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Optimal pressing route for continued equal channel angular pressing by finite element analysis

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Abstract

In this paper, the deformation distribution of billets after multi-passes by using equal channel angular pressing (ECAP) routes is investigated by 3D finite element models. The simulation results show that the deformation distribution is more homogenous after two passes by using pressing route C. But if the deformation character of different routes was considered, it may be deduced that route B_C is the most effective for deformation homogeneity after multi-pressing as long as the total pressing passes are times of four. The above deduction is ultimately proved by the simulation results of four passes of ECAP process. It means that this route is the most favorable for achieving ultra-fine grained material with more homogenous microstructure.

Keywords: Equal channel angular pressing (ECAP); 3D finite element simulation; Equivalent plastic strain; Optimal pressing route

1. Introduction

Since ultra-fine grained (UFG) materials have shown many unique properties such as high strength and superplasticity, a considerable interest has been concentrated on these special materials over the past few years. Recently, equal channel angular pressing (ECAP) has become an important method to produce bulk UFG materials because it is very effective in producing UFG structures and can produce UFG billets large enough for various structural applications [1,2]. The microstructure and mechanical behavior of many metals and alloys after ECAP have been widely investigated [3–7]. The influence of pressing speed, temperature and routes on the grain refinement of ECAP processed materials was also analyzed via experimental method [5,8–13]. Besides, the finite element method (FEM) was also used to study the influence of such factors as material property, corner angle of ECAP dies and friction between billet and dies, on the deformation distribution in billet [14–16].

During ECAP, the direction and times of billet passing through the channels are very important for microstructure refinement. In papers [17,18] the following routes of billets were considered: orientation of a billet is not changed at each pass (route A); after each pass a billet is rotated around its longitudinal axis through the angle 90° in the same direction (route B_C) or inverse direction (route B_A); after each pass a billet is rotated around its longitudinal axis through the angle 180° (route C). Although the difference of these routes on microstructure of ECAP processed materials were also analyzed by many researchers both on theoretical and experimental methods, the effects of different pressing routes on the deformation homogeneity of ECAP processed materials were seldom considered. The route that is optimal for achieving ultra-fine grained material with more homogenous microstructure is still in investigation [11–13].

According to some previous studies [19,20], for achieving ultra-fine grained material, the raw material must be processed at least four to eight passes. Due to the complexity of deformation procedure during multi-passes ECAP, it is impractical to analyze the distribution of plastic deformation of the multi-passes billet truly via theoretical and 2D finite element methods.

In this paper, the 3D finite element method was employed to study the deformation distribution of billets after multi-passes by using different pressing routes. The optimal pressing route was founded by comparing the deformation homogeneity on the section planes of billets.

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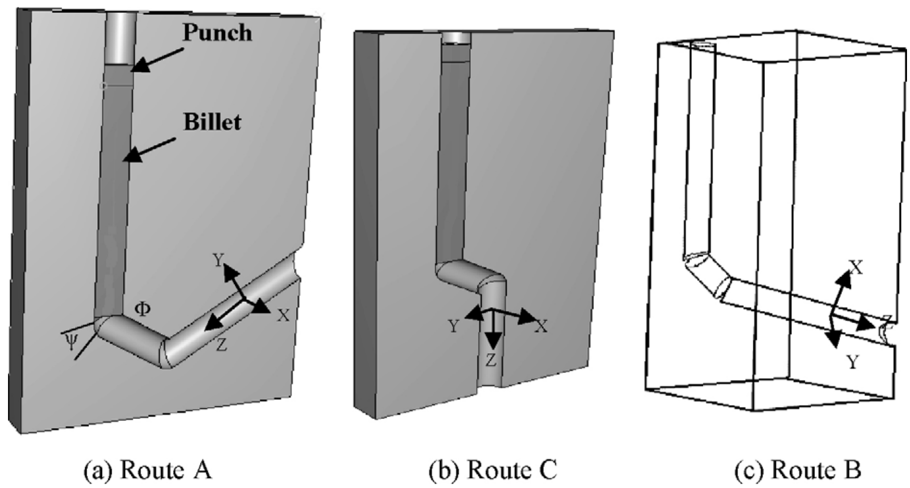

Fig. 1. (a–c) FEM models of continued ECAP.

