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Investigation into equal channel angular extrusion process of billet with internal defects

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ABSTRACT

The shear plastic deformation behavior of a material during equal channel angular (ECA) extrusion is governed primarily by the die geometry, the material properties, and the process conditions. This study uses the commercial DEFORM^{TM} 2D (two-dimensional) rigid-plastic finite element code to investigate the plastic deformation behavior of materials with internal defective voids during 1- and 2-turn ECA extrusion processing. The present simulations investigate the damage factor distributions, the total velocity distributions, the rotation angle distributions, the void dimension, and the stress–strain distributions around the defective voids under various extrusion conditions. The mesh element increase of the billet mesh in the 2-turn ECA extrusion process is also investigated. The present numerical results provide valuable insights into the shear plastic deformation behavior of materials containing defective voids in the ECA extrusion process.

1. Introduction

Methods of severe plastic deformation such as rolling, extrusion and forging are those in which materials are subjected to a very high strains with the subsequent changes in physical and mechanical properties. It has long been known that there are significant benefits to be gained from deforming metallic alloys under very high plastic strains. The equal channel angular (ECA) extrusion or ECA pressing was first developed by Segal (1977) and Segal et al. (1981) as a process for introducing large plastic strains in a metal without a substantial change in the outer dimensions of the workpiece. Liu et al. (2000) presented the novel changing channel extrusion (CCE) method, which was designed to reduce the tensile stress and increase the hydrostatic pressure in the workpiece during extrusion. Rosochowski and Olejnik (2002) employed a finite element method to investigate the mechanisms involved in the 2-turn equal ECA extrusion process. In the ECA extrusion process, the workpiece is extruded through two or more interconnecting channels, which are typically orientated at angles of between 90° and 135° to one another. Iwahashi et al. (1996) reported that ECA pressing is a simple and attractive procedure for producing materials with ultra-fine grain size. Wu and Baker (1997) found that the shear strain accumulation in the workpiece after three passes through a 90° round-corned jig is equivalent to that accumulated after seven passes through a 120° round-cornered jig. Prangnell et al. (1997) employed the DEFORM^{TM} code to perform finite element simulations of the ECA extrusion process. The validity of the numerical results was demonstrated by comparing the FE modeling results with the shape changes observed in a commercial pure aluminum (99.75% Al) sample following partial passage through a steel die with an internal angle of 100°.

Srinivasan (2001) established that the magnitude of the maximum strain in a single pass through a die is determined by the value of round-cornered. Suh et al. (2001) developed a simple two-dimensional plane strain model to investigate the material flow in ECA pressing. Segal (1999) investigated

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Nomenclature

k	the local flow stress in shear
m	the friction factor
S_f^w	the tractional boundary surface of the workpiece
V^w	the volume of the workpiece

Greek symbols

α	the work-hardening effect constant
γ	the magnitude of the shear strain
ε	the effective strain per pass
ϕ	the internal angle between the two die channels

the stress, strain, and shear developed in multi-pass ECA extrusion processing and analyzed the steady and localized material flows. Bowen et al. (2000) reported that the strain induced in the workpiece is related to the die angle, the friction conditions, and the application of a back pressure. These factors are all known to have a significant effect on the microstructure and strain inhomogeneity within the processed billet. Kim et al. (2000) and Kim (2001) performed finite element analysis using DEFORM^{TM} 2D to investigate the corner gap formation between the die and the workpiece during the plane strain ECA pressing process. The present study also uses the commercial DEFORM^{TM} 2D software, and analyzes the plastic deformation behavior of materials with internal defective voids during 1- and 2-turn ECA extrusion.

