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Materials Science and Engineering A 476 (2008) 224–229

MATERIALS SCIENCE & ENGINEERING A

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Investigation on the geometrical aspect of deformation during equal-channel angular pressing by in-situ physical modeling experiments

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Received 10 December 2006; received in revised form 23 April 2007; accepted 27 April 2007

Abstract

The deformation mechanism of equal-channel angular pressing (ECAP) was investigated by in-situ physical modeling experiment, in which the billet consisting of two kinds of color grains with designed patterns was pressed through an ECAP die made of a transparent plexiglass. It was found that the evolution of the flow patterns was governed by the geometric character of ECAP die, and a deformation zone with a sector shape was formed in billet during the experiments. Based on the observations in the in-situ physical modeling experiment, a simple flow line field and the corresponding geometrical aspect of shear deformation were proposed.

Keywords: Deformation mechanism; Equal-channel angular pressing (ECAP); Physical modeling; Deformation zone; Flow line field

1. Introduction

Equal-channel angular pressing (ECAP) is one kind of the most promising severe plastic deformation (SPD) methods and has become very successful in producing microscale and nanoscale microstructures for bulk metals and alloys [1–3]. So far, significant progress has been made in the understanding of fundamental properties and microstructures of the ECAPed materials by using theoretical analysis and experimental methods [4–7]. Among those investigations, not only the microstructural characterization and properties of the ECAPed materials have been paid much attention, but also the corresponding deformation mechanisms during ECAP have given rise to wide interest [8–14].

Segal [15], one of the pioneers in the filed of ECAP, had proposed the plastic deformation mechanism during ECAP. At first, he considered that the plastic deformation is mainly achieved by simple shear in a thin layer along the crossing plane of the die channel during ECAP. Therefore, his main argument is that the simple shear along the intersection direction plays an important role in the formation of the deformation zone boundaries in an ECAP die. However, the deformation is often slightly changed due to the effect of contact friction [9,10]. Later, he applied continuum plasticity method—slip line solution to characterize the deformation processes of ECAP by considering the effects of contact friction, geometry of channels, strain rate, billet shape and punch pressure [9,10]. According to the theory of shear deformation along intersection plane (at an angle of 45° with respect to the extrusion direction for right angle die), it should be expected to find a group of elongated structures along those planes for the metals processed with the right angle ECAP die. However, the subsequent experimental observations clearly indicated that a group of shear flow lines often appear along the plane at an angle of 26.6° with respect to the extrusion direction [16–18], which is inconsistent with the theory analysis of the simple shear and needs further investigation [9,10,15].

Besides, finite element method (FEM) was proved to be an effective tool for the estimation of integral parameters, such as flow pattern, microstructure distortion and strain distribution of the materials subjected to one-pass ECAP [19–21]. Li et al. [22–23] figured out the deformation zones for different shapes of ECAP die, which are similar to the results of slip line solution [9,10]. In addition to FEM, other methods were applied to model the material flow feature during ECAP [24–27]. For example, the pure aluminum billet with regular grids on its surface was

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0921-5093/$ – see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.msea.2007.04.114

