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Analysis of plastic deformation behavior during back pressure equal channel angular pressing by the finite element method

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A B S T R A C T

It is generally known that equal channel angular pressing with back pressure (BP-ECAP) not only applies higher hydrostatic stress and more deformation compared to what a regular ECAP can apply to a workpiece, but also prevents surface defects in the workpiece during the processing. In this study, the plastic deformation behavior of the materials during the BP-ECAP process was investigated using the finite element method. The homogeneity within the workpiece was analyzed in terms of contours, path plot, and statistics of strain distribution under different conditions regarding back pressure, strain hardening, friction, and corner angle. The simulation results shed some lights on the optimum design of ECAP for homogeneous and large severe plastic deformation.

1. Introduction

In recent years, there have been numerous studies on the distinguished mechanical properties of ultra-fine grained (UFG) materials. Especially, the fields of mechanical and materials science and engineering have explored a lot of novel methods to obtain those physical properties. Among such methods, severe plastic deformation (SPD), a typical top-down method, has been studied over the years as a typical process to produce bulk UFG materials [1–5]. There have been many reports that the SPD processing enhances the strength and ductility of materials by decreasing the grain size of polycrystalline materials down to submicron or nanometric size [6,7]. Equal channel angular pressing (ECAP), the most popular process in SPD, is applied to materials through a die of two angular channels with the same cross section; hence, the deformation mode applied to the materials nominally is a simple shear [6–9]. Because the initial cross sections of the materials do not decrease even in case of large deformations, repeated processes are possible to obtain severe deformation and to control the amount of strain. Much experimental research on stress and strain distributions during the ECAP processing and numerical approaches for the processing parameters have been undertaken to control the microstructure of metallic materials [10–13].

For the improvement of the ECAP process, back pressure (BP) to the exit channel of a die was introduced to obtain a uniform strain distribution inside of the workpiece and to prevent defect formation on the surface of the workpiece materials, see Fig. 1. The back pressure equal channel angular pressing (BP-ECAP) [14–16] presented successful results even for hard-to-deform materials such as Mg alloys, Ti alloys, and even powders [14–17]. In the SPD community back pressure is regarded as the remedy to prevent defects during ECAP and to achieve uniform plastic deformation. However, despite that most of the experimental research posed successful results, only a handful of numerical approaches have been carried out for the processing and flowing behavior of materials during BP-ECAP [14–17]. Therefore, it is necessary to investigate the effect of the BP combined with the well-known processing parameters on the plastic deformation behavior in BP-ECAP [17,18].

In this paper, we analyze the effects of the BP, combined with material condition (strain hardening), geometric condition (corner angle), and processing condition (friction) on the processing results in terms of load, geometry, average strain, and strain distribution.

2. Finite element analysis procedure

Segal [6] and Iwahashi et al. [7] derived the Eq. (1) for the strain development considering the geometries of dies by assuming simple shear.

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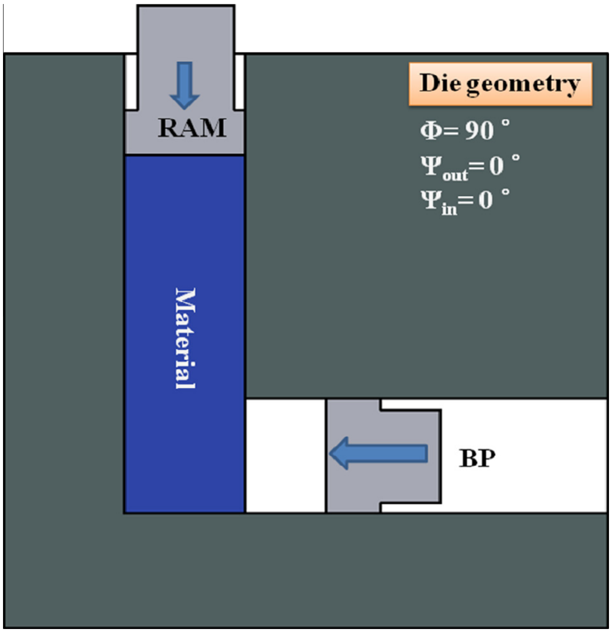

Fig. 1. Schematic of equal channel angular pressing dies for applying the BP.

$$\varepsilon = \frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\psi}{2}+\frac{\phi}{2}\right)+\psi\ \mathrm{cos\,ec}\left(\frac{\psi}{2}+\frac{\phi}{2}\right)\right]. \tag{1}$$

The channel angle and the corner angle were reported to be the most significant parameters controlling strain development in ECAP processed materials. To calculate the deformation behavior in ECAP, the rigid-plastic finite element method code DEFORM2D [19] was used. The simulation conditions are following: The dimension of the workpiece was 10 × 10 × 60 mm^3. Loading was applied by forward moving ram in the entrance channel, while constant BP was applied to the material backward in the outlet channel from 5 s after staring BP-ECAP [17,18].

