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Investigation of the dislocation slip assumption on formability of BCC sheet metals

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ABSTRACT

This paper explores the right-hand side of the forming limit diagram (FLD) for a BCC material in order to test the crystallographic slip assumptions. BCC crystals are considered with either 24 or 48 slip systems (BCC24 or BCC48). Identical uniaxial stress responses are assumed in order to compare the predicted FLDs. FLDs are performed using a rate-dependent polycrystal viscoplastic model together with the Marciniak–Kuczynski (M–K) approach. It is verified that the predictions of the limit strains carried out with the full-constraints (MK-FC) model are strongly affected by the selected deformation modes, showing unrealistically high limit strains in balanced-biaxial tension. Much more reliable values are found with the viscoplastic self-consistent (MK-VPSC) approach using either a BCC24 or BCC48 assumptions, enhancing the relevance of the selected transition scale model. Discrepancies between the numerical results, obtained using MK-FC and MK-VPSC, are interpreted in terms of the differences in the active slip systems selected by each model, and consequently, in the predicted lattice rotations and local curvature of the yield locus. Finally, it is found that the calculation of the FLD with MK-VPSC, using 48 slip systems, successfully predicts the right-hand side experimental tendency observed in a low carbon steel sheet metal obtained by bulge test.

1. Introduction

Since the concept of the forming limit diagram (FLD) was introduced by Keeler and Backofen in 1964 [1], this realistic and general method for analyzing plastic instability has been widely used for studying the formability of sheet metals. Through recent advances, the theoretical analysis of plastic instability has the potential to predict the near failure conditions measured by Keeler's technique. The FLD is an important tool for sheet metal formability investigations. It is a collection of limit-strain values plotted for different strain paths, varying from uniaxial tension, through plane strain to the biaxial-tension condition. The forming limit curve (FLC) shows the highest strain that a material sheet can resist before the failure, as a function of the major and minor strains in the sheet plane. Because of the importance of being able to avoid fracture in sheet-metal forming, a safety margin is frequently introduced in forming limit diagrams. In most of the metals used in the automotive industry, the minimum of the FLC is observed in the in-plane plane-strain condition (assuming that no pre-strain effects are involved). Experimental measurement of the FLD is not an easy task, requiring a wide range of sample geometries and even more than one type of mechanical test. Also, many test factors have a measurable influence in the limit-strain determination: friction conditions, small deviations in loading paths due bending effects, and strain-measurement procedures. Similarly, several physical factors related to material properties (e.g. plastic anisotropy, work hardening, strain-rate sensitivity) have an important influence in the development of localized necking or failure. Numerical simulation promotes a better understanding of deformation and failure in polycrystal sheet metal aggregates, by examining issues related to crystal anisotropy and stress/strain heterogeneity.

Most theoretical studies for predicting the FLD behavior are based either on a bifurcation analysis [2] or a model where the strain instability appears in the deformation process due to an imperfection already present in the material [3]. In recent years, research has shown that the localization of plastic flow is influenced by deformation anisotropy [4–7]. Thus, crystal-plasticity models should provide a framework for better understanding of the relation between flow localization and material microstructure. Issues such as yield-surface shape, changes in sharpness, material anisotropy, crystal reorientation are directly addressed within a polycrystalline model. It is widely recognized that the crystallographic texture strongly affects forming limit diagrams and the macroscopic anisotropy of polycrystalline sheet metals. Numerous authors have adopted the Marciniak and

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Kuczynski model [3] (M–K) to describe strain localization in rolled sheets [6,8–12]. For the FLD simulations, crystallographic effects are taken into account by combining the M–K approach with a viscoplastic (VP) self-consistent (SC) crystal-plasticity model, MK-VPSC [13]. Based on this approach, we have examined how hardening behavior and plastic anisotropy influence limit strains. Signorelli and Bertinetti [14] have recently characterized the effect of an initial cube texture and its evolution on the predictions of forming limit diagrams in a FCC textured material. Their results indicate that the selected homogenization scheme is critically important in order to correctly predict the behavior of materials that evolve crystallographically – hence anisotropically – during deformation. Consequently, it is impossible to understand the influence of crystallographic slip without the proposed scale-transition model linking the crystal to the polycrystal behavior.

In this work, we consider in detail the deformation of BCC metals. The identification of the active slip systems is a widely discussed issue in the plastic deformation of BCC crystals. The most common mode of deformation is $\{1\,1\,0\}\langle 1\,1\,1\rangle$, but BCC materials also slip on other planes, $\{1\,1\,2\}$ and $\{1\,2\,3\}$, with the same slip direction. In the literature, frequently two sets of possible slip systems that describe BCC plastic behavior have been considered: $\{1\,1\,0\}\langle 1\,1\,1\rangle$, $\{1\,1\,2\}\langle 1\,1\,1\rangle$ (BCC24); or $\{1\,1\,0\}\langle 1\,1\,1\rangle$, $\{1\,1\,2\}\langle 1\,1\,1\rangle$, $\{1\,2\,3\}\langle 1\,1\,1\rangle$ (BCC48).