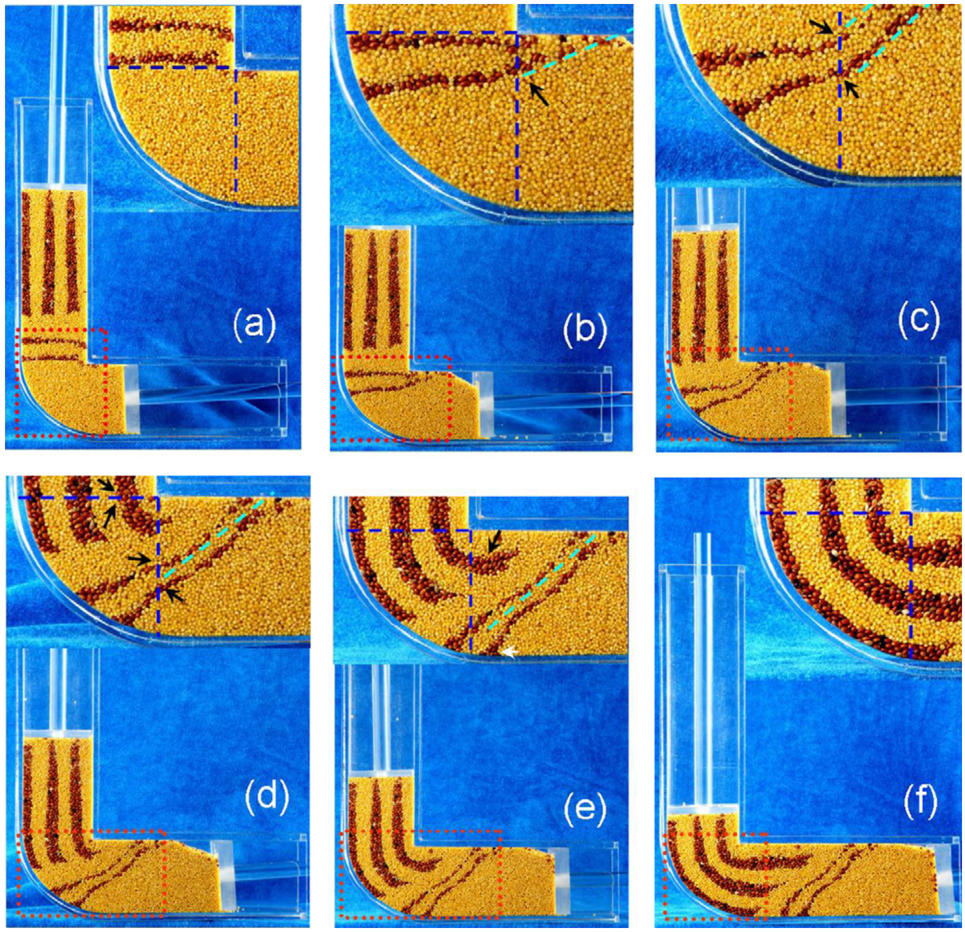

Fig. 1. In-situ observations of grain flow behavior in round corner ECAP die ($\phi = 90°$).

processed by ECAP using a die with a corner at an angle of 90° [24]. Plasticine was also used to simulate the multi-ECA pressing, and some interesting results were found in their experiments [25–26]. But there is no further mechanism-related investigation conducted in the work mentioned above.

Concerning the flow patterns of the materials subjected to ECAP, to the best of our knowledge, there is only one theoretical expression of flow line field given by Toth et al. [28]. The main argument of their model is that, in practice, the flow lines become round even the two channels are connected without any rounding. It is reasonable because there is a "dead metal zone" in the outer corner region of the ECAP die [9,10], but the shape of the flow lines suggested by them is lacking of experimental support. In this research, we designed a special experiment in order to reveal the geometrical aspect of deformation during ECAP from the view of material flow. In particular, by taking the in-situ physical modeling experiment, it is possible to further reveal the evolution of flow patterns, the deformation zone and the corresponding geometrical aspect of deformation mechanism for the material subjected to ECAP.

2. Experimental procedures

Two dies made of transparent plexiglass with a channel in a square cross-section by 50 mm × 50 mm and with different die angles of 60° and 90°, respectively, were used for this study. The experiment utilized two kinds of color millet grains in an ellipse shape and by a size of about 1 mm as component of the billet to model the evolution of flow pattern in the die during ECAP. Because the grains do not bond tightly each other, a plunger with a backpressure was used to make the grains form a whole body and move slowly with the same moving speed during extrusion process. It should be pointed out that the usage of the millet grains can effectively demonstrate the flow behavior of materials in ECAP die, to some extent, it is a feasible method to model the metal flow by using millet grains. Two dies with fully filled grains are shown in Figs. 1(a) and 2(a), respectively. The horizontal red grain bands were designed to observe the deformation zone, and the vertical red grain bands were used to get a good reference frame for observing the flow pattern within the die during ECAP. These grain work pieces used for modeling were subsequently pressed in the two ECAP dies made of transparent plexiglass for an intuitionistic effect. The flow patterns of the grain work pieces and its evolution at different stages were recorded by digital camera during pressing. In order to further verify the feasibility of the millet grains as the component of billet to model the deformation mechanism, a steel billet was processed by an ECAP die with right angle corner at room temperature and lubricated by MoS_2 during pressing. It is found that the flow line patterns observed by optical microscopy are comparable with the observations in the in-situ physical modeling experiments.

