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A physically based model for dynamic failure in ductile metals

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Abstract

It is well established that high rate failure of structural materials takes place by rate processes occurring at the microscopic level and involving nucleation, growth, and coalescence of voids or cracks. At the submicroscopic level, the mechanism of failure in polycrystalline metals is often dislocation controlled. In the present work, we propose a physically based model describing these processes at high deformation rate such as under the planar impact test. This model combines the mechanical threshold stress (MTS) theory for the evolution of the flow stress and a mechanistic model for failure behavior by cumulative nucleation and growth of voids. This paper describes the approach used to obtain the constitutive equations and the resulting computational modeling for predicting dynamic failure in ductile metals. The model formulation is three-dimensional and is suitable for a general state of stress and strain. Results from the simulations of the planar impact problems for different configurations are presented and compared with the experimental results for OFHC copper and HY-100 steel. This comparison shows the model capabilities in predicting the experimentally measured free surface velocity profile as well as the observed spall pattern respectively in the copper target of a planar impact test and in the steel target of a plate-conic impact. We have also compared the results from this model to those of the phenomenological model of Johnson–Cook.

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1. Introduction

Dynamic failure is a rate process involving the evolution of micro-failures: either spherical voids for ductile materials or planar microcracks for more brittle materials. It also involves the effects of mass inertia, thermal inertia, thermal activation and viscosity. Therefore, to understand failure one must understand both the threshold conditions that trigger this process and the kinetics by

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which it proceeds. The damage kinetics interact with the load kinetics to make failure of solids a highly rate and history dependent nonlinear process. A detailed knowledge of how loading conditions and microstructural features influence micro-failure (nucleation, growth, and coalescence) would help in designing more failure-resistant structures or tailor structures to have a prescribed toughness. The difficulty is that failure processes are not easily accessible for modeling and analysis. This had led to the development of several engineering models using modern numerical methods to predict failure of different materials at different loading rates and temperatures. One important consideration is that these models of failure must be developed to describe, as closely as possible, experimental results and microscopic observations.

It has been observed through planar impact experiments that dynamic failure is dependent on the amplitude and duration of the stress pulse. If a pulse has a long duration, the stress required to cause fracture is lower than that for a pulse of shorter duration (Novikov et al., 1965; Chevier and Klepaczko, 1996). Based on these observations, Tuler and Butcher (1968) proposed a failure criterion that is a cumulative relation between various loading conditions, spall fracture and the time dependence of dynamic fracture. The spalling is related to the overstress, which is the difference between the applied stress and some threshold stress, and time duration of the pulse at the spall plane. According to this criterion, the critical time for spalling can approach infinity as the applied stress approaches the threshold value for fracture. This is not the case practically as the longest critical times observed experimentally are finite and relatively short.

Cochran and Banner (1977) used the peak of the velocity formed at the free surface of the target to determine the critical conditions for spalling. In such cases, the free surface velocity did not return to zero. The ratios between the free surface velocities of the spall to the compression pulse peaks provided a good correlation with the densities of the void formed at the spall plane.

It is an accepted fact that the thermally activated processes like plasticity and fracturing are influenced by rate and temperature effects. Zhurkov (1965) worked on the concept that thermal activation is involved in material separation during fracture processes. He therefore suggested, based on the kinetic concept for failure mechanisms, a universal rate relation between time to failure, stress, energy barrier and temperature. Following this approach, Klepaczko (1990) proposed a cumulative failure criterion for short and very short times. Here, the rate of damage is a function of the free energy of activation and the temperature. The time interval of micro-crack growth is assumed to be very short in comparison to the critical time of loading. A review of these dynamic failure criteria and their extention to include temperature and pressure effects is given in the work of Hanim and Ahzi (2001).

Different failure models have also been proposed considering the porosity of the material. The foremost among them is the Gurson model (1977) where the plastic flow potential is a function of the Cauchy stress tensor, the void volume fraction and the strength of the matrix material. This plastic potential was later modified by Tvergaard (1982). Based on the Gurson type modeling, Rajendran et al. (1988) proposed a model for dynamic plasticity and failure in ductile metals. In this model, the nucleation of voids/cracks is assumed to occur by the debonding which can either be stress or strain driven. The nucleation function takes into account the mean equivalent stress and strain around which the nucleation stress and strain are distributed in a Gaussian manner (Chu and Needleman, 1980). The standard deviations of these distributions control the ranges of stress and strain over which the voids can be nucleated. The void growth is directly related to the inelastic volumetric change in the aggregate. The evolution equation for the void volume fraction is an additive function of the void nucleation rate and the void growth rate. Another type of nucleation-and-growth (NAG) based models is the work proposed by Curran et al. (1987). In this microstructural approach to failure, a number of material constants have to be determined experimentally with the application of statistical methods.