The simulation conditions are as follows: Plane strain state and isothermal condition of 20 °C were assumed. Total 3000 4-noded isoparametric elements were utilized. A constant ram velocity of 1 mm/s, and the BP values of 0 (i.e. no back pressure), 30, 60, and 100 MPa were applied to investigate the effect of the BP. Al100 alloy with strain hardening and quasi-perfect plastic Al6061-T6 were considered for the workpiece materials [10]. Geometric condition (corner angle 0, 9, 27, 45, and 90°) [20] and processing condition (friction 0, 0.1, and 0.2) were varied to examine the effect of the BP combined with the well-known parameters on the plastic deformation behavior in BP-ECAP.As a statistical approach to evaluate the proper homogeneity index in the BP-ECAP processed material, the degree of deformation homogeneity was indexed by the standard deviation H, Eq. (2), of the effective strain. Here, x_i is the effective strain of the ith element, f_i is its frequency, and m means the average effective strain of the whole elements [21]

$$H = \sqrt{\frac{\sum(\varepsilon_i - m)^2 f_i}{\sum f_i}}, \tag{2}$$

where uniform deformation is presumable if the homogeneity index H, i.e. standard deviation of the effective strain, is small.

3. Results and discussion

The finite element simulations were performed in order to investigate both the sole effect of BP and the effect of BP combined with different conditions such as material condition (strain hardening), geometric condition (corner angle), and processing condition (friction) on the processing. The simulation results are analyzed in terms of load, geometry, average strain, and strain distribution.

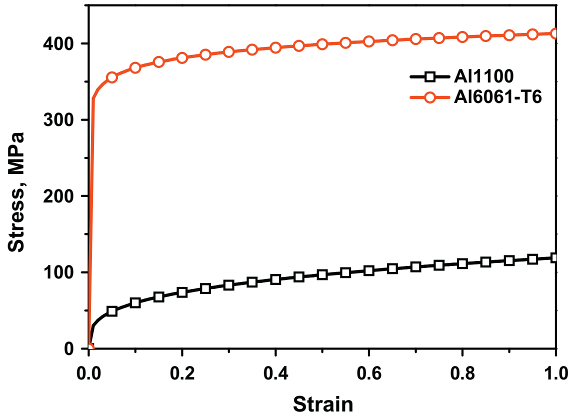

Fig. 2. Stress–strain curves for 1100Al (strain hardening material) and 6061Al-T6 (nearly non-hardening material) [10].

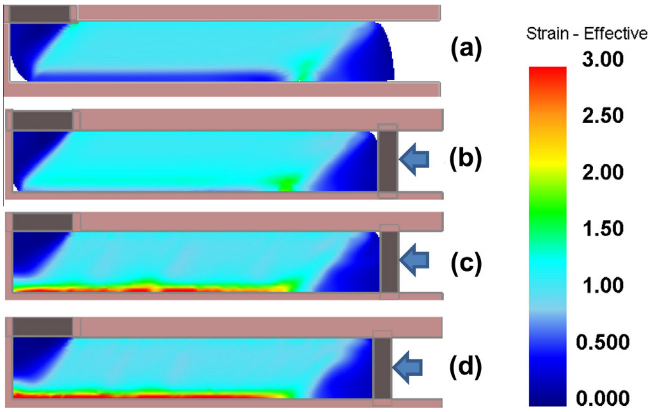

Fig. 3. Simulated effective strain distribution after BP-ECAP: (a) without front pressure, (b) 30 MPa, (c) 60 MPa, and (d) 100 MPa.

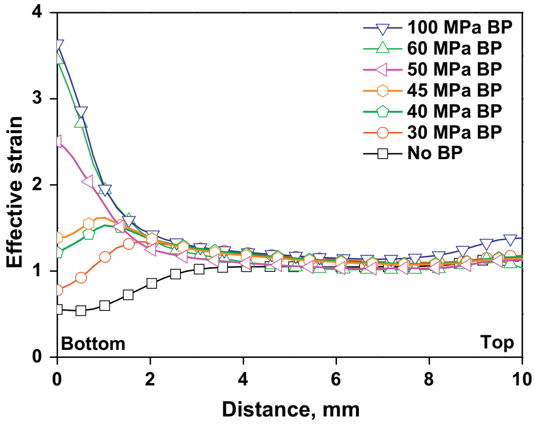

Fig. 4. Effective strain distributed along the path of the workpieces normal to the pressing direction in the steady state region as a result of different BP conditions.

3.1. Back pressure effect

In order to understand the effect of BP during BP-ECAP, the finite element analysis on Al1100 was employed by varying the BP to 0, 30, 60, and 100 MPa, under the geometric condition of the