3. Results

Figs. 1 and 2 demonstrate the in-situ deformation processes of grain work pieces in the two transparent ECAP dies. The starting assemblies of the two kinds of color grains are almost with the same bands patterns for the two different dies, as shown in Figs. 1(a) and 2(a), respectively. The detail of grain work piece at corner part during deformation is shown in the upper side of each picture. Fig. 1(a)–(f) present the deformation processes of grain work piece in the ECAP die with round corner ($\phi = 90°$). From these pictures, the evolution features of the flow patterns can be outlined as different stages. Firstly, the deformation starts at the upper boundary and ends at the lower boundary of the quadrant, as marked by the arrows in Fig. 1(d) and (e). In other words, the deformation zone is just the region of quadrant. Secondly, the horizontal straight red grain bands evolve to the curved bands within the deformation zone, and once passing through the deformation zone, they turn into oblique but approximately straight bands, which are at an angle with respect to the extrusion direction, as shown in Fig. 1(b)–(e). Besides, it can be seen that the flow patterns at the bottom of the channel are different from those in the inner part, which is caused by the influence of friction, as indicated by white arrow in Fig. 1(e). Finally, the vertical red grain bands pass through the quadrant of the die following the out circular arc of ECAP die, as shown in Fig. 1(f). In particular, the horizontal lines display a variation on the width after crossing the ECAP channel, which was caused by the elongation of the lines during deformation.

Fig. 2(a)–(f) demonstrate the flow behavior of the grain work piece in the ECAP die with a corner angle of 60°. It is apparent that the flow behaviors in this die are similar to those in the ECAP die with a round corner. Firstly, the deformation also starts at the upper boundary and ends at the lower boundary of the 60° sector, as shown in Fig. 2(c) and (e). Secondly, the horizontal red grain bands also evolve into the oblique bands, as illustrated in Fig. 2(b)–(f). But a horizontal band can be divided into three parts according to Fig. 2(b). The bands above the sector still keep horizontal, however, the bands inside the sector become bended. Meanwhile, segments of the bands out the sector are turned into oblique bands and make a rather larger angle with respect to the extrusion direction, as marked by the three white arrows in Fig. 2(b). Finally, the vertical red grain bands pass through the channel of die following the out circular arc within the sector, and the flow routes still keep straight and parallel to the extrusion direction in the area outside the sector, as shown in Fig. 2(e) and (f). Meanwhile, there is certain influence of friction on the band shape at the bottom of the channel, as indicated by white arrows in Fig. 2 (e) and (f). From the in-situ observations above, it can be concluded that the evolution of flow patterns of

