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Modelling of microstructure effects on the mechanical behavior of aluminium tubes drawn with different reduction areas

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ABSTRACT

The elastoplastic self-consistent model is one of the effective models to study the initial microstructure effect on the mechanical behavior of bulk materials. However, the use of this micromechanics-based model which only takes into account the Hall–Petch relationship at grain level for predicting the grain size effects on the strength of the deformed materials is not accurate yet. This is because of the fact that the dislocation density also contributes to the strengthening of deformed materials. In this study, a modification made to the Hill-Hutchinson elastoplastic self-consistent model was proposed for investigating the microstructure dependence of the mechanical behavior of deformed materials. Meanwhile, the application of the proposed model for the prediction of mechanical behavior of cold-drawn 6063 aluminium tubes with variable wall thickness was studied. Because of the novel modification, an optimization procedure with two objectives was required to identify the parameters of this micromechanical model. An acceptable agreement between experimental and theoretical stress-strain curves was achieved.

1. Introduction

Tubes with complex geometry have very important industrial applications, particularly in automobile industry. One of the fastest and less expensive methods for production of these kinds of tubes is tube hydroforming process which usually is accompanied with some preforming steps like tube drawing, bending and annealing heat treatment processes. Among these, the tube drawing process is widely used to reduce the outer and inner diameters of tubes. Depending on the tube size, more than one drawing pass is often required. A multiple-pass tube drawing process is usually used to obtain large cross-sectional reductions (CSR) in tubular components. These metal forming processes require knowledge of the evolution of elasto-plastic behavior of the material during the deformation operations. Cold drawing of tubes not only improves the inside and outside surface finishes but also increases their strengths although it causes striking decrease in the ductility of tubes. Thus annealing heat treatment processes are usually used between two drawing steps or between drawing step and the next forming process to recover ductility of tubes.

Because of the requirement of production of high quality tubes at low cost in a short time, engineers try to reduce the number of forming processes and also to avoid the heat treatment process. Several previous works showed that the annealing heat treatment step is not necessary between two processes steps. Kang et al. (2005) mentioned that the size of initial tube is one of principal factors which influence the hydroformability. The authors showed that for ensuring high formability in tube hydroforming, it is of great importance to select a starting tube with the largest possible diameter through precise

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examination on tube crushing behavior during tool closing. Trana (2002) indicated that the performing process can be carried out during the closing of the hydroforming tool. The author showed that after closing of the tool, the geometry of tube was close to the final geometry. Thus, small deformations in the tube occurred during the hydroforming step and so the risk of tube buckling was reduced. Both of the above-mentioned papers indicated that the formability of hydroformed tube could be improved using several ways. Therefore, the drawn tube (even at its low ductility) can be used directly in the following processes and the annealing heat treatment step can be avoided to reduce production time costs.

Nowadays, forming and manufacturing processes of metallic materials are simulated numerically using finite element method (FEM). Several works simulated the tube drawing process with at least two combined passes using FEM and optimized the processes to reduce the number of drawing passes. Karnezis and Farrugia (1998) developed an optimization procedure using the FEM combined with the workability failure criterion to reduce the number of passes from two to one. Guozheng et al. (2008) investigated two-pass drawing of an aluminium tube from circular to a rectangular section using elasto-plastic FEM. Most of these studies used the same phenomenological constitutive laws (stress–strain curve) for both passes; also in the second pass they used the extension of this stress-strain curve in the FEM model. However, it is well-known that compared to the initial tube, the microstructure, mechanical properties and anisotropy of drawn tube after the first pass will be changed. Recently, Bui et al. (2011a) studied the effect of cross-section reduction on the mechanical properties of aluminium tubes drawn with variable wall thicknesses. The results showed that after 36% cross section reduction, the yield strength of deformed tube was three times higher while its elongation showed to be about four times smaller than that of the initial tube. Therefore, the use of the extension of the initial stress-strain curve in the FEM model for simulating the second pass seems not to be accurate. The characterization of the mechanical properties of deformed complex tubes is sometimes practically impossible because of the infinity of loading and straining paths that can occur during a forming process. On the other hand, sometimes tubes do not have required dimensions for preparing the compression or tensile samples. In addition, the mechanical properties of deformed complex geometry tube are not homogeneous because of the different cold forming degrees of different tube positions (Bui et al., 2011a). Thus, in order to improve the productivity of material models used with FEM for simulating the two or multi-step metal forming processes, it is necessary to predict the mechanical properties of deformed materials.

