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Investigating the effects of hardening of aluminium alloys on equal-channel angular pressing—A finite-element study

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ABSTRACT

Equal-channel angular pressing (ECAP) is a promising severe plastic deformation method for production of ultrafine-grained bulk metals and alloys with considerably improved mechanical properties. In this study, numerical experiments were carried out to investigate the effect of strain hardening of aluminum alloys on the process performance of ECAP via finite element modeling. In the constitutive model, isothermal-plane strain, frictionless condition was assumed. The numerical results showed that strain hardening behavior strongly affects the deformation homogeneity and process performance, mainly due to corner gap formation in the workpiece.

1. Introduction

To have enhanced mechanical properties, grain size refinement is known to be a very effective method for polycrystalline solids [1]. For Al and its alloys having FCC crystal structure, the unpinning constant in the Hall–Petch equation, which relates the increase in stress experienced to decrease in grain size, is comparatively lower. Therefore, grain refinement by conventional deformation processes may not be sufficient to achieve the desired mechanical properties as well as they may not be capable of resulting in sub-micron sized grains. To achieve ultrafine-grained structure, severe plastic deformation methods are known to be very effective by introducing very high pure shear strains to the bulk material without changing the physical dimensions. Equal-channel angular pressing (ECAP) developed by Segal et al. [2] has a great potential for employing the method in industrial and commercial forming applications [3–18].

The ECAP die is formed of two channels that have same cross-sections, intersecting at a predefined angle Φ (die channel angle) which generally ranges from 90° to 150°, however, some studies on acute angled dies are also present [19]. The billet, which is to be deformed, is fit into the upper channel with nearly zero tolerance and forced to pass from the shear plane formed at the corner of intersection by means of a flat faced ram. Another important parameter is the die corner curvature, ψ, ranging from 0° to $180^\circ - \Phi$ [15]. In this study, a third parameter, the corner gap angle of the workpiece in the shear deformation zone of the ECAP die (α) was added to the classical approach (Fig. 1).

Assuming frictionless condition and the billet moving inside the channel as a rigid body; it fills the channel perfectly, and undergoes homogeneous deformation. Segal [20] developed the equation for total equivalent plastic strain using the slip line field theory as

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \cot \; \Phi \tag{1}$$

Iwahashi et al. [21] modified this equation including the effect of die corner curvature angle ψ:

$$\bar{\varepsilon} = \frac{1}{\sqrt{3}} \left[2 \cot \left(\frac{\Phi}{2} + \frac{\psi}{2} \right) + \psi \operatorname{cosec} \left(\frac{\Phi}{2} + \frac{\psi}{2} \right) \right] \tag{2}$$

Some analytical studies which give better results compared to those obtained by Eqs. (1) and (2) exist in the literature, but they still do not consider many effects including the die parameters and material characteristics such as strain hardening behavior [3–5,8,11–13,17,19–27]. The first finite element model of ECAP was proposed by Prangnell et al. [28], then, various studies on simulation of ECAP processes have been published [28–45]. Many studies showed that the homogeneity of the deformation and the strain values achieved in the billet was different from expected as stated in the preceding sections. In the previous study [30], a similar effect was also observed: the lower parts of the billets exhibited lower strain values compared to the upper regions; the die angle which yielded the highest strain value was found to be 90°, and the deformation was observed to be quite homogeneous for this die channel angle.

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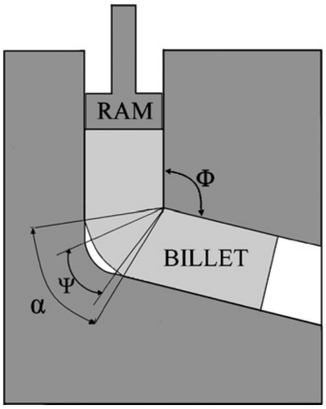

Fig. 1. Schematic diagram of the ECAP process.

While designing an ECAP die, not only the geometry of the die, but also the material properties of the billet should be considered. Several authors have discussed the effect of strain hardening characteristics on corner gap formation, but the literature lacks a systematic and quantitative study in understanding the effect of plastic flow properties on deformation behavior. This study investigates the effect of material behavior on the deformation in terms of the dependence of the corner angle (α) on the strain hardening multiplier (K) and the strain hardening exponent (n) of Hollomon's equation. The constants used in the simulations are selected to cover a wide range of Al alloys.

