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Anisotropic yield function based on stress invariants for BCC and FCC metals and its extension to ductile fracture criterion

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ABSTRACT

It is essential to accurately model the anisotropic plastic deformation and ductile fracture of metals in order to guarantee the reliable numerical analysis and optimization of metal forming. For this purpose, the Drucker function is revisited. Effect of the third stress invariant in the Drucker function is analyzed and calibrated for metals with body-centered cubic (BCC) and face-centered cubic (FCC) crystal systems based on the yielding and plastic flow of both crystal plasticity and biaxial tensile experiments. The calibrated Drucker function is extended into an anisotropic form using a fourth order linear transformation tensor. The anisotropic flexibility is enhanced by two approaches: non-associate flow rule (non-AFR) and the sum of n-components of the anisotropic Drucker function. The proposed anisotropic Drucker function is applied to model the anisotropic behavior of both BCC and FCC metals. The predicted anisotropic behavior is compared with experimental results. The comparison demonstrates that the anisotropy is accurately modeled for both BCC and FCC metals by the anisotropic Drucker function. The anisotropic Drucker function is also implemented into numerical analysis of tension of specimens with a central hole to investigate its computation efficiency under spatial loading compared with the Yld2000-18p function. It is found that the proposed anisotropic Drucker function can reduce about 60% of computation time in case that the Yld2000-18p function is substituted by the anisotropic Drucker function in numerical computation due to its simplicity compared to the Yld2000-18p function. A ductile fracture criterion is also developed by coupling the Drucker function with the first stress invariant. The modified Drucker function is reformulated to investigate the effect of the stress triaxiality and the normalized third invariant on ductile fracture. Comparison of the modified Drucker fracture locus with the experimental results of AA2024-T351 demonstrates that the modified Drucker criterion accurately illustrates the fracture stress of the alloy in wide stress states with the stress triaxiality ranging from -0.5 in plane strain compression to 0.6 in tension of notched specimens. The modified Drucker fracture criterion is expected to be less sensitive to the change of strain path considering that the criterion describes fracture in the stress space. Accordingly, the anisotropic Drucker yield function and the pressure-coupled Drucker fracture criterion are suggested to model anisotropic plastic deformation and to predict the onset of failure for both BCC and FCC metals due to simple implementation in numerical analysis under spatial loading and computation efficiency with brick elements.

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1. Introduction

Accurate modeling of anisotropic plastic deformation and ductile fracture has been one of the key issues in sheet metal forming researches. Dozens of anisotropic yield functions were developed with different accuracy and distinct applications. Hill (1948) proposed the first function to describe anisotropic behavior of metals based on the isotropic von Mises yield function. Thereafter, various anisotropic yield functions (i.e. Aretz and Barlat, 2013; Hill, 1948, 1979, 1990, 1993; Hosford, 1979; Barlat and Lian, 1989; Barlat et al., 1991, 1997, 2003, 2005; Banabic et al., 2005; Cazacu et al., 2006; Karafillis and Boyce, 1993; Lou et al., 2013a) were developed to introduce more anisotropic coefficients for the improvement of accuracy. Most of these yield functions can only describe yielding behavior under plane stress, while the other yield functions for spatial loading are generally expressed as a function of principal stresses of a linear transformed stress tensor. However, the computation of the principal stresses is complicated for spatial loading. It is even lengthy to calculate the derivatives of yield functions for their implementation in numerical analysis.

Soare (2008) and Soare and Barlat (2010) tried to model anisotropic plastic deformation using homogeneous polynomials. The yield functions are expressed directly by stress components. These yield functions are user-friendly for numerical application under spatial loading since principal stress components are not required for computation. The problem lies in that the convexity of the polynomials must be considered first for some specific cross sections of a 3D yield locus. Besides, the polynomial yield functions cannot differentiate between face-centered cubic (FCC) and body-centered cubic (BCC) metals.

Another branch of yield functions is developed based on three stress invariants of the stress tensor. Examples of these yield functions are Drucker (1949), Cazacu and Barlat (2001, 2004), Gao et al. (2011), Yoshida et al. (2013), Yoon et al. (2014), Smith et al. (2015), and Cazacu and Revil-Baudard (2017). The advantage of these yield functions is that the yield functions can be utilized under both plane stress condition and the spatial loading cases conveniently, and the derivatives can be easily computed analytically. Moreover, the convexity is automatically guaranteed by setting a coefficient in these functions in a specified range, which is the merit of these functions over polynomial functions. Their drawback is that they do not differentiate between BCC and FCC metals.

