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Complex unloading behavior: Nature of the deformation and its consistent constitutive representation

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ABSTRACT

Complex (nonlinear) unloading behavior following plastic straining has been reported as a significant challenge to accurate springback prediction. More fundamentally, the nature of the unloading deformation has not been resolved, being variously attributed to nonlinear/reduced modulus elasticity or to inelastic/"microplastic" effects. Unloading-and-reloading experiments following tensile deformation showed that a special component of strain, deemed here "Quasi-Plastic-Elastic" ("QPE") strain, has four characteristics. (1) It is recoverable, like elastic deformation. (2) It dissipates work, like plastic deformation. (3) It is rate-independent, in the strain rate range 10^{-4}–10^{-2}/s, contrary to some models of anelasticity to which the unloading modulus effect has been attributed. (4) To first order, the evolution of plastic properties occurs during QPE deformation. These characteristics are as expected for a mechanism of dislocation pile-up and relaxation. A consistent, general, continuum constitutive model was derived incorporating elastic, plastic, and QPE deformation. Using some aspects of two-yield-function approaches with unique modifications to incorporate QPE, the model was implemented in a finite element program with parameters determined for dual-phase steel and applied to draw-bend springback. Significant differences were found compared with standard simulations or ones incorporating modulus reduction. The proposed constitutive approach can be used with a variety of elastic and plastic models to treat the nonlinear unloading and reloading of metals consistently for general three-dimensional problems.

1. Introduction

Highly nonlinear unloading following plastic deformation has been widely observed (Morestin and Boivin, 1996; Augereau et al., 1999; Cleveland and Ghosh, 2002; Caceres et al., 2003; Luo and Ghosh, 2003; Yeh and Cheng, 2003; Yang et al., 2004; Perez et al., 2005; Pavlina et al., 2009; Yu, 2009; Zavattieri et al., 2009; Andar et al., 2010), with the apparent unloading modulus reduced by up to 22% for high strength steel (Cleveland and Ghosh, 2002) and 70% for magnesium relative to the bond-stretching value (Caceres et al., 2003). The magnitude of the reduction depends on the plastic strain and alloy. In addition, the effect can differ with rest time after deformation, heat treatment and strain path (Yang et al., 2004; Perez et al., 2005; Pavlina et al., 2009).

Nonlinear unloading behavior has been variously attributed to residual stress (Hill, 1956), time-dependent anelasticity (Zener, 1948; Lubahn and Felgar, 1961), damage evolution (Yeh and Cheng, 2003; Halilovic et al., 2009), twinning or kink bands in HCP alloys (Caceres et al., 2003; Zhou et al., 2008; Zhou and Barsoum, 2009, 2010), and piling up and relaxation of dislocation arrays (Morestin and Boivin, 1996; Cleveland and Ghosh, 2002; Luo and Ghosh, 2003; Yang et al., 2004).

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