2. Finite element analysis (FEA)

The commercial FEA code Msc.Marc was employed for ECAP process simulations. The two-dimensional model was constructed by assuming plane strain condition and a plane passing through the center of the die and billet was simulated accordingly. The process was accepted to be isothermal for a low ram speed of 1 mm/s employed. The die and the ram are modeled as analytical rigid bodies. A small fillet radius was given to the inner corner to avoid convergence problems. No damage criterion was considered. The effect of friction was neglected, and there is no corner curvature in the models constructed. An automatic time-stepping procedure based on plastic strain increment was used. ECAP of a rectangular billet having dimension of 50 mm × 10 mm was simulated. The billet was meshed into 2000 finite elements with an average edge length of 0.5 mm. Global re-meshing was employed when element distortion, strains and rotations reached to a critical value.

Simulations were carried out considering the plastic deformation behavior of the materials in terms of Hollomon's equation, which is given in the form of

$$\bar{\sigma} = K\bar{\varepsilon}_{\mathrm{p}}^{n} \tag{3}$$

where $\bar{\sigma}$ is the flow stress, $\bar{\varepsilon}_{\mathrm{p}}$ is the equivalent plastic strain, K and n are the strain hardening coefficient and strain hardening exponent, respectively. Elastic modulus, Poisson's ratio and the mass density of the material were selected as 69 GPa, 0.3 and 2.7 g/cm^3. In the simulations, K and n values were selected in the 50–500 MPa range with 50 MPa increments and in the 0–0.5 range with 0.05 increments. All combinations of K and n values were used to investigate the effect of material properties, which gave rise to a total number of 100 simulations.

3. Results and discussion

The deformation inhomogeneity was attributed to the gap formed at the corner of the die. The formation of the corner gap can be explained considering the flow velocity differences between the top and the bottom of the deformation zone. This difference is mainly caused by path difference of plastic deformation, friction, and the strain hardening behavior of the material. Path difference is negligible for small channel widths. If the friction conditions for the upper and lower parts of the die are the same, the effect of friction may also be neglected unless the extrusion channel is too large or the friction is too high, since it only amplifies the effect of the path difference. It should be noticed that a higher friction coefficient for the bottom of the exit channel, compared to the upper part, can be used to minimize the corner gap. Finally, the major reason for velocity differences is the strain hardening of the material. For a quasi-nonstrain hardening material, this difference is negligible, and hence no corner gap formation was observed for such kind of materials [33].

According to the flow rule and the normality principle, the plastic strain increment is proportional to the variation of the yield functional with respect to the stress state. Thus, anything that increases the variation of the local flow stress in the deformation zone will cause an increase in the flow-velocity gradient, which results in the formation of larger corner gaps. This variation may be due to the strain hardening behavior or strain rate sensitivity of the material. In this study, only the effect of strain hardening of the material was investigated.

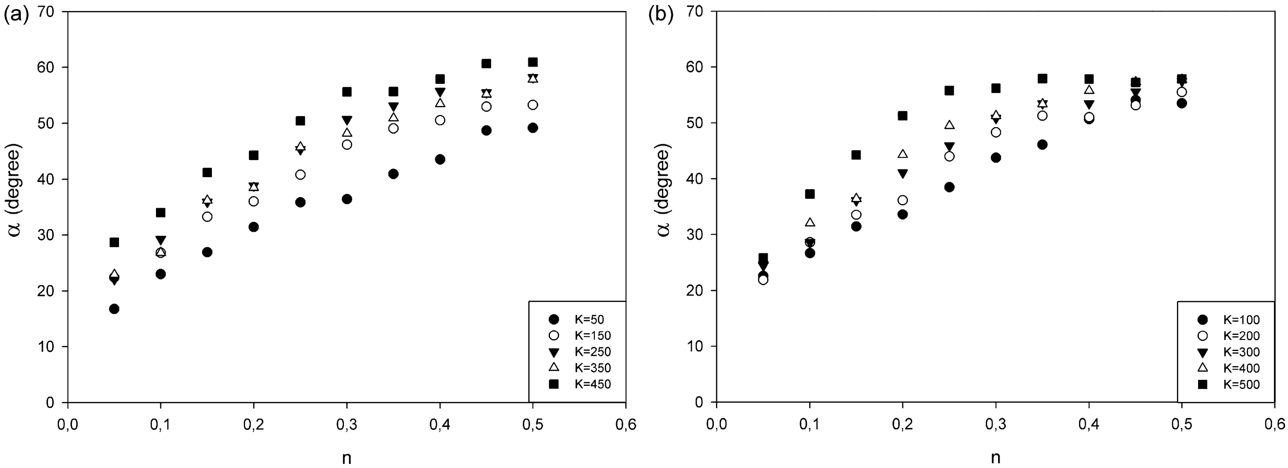

Fig. 2. The change of the corner gap angle with the strain hardening multiplier (K) for different strain hardening exponent (n) values.