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ScienceDirect
International Journal of Plasticity 24 (2008) 1071–1096
INTERNATIONAL JOURNAL OF Plasticity
www.elsevier.com/locate/ijplas

A new model of metal plasticity and fracture with pressure and Lode dependence

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Received 28 June 2007; received in final revised form 28 August 2007
Available online 14 September 2007

Abstract

Classical metal plasticity theory assumes that the hydrostatic pressure has no or negligible effect on the material strain hardening, and that the flow stress is independent of the third deviatoric stress invariant (or Lode angle parameter). However, recent experiments on metals have shown that both the pressure effect and the effect of the third deviatoric stress invariant should be included in the constitutive description of the material. A general form of asymmetric metal plasticity, considering both the pressure sensitivity and the Lode dependence, is postulated. The calibration method for the new metal plasticity is discussed. Experimental results on aluminum 2024-T351 are shown to validate the new material model.

From the similarity between yielding surface and fracture locus, a new 3D asymmetric fracture locus, in the space of equivalent fracture strain, stress triaxiality and the Lode angle parameter, is postulated. Two methods of calibration of the fracture locus are discussed. One is based on classical round specimens and flat specimens in uniaxial tests, and the other one uses the newly designed butterfly specimen under biaxial testing. Test results of Bao (2003) [Bao, Y., 2003. Prediction of ductile crack formation in uncracked bodies. PhD Thesis, Massachusetts Institute of Technology] on aluminum 2024-T351, and test data points of A710 steel from butterfly specimens under biaxial testing validated the postulated asymmetric 3D fracture locus.
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Keywords: Pressure effect; Lode dependence; Yield surface; Fracture locus; Calibration method

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0749-6419/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijplas.2007.09.004

1. Introduction

The classical J2 theory of metal plasticity assumes that the effect of hydrostatic pressure σ_m on plastic flow is negligible, and further assumes that the flow stress is independent of the third stress invariant of the stress deviator. For application to ductile fracture, these assumptions must be carefully examined. Ductile fracture is a local phenomenon and the state of stress and strain in potential fracture locations must be determined with great accuracy. Fracture initiation is often preceded by large plastic deformation and there are considerable stress and strain gradients around the point of fracture. In these situations, the infinitesimal J2 theory of plasticity is not accurate enough, and more refined plasticity models has to be introduced.

The soil and rock mechanics community has long recognized a need for incorporating the hydrostatic and deviatoric (Lode angle parameter) stress invariants into a constitutive descriptions (see for example Bardet, 1990; Menetrey and Willam, 1995). More recently Bigoni and Piccolroza (2003) proposed a general failure surface for geomaterials in the space of principal stresses that reduces in limiting cases to the Tresca hexagon or the von Mises circle. The Sandia GeoModel (Fossum and Brannon, 2006) is also formulated in the space of three invariants. The developments in geomaterials was proceeding over the decades independently of metal plasticity with the latter lagging behind the former.

Based on an extensive experimental study, Richmond and Spitzig (Richmond and Spitzig, 1980; Spitzig and Richmond, 1984) were first to demonstrate the effect of hydrostatic pressure on yielding of aluminum alloys. This conclusion has recently been confirmed by Wilson (2002), who studied notched 2024-T351 aluminum bars in tension. The concept of a shrinking yield surface with hydrostatic pressure was put forward independently by Gurson (1975) and later by Needleman and Tvergaard (1984) in their studies of ductile fracture by the nucleation, growth and coalescence of voids. The common shortcoming of these various theories of porous plasticity has been an ill-defined calibration procedure.

In general, the hydrostatic pressure is controlling the size of the yield surface while the Lode angle parameter is responsible for its shape. The determination of an adequate shape of the yield surface has become an issue in the sheet metal forming industry. It was found a long time ago that the von Mises plane stress ellipse does not lead to a correct prediction of the necking instability. There are an abundance of various modifications and generalizations of the plane stress yield curve to bring the prediction closer to reality (Karafillis and Boyce, 1993; Barlat et al., 1991, 1997, 2005; Vegter and van den Boogaard, 2006). However, most of the above theories included the effect of an in-plane anisotropy and the connection between the shape of yield condition and the Lode angle parameter has only been noticed recently. In particular, the effect of the Lode angle parameter (or the third deviatoric stress invariant) on plastic yielding has been studied by Cazacu and Barlat (2004), Cazacu et al. (2006), Racherla and Bassani (2007). Their models incorporate the difference in strength under compression and tension. They showed that the forming limit diagram of sheets was sensitive in that difference. However, their models did not have enough flexibility to predict plane strain yielding. Such a generalization is proposed in the present paper.

The paper is divided into two parts. The first part is concerned with a development of a more general plasticity model. Results of 21 tests on three groups of specimens are analyzed through a finite element simulation. It is shown that the parameters of the J2 plasticity model with power hardening rule, determined from one test, can not predict correctly the load–displacement responses in the all remaining tests. A new plasticity

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