearing modulus T_R is found. The scaling of the full statistics of the fracture surface roughness is investigated using the α-stable distribution and this gives a possible characterizing parameter that correlates with the crossover between regimes of crack growth/diffuse damage. Possible explanations for the variation in the quantities characterizing toughness and roughness with the loading rate are suggested in terms of the extent of damage evolution and in terms of the relative amounts of total plastic dissipation and plastic dissipation associated with damage evolution.