2. Details of finite element analysis

As the billet is rotated by 90° around its axis between each pass in both routes B_A and B_C, in two pass simulation they can be simplified to one route. Thus, the four commonly used pressing routes can be classified into three: A (refer to no rotation), B (refer to rotation by 90° between each pass) and C (refer to rotation by 180° between each pass). As the finite element model for route A and C is symmetrical about the middle plane of the ECAP die, half of the billet and die was considered (see Fig. 1(a and b)) and the symmetrical boundary conditions were applied. While for rout B, whole billet and die were considered in FE analysis (see Fig. 1(c)).

The simulation was carried out under the following assumptions: (1) the material of billet is an elastic–plastic material having strain hardening with a Young's modulus of 60 GPa, Poisson's ratio of 0.3 and yield stress of 98 MPa, while the punch was regarded as an elastic material with a Young's modulus of 210 GPa and Poisson's ratio of 0.33; (2) the system is isothermal; (3) the von-Mises flow rule is used to construct the constitutive relation in the simulation; (4) friction between the surface of the material and the die channel were selected as 0, 0.05 and 0.10, respectively; and (5) for the sake of simplicity, the dies were considered to be rigid. The top end of the punch moved down along the inlet channel with a velocity of 5 mm/s. The cross sections of channels of the FE models were circle with the diameter 8 mm. The punch and billet both were cylindrical with the diameter of 8 mm and the length of 5 and 60 mm, respectively. The rigid ECAP dies have the geometry with the inner corner angle $\Phi = 120°$ and outer corner angle $\psi = 20°$, and the channels have the same diameter as the billet. For simulating the deformation process of multi-passes directly, a middle channel was added in each model to connect mutil-conners (see Fig. 1(a–c)). To ensure sufficient deformation of the billet during each pass, the distance between two corners was set to 16 mm.

For the convenience of discussion, a local coordinate was also established according to the geometry of the deformed billets (see Fig. 1). The planes normal to *X*, *Y* and *Z* axis are, respectively, referred to as *X*-plane, *Y*-plane and *Z*-plane.

3. Finite element results

The continued ECAP was simulated by using ABAQUS. During simulation, it was found that if the friction between the billet and ECAP channel was too severe, a few elements in local region were distorted severely which would lead to the simulation interrupted. So the maximum friction coefficient in simulation was set up 0.1 for route A and C, 0.05 for route B, respectively.

Fig. 2(a–c) illustrates distributions of the equivalent plastic strains in *X*-plane of processed billets by using different pressing routes. Along the billet axis, there is a steady deformation region in the area that has passed through the second corner of the channel. Comparing with other region the equivalent plastic strains are much more uniform and larger along the axis in this steady deformation region.

The contours of equivalent plastic strain on the cross section of the billets are also shown in Fig. 3(a–c). The arrows marked the region passing though the inner corner of the die channels during two passes. It should be pointed out that the contours of plastic strain in Fig. 3 were taken from the same section plane in the steady deformation region which was shown in the equivalent plastic strain contours on *X*-plane (see in Fig. 2). By previous FEM simulation of one pass ECAP, it has been shown that during deformation, the region near the inner corner of the die channel deformed more severe than that near the outer corner [16]. As the result, for different pressing routes, this severer deformation region may be different during two continued passes.

To quantify the degree of deformation inhomogeneity on the section plane, a deformation inhomogeneity index $\bar{C}$ is defined as:

$$\bar{C} = \frac{\bar{\varepsilon}^{eq}_{max} - \bar{\varepsilon}^{eq}_{min}}{\bar{\varepsilon}^{eq}_{ave}} \qquad (1)$$

where $\bar{\varepsilon}^{eq}_{max}$, $\bar{\varepsilon}^{eq}_{min}$ and $\bar{\varepsilon}^{eq}_{ave}$ denote the maximum, minimum, and average of equivalent plastic strains in the cross section plane, respectively. The maximum, minimum, average equivalent plastic strains and deformation inhomogeneity indexes on the cross section after two passes by using different pressing routes are also listed in Table 1.