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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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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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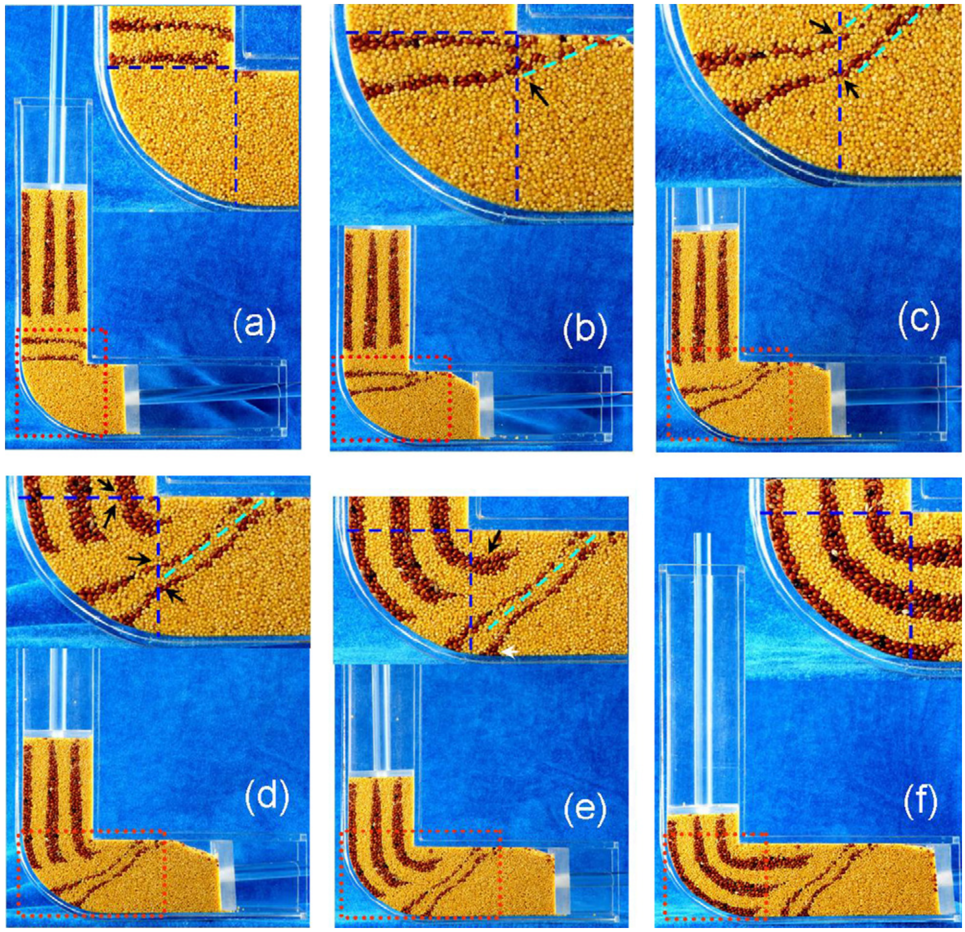

Fig. 1. In-situ observations of grain flow behavior in round corner ECAP die ($\phi = 90^\circ$).

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 com-