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Strain-induced damage of metals under large plastic deformation: Theoretical framework and experiments

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ABSTRACT

Based on a micromechanical concept of the void growth and a change in the void shape the dissipation potential and constitutive equations for ductile damage of metals are presented. Multiplicative decomposition of the metric transformation tensor and thermodynamic formulation of the constitutive equations lead to a symmetric second order tensor of damage which is physically meaningful. Its first invariant defines the damage related to plastic dilatation of the material due to the void growth. The second invariant of the deviatoric tensor accounts for the damage associated with a change in the void shape. Two physically motivated normalized measures allow us to represent the kinetic process of strain-induced damage including the limit conditions for the onset of void coalescence and ductile fracture. A relation of the equivalent damage measure to the well-known criteria is shown. The evolution of damage is experimentally determined in uniaxial tensile and upsetting tests for three ductile metals: steel DC01, aluminum–magnesium alloy $AlMg_3$ and pure copper. Void distribution, growth and changes in shapes are analyzed using scanning electron microscopy. The equilibrium point for the kinetics of damage growth and healing is revealed. It is shown that if the strain does not reach the limit value prior to that equilibrium point then the further compression of the material is accompanied by the growing effect of negative stress triaxiality on closure and healing of defects which prevents the fracture. A tensorial framework for strain-induced damage and its thermodynamically consistent mathematical models can be applied to the analysis of metal forming processes in which materials are subjected to large plastic deformations and non-proportional loading paths.

1. Introduction

Measures of ductile damage under large finite deformations are of great importance in metal forming problems. The accurate prediction of damage is – in particular – required when manufacturing metal products with defect-free mesoscopic structure and high performance characteristics. Such products must operate under intense mechanical and thermal loading, high strain rates, and violent chemical conditions. Damage of metals subjected to large plastic strains is mainly governed by void nucleation, growth and coalescence. It is well known that void coalescence is followed by the formation of large cavities,

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especially under large deformations. In addition such cavities can be sources of localized strain bands which can result to ductile fracture of the material (cf., e.g., Yokobori, 1968).

Different approaches for a better understanding of ductile damage behavior were developed by many researchers. Important results were obtained in experimental research and formulation of strain-induced damage criteria under various temperature-rate conditions. According to these investigations the role of void volume growth as an important factor for the assessment of ductile damage is unquestioned. In a number of models starting from the pioneering works of McClintock (1968), Rice and Tracey (1969) and Gurson (1977) the moment of macro-fracture is associated with the critical void volume fraction (critical plastic dilatation). Such models are able to describe the evolution of isotropic damage in processes with small plastic deformations (small deviatoric strains) satisfactorily when there is mainly a change in void volume but not in void shape.

In many metal forming processes the deformed material is subjected to the large deviatoric strains. Initially spherical voids become prolate or oblate ellipsoids under large plastic deformations, depending on the stress state. At the same time it turns out that the spatial orientation of the principal axes of an ellipsoidal void is related to the directions of the principal strains ε_1, ε_2, ε_3 of the material particle containing a void. It has also been observed that the nucleation and growth of voids as well as their orientation depend significantly on the direction of the applied stress or strain and, hence, are generally anisotropic (cf., e.g., Onat and Leckie, 1988; Murakami, 1988). A change of the void shape effects significantly on the evolution of strain-induced damage and finally on the ductile macro-fracture (cf., e.g., Gologanu et al., 1993; Ponte Castañeda and Zaidman, 1994, etc.).

Another type of criteria, the continuum damage mechanics (CDM)-based criterion, introduces a macroscopic damage indicator as an internal variable to describe the damage evolution and progressive degradation of materials. Compared with the micromechanical models, the CDM-based models are formulated in a phenomenological manner within the thermodynamics framework and are relatively simple, with fewer material constants involved (cf., e.g., Kachanov, 1986; Chaboche, 1993; Lemaitre and Desmorat, 2007, etc.).

An important issue is the appropriate choice of the physical nature of variables describing the damage state of a material. Various approaches to the phenomenological or micromechanical definition of damage variables were discussed and, therefore, different models were proposed. A substantiated model of damage evolution should be thermodynamically consistent and be able to describe the gradual internal deterioration of the material at the mesoscale. Considerable effort has been made to formulate thermodynamically consistent tensorial models of damage including the dissipation potential and internal state variables (cf., e.g., Brünig, 2003; Voyiadjis and Dorgan, 2007; Einav et al., 2007). Many authors have shown that a thermodynamically consistent framework for ductile damage should be based on multiplicative decomposition of the metric transformation tensor (for a more detailed survey see Bammann and Solanki (2010). Undamaged configurations are introduced to formulate effective elastic and effective plastic strain rate tensors. They are related to the damaged configurations via associated metric transformations which allow for an interpretation as damage tensors. As a consequence, the appropriate damage tensor is explicitly characterized in terms of a kinematic measure of damage (cf., e.g., Brünig, 2001). For metals a multiplicative decomposition of the deformation gradient is physically motivated by the mechanisms underlying lattice deformation, plastic flow, and the evolution of damage in polycrystalline materials. Bammann and Solanki (2010) show that prescribing plasticity and damage evolution equations in their physical intermediate configurations lead to physically justified evolution equations in the current configuration.

In general, starting from different models, damage may be described by vector or tensors of different orders, in case we have a sound theoretical basis and experimental data to support correctness and to show the realm of applicability of these models. From a practical point of view a model should be simple enough to allow efficient numerical treatment and easy experimental identification of material parameters. At the same time, its simplicity should not eliminate the essential features of the mechanical behavior within the intended range of application. In a number of works starting from Murakami und Ohno (1980) and Betten (1983) anisotropic damage is suitably characterized by a second-order symmetric tensor of damage which has been used extensively to study various aspects of damage problems, particularly, those arising in many sheet metal forming processes. Detailed discussions of the order of a damage tensor is presented in Betten (1983), Brünig (2001) and Lii and Chen (1989).

Since the detailed surveys of different-type damage models have been presented by Besson (2010) and Benzerga and Leblond (2010) we will mention only some of numerous excellent results in damage modeling that have been published most recently and are closely related to the present study. Malcher et al. (2012) performed a numerical assessment of three isotropic constitutive models in order to identify their applicability and reliability in the prediction of ductile failure under a wide range of stress triaxiality. Danas and Ponte Castañeda (2012) investigated failure in porous elasto-plastic solids under general triaxial loading conditions. Their model incorporates dependence on the porosity and average pore shape, whose evolution is sensitive to the stress triaxiality and Lode parameter. Tekoğlu et al. (2012) critically assessed the predictive capabilities of different coalescence criteria without shear effect and fine-tuned the expressions involved in the original Thomason criterion. The predictions of this new coalescence criterion are in good agreement with the results produced by 3D finite element calculations, for both loadings involving and not a shear component. Madou and Leblond (2012) extend the Gurson's (1977) model to general non-spheroidal ellipsoidal cavities, through approximate homogenization of some representative elementary porous cell. The results obtained suggest approximations leading to explicit approximate expressions of the overall dissipation and yield function. Tvergaard (2012) obtained new results studying the unstable growth of a cavity affected by neighboring voids. Komori (2013) proposed an ellipsoidal void model for simulating ductile fracture behavior. It was shown