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Orthotropic yield criteria for description of the anisotropy in tension and compression of sheet metals

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Abstract

In this paper, yield functions describing the anisotropic behavior of textured metals are proposed. These yield functions are extensions to orthotropy of the isotropic yield function proposed by Cazacu et al. (Cazacu, O., Plunkett, B., Barlat, F., 2006. Orthotropic yield criterion for hexagonal close packed metals. Int. J. Plasticity 22, 1171–1194). Anisotropy is introduced using linear transformations of the stress deviator. It is shown that the proposed anisotropic yield functions represent with great accuracy both the tensile and compressive anisotropy in yield stresses and *r*-values of materials with hcp crystal structure and of metal sheets with cubic crystal structure. Furthermore, it is demonstrated that the proposed formulations can describe very accurately the anisotropic behavior of metal sheets whose tensile and compressive stresses are equal.

It was shown that the accuracy in the description of the details of the flow and *r*-values anisotropy in both tension and compression can be further increased if more than two linear transformations are included in the formulation. If the in-plane anisotropy of the sheet in tension and compression is not very strong, the yield criterion CPB06ex2 provides a very good description of the main trends.
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Keywords: Hexagonal metals; Tension/compression asymmetry; Anisotropic yield function; Linear transformations

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1. Introduction

Characterization and modeling of the anisotropy in the plastic response of metals with cubic crystal structure is well advanced. Anisotropic yield functions that capture with increased accuracy both the anisotropy of the yield strengths and the anisotropic distributions of the Lankford coefficients have been proposed (see Cazacu and Barlat, 2003; Barlat et al., 2005; Hu, 2005; etc). For metals with cubic crystal structure, the basic deformation mechanism is slip. Since slip does not depend on the sign of the shear stress i.e. can operate both forward and backward, the tensile and compressive yield stresses are equal so the yield functions are symmetric about the origin in the stress space. Metals with hexagonal close packed (hcp) crystal structure deform plastically by slip and twinning. As opposed to slip, twinning is a directional shear mechanism: shear in one direction can cause twinning while shear in the opposite direction cannot. For example, in magnesium alloys sheets twinning is not active in tension along any direction in the plane of the sheet, but is easily activated in compression. As a result the average initial in-plane compressive yield stress is about half the average in-plane tensile yield stress (e.g. see Lou et al., 2007). Thus, the yield surfaces are not symmetric with respect to the stress free condition. Since hcp metals sheets exhibit strong basal textures (*c*-axis oriented predominantly perpendicular to the thickness direction), a pronounced anisotropy in yielding is observed. To account for both strength differential (SD) effects and the anisotropy displayed by hcp metals, Hosford (1966) proposed the following modification of Hill's (1948) orthotropic yield criterion:

$$A\sigma_{xx} + B\sigma_{yy} + (-B - A)\sigma_{zz} + F(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2 = 1, \tag{1}$$

where A, B, F, G, H are material coefficients and **x**, **y**, **z** are normal to the mutually orthogonal planes of symmetry of the material . Since the criterion does not involve shear stresses, it cannot account for the continuous variation of the plastic properties between the material axes of symmetry. Liu et al. (1997) have proposed an extension of Hill (1948) yield criterion in the form:

$$\begin{aligned}&\{F(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2 + 2L\sigma_{yz}^2 + 2M\sigma_{xz}^2 + 2N\sigma_{xy}^2\}^{1/2}\\&\quad + I\sigma_{xx} + J\sigma_{yy} + K\sigma_{zz} = 1.\end{aligned} \tag{2}$$

In the above equation, F, G, H, L, M, N, I, J, K are independent material coefficients. Although this yield criterion captures SD effects, the asymmetry in yielding is due to pressure effects. The effects of hydrostatic pressure on macroscopic plastic flow have been reported by Spitzig and Richmond (1984) for fully dense metals (e.g. steels). However, these effects are small at low pressure levels and lead to yield stresses which are larger in compression than in tension. For HCP metals, the predominant mechanism responsible for SD effects is twinning (Hosford and Allen, 1973), which typically leads to lower initial yield stresses in compression than in tension for in-plane loadings of rolled sheets. Therefore, the criterion in Eq. (2) may not capture with accuracy the behavior of HCP metals. Recently, based on results of polycrystalline simulations, Cazacu and Barlat (2004) have proposed a macroscopic isotropic yield criterion expressed in terms of the invariants of the stress deviator, which captures the asymmetry in yielding between tension and compression. To describe both the asymmetry and anisotropy in yielding of magnesium and magnesium alloys sheets, an extension of this criterion to orthotropy was formulated using the generalized invariants approach proposed by Cazacu and Barlat (2001). For full stress state (3D) conditions, anisotropy is described by eighteen coefficients. This orthotropic

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