2. Analytical method

Although the deformation process in ECA extrusion has been treated analytically (Iwahashi et al., 1996; Segal, 1999), a review

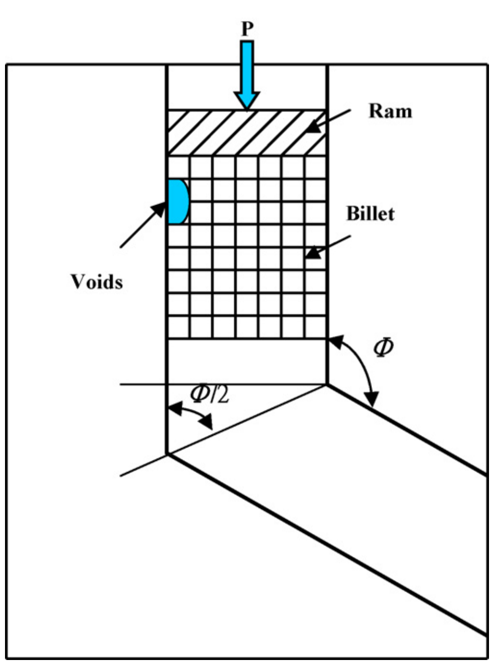

Fig. 1 – Schematic view of ECA extrusion process.

Table 1 – The stress–strain relationship of the aluminum A1100 flow stress = *f* (temperature 550 °C, strain rate 4, strain) (MPa)

Strain	Strain rate 4
0.105	18.169
0.223	19.82
0.338	20.963
0.512	20.548
0.695	20.519

of the literature suggests that a finite element analysis of the passage of a sample through an ECA extrusion die has yet to be reported. According to Segal (1999), the deformation behavior in ECA extrusion is characterized by homogeneous plane shear throughout the majority of the sample. Hence, the effective strain per pass, ε, is given by

$$\varepsilon = \frac{2}{\sqrt{3}} \cot\left(\frac{\phi}{2}\right) \tag{1}$$

where ϕ is the internal angle between the two die channels (see Fig. 1). Under these conditions, the magnitude of the shear strain, γ, is calculated as

$$\gamma = 2\cot\left(\frac{\phi}{2}\right) \tag{2}$$

According to Kim and Yang (1985), the finite element formulation for rigid-plastic deformation in a material subject to a work-hardening effect is given by

$$\int_{V^w} (\bar{\sigma}+\alpha\Delta t\dot{\bar{\varepsilon}}H')\delta\dot{\bar{\varepsilon}}\, dV + K\int_{V^w} \dot{\varepsilon}_V \delta\dot{\varepsilon}_V\, dV - \int_{S_f^w} (f+\alpha\Delta f_i)\delta v_i\, dS = 0 \tag{3}$$

where $\bar{\sigma} = \sqrt{(3/2)\sigma'_{ij}\sigma'_{ij}}$, $\dot{\bar{\varepsilon}} = \sqrt{(2/3)\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}}$, and $\dot{\varepsilon}_V = \dot{\varepsilon}_{ii}$. Furthermore, K, σ'_{ij}, H' and α are the penalty constant, deviatoric stress, strain-hardening rate and the work-hardening effect constant ($0 \leqq \alpha \leqq 1$), respectively. Finally, V^w and S_f^w are the volume and tractional boundary surface of the workpiece, respectively.

The frictional boundary condition is given by Yoon and Yang (1988) and Chen and Kobayashi (1978):

$$f = -\frac{2}{\pi} mk \tan^{-1}\left(\frac{|V_s|}{u_0}\right) t \tag{4}$$

where m is the friction factor, k is the local flow stress in shear and u_0 is a positive number whose value is very small compared to $|V_s|$. V_s is the velocity vector of the workpiece relative to the die and t is the unit vector in the direction of V_s. An initial velocity field can be generated by assuming the billet to be a linear viscous material. The velocity boundary conditions and the frictional boundary conditions on an arbitrarily curved surface are imposed via the successive application of a skew boundary condition (Yoon and Yang, 1988; Yang et al., 1989).

This study applies the commercial finite element code DEFORM^{TM} 2D to simulate the plastic deformation behavior during the ECA extrusion processing of a material with internal defective voids. The finite element code is based on the