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PII: S0022-5096(17)30181-3
DOI: 10.1016/j.jmps.2017.07.020
Reference: MPS 3163

To appear in: *Journal of the Mechanics and Physics of Solids*

Received date: 8 March 2017
Revised date: 1 July 2017
Accepted date: 31 July 2017

Please cite this article as: Thao Nguyen, D.J. Luscher, J.W. Wilkerson, A dislocation-based crystal plasticity framework for dynamic ductile failure of single crystals, *Journal of the Mechanics and Physics of Solids* (2017), doi: 10.1016/j.jmps.2017.07.020

A dislocation-based crystal plasticity framework for dynamic ductile failure of single crystals

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MANUSCRIPT INFO

Manuscript history:
Dated: August 2, 2017

Keywords:
Crystal plasticity
Damage
Dislocation
Dynamics
Failure
Fracture
Strain rate
Shock
Spall
Void

ABSTRACT

A framework for dislocation-based viscoplasticity and dynamic ductile failure has been developed to model high strain rate deformation and damage in single crystals. The rate-dependence of the crystal plasticity formulation is based on the physics of relativistic dislocation kinetics suited for extremely high strain rates. The damage evolution is based on the dynamics of void growth, which are governed by both micro-inertia as well as dislocation kinetics and dislocation substructure evolution. An averaging scheme is proposed in order to approximate the evolution of the dislocation substructure in both the macroscale as well as its spatial distribution at the microscale. Additionally, a concept of a single equivalent dislocation density that effectively captures the collective influence of dislocation density on all active slip systems is proposed here. Together, these concepts and approximations enable the use of semi-analytic solutions for void growth dynamics developed in (Wilkerson and Ramesh, 2014), which greatly reduce the computational overhead that would otherwise be required. The resulting homogenized framework has been implemented into a commercially available finite element package, and a validation study against a suite of direct numerical simulations was carried out.

1. Introduction and background

A deeper understanding of and control over the fundamental processes governing deformation and failure of ductile metals subject to dynamic loading is vital to the advancement of a number of applications, e.g. personal and vehicular protection systems, spacecraft shielding, automotive crash safety, and advanced manufacturing. Despite this technological importance, many fundamental aspects of dynamic ductile failure are poorly understood and the sophistication of constitutive models for dynamic ductile failure has lagged behind their quasi-static counterparts. Our aim here is to advance the state-of-the-art in this area through the development of what is to our knowledge the first dislocation-based crystal plasticity framework for dynamic ductile failure.

The earliest models of ductile failure were based on the analytic analysis of an isolated void in an otherwise homogeneous infinite medium, e.g. (Bishop et al., 1945; Hill, 1950; McClintock, 1968; Rice and Tracey, 1969; Ball, 1982; Huang et al., 1991). While these early models provided valuable insights into the initial stages of void growth, such models failed to capture the important effect of an evolving void volume fraction, i.e. porosity, thereby limiting their utility in ductile fracture analysis. This shortcoming was remedied by Gurson (1977), who proposed a pioneering micromechanics-based framework capable of modeling the progressive failure of porous materials. In the subsequent decade, Gurson's model was modified into what would become known as the Gurson-Tvergaard-Needleman (GTN) model (Chu and Needleman, 1980; Tvergaard,

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