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An evolving plane stress yield criterion based on crystal plasticity virtual experiments

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ABSTRACT

This paper presents a new hierarchical multi-scale framework that allows taking into account evolution of the plastic anisotropy during sheet forming processes. The evolution of crystallographic texture, which is identified as the main source of the plastic anisotropy, is predicted by the ALAMEL crystal plasticity model. An extension to the phenomenological anisotropic plane-stress yield criterion BBC2008 is proposed, which provides adaptive updates of the local anisotropy in the integration points of the macroscopic finite element model. To this end, the BBC2008 is systematically recalibrated to data provided by the crystal plasticity virtual experiment framework (VEF). An enhanced identification algorithm is proposed. The new algorithm exploits comprehensive material characterization delivered by the VEF.

The deep drawing of cylindrical cups is used as a benchmark case. An industrial-grade aluminium alloy AA6016 is chosen for the test case. The experimental part of the study includes X-ray diffraction measurements of the texture as well as mechanical testing, which comprises uniaxial tensile tests, a bulge test and the deep drawing of cylindrical cups. A noticeable through-thickness gradient in terms of both the texture and the plastic anisotropy is identified in the initial material. This issue is taken into consideration in the study.

Three groups of simulations have been performed, in which (i) the BBC2008 was calibrated by means of the mechanical tests, (ii) the BBC2008 was calibrated by means of the VEF based on the initial texture, but kept constant throughout the simulation, and (iii) the BBC2008 was systematically recalibrated by means of the VEF to reflect the effects of texture evolution. The earing profiles measured in the experimentally drawn cups are compared to the ones predicted by the simulations. It is found that the cup profile predictions by (i) are clearly inferior compared to both (ii) and (iii). However, in the considered process (iii) provides only a moderate improvement over the results of (ii). The explanation of this limited impact of the anisotropy evolution is based on the analysis of the evolved texture and associated plastic anisotropy.

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1. Introduction

The plastic anisotropy, as well as many other properties of polycrystalline metals, is generally attributed to the microstructure of the material. One of the most prevailing microstructural factors that controls plastic anisotropy is crystallographic texture. There is a broad variety of attempts in literature to take this fact into account in numerical simulations of metal forming processes.

The microstructure can be explicitly dealt with if a physics-based model is employed. Crystal plasticity theories allow one not only to derive macroscopic mechanical response of the polycrystalline material, but they also provide insights on how the microscopic state evolves with an increasing deformation. Several crystal plasticity frameworks have been proposed over the last decades to answer these challenges.

A first approximation, which is attributed to Sachs (1928), is to use an iso-stress assumption for all grains in a representative volume of polycrystal. The Full Constraints (FC) Taylor–Bishop–Hill homogenization scheme, which was originally proposed by Taylor (1938) and later taken up again by Bishop and Hill (1951b), who proposed a different but equivalent solution method, assumes identical deformation throughout all the grains in the considered volume of the material. These authors proposed two different solution methods, which are both based on the Generalized Schmid Law as the constitutive model for a metallic crystal. An approximate but mathematically convenient alternative is the visco-plastic method by Asaro and Needleman (1985).

Unfortunately, the simple homogenization schemes unrealistically neglect interactions between the grains. To address this issue, several more elaborated homogenization schemes have been established. The Visco-Plastic Self-Consistent (VPSC) model, e.g. Molinari et al. (1997), Lebensohn and Tomé (1993), Lebensohn et al. (2007) considers every crystal in the polycrystalline as an ellipsoidal inclusion embedded in an effective medium. Since the medium comprises all the grains in the considered volume, long-range interactions are captured. Another approach is used by 'cluster' models, which assume that the average plastic velocity gradient of the cluster is equal to the macroscopic velocity gradient. The Grain InterAction (GIA) model proposed by Crumbach et al. (2001) and extended by Engler et al. (2005), as well as the RGC model by Tjahjanto et al. (2010), take into account short-range interactions between next-neighbour grains in an aggregate consisting of eight hexahedral grains. The Advanced LAMEL (ALAMEL) was proposed by Van Houtte et al. (2005) as a generalization of the LAMEL (Van Houtte et al., 1999), which both consider interactions in clusters of two grains. Several improvements to the ALAMEL scheme have been recently proposed, for example by Mánik and Holmedal (2013), Zhang et al. (2015), Arul Kumar et al. (2011), Mahesh (2010).

All these frameworks have an important limitation in common: the microstructure is represented in a statistical way, thus a substantially simplified shape of the grains is generally assumed. The Crystal Plasticity Finite Element Method (CPFEM), e.g. (Peirce et al., 1982; Bate, 1999; Roters et al., 2010) takes a step far forward by explicitly treating complex microstructural morphology in a representative volume element. Recently, considerable attention has been attracted by the Crystal Plasticity Fast Fourier Transform (CP-FFT) method (Lebensohn, 2001; Prakash and Lebensohn, 2009; Roters et al., 2012; Lebensohn et al., 2012; Eisenlohr et al., 2013), which promises substantial improvement over the CPFEM in terms of calculation time, while keeping high spatial resolution in order to capture the details of complex microstructures.

The crystal plasticity models mentioned above provide homogenization framework that allows one to derive macroscopic quantities, such as macroscopic stresses, from relevant quantities at the length scale of grains or even finer. Macroscopic forming processes can in essence be simulated by means of a crystal plasticity model implemented directly into an FE code. A clear advantage of the direct coupling is that the crystal plasticity model locally follows the evolution of anisotropy due to the evolving microstructure, including texture and possibly substructure. A recent review by Roters et al. (2010) provides a detailed overview about the incorporation of crystal plasticity models into the FEM. A remarkable part of recent developments in this field has been focused on materials that pose challenges both in modelling and processing, such as hcp alloys, e.g. Segurado et al. (2012), Izadbakhsh et al. (2012), Knezevic et al. (2013), Galán et al. (2014). This kind of multi-scale computations is computationally very intensive. For detailed analyses of complex forming processes, a more robust micro-macro coupling scheme is desirable.

At the other end of the spectrum, the phenomenological models neglect the microstructural effects and focus on macroscopic mechanical response of the material. The phenomenological yield criteria consider the polycrystalline material as homogeneous at the macroscopic level, and the yield surface depends merely on the macroscopic stress, strain rate, certain strain measures as well as their rates. The microstructural features of the material, such as crystallographic texture, can be indirectly taken into account by means of extensive parametrization of these models. Numerous successful efforts have been made in the last decades to improve the macroscopic anisotropy models, for example Hill (1948), Hosford (1979), Barlat et al. (1991, 1997a,b, 2003b, 2005, 2007), Banabic et al. (2000), Aretz and Barlat (2012, 2013), Banabic et al. (2003, 2005), Comsa and Banabic (2008), Banabic et al. (2010), Yoon et al. (2004, 2006, 2010, 2014), Yoshida et al. (2013), Cazacu et al. (2006), Cazacu and Barlat (2004), Plunkett et al. (2006, 2008), Soare et al. (2008), Soare and Barlat (2010), Van Houtte and Van Bael (2004), Van Houtte et al. (2009), Vegter et al. (2003), Vegter and van den Boogaard (2006). The phenomenological yield loci are generally limited to the initial anisotropy of the material, since it is hardly possible to accurately predict the evolution of the yield surface without taking into account how the microstructure develops during the deformation. Usually it is assumed that the changes to the initial yield locus are negligible. The assumption is approximately valid if the plastic strains are not too large, which admittedly holds in some sheet metal forming processes. Nonetheless, when used in a combination with flow theories, such as the normality flow theory, the phenomenological yield loci provide an efficient technique for capturing the