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Anisotropic Yield Criterion for Metals Exhibiting Tension–Compression Asymmetry

Lei Chen[1], Jian Zhang[1,2,*] and Hongjian Zhang[3]

[1] *Faculty of Civil Engineering and Mechanics, Jiangsu University, Zhenjiang, Jiangsu 212013, China*
[2] *National Center for International Research on Structural Health Management of Critical Components, Jiangsu University, Zhenjiang, Jiangsu 212013, China*
[3] *College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China*

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Abstract. The present study is devoted to developing a yield criterion that can model both the yielding asymmetry and plastic anisotropy of pressure-insensitive metals. First, a new isotropic yield criterion which can model the yielding asymmetry of pressure-insensitive metals is proposed. The main advantage of the proposed criterion is that it leads to a good approximation of yield loci calculated by the Taylor-Bishop-Hill crystal plasticity model. Further, the isotropic criterion is extended to orthotropy to take plastic anisotropy into account. The new anisotropic criterion is general and can be used in three-dimensional stresses. The coefficients of the criterion are determined by an error minimization procedure. Applications of the proposed theory to a hexagonal close packed (HCP) magnesium, a Cu-Al-Be shape memory alloy and a Ni3Al based intermetallic alloy show that the proposed theory can describe well the plastic anisotropy and yielding asymmetry of metals and the transformation onset of the shape memory alloy, showing excellent predictive ability and flexibility.

AMS subject classifications: 74C05, 74D10, 74E10

Key words: Yield criterion, yielding asymmetry, plastic anisotropy, magnesium alloy, shape memory alloy, intermetallic alloy.

1 Introduction

In modern industry, virtual manufacturing technology is one of the most efficient methods to reduce production cycles and improve the quality of products. As a part of virtual

*Corresponding author.
Email: jianzhang@ujs.edu.cn (J. Zhang)

manufacturing, numerical simulation of metal forming processes has always been a research hotspot [1, 2]. The traditional manufacturing process analysis and mold design rely mainly on the designer's experience. In order to avoid defects such as wrinkles and cracks, it is necessary to continuously test and repair molds, which results in long mold production cycles and low efficiency. With the rapid development of computer technology, metal sheet forming is gradually assisted by numerical simulations, which can not only reduce the cost of mold testing, but also shorten the production cycles [3]. This is a great progress in the field of metal plastic forming. It is generally known that the plastic analysis of metal forming processes depends on the yield criterion and associated plastic flow rules employed. In order to improve the accuracy of numerical plastic forming simulations, it is essential to develop appropriate yield criteria involved. Given their importance to plastic forming analysis, tremendous yield criteria for different metals have been proposed by researchers at home and abroad.

For isotropic metals, the von Mises and Tresca criteria are the ones most used to predict the plastic behavior of materials. And the von Mises criterion has been widely implemented in commercial FEM software packages such as ANSYS and ABAQUS. However, there are numerous other isotropic criteria in literature [4–6]. Actually, research on yield criteria for isotropic metals has been done quite thoroughly and the plastic forming simulations are accurate enough in most cases. However, due to their complicated plastic behavior, yield criteria for anisotropic metals are far from being thoroughly studied. In general, the pre-machined or pre-rolled metal sheet exhibits significant anisotropy, which has significant effects on the plastic forming process. In order to model the plastic behavior of anisotropic materials, Hill proposed the first orthotropic yield criterion, which reduces to von Mises criterion for isotropic conditions [7]. So far, because of its simplicity, this famous criterion has been widely used in analytical or numerical simulations of forming processes. Later, tremendous anisotropic yield cri-teria have been proposed. For reviews concerning yield criteria of metals one may refer to [8,9]. Subsequently, outstanding contributions have been made by Hill [10–13], Hosford [14–17] and Barlat [18–21]. For latest research concerning yielding behavior of solids, one may refer to [22–27]. For metallic materials, slip of dislocations and twinning are the main plastic deformation mechanisms. For both conditions, shear strains occurred on certain crystallographic planes and along certain directions. If the shear mechanism is reversible, yielding is insensitive to the sign of the stress but is only related to the magnitude of the re-solved shear stress. Thus, we get equal tensile yield stress and compressive yield stress. Most yield criteria in literature, expressed by even functions of the stress components, are based on the hypothesis of tension-compression asymmetry. This is true for metals deforming by reversible shear mechanism. However, not all metallic materials are tension-compression symmetric. Due to the directionality of twinning, a remarkable strength differential (SD) effect is observed in HCP materials at low strain levels. In general, the yield stress in tension is much higher than that in compression [17]. For Ll_2-long-range ordered intermetallic alloy, SD effect is observed for its violation of Schmid's law [28]. To model the strength differential effect of pressure insensitive metals, yield functions that can describe SD ef-