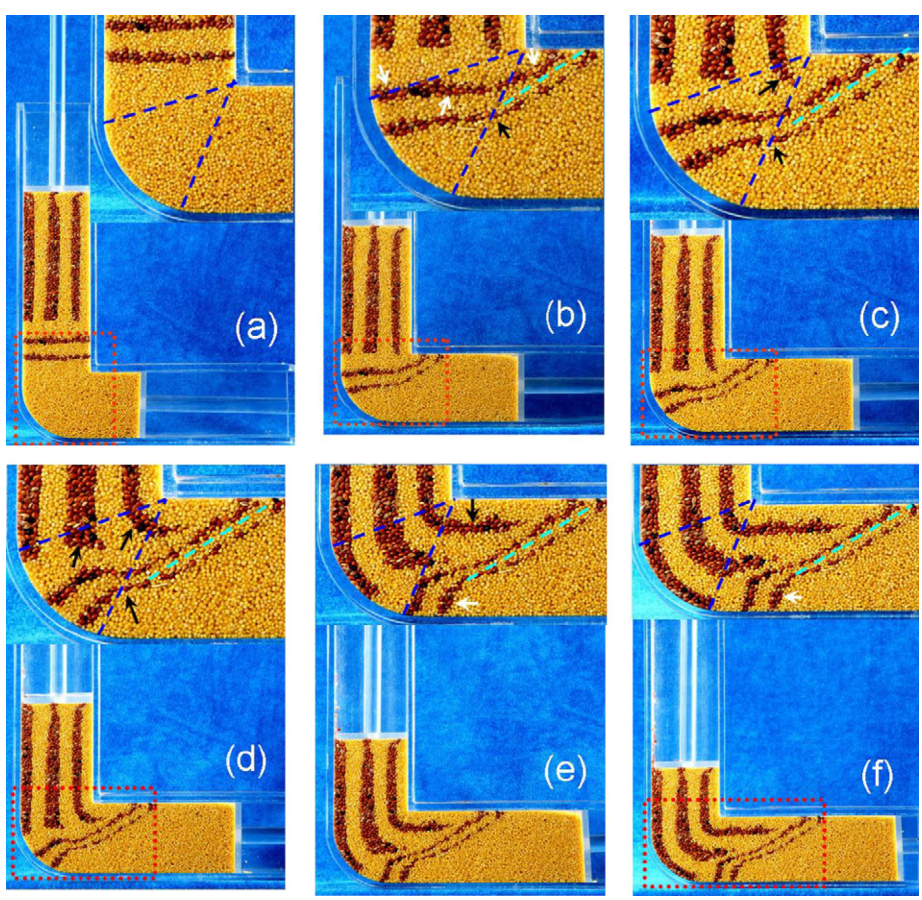

Fig. 2. In-situ observations of grain flow behavior in an ECAP die with $\phi = 60°$.

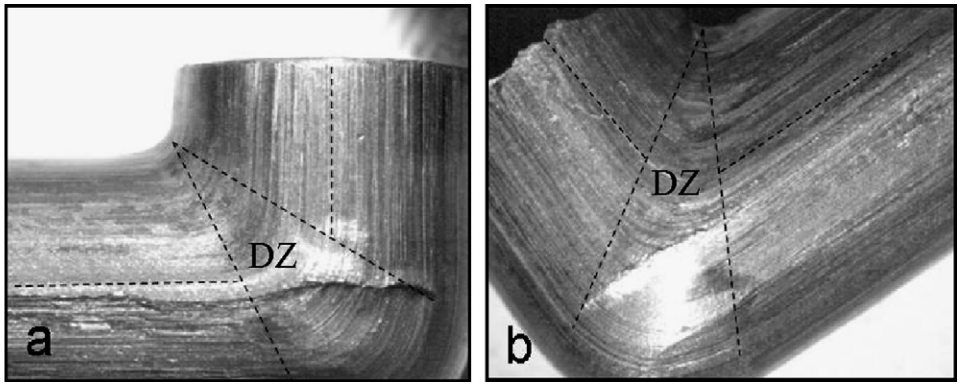

Fig. 3. Illustration of the flow traces on the surface of the real metals processed by ECAP. Figures (a) and (b) are viewed from two opposite directions in order to show the flow trace clearly.

the grain work piece in ECAP die is governed by the geometric character of die; while the deformation only occurs within a small sector area at the corner in the die during ECAP.

Fig. 3(a) and (b) display the flow traces on the surface of steel, which was viewed from the two opposite directions, those flow traces can reflect the deformation behavior of steel during ECAP. It can be found that the shape of the flow traces and the deformation zone (DZ) are similar to the physical modeling results above, as marked by the black dash line in Fig. 3(a) and (b). This result indicates that it is reliable to use the physical modeling experiment for the investigation on the macroscopic geometrical characteristics of materials deformed in ECAP die. Furthermore, the modeling experiment by the specific billet designed above can not only display the final state of extruded billet, but also demonstrate the whole visible processes and the details of deformation during ECAP.

