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A computationally efficient ductile damage model accounting for nucleation and micro-inertia at high triaxialities

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Abstract

The computational formulation of a micro-mechanical material model for the dynamic failure of ductile metals is presented in this paper. The statistical nature of porosity initiation is accounted for by introducing an arbitrary probability density function which describes the pores nucleation pressures. Each micropore within the representative volume element is modeled as a thick spherical shell made of plastically incompressible material. The treatment of porosity by a distribution of thick-walled spheres also allows for the inclusion of micro-inertia effects under conditions of shock and dynamic loading. The second order ordinary differential equation governing the microscopic porosity evolution is solved with a robust implicit procedure. A new Chebyshev collocation method is employed to approximate the porosity distribution and remapping is used to optimize memory usage. The adaptive approximation of the porosity distribution leads to a reduction of computational time and memory usage of up to two orders of magnitude. Moreover, the proposed model affords consistent performance: changing the nucleation pressure probability density function and/or the applied strain rate does not reduce accuracy or computational efficiency of the material model. The numerical performance of the model and algorithms presented is tested against three problems for high density tantalum: single void, one-dimensional uniaxial strain, and two-dimensional plate impact. The results using the integration and algorithmic advances suggest a significant improvement in computational efficiency and accuracy over previous treatments for dynamic loading conditions.

Keywords: Micro-inertia; High strain rate; J_2 plasticity; Computational formulation; Chebyshev collocation; Porosity distribution

1. Introduction

Research of the past six decades has shown tremendous progress in the ability to represent the process of ductile damage under dynamic loading conditions. Even though good progress has been made, many challenges remain in effectively representing this complex physical process accurately, and without numerical artifacts. Work discussed in this chapter is a current representation of developments which have taken place over several years, beginning

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with the work of Johnson [1] and the development of a constitutive model for shock loaded copper representing nonlinear elasticity, plasticity, and evolution of local porosity. Johnson [1] recognized the significance of the aggregate nature of polycrystalline metallic materials and used a unit cell analysis of the elastic–plastic response of the material under rapidly loaded conditions. Micro-inertial effects were recognized as important but were not included in the analysis of copper presented. The model was applied to problems of plate impact, explosively loaded material, and an expanding ring. Much later, this model was also applied to the study of loading pulse duration in copper [2]. Addessio and Johnson [3] improved upon the work of Johnson [1] by proposing a modified Gurson [4] type model, which also employed an overstress equation for the plastic flow rule of the material. This equation introduces a length scale into the series of equations and assists in regularizing the problem. This helps to alleviate issues of numerical stability and severe mesh sensitivity. The authors also clearly recognized the possibility that relying upon deformation rate sensitivity within the model would not always solve the regularization issue, but that additional length scales (e.g. spatial gradients in physically based internal state variables) may be required in general. A void nucleation model was not proposed and the model was tested against copper plate impact experiments. It was demonstrated that for the problems examined, the use of the overstress model reduced the mesh sensitivity of the simulated results.

There has also been a body of work which has advocated for some role of micro-inertial effects in limiting the rate of growth of pores under the conditions of loading considered here. A subset of that work is particularly germane to developments presented here. In addition to the work of Johnson [1], Ortiz and Molinari [5] examined the growth of a pore within an infinite medium of rate-dependent material. The analytical study considered the hardening of the material as well as the effect of the acceleration of mass. They showed that all three effects have significant influence on the growth trajectory of the void and in particular, they found that the influence of each of the three physical features changes with time. Micro-inertial effects was prominent in the consideration of pore growth in the work of Tong and Ravichandran [6] who also considered its influence in the context of a viscoplastic material and dynamic loading. These authors also suggested that micro-inertial effects contribute to the growth rate of pores and offered modifications to the Gurson–Tvergaard–Needleman model [4,7,8] to approximate the influence. Molinari and Mercier [9] offered a more comprehensive approach to the inclusion of inertial effects by considering the pore within the boundary value problem of a thick-walled sphere rather than an infinite medium. They of course considered the problem in the context of rate-dependent material behavior. Given the competing rate dependencies of plasticity and inertial effects, the entire field of pores must be considered in the context of an entire nucleated field of pores and so the total number of pores available for growth must also be accounted for. Czarnota et al. [10,11] introduced the concept of a distribution of pores represented once again as thick-walled spheres of distributed dimensions. These authors applied their models to the plate impact loading of high density tantalum and offered important insights of real material response. Of course in all of this work, the length scales of the pores are generally small in comparison with the grain size of the material, yet plasticity is represented by simple models for plasticity which cannot account for the geometric resistance to pore growth possible for single crystal loading in materials of varying symmetries. Recent work now begins to address the micromechanics of this local scale process [12–16].

Recognizing that void nucleation and growth is a stochastic process, it is critical for a material model to consider the statistical nature of porosity to successfully predict ductile damage and failure. The statistical nature of the process is dependent on the heterogeneity of the material, heterogeneity largely related to defects in the material's micro structure. At high strain rates, those typical of flyer plate impacts, the micro-inertial effects associated with porosity growth may play an important role and it is hence necessary to move from the classical static Gurson surface approach [4,17,18] towards micro-mechanical models based on the explicit representation of porosity growth [19]. Inclusion of micro-inertial effects plays a favorable role also from a numerical point of view: the ill-posedness typical of the softening response caused by damage is alleviated by including the inertial terms. Post-mortem inspection of failed materials can be used to compute the number of pores and their sizes, and hence infer the size of the representative volume element (RVE) encompassing the pores. A material constitutive model having all the aforementioned characteristics has been presented by Czarnota et al. in [11], and this model will be used as a backbone for further improvements presented here. Although the emphasis of this paper is on developing numerical efficiency and accuracy within a model framework which accounts for both a distribution of nucleated pore sizes and micro-inertial effects, we recognize that the later stage processes such as coalescence play an important role for many materials. This has been demonstrated by the work of Molinari et al. [20] and Bronkhorst et al. [18] for shock loading conditions and will be considered in future work.

A key aspect for ensuring mesh independence of the solution is that the size of the RVE does not change during the simulation. Upon nucleation of new pores it is hence necessary to redistribute the material within the RVE to ensure