Recently, Tuninetti et al. (2015) modeled the anisotropy and tension-compression asymmetry of Ti-6Al-4V at room temperature. Gawad et al. (2015) developed an evolving plane stress yield criterion based on crystal plasticity virtual experiments. Yoshida et al. (2015) introduced a framework for constitutive modeling of anisotropic hardening and Bauschinger effect for sheet metals. Kuwabara et al. (2017) conducted biaxial tensile tests of AA6016-O and AA6016-T4 and found that the strength under plane strain tension modeled by the quadratic von Mises and Hill48 yield functions is much higher than experimental results. Non-quadratic yield functions with high exponents can provide good description of yield stress around plane strain tensile condition. Raemy et al. (2017) developed a yield function based on Fourier series to model asymmetry and anisotropy in HCP metals under plane stress loading. Li et al. (2017) modeled anisotropic and asymmetrical yielding and its distorted evolution of titanium tubular metals with the shear stress-based CPB′2006 yield function (Cazacu et al., 2006) and a stress invariants-based model (Yoon et al., 2014).

In the last decade, a number of uncoupled ductile fracture criteria were proposed based on the experimental results of Bao and Wierzbicki (2004). Xue (2007) first introduced the effect of the Lode angle on ductile fracture. Bai and Wierzbicki (2008) proposed a phenomenological ductile fracture criterion with dependence on the stress triaxiality and the normalized Lode angle. Bai and Wierzbicki (2010) modified the Mohr-Coulomb criterion for the ductile fracture prediction of metals. Li et al. (2011) comprehensively compared the predictability of various ductile fracture models. Stoughton and Yoon (2011) provided an efficient method for the analysis of necking and fracture limits for sheet metals. Stoughton and Yoon (2012) proposed a new type of forming limit curves based on a polar representation of the effective plastic strain. Khan and Liu (2012a, 2012b) established a phenomenological fracture criterion using the magnitude of stress vector and the first invariant of stress tensor and considered effect of strain rate and temperature on ductile fracture in the proposed model. Lou et al. (2012, 2014, 2017) proposed a series of models to describe ductile fracture taking place along the maximum shear stress for metals with high ratio of strength to density. The Lode dependence of ductile fracture is also correlated with the effect of the maximum shear stress on the coalescence of voids along the maximum shear stress (Lou and Huh, 2013b). These criteria were successfully applied to predict onset of ductile fracture in various metal forming processes, such as limited dome height at the onset of ductile fracture for DP780 (Lou et al., 2013b), edge fracture prediction in hole expansion (Mu et al., 2017), fracture in high velocity perforation (Vershinin, 2015), and a series of independent validation experiments including a hole tension test, a conical and flat punch hole expansion test, and a hemispherical punch test (Anderson et al., 2017). Cao et al. (2014) modified the Lemaitre model to describe ductile fracture at low stress triaxiality. Mohr and Marcadet (2015) proposed a phenomenological Hosford-Coulomb model to depict ductile fracture at low stress triaxiality. Lee et al. (2017) predicted fracture based on a two-surface plasticity law for anisotropic magnesium alloys. Lou and Yoon (2017a, 2017b) modified the DF2012 criterion to take into account the anisotropic behavior of ductile fracture based on linear transformation. Sebek et al. (2017) coupled Lode dependent plasticity with nonlinear damage accumulation for prediction of ductile fracture of aluminum alloy. Cao et al. (2018) developed a modified elliptical fracture criterion based on two kinds of strain energy density.

The purpose of this paper is twofold. On the one hand, the stress invariant-based Drucker function is revisited. The effect of the third stress invariant is calibrated for BCC and FCC metals for the Drucker yield function based on the comparison of the Drucker yield surface with the non-quadratic Hershey function. The calibrated Drucker yield function for BCC and FCC metals is applied to model the yielding and plastic flow computed for randomly oriented polycrystals for the further verification of the calibrated effect of the third stress invariant. The Drucker function for BCC and FCC metals is extended into an anisotropic form using a fourth order linear transformation tensor. Two approaches are proposed to improve the predictability of the anisotropic Drucker function. Both approaches are applied to model anisotropic behavior of BCC and FCC metals for the verification of the calibrated Drucker-based function for the modeling of anisotropic yielding and plastic flow directions. The proposed anisotropic Drucker yield function is further implemented into numerical analysis of tension of specimens with a central hole to investigate its computational efficiency.