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A micromorphic model for the multiple scale failure of heterogeneous materials

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Abstract

The multi-scale micromorphic theory developed in our previous paper [Vernerey, F.J., Liu, W.K., Moran, B., 2007. Multi-scale micromorphic theory for hierarchical materials. J. Mech. Phys. Solids, doi:10.1016/j.jmps.2007.04.008] is used to predict the failure of heterogeneous materials illustrated by a high strength steel alloy possessing two populations of hard particles distributed at two distinct length scales in an alloy matrix. To account for the effect and size of microstructural features during fracture, additional kinematic variables are added, giving rise to the couple stresses associated with each population of particles. The various stress and strain measures must satisfy a set of coupled multi-scale governing equations derived from the principle of virtual power. A three-scale constitutive model is then developed to represent the failure of the alloy from nucleation, growth and coalescence of voids from each population of particles. For this, three distinct yield functions, each corresponding to a different scale, are introduced. Cell model simulations using finite elements are performed to determine the constitutive relations based on the key microstructural features. Two-dimensional failure analyses are then presented in tension and in shear, and show good agreement with direct numerical simulation of the microstructure.

Keywords: Multi-scale micromorphic theory; Homogenization; Finite elements; Constitutive relations; Materials stability

1. Introduction

Macroscopic properties are a key factor in the choice of material for a specific engineering application. Nevertheless, the origins of a material's behavior reside in the properties and their interactions that take place at the scale of its microstructure. More specifically, materials fracture strongly depends on the size, geometry, distribution and various properties of microscopic heterogeneities that can be found

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in the form of grains, fibers or different size particles. In this work, we propose to use the multi-scale micromorphic theory (Vernerey et al., 2007) to study the failure of a class of heterogeneous materials that possess a hierarchical microstructure by considering the particular case of a well-studied engineering material: high strength steel.

Many pure polycrystalline metals can be considered very ductile but are generally not strong enough for most engineering applications. A way to improve strength is to add specific reinforcements in the form of particles. In the case of high strength steel, there are typically two populations of particles distributed at different length scales, commonly termed the primary and secondary particles. Secondary particles (such as titanium carbide), ranging from tens to hundreds of nanometers in size, have the effect of refining grain size during thermal processing, and hence, increase the material's strength. Primary particles (such as titanium nitride) are byproducts of manufacturing process and are generally too large (approximately 1 μm in size) to increase the material's strength.

Ductile fracture of high strength steel is known to be controlled by the nucleation, growth and coalescence of voids around both populations of inclusions. Within the past decades, substantial efforts have been devoted to the development of continuum models based on the nucleation, growth, and coalescence from populations of inclusions. One of the best-known micromechanical models was derived by Gurson (1977); he studied the loss of load carrying capacity of a voided material during plastic deformation. In Gurson (1977), a yield criterion is derived based on the evolution of a damage parameter, the void volume fraction. Similarly, Rice and Tracey (1969) derived a model for the evolution of a void in an infinite plastic matrix. A semi-empirical relationship was developed between void straining and remote stresses in the matrix. Numerous extensions of the Gurson model have been presented in the literature. Based on numerical simulations, Needleman and Tvergaard (1984) modified the material constants of the Gurson model to provide a better description of neighboring void interactions. The interaction of voids with particles, and especially the stage of void nucleation from particles were investigated by Saje et al. (1982) and Goods and Brown (1979). Other models include a more detailed description of the void growth mechanisms. For instance, Gologanu et al. (1995) investigated the effect of void shape by considering an internal variable characterizing the eccentricity of elliptic voids. This model was later extended by Pardoen and Hutchinson (2000) to provide a more accurate description of void coalescence.

One of the major drawbacks of the above models together with all other local softening plasticity models is that they are unable to capture the size of the localization region after the onset of softening (Bazant and Jirasek, 2002). To overcome this issue, nonlocal models with the introduction of a parameter that characterizes the typical length scale of the microstructure were developed (Pijaudier-Cabot and Bazant, 1987). In this context, Leblond et al. (1994) and Tvergaard and Needleman (1995, 1997) proposed a Gurson-type model that was modified by introducing a nonlocal evolution for porosity. This method provides a convenient way of introducing a length scale in the formulation but has two main limitations: first, it is not based on the underlying failure mechanisms and second, only the scale of primary particles is accounted for. In fact, fracture of high strength steels is a complex process that involves localizations of the deformation across several length scales, given by primary and secondary particles. This paper proposes to utilize the multi-scale micromorphic theory (Vernerey et al., 2007) to incorporate deformation and length scales associated with both populations of particles. The resulting multi-scale model of high strength steel possesses several characteristics. First, it accounts for material deformation and damage across three scales, namely, the macro, or specimen scale, micro or primary particle scale, and submicro, or secondary particle scale. Second, the constitutive relation is derived from mechanism based averaging operations. Third, it remains a continuum model and therefore remains computationally affordable.

The organization of this paper is as follows. After briefly reviewing the fracture mechanisms of high strength steel, we propose a multi-scale decomposition of the material's microstructure. This gives rise to a set of equations governing the physics of material failure at each scale of interest. The constitutive relation is then introduced in the form of a multi-potential plasticity model and a nested homogenization procedure is employed at each scale of analysis. In this procedure, the micro and submicro-scale physics are related to the macroscopic stress–strain law. Finally, the model is evaluated through a one-dimensional and a two-dimensional numerical analysis of the failure of a specimen under both tensile and shear loading.