4. Discussion

Fig. 4 presents the schematic of a general ECAP die with an arbitrary angle ϕ and a channel width R. The coordinate system

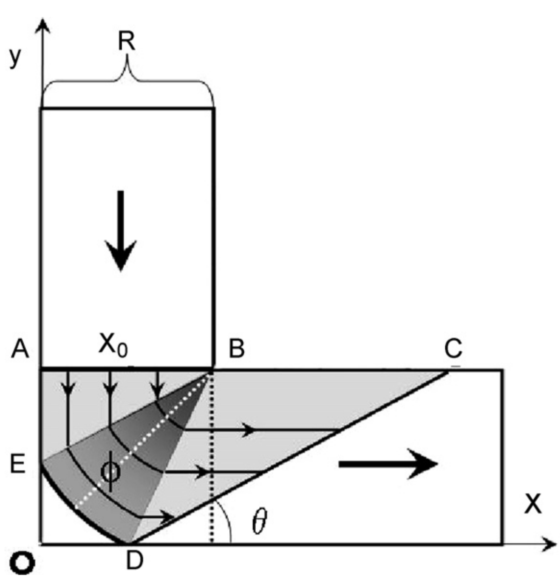

Fig. 4. Illustration of the flow behavior in an ECAP die with an arbitrary angle ϕ.

xoy is established along two boundaries of ECAP die. According to the modeling experiment results above, the material flow routes can be divided into three segments, which are mainly governed by the shape of the ECAP die. As a result, it should require three equations for describing the three piecewise functions of the flow line field formed with a general ECAP die, as shown by ABCDE in the shadow region of Fig. 4. Firstly, in the region ABE, the flow line equation for the vertical straight segment is

$$x = x_0,\ \left[R - (R - x_0)\tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \leq y \leq R\right], \tag{1a}$$

where x_0 is the coordinate of any point on starting line AB. Secondly, in the deformation zone BDE, the flow line equation for the circular arc segment is

$$y = R + \left[(R - x_0)^2 \sec^2\left(\frac{\pi}{4} - \frac{\phi}{2}\right) - (x - R)^2\right]^{\frac{1}{2}}$$

$$x_0 \leq x \leq R - (R - x_0)\tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \tag{1b}$$

Finally, in the region BCD, the flow line equation for horizontal straight segment is

$$y = x_0 \quad x \geq R - (R - x_0)\tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \tag{1c}$$

The equations above clearly describe the flow routes starting at line AB and ending at line CD. The segment AB will deform piece by piece during pressing and, finally, transform into the oblique segment CD in the region of BCD, as demonstrated in Fig. 4. This process can be clearly seen in Figs. 1 and 2. Since the points on line AB move with a constant speed in ECAP channel, their lengths of routes should be identical during pressing. Therefore, in the ABCDE region, the total length of a flow route for any point on segment AB should be equal to that for point A flowing along the out circular boundary and also equal to that for point B flowing along the inner boundary, as shown in Fig. 4. Thus, the lengths of flow routes BC and AED can be calculated by

$$L_{\mathrm{BC}} = L_{\mathrm{AED}} = R\tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) + R\sec\left(\frac{\pi}{4} - \frac{\phi}{2}\right)\phi \tag{2a}$$

For any point on the segment AB, the flow line length, L, is made up of three parts, as illustrated in Fig. 4, and can be calculated by

$$L = R\tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right) + R\sec\left(\frac{\pi}{4}-\frac{\phi}{2}\right)\phi \qquad (2b)$$

It is evident that the above flow line field is reasonable for the general ECAP die. According to the modeling experimental results (see Figs. 1 and 2), line AB will be changed into the oblique line CD after pressing, forming an angle with respect to the extrusion direction. This angle can be expressed as

$$\theta = arc\cot\left[2\tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right) + \phi\sec\left(\frac{\pi}{4}-\frac{\phi}{2}\right)\right] \qquad (3)$$

