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Modeling of ductile fragmentation that includes void interactions

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ABSTRACT

The failure and fragmentation of ductile materials through the nucleation, growth, and coalescence of voids is important to the understanding of key structural materials. In this model of development effort, ductile fragmentation of an elastic–viscoplastic material is studied through a computational approach which couples these key stages of ductile failure with nucleation site distributions and wave propagation, and predicts fragment spacing within a uniaxial strain approximation. This powerful tool is used to investigate the mechanical and thermal response of OFHC copper at a strain rate of 10^5. Once the response of the material is understood, the fragmentation of this test material is considered. The average fragment size as well as the fragment size distribution is formulated.

1. Introduction and background

Ductile materials exhibit plastic deformation before failure, and the first stage of ductile failure is the nucleation of voids within the plastically deforming material. Void nucleation typically occurs at the sites of microstructural heterogeneities (precipitates, dispersoids, triple junctions, grain boundaries, etc.). These heterogeneities are active in most polycrystalline engineering materials. When these sites are not present, as in an annealed single crystal of a pure metal, voids may nucleate in regions of localized plastic deformation, in heterogeneities arising from dislocation substructure patterning (e.g. cell walls) and as a consequence of dislocation intersections. Vacancy diffusion can also generate voids, but this requires time and usually high temperatures.

After a void is nucleated, void growth in ductile materials typically occurs through dislocation plasticity. At some size, neighboring voids begin to interact as their domains of influence overlap. This interaction leads to the linking or coalescence of voids and eventually to the formation of a fracture surface. In dynamic problems, it is likely that multiple locations in a material will nucleate voids that grow simultaneously, and the subsequent coalescence and localization results in the formation of multiple fracture surfaces. The final fragment size distribution resulting from dynamic loading is of interest for a number of applications, particularly those involving impact.

The first scientific interest in fragmentation resulted from the mining industry, and this was rapidly followed by interest in the fragmentation of shells for munitions. Early fragmentation theories were based on the geometric break up of a body into smaller fragments (Mott and Linfoot, 1943), and while insightful, such approaches do not account for the physics of

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ductile failure and the fragment size distribution is a strong function of the algorithm used. Mott (1947) assumed a statistical distribution of failure locations and failure strains in the fragmentation of elastic rings, and used the argument that unloading or release waves from a given failure location can prevent the failure of nearby locations that have perceived the unloading. This insight has played a key role in a number of later fragmentation models.

Modern efforts in fragmentation modeling have largely been based on energetics, dynamics, and consideration of initial defects. The primary question addressed by most fragmentation models is that of computing the distributions of fragments that result from the completed fragmentation process. There are typically three distributions of interest: the fragment size distribution, the fragment shape distribution, and the fragment velocity distribution. Most fragmentation models in the literature focus on the size distribution, and sometimes limit themselves to seeking to define an average fragment size. Shape distribution assessments require 2D or 3D fragmentation models, and velocity distribution assessments typically require large scale explicit simulations.

Some of the most fundamental results in the field are due to Grady, who explored the subject in a series of landmark papers together with Kipp beginning in the early 1980s (Grady and Kipp, 1985). The first results were based on the direct comparison of the available kinetic energy with the necessary fracture energy, while later versions compared the elastic strain energy in the deforming body to the fracture energy needed to create new surfaces. In both cases the resulting energy comparison provided an expression for the mean fragment size $\bar{s}$ as a function of the applied strain rate $\dot{\epsilon}$, leading to $\bar{s} \propto \dot{\epsilon}^{2/3}$. Glenn and Chudnovsky (1986) added a low-rate correction term to Grady's model to account for the stored strain energy in the system, important at low strain rates. More recent work by Grady points out that the dynamic failure process does not lend itself to these direct energy comparisons, and that a further characterization of the dynamic failure process itself is needed for such “non-equilibrium” fragmentation problems (Grady, 2010).

Such problems have been explored by others in the literature by explicitly considering dynamic fracture processes and the interactions of loading and unloading waves with pre-existing defect distributions in the material. Generally these approaches have explored 1D problems. With advances in computational power, simulations of fragmentation (Miller et al., 1999; Drugan, 2001; Shenoy and Kim, 2003; Zhou et al., 2005) have modeled both the distribution of defects in a material as well as the interaction and wave propagation between failures. Such simulations can compute the entire distribution of fragments produced as opposed to only the average fragment size. Shenoy and Kim (2003) incorporated cohesive elements into a 1-D domain with an applied strain rate. Their simulations incorporated defects as equally spaced cohesive elements. Zhou et al. (2006a) extended these simulations to allow fragmentation at each node and simulated a wider range of strain rates as well as defect distributions. Although there are many common elements to the fragmentation of brittle and ductile materials, the physics of void growth in a plastically deforming material generates timescales and length scales that are fundamentally different from those in brittle fragmentation.

For ductile materials, Zhou, Molinari, and Ramesh computed the spacing of shear bands in a 1-D domain when subjected to pure shear loading. These simulations included the wave propagation of the brittle fragmentation case but also incorporated the plasticity associated with a ductile material with a staggered thermo-mechanical integration scheme (Zhou et al., 2006b). In this paper, the Zhou–Molinari–Ramesh simulation framework is extended to capture the fragmentation of ductile materials due to void nucleation, growth and coalescence.

The governing equations are presented in the next section, and a staggered thermo-mechanical integration scheme is outlined for integration on a one dimensional finite difference framework. Next, the simulations are utilized to investigate the evolution of the failure processes leading to the fragmentation of OFHC copper as a model material. The simulations give insight into the thermo-mechanical process of fragmentation and the communication between failures. For OFHC copper, mechanistic details of the fragmentation at a strain rate of 10^5 are investigated to determine an average fragment size as well as a fragment size distribution.

2. A two-scale porosity model for interaction of failures and ductile fragmentation

2.1. Kinematics and dynamics

A uniaxial strain approximation is used in order to develop a one-dimensional model that is relevant to ductile fragmentation. The uniaxial strain condition is developed in plate impact experiments such as the spall experiment that provide a basis to diagnose and study dynamic void growth and coalescence. The loading direction x_1 is labeled as the axial direction while the other two perpendicular and essentially equivalent directions are labeled transverse. The uniaxial strain kinematics in the domain requires that there is no total rate of deformation in either of the transverse directions, so that the velocity gradient contains a single component, d_{11}, which is the gradient of the axial velocity with respect to the axial direction. The symmetric part of the velocity gradient, or the rate of deformation tensor, is identically equal to the velocity gradient, and the antisymmetric portion of the velocity gradient or spin tensor, is zero. This gives $d_{11} \neq 0$, while $d_{22} = d_{33} = 0$.

Conceptually, the problem is formulated as a two-scale problem, with the governing equations integrated at the macroscale but with the effective material behavior defined by subscale micromechanics based on the statistical dynamic void nucleation and growth model of Wright and Ramesh (2008). While the idealization of the uniaxial strain problem to one dimension essentially introduces an averaging of the material response across the transverse directions, this is analogous to the effective averaging of information across the spall plane introduced when spall pullback velocities are measured using a