Many investigations modeling BCC rolling textures have been performed considering BCC24 or BCC48 crystallographic slip. Van Houtte et al. [15] analyze two and three-level multiscale models, including a full-constraints (FC) Taylor model, crystal-plasticity finite-element (CPFEM) models and grain-interaction models GIA, LAMEL and ALAMEL. Particularly, for the latter, they showed that including the $\{1\,2\,3\}\langle 1\,1\,1\rangle$ slip systems does not qualitatively change the development of a 70% reduction, cold-rolling, IF-steel texture. Similar results can be found in Bate and Quinta da Fonseca's work [16] using CPFEM. Li et al. [17] studied microstructure and texture evolution in equal-angle channel extrusion of an IF steel by changing the processing routes. Using transmission electron microscopy, they identified that mainly the activation of the $\{1\,1\,0\}\langle 1\,1\,1\rangle$ and $\{1\,1\,2\}\langle 1\,1\,1\rangle$ slip systems accommodated plastic deformation. Also, using a viscoplastic self-consistent model the measured textures were correctly predicted. Radhakrishnan and Sarma [18] modeled the deformation of BCC polycrystals using 24 slip systems. In their simulations, the $\{1\,2\,3\}\langle 1\,1\,1\rangle$ slip systems were not considered since these slip systems do not extensively operate during room-temperature deformation of iron. Their simulations consistently predicted the expected evolution of the recrystallization texture. Delannay et al. [19] evaluated the influence of grain shape on the planar anisotropy of rolled steel sheets, using a VPSC calculation with the BCC24 slip condition; employing the same numerical code, Canadinc et al. [20] simulated pearlitic and bainitic microstructure by considering only the primary slip $\{1\,1\,0\}\langle 1\,1\,1\rangle$ systems. Many other authors have also included the $\{1\,2\,3\}\langle 1\,1\,1\rangle$ crystallographic slip mode in their simulations and satisfactorily described the basic features of BCC rolling textures and plastic anisotropy [21–25].

In the case of forming limits, most crystal-plasticity investigations have been done for FCC materials, like aluminum alloys. Investigations of BCC metals are more limited. Inal et al. [10] performed numerical FLD simulations using 24 slip systems and a rate-sensitive Taylor-type polycrystal-plasticity model in conjunction with M–K to compare the response of FCC and BCC sheets. They found that a BCC24, MK-FC approach predicts an unrealistically high limit strain in balanced-biaxial stretching. We verified these results and found that the number of crystallographic slip systems and type of crystal plasticity model strongly affects the calculated limit strains. When BCC48 is assumed the simulated limit strain decreases appreciably, but still remains unrealistically high. More realistic values are found with the MK-VPSC approach using either a BCC24 or BCC48 microstructure.

The aim of this paper is to explore the right-hand side (RHS) of the FLD for a BCC material using the proposed MK-FC and MK-VPSC approaches, and to test the crystallographic slip assumption. We begin Section 2 with a review of the basic equations and definitions for the M–K and VPSC theories and an analysis of the rate-dependent yield potential, as an aid to interpret the forming limit behavior. Our methodology is applied to simulate the FLDs of a randomly textured material. The advantages of using the VPSC material model in the M–K approach are discussed in Section 3, in terms of the crystallographic slip systems assumption. The model's predictions of a cold-rolling process beginning with annealed steel sheet are shown in Section 4. Finally, we state our conclusions in Section 5.

2. Theoretical framework

2.1. MK-VPSC formulation

In the present work, to simulate the polycrystal response, we implemented a VPSC model, which was initially proposed by Molinari et al. [26] and Lebensohn and Tomé [27]. Unlike the FC model, for which the local strains in the grains are considered to be equal to the macroscopic strain applied to the polycrystal, the SC formulation allows each grain to deform differently, according to its directional properties and the strength of the interaction between the grain and its surroundings. In this sense, each grain is in turn considered to be an ellipsoidal inclusion surrounded by a homogeneous effective medium (HEM) that has the average properties of the polycrystal. The interaction between the inclusion and the HEM is calculated by means of Eshelby's formalism [28]. The properties of the HEM are not known in advance because they result from an average of the individual grain behaviors, once convergence is achieved. Here, we outline the main equations of the VPSC model. An exhaustive presentation and discussion of the VPSC formulation can be found in Lebensohn and Tomé [27]. The VPSC formulation for modeling the aggregate behavior is implemented in conjunction with the well-known M–K approach (Fig. 1). The MK-VPSC model was discussed in detail in Signorelli et al. [13,14]. However, for completeness the

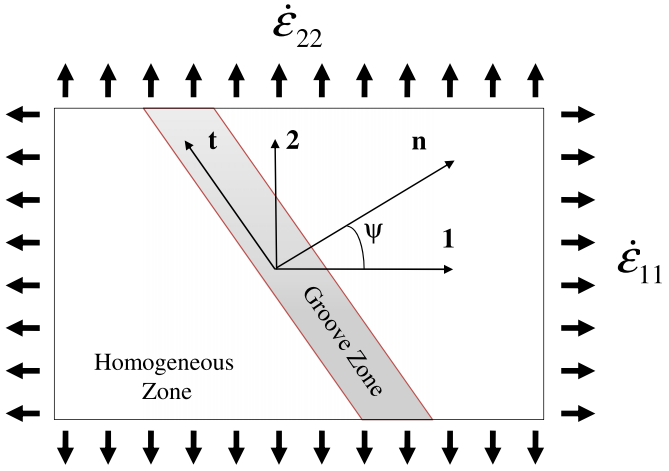

Fig. 1. Initial defect approach.