The general flow line field is consistent with that of the above modeling experiment within the sector deformation zone. It should be pointed out that this flow line field is different from that proposed by Toth et al. [28]. According to Toth's flow line theory, the deformation zone is within the whole corner region with approximately a square shape, while the ECAP experiment conducted using single crystal indicated that the deformation zone is a fan shape rather than a square shape [29], which is also confirmed by the results of our modeling experiment and the real extrusion of metals (see Figs. 1–3). Besides, it has been widely observed that the size of deformation zone is different for various metals and alloys even though they are all processed by the same right angle ECAP die [9,24]. Therefore, the flow line field proposed by Toth et al. is hard to apply in a wide range. While for the present flow line field, the value of parameter ϕ can be directly measured from corresponding metal during experiment (as demonstrated in Fig. 3) and employed to various cases. This point is different from the definition by Iwahashi et al. [4], who utilized parameter ϕ only to describe the shape of ECAP die. While in the present research, the parameter ϕ can reflect both the dimension of deformation zone for various metals and alloys and the shape of ECAP die, and it can be selected in a given case and will be discussed in details below.

4.1. For $\phi = 90°$

By substituting $\phi = 90°$ into Eq. (1), for the ECAP die with round corner or for certain metal with a round deformation zone, the flow line field can be expressed as

$$y = \begin{cases} R + \left[(R-x_0)^2 - (x-R)^2\right], & [x_0 \le x \le R] \\ x_0, & [x \ge R] \end{cases} \qquad (4)$$

The corresponding flow line field is shown in Fig. 5, which is consistent with that of physical modeling experiments, as demonstrated in Fig. 1. For this case, there is no dead metal zone during extrusion, therefore, the parameter ϕ can describe the die shape and the size of deformation zone simultaneously. The deformation starts at AB and ends at DB, while the horizontal line AB gradually evolves to the oblique line CD at an angle of 32.5° with respect to the extrusion direction, which is well consistent with those of the previous observations by Segal [9] and Li et al. [23].

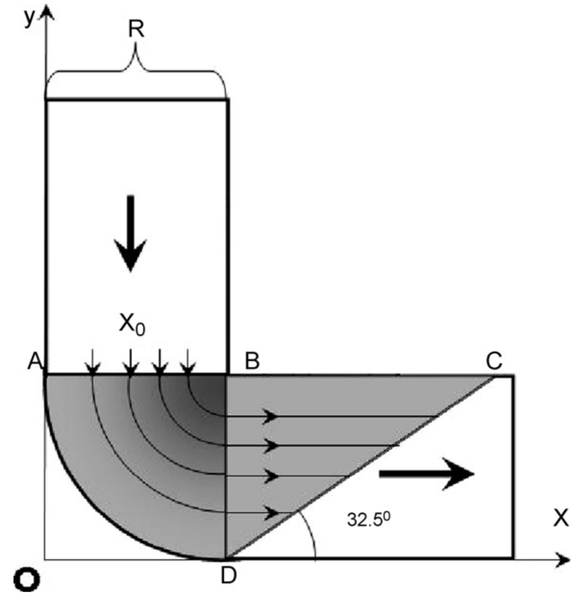

Fig. 5. Illustrations of the flow behavior in a round corner ECAP die.

4.2. For $\phi = 0°$

By substituting $\phi = 0°$ into Eq. (1), the flow line field is expressed with a simple equation for right angle ECAP die, i.e.

$$\begin{cases} x = x_0, & [x_0 \le y \le R] \\ y = x_0, & [x_0 \le x \le R] \end{cases}. \qquad (5)$$

The corresponding flow line field is demonstrated in Fig. 6, it can be seen that the material flow in the right angle ECAP die will have a sudden turning at the intersection plane. The line AB evolves into the oblique line CD at an angle of 26.6° with respect to the extrusion direction, which is only an ideal case of shear flow lines as observed in many experiments [16–18]. Obviously,