Micromechanical modeling is one of the most effective methods to investigate the microstructure effects on the mechanical properties of bulk materials. The main source of anisotropy of polycrystals was considered to be due to crystallographic textures. In the past years, the crystal plasticity finite element model was mostly used to model deformation and texture evolution of polycrystals (Kalidindi et al., 1992; Zhao et al., 2001; Zhang et al., 2007; Shenoy et al., 2008; Abdolvand et al., 2011). Besides the crystal plasticity finite element approach, the self-consistent models can be used to predict the mechanical behavior and to study the texture development of polycrystals during deformation. An advantage of self-consistent approach is lower computational costs relative to finite element methods. The self-consistent approach was originally proposed by Kroner (1958). Based on Eshelby's solution theory (Eshelby, 1957) for an ellipsoidal inclusion in a linear elastic matrix, the self-consistent scheme was introduced in the Kroner (Kroner, 1961) and Budiansky–Wu (Budiansky and Wu, 1962) models. These models use a fully elastic coupling between the grains and the matrix, and hence they predict a very low deformation heterogeneity in the polycrystal. Hill (1965) proposed an incremental elastoplastic self-consistent model (EPSC) which takes into account the plastic interactions between the inclusion and the surrounding matrix. This model was then implemented to simulate polycrystalline deformations by Hutchinson (1970), later it was simplified to a secant formulation for proportional loading by Berveiller and Zaoui (1979). Turner and Tomé (1994) accounted for the thermal dilatation effects and the full anisotropy in the properties of grains and polycrystal in Hill's formulation. An extension of Hill's incremental approach to study polycrystals at large elastic–plastic deformations was proposed by Iwakuma and Nemat-Nasser (1984). The elastoplastic self-consistent models were later developed further by many researchers to include small (Lebensohn et al., 1996; Clausen et al., 1998) and large elastic–plastic deformations (Lipinski and Berveiller, 1989).

In some cases, viscosity effects are quite important and a rate-sensitive approach must be considered that can be performed in the framework of viscoplastic self-consistent models (VPSC). This method was first used by Hutchinson (1976) for modeling steady creep of polycrystals. Molinari et al. (1987) developed a non-incremental self-consistent model by using the tangent modulus-based formulation for modeling the texture development associated with large deformations of cubic polycrystals. Lebensohn and Tomé (1993a) used this non-incremental scheme to simulate large plastic deformations in hexagonal, orthorhombic and trigonal materials with full anisotropic overall tangent modulus.

The VPSC model developed by Lebensohn and Tomé (1993a) has experienced several extensions and improvements and is nowadays widely used to simulate plastic deformation of polycrystalline materials (Ostapovets et al., 2012). Also, it is used to understand experimental evidence of metallic, polymeric and geological materials (see Lebensohn et al., 2007). In the work of Segurado et al. (2012), the VPSC model has been implemented inside a user-defined material (UMAT) subroutine of the FE code for the potential of multiscale simulation. In this kind of approach, each integration point of the FE model is considered as a polycrystal with a given initial texture that evolves with deformation.

Wang et al. (2010) developed a finite strain elastic–viscoplastic self-consistent (EVPSC) constitutive model for polycrystalline materials. The EVPSC is considered as a completely elastic–viscoplastic self-consistent model which predicts a smooth elasto-plastic transition, while VPSC model gives a discontinuous response due to lack of elastic deformation.

Jiang and Weng (2004) developed a generalized elastoplastic self-consistent (GEPSC) formulation for investigating the yield strength and stress-strain relation of nanocrystalline (NC) materials. They considered the NC material as a composite material that takes each oriented grain and its immediate grain boundary to form a pair, which in turn is embedded in the