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Numerical analysis of damage evolution for materials with tension-compression asymmetry

Shenghua Wu[a]*, Nannan Song[b], F.M.Andrade Pires[a]

[a]*Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias 4200-465 Porto, Portugal*
[b]*INEGI , Rua Dr. Roberto Frias 4200-465 Porto, Portugal*

Abstract

In recent decades, with the increasing attention to the carbon emission problem and shortage of energy, the development of lightweight metallic materials with Hexagonal closed packed (HCP) crystal structures, such as magnesium and titanium alloys, has become an important topic of research. The study and prediction of their mechanical behavior has become increasingly more important and has attracted growing interest in both academic and industrial communities. Metallic materials with a Hexagonal closed packed (HCP) crystallographic microstructure have an unconventional mechanical behavior including an anisotropic plastic response and a strength differential effect (SD) in tension and compression. This behavior poses considerable challenges that are intensified in the presence of microstructural damage processes.

In this contribution, a fully coupled continuum damage model with elasto-plastic Cazacu's orthotropic plasticity criterion has been implemented. The coupling between damaging and material behaviour is accounted for within the framework of Continuum Damage Mechanics (CDM). The closest point projection methods (CPPM) are used to implement the continuum damage constitutive model in an implicit quasi-static finite element environment to update stress and state variables. Finite element simulation of damage evolution and fracture initiation in ductile solids is investigated. The results obtained are compared against both numerical and experimental results available in the literature and good agreement is found between them.

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Keywords: Fracture, strength differential (SD) effect, Continuum Damage, Constitutive modelling, HCP Metals.

* Shenghua Wu. Tel.: +351 939786091; fax: +351 225574199.
E-mail address: shwoo2001@gmail.com

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1. Introduction

In an effort to improve the fuel efficiency for saving energy, an efficient way for reducing eventually the climate-changing CO_2 emissions is provided by the application of lightweight materials to reduce the overall weight of vehicles in the defense applications, aerospace, and automotive industries *etc* (Ian Polmear, 2005). Although composites, particularly those being fiber-reinforced, are currently being heavily investigated and developed for that purpose, lightweight metals such as titanium alloy and magnesium alloy remain the most frequently made choices due in part to their low density and high specific strength (Khan, 2007; Nixon, 2010). Most of these components were produced by metal forming process. In the design early stages, the correct prediction of damage and fracture in these ductile metallic materials has become an issue of great importance for metal forming industries. A large number of mathematical models have been formulated to describe the mechanical behavior of macro and microscopic ductile damage in metallic materials. A classification can be made based on the interaction between the damage model and the material behavior (Leon, 2001; Wohua Zhang, 2009). Generally, these damage models can be categorized into uncoupled and coupled, based on the material flow behavior and damage evolution in the field of continuum mechanics. The uncoupled model is a kind of posteriori damage criteria to calculate the damage distribution without taking into account its effect on the other thermomechanical fields. Damage accumulation is formulated empirically or semi-empirically to calculate the damage distribution using the stress and strain fields at each of finite element step. The typical these uncoupled damage model include Oyane (1980) ductile fracture criteria, Cockroft and Latham (1968), Rice and Tracey (1969) etc. Although the uncoupled damage criteria is easily implemented in any numerical code, The uncoupled criteria neglect the effects of damage on the yield surface of the material, accordingly, it is important to use fully coupled constitutive equations accounting for the damage influence of all the mechanical fields according to the appropriated coupling theory. This will be helpful for the damage initiation and growth during some bulk and sheet metal forming processes as forging, deep drawing. It is worth noting that, taking into account the ductile damage in metal forming necessitates not only the availability of the damage evolution equations, but also its effect (or coupling) on the other mechanical fields under concern. Within the coupled damage models, Gurson (1977) and Needleman (1984) conducted an upper bound analysis of simplified models containing voids. Hence, only the effect of the ductile damage on the plastic behaviour is taken into account, leaving the elastic stiffness completely insensitive to the damage occurrence. After that, based on Continuum Damage Mechanics (CDM), Lemaitre (1985)assume that damage refers to the loss of mechanical stiffness and treat damage evolution in a macroscopic and phenomenological way by introducing an internal variable D to quantify the microscopic material degradation. Pires (2003) *et al* extends the Lemaitre's model by considering the damage closure. Filipe (2009) *et al* study the mesh dependent and propose an integral non-local continuum damage model.

The improvement of numerical simulations of industrial forming processes also requires reliable constitutive models and damage criteria. The ability to predict orthotropic material failure entirely depends on how accurately the selected material model can replicate the actual material behaviour. However, their Hexagonal Closed Packed (HCP) crystallographic structure promotes a very different mechanical behavior when compared to other metals with FCC and BCC structures, such as steel, aluminum etc. At room temperature, materials with HCP crystal structure show a strong anisotropy and asymmetrical tension-compression strength. The commonly used phenomenological yield functions such as Hill (1948) Barlat and Lian (1989), *et al*, fail to capture this unconventional mechanical behavior. Cazacu *et al*. (2006) have proposed generic yield criteria, by using the transformed principal stress with a 4th-order linear transformation operator on the Cauchy stress tensor, to account for the initial plastic anisotropy and SD effect simultaneously.

In order to determine the state of deformation and damage in materials with tension-compression asymmetry, in this contribution, an anisotropic plastic continuum damage constitutive model is extended. Cazacu's orthotropic yield criterion is used to replace the original isotropic von Mises yield function to describe the material plastic anisotropy. Then the Lemaitre's continuum damage formulation coupled with Cazacu06 yield criterion was implemented using a primal Closest Point Projection Method (CPPM) within an implicit quasi-static finite element environment. The influence of damage parameters on the mechanical behaviors was also evaluated.