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Multi-level modelling of mechanical anisotropy of commercial pure aluminium plate: Crystal plasticity models, advanced yield functions and parameter identification

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ABSTRACT

The mechanical anisotropy of an AA1050 aluminium plate is studied by the use of five crystal plasticity models and two advanced yield functions. In-plane uniaxial tension properties of the plate were predicted by the full-constraint Taylor model, the advanced Lamel model (Van Houtte et al., 2005) and a modified version of this model (Mánik and Holmedal, 2013), the viscoplastic self-consistent model and a crystal plasticity finite element method (CPFEM). Results are compared with data from tensile tests at every 15° from the rolling direction (RD) to the transverse direction (TD) in the plate. Furthermore, all the models, except CPFEM, were used to provide stress points in the five-dimensional deviatoric stress space at yielding for 201 plastic strain-rate directions. The Facet yield surface was calibrated using these 201 stress points and compared to in-plane yield loci and the planar anisotropy which were calculated by the crystal plasticity models. The anisotropic yield function Yld2004-18p (Barlat et al., 2005) was calibrated by three methods: using uniaxial tension data, using the 201 virtual yield points in stress space, and using a combination of experimental data and virtual yield points (i.e. a hybrid method). Optimal yield-surface exponents were found for each of the crystal plasticity models, based on calibration to calculated stress points at yielding for a random texture, and used in the latter two calibration methods. It is found that the last hybrid calibration method can capture the experimental results and at the same time ensure a good fit to the anisotropy in the full stress space predicted by the crystal plasticity models.

1. Introduction

During thermo-mechanical processing, crystallographic texture will evolve in sheet metals. Texture, i.e. preferred crystallographic orientations of the grains, is the primary source of plastic anisotropy. This anisotropic plastic behaviour should be taken into account in finite element simulations of metal forming processes and in predictions of sheet formability.

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Two main approaches exist to describe the plasticity of polycrystalline metallic metals. In the first, a phenomenological yield function is used. The Tresca (1864) and the von Mises (1913) yield criteria are widely used for isotropic materials. Hill (1948) proposed a quadratic yield function for materials with orthotropic symmetry, while Hosford (1972) introduced a non-quadratic yield function with a variable exponent for isotropic polycrystalline metals. Based on full-constraint (FC) Taylor model calculations of metals with random textures, the exponent was suggested as 6 and 8 for body-centered cubic (BCC) and face-centered cubic (FCC) metals, respectively. This criterion was then generalized to anisotropic materials by Hosford (1979). Barlat and Lian (1989) further extended Hosford's criterion. Later on, Barlat et al. (1991, 1997, 2003a, 2005), Karafillis and Boyce (1993), Banabic et al. (2003, 2005) and Aretz and Barlat (2013) proposed yield functions, where anisotropy is introduced by means of linear transformations of the stress tensor. A detailed overview of linear transformation-based yield functions can be found in Barlat et al. (2007). Nowadays, phenomenological yield functions are commonly used in finite element simulations by the sheet forming industry. One drawback by applying a flexible yield function is that a significant number of material tests are required (Barlat et al., 2005). Among the linear transformation-based yield functions, the Yld2004-18p criterion, proposed by Barlat et al. (2005) and implemented by Yoon et al. (2006) into a finite element code, has been proven as an accurate and flexible yield function capable of predicting six or eight ears in deep drawing of aluminium plates. Due to severe experimental limitations, a fundamental problem with the phenomenological approach is that most of the stress space is left unexplored when fitting the parameters of the yield function.