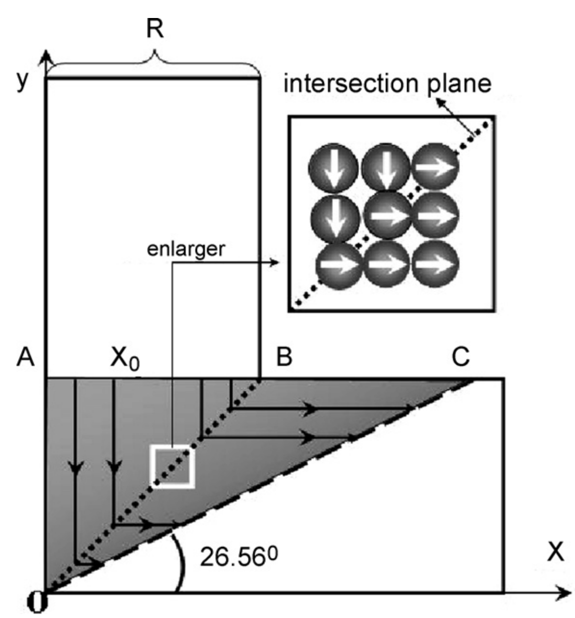

Fig. 6. Illustrations of the flow behavior in a right angle ECAP die.

from the view of material flow, it is not difficult to understand why a group of shear flow lines are formed and have an angel of about 27° with respect to the extrusion direction for the polycrystalline materials processed by one-pass ECAP. The inset at the upper right in Fig. 6 gives out a possible microscale deformation mechanism of ECAP. Assuming that the ball in the picture stands for the basic element of material (the element here does not stand for the atom or grain). During pressing, the basic deformation consists of three processes, i.e. the element moves down to the intersection plane, then changes its direction suddenly at the intersection plane, and finally flows towards the extrusion direction. Before and after passing through the intersection plane, the neighboring elements have no relative movement among them; as a result, no deformation takes place. This indicates that the deformation only occurs on the intersection plane for the right angle ECAP die. Li et al. [23] utilized FE method to analysis the plastic deformation zone (PDZ) for various cases, such as for outer corner angle with an outer corner angle of 0°, 45° and 90°, etc. They also found that the PDZ is confined in a narrow region around the intersection plane for $\phi = 0°$, which is consistent with the current result. Besides, Oh and Kang [13] found that the corner shape is the strongest factor to control the deformation during ECAP. In this study, we also found that the values of parameter ϕ have a remarkable influence on the shape of flow lines, while the shape of flow lines determines the magnitude of the shear strain during deformation.

From the results above, the deformation mechanism of ECAP can be inferred as follows. The basic mechanism of shear deformation is the difference in the flow route or path induced by the ECAP die. The moving speed of every material element in channel of ECAP die can be considered as approximately identical, while there are still some relative movements among those elements, which is caused by the difference in the flow routes for each one. The flow line field is utilized to describe the material flow behavior in ECAP die with different character, and the shear strain is determined by the shape of flow routes. Therefore, it is more reasonable and easier to understand the deformation from the view of metal flow than from the general view of simple shear deformation along the intersection plane. Furthermore, the current understanding on the deformation mechanism will be beneficial to those the optimum properties for the ECAPed materials and the application of ECAP technique.

5. Conclusions

The in-situ physical modeling experiment was employed to investigate the geometrical aspect of deformation during ECAP. The experiment results indicate that the deformation only takes place in the region of deformation zone with a fan shape, and it starts and ends at the boundaries of that zone. Normally, the geometry shape of the ECAP die has a remarkable influence on the flow behavior of the material. A piece-wise equation for the flow line field has been presented to describe the metal flow in ECAP die based on the result of the in-situ modeling experiments. The geometrical aspect of deformation mechanism during ECAP was deduced from the flow line field. It is suggested that the basic mechanism of shear deformation is the difference in the flow route or flow path induced by the geometrical character of the ECAP die.

Acknowledgements

The authors thank H.J. Yang and S. Qu for their assistance in experiments. This work was financially supported by National Natural Science Foundation of China (NSFC) under grant nos. 50471082, 50371090 and 50571102. Z.F. Zhang would like to thank the financial support of “Hundred of Talents Project” by the Chinese Academy of Sciences and the National Outstanding Young Scientist Foundation under grant no. 50625103.

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