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Study of ECAP based on stream function

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ABSTRACT

In the present study, for the first time velocity fields in ECAP's deformation zone was extracted using stream function approach which is a powerful method in fluid mechanic. The extracted velocity field is based on the geometry of die and shape of streamlines. Considering the exponent of stream function (n), countless kinematically admissible velocity fields were derived. Then, the real field that minimizes the kinematically computed power was determined by the upper bound theorem. Lagrangian descriptions of motion as well as flow pattern of evolving material for different values of (n) were obtained. The flow pattern that was on the basis of the calculated velocity field was fairly well correlated to experimental results.

1. Introduction

Various methods such as powder metallurgy, thermo mechanical processing and severe plastic deformation (SPD) have been already proposed in order to manufacture ultra-fine grained materials. Full dense and large scale nanostructured materials as well as manufacturing products with no impurities are the advantages of SPD over other techniques. Equal channel angular pressing (ECAP) which was invented by SEGAL is known as one of the techniques for imposing severe deformation on materials. In this method, the initial dimensions of a workpiece remain unchanged. Thus, it is possible to repeat this process for a number of passes to refine grains (Valiev and Langdon, 2006). A lot of studies and experiments have been carried out by researchers for having better understanding of the process. It has been reported that the ductility and the mechanical strength of 316LVM stainless steel were improved by the combination of sever plastic deformation and annealing (Krawczynska et al., 2013). Microstructural measurement showed that the enhancement of properties were due to nano-twins as well as shear bands which are normally observed in ultra-grained material. The texture of electrolytic tough pitch copper evolved by ECAP has been examined using oriented image microscopy. Furthermore, the activation energy as well as the recrystallization temperature was measured by differential scanning calorimetry (Higuera and Cabrera, 2013). Results show that the stored energy increases on increasing ECAP deformation, while the recrystallization temperature decreases significantly. The effects of friction, backpressure and tool design have been analyzed using slip line field. Simple shear and shear along slip lines were reported as a mechanism of deformation (Segal, 2003). SEGAL showed that friction has moderate effect on the equivalent strain. But, strain distribution depends noticeably on the friction uniformity. Finite element method (FEM) that is known as an effective method in the process modeling, have been widely used by researchers in order to clarify more obscurity about the parameters of ECAP (Esmailzadeh and Aghaie-Khafri, 2012). The influence of process parameters such as die geometry, ram speed, extrusion temperature and back pressure on the strain distribution of high-density polyethylene whose mechanical properties had been numerically deduced from compressive tests, were investigated (Aour et al., 2008). Coupled effect of material response, outer corner angle and friction on plastic deformation zone as well

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as working load vs. ram displacement curves have been studied by two dimensional FEM (Li et al., 2004). A three dimensional finite element simulation for understanding the influence of channel angle on the material flow and strain inhomogeneity has been applied (Patil Basavaraj et al., 2009). Results indicated that a larger channel angle leads to a lesser average strain and superior homogeneity.

Recently, FEM associated with crystal plasticity has drawn a considerable attention for prediction of process parameters. The reported results were in a good agreement with experiments and the applied approach showed considerable potential for texture measurement (Kalidindi et al., 2009; Lu et al., 2011). In addition, deformation mode in ECAP has been experimentally investigated by plasticine and in-situ physical modeling (Han et al., 2008).

Several upper bound models based on kinematically admissible velocity fields have been proposed for calculating required force and pressure (Luis Pérez and Luri, 2008; Narooei and Karimi Taheri, 2010). The effects of different variables of ECAP process were also considered by these works.

Various numerical and analytical models are available for analyzing ECAP process. However, the ability of velocity field for performing an analysis and determining the process characteristics of ECAP has been ignored. It should be mentioned that Talbert and Avitzur made a considerable contribution in the field of metal forming science by applying stream functions in the solid mechanic (Talbert and Avitzur, 1996). The present work attempts to give a compressive and kinematical study of the ECAP process on the basis of streamline functions and velocity fields. Flow trace of material in the deformation zone is studied using Eulerian and Lagrangian description that is obtained by the velocity field. Finally, it is shown that results which were obtained via upper bound model fairly well correlated to experiments.

2. Analysis

2.1. Stream function approach

The motion of a deformable body is normally studied via material description which is a vector based field and typically is difficult to be extracted for a certain metal forming process. Stream function which is a scalar quantity is considered as a capable and a robust technique. Considering that a velocity vector at any given point along a streamline is always tangent to it, the following equation is derived by integrating the stream function.

$$\frac{dx}{V_x} = \frac{dy}{V_y} \tag{1}$$

where v_x and v_y are components of the velocity vector along the axes of coordinates. Concerning Eq. (1), streamlines of moving particles can be extracted.

It should be noted that velocity vectors are unknown. Thus, stream function should be computed from streamline equations. These equations can be predicted from the geometry of a die profile. Then, velocity fields can be derived from the stream function as follows:

$$V_x = \frac{\partial \psi}{\partial y} \quad V_y = -\frac{\partial \psi}{\partial x} \tag{2}$$

It is important that in the present study, a stream function that is usually used for analyzing axisymmetric, plane or two dimensional forming processes is used to derive a velocity field. Then, the analysis is completed based on the derived velocity field. In the present work, stream function is used for two major reasons (Talbert and Avitzur, 1996):

1. Dealing with a scalar field is significantly easier than working with a displacement field that is a vector-based quantity.
2. Many of the velocity fields that are derived from other methods are rejected since they violate the incompressibility requirement. In contrast, velocity fields derived from stream functions automatically satisfy the volume constancy requirement.

2.2. Derivation of a velocity field

In order to derive streamlines relations, it is assumed that material in a deformation zone moves through infinite concentric circles centered at the pint "o" (Altan et al., 2005; Eivani and Karimi Taheri, 2007). Fig. 1 shows four streamlines including outer and inner corner of a die. Corresponding equations are expressed as:

$$\begin{aligned} x^2 + y^2 &= b_1 R^2 = R_{\text{int}}^2 \\ x^2 + y^2 &= b_2 R^2 \\ x^2 + y^2 &= b_3 R^2 \\ x^2 + y^2 &= b_4 R^2 = R_{ext}^2 \end{aligned} \tag{3}$$

where constants b_i are positive real numbers. When these constants are multiplied by R (the radii of an arbitrary streamline) the radius of streamlines which pass through the deformation zone are calculated. Stream function F in term of R^2 and $x^2 + y^2$ is derived in such a way that it always remains constant. For example:

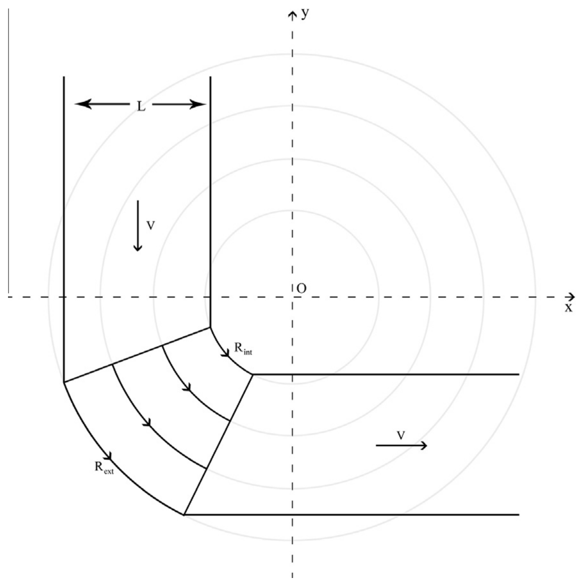

Fig. 1. Circular streamlines pass through the deformation zone.