The other approach is to use polycrystal plasticity models. The oldest one was proposed by Sachs (1928) with the iso-stress assumption for all grains in the polycrystal representative volume element. In contrast, the full-constraint Taylor model (Taylor, 1938; Bishop and Hill, 1951 a,b) assumes that each grain experiences the same deformation as the aggregate, and the deformation is accommodated by at least five slip systems according to the principle of maximum plastic work or the complementary minimum principle, which follows from the yield criterion at the slip system level. Some relaxed-constraint Taylor models have also been developed to increase the freedom of single grains (Kocks and Chandra, 1982; Van Houtte, 1982, 1988). The Lamel model (Van Houtte et al., 1999, 2002) is also a relaxed-constraint Taylor model particular for the rolling process which considers two grains at the same time. Since the model considers a pair of grains, it is called a two-site model.

Over the past few decades, materials scientists have become more aware of the important role played by the distribution and connectivity of different grain boundary types in governing various mechanical and functional properties of materials (Patala et al., 2012). It has been shown that the grain boundary can be of importance to texture and microstructure evolution during deformation (Chang et al., 2010). Grain boundary characteristics can be expressed by five degrees of freedom, i.e. the misorientation between the two neighbouring grains (three parameters) and the boundary plane normal (two parameters). It is now possible to obtain complete three-dimensional boundary information owing to the development of three-dimensional X-ray diffraction methods and automated serial sectioning methods combined with Electron Backscatter Diffraction (EBSD). The Taylor-type advanced Lamel model (ALAMEL) (Van Houtte et al., 2005) was developed to account for grain boundary orientations and general deformation modes. Recently, a modified version has been suggested, taking into account the so-called Type III strain constraint relaxation (Mánik and Holmedal, 2013). There are also other similar *N*-site Taylor-type models, such as the GIA model (Crumbach et al., 2001) and the *N*-'stack' model (Arul Kumar et al., 2011). In these *N*-site rate-independent crystal plasticity models, the local interaction at the grain boundary is introduced by relaxation of strain components and stress equilibrium is partially obtained.

Another popular class of polycrystal plasticity models is based on the self-consistent approach, originally proposed by Kröner (1958) for the elastic case and later extended to elastoplasticity (Hill, 1965) and viscoplasticity (Hutchinson, 1976). The viscoplastic self-consistent (VPSC) model regards each grain of the polycrystalline material as an ellipsoidal inclusion embedded in a homogeneous effective medium whose mechanical response corresponds to the volumetric average of all grains. Among various self-consistent plasticity models, the VPSC model developed by Molinari et al. (1987), and extended by Lebensohn and Tomé (1993, 1994) to account for anisotropy, has been widely used to simulate large strain behaviour and texture evolution. In addition to various first-order linearization schemes, a second-order approximation scheme is also available now (Lebensohn et al., 2007).

Since it was first introduced by Peirce et al. (1982), the crystal plasticity theory implemented in the finite element method (CPFEM) has matured into a whole family of constitutive and numerical formulations that has been applied to a broad variety of crystal mechanics problems (Roters et al., 2010). The CPFEM has both theoretical and practical advantages. Firstly, grains are represented by single or multiple elements where both stress equilibrium and strain compatibility are fulfilled at the boundaries. Secondly, complex boundary conditions are easily specified in the FEM code. Hence, the CPFEM is applicable to simulations of engineering processes. One main drawback of CPFEM is the huge computational time cost (Dumoulin et al., 2009). Recently, a full-field method based on the Fast Fourier Transform algorithm has been developed for polycrystal plasticity (Lebensohn, 2001; Lebensohn et al., 2012; Eisenlohr et al., 2013). Compared with the CPFEM, it shows much higher time efficiency (Prakash and Lebensohn, 2009).

To combine the strength of phenomenological yield functions and crystal plasticity models, hierarchical modelling schemes have recently become of interest. In such context, virtual experiments are performed using crystal plasticity models to provide data points; advanced yield functions are then identified using virtual experimental data. Barlat et al. (2005) used experimental data plus some out-of-plane stress points calculated by the VPSC model to identify the parameters of the Yld2004-18p yield function. Grytten et al. (2008) evaluated different methods for identifying the parameters of the Yld2004-18p yield function, including only experimental data, only virtual experiments with the FC-Taylor model and a