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International Journal of Plasticity 24 (2008) 1039–1070

INTERNATIONAL JOURNAL OF Plasticity

www.elsevier.com/locate/ijplas

On the modeling of hardening in metals during non-proportional loading

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Received 12 November 2006; received in final revised form 23 July 2007
Available online 5 September 2007

Abstract

The purpose of the current work is the formulation and initial application of a phenomenological model for hardening effects in metals subject to non-proportional loading histories characterized by one or more loading-path changes. This model is closely related to the incremental model of Teodosiu and Hu [Teodosiu, C., Hu, Z., 1995. Evolution of the intragranular microstructure at moderate and large strains: modelling and computational significance. In: Shen, S.F., Dawson, P.R. (Eds.), Simulation of Materials Processing: Theory, Methods and Applications. Balkema, Rotterdam, pp. 173–182; Teodosiu, C., Hu, Z., 1998. Microstructure in the continuum modelling of plastic anisotropy. In: Proceedings of 19th Risø International Symposium on Material's Science: Modelling of Structure and Mechanics of Materials from Microscale to Product. Risø National Laboratory, Roskilde, Denmark, pp. 149–168]. Like their model, the current model captures in particular hardening stagnation after a load reversal as well as cross-hardening after orthogonal loading-path changes. On the other hand, the two models predict qualitatively different behavior during loading-path changes which take place purely in the inelastic range. Such is the case for example during orthogonal loading-path changes from uniaxial tension to simple shear without release, or during monotonic simple shear, or during deep-drawing. As shown by the experimental results reported on in the current work for the mild steel DC06, significant cross-hardening can occur during continuous orthogonal loading-path changes. Beyond this, the current model accounts in an approximate way for the possible effects of texture development on the material behavior with the help of the plastic spin. After investigating the behavior of the current model for various ideal two-stage loading histories (e.g., tension-shear), the current work ends with a comparison of standard combined hardening and current

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doi:10.1016/j.ijplas.2007.08.009

approaches in the context of the simulation of internal stress development and residual stresses during deep-drawing and the resultant springback after ring-splitting.

Keywords: Induced anisotropy; Cross-hardening; Non-proportional loading; Metal forming; Springback

1. Introduction

Despite the tremendous progress made over the last years, the modeling and simulation of metal forming processes continues to represent a great challenge. In particular, such processes are based on complex, non-proportional, non-uniform loading of the material resulting in large inelastic deformation and evolving material behavior. In polycrystalline metals, such loading drives non-trivial microstructural evolution in the form of: (i) oriented grain structure in the material (*i.e.*, texture), and (ii) oriented dislocation structures in the grains. From the phenomenological point of view, this generally results in an evolution of the inelastic (and in particular hardening) behavior going beyond that described by initial Hill flow orthotropy plus combined (*i.e.*, isotropic plus kinematic) hardening. In particular, these include the experimentally-observed (*e.g.* Bouvier et al., 2006) effects of: (i) hardening stagnation after load reversal, and (ii) cross-hardening after orthogonal loading-path changes.

The influence of a developing microstructure on the hardening behavior in polycrystalline materials during complex loading histories has been the subject of a number of investigations (*e.g.*, Barlat et al., 2003, 2007; Ghosh and Backofen, 1973; Hiwatashi et al., 1997; Hiwatashi et al., 1998; Hoc and Forest, 2001; Lopes et al., 2003; Rauch and Schmitt, 1989; Rauch and Thuillier, 1993; Strauven and Aernoudt, 1987; Thuillier and Rauch, 1994; Wilson and Bate, 1994). An example of models accounting for the effects of combined hardening as well as of texture evolution on the material behavior is that of Choi et al. (2006a,b,c). In their work, texture evolution is represented as a rotation of the symmetry axes of the initial flow anisotropy due to initial texture. They apply their model to simulate the inelastic and in particular hardening behavior during reverse (uniaxial tension-compression) and orthogonal (uniaxial tension-simple shear) loading. In motivating their approach, Choi et al. (2006a) refer to the micromechanical approach of Peeters et al. (2001a,b), who ascribe the evolution of flow anisotropy in bcc systems mainly to the evolution of dislocation structures and local reorientation of the preferred directions. Although Peeters et al. (2001a,b) calculated no yield surfaces, Choi et al. (2006a) interpreted their results to imply that the development of dislocation structures is responsible for isotropic and kinematic hardening, whereas texture development leads to a rotation of the yield surface. In later work, Peeters et al. (2002) calculated yield surfaces and demonstrated that cross-hardening (at least in bcc systems) is predominantly due to dislocation structure development, and not to texture. Indeed, the results of Peeters et al. (2002) indicate that cross-hardening would occur even in the absence of initial texture. On the other hand, initial texture and texture development may affect quite strongly the elastic anisotropy and so any springback behavior.

Among the material models accounting for cross-hardening due to dislocation structure development as well as hardening stagnation after load reversal, that of Teodosiu and Hu (1995, 1998) (see also Hu et al., 1992) has been employed by a number of authors