

On the strain distribution during extrusion through a bent channel

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ABSTRACT

The concept of equal channel angular pressing (ECAP) as a method of imparting significant amount of work to materials without causing reduction in section size to produce fine grain structure was developed in early 1980s. Several modifications are being made to the theory to accommodate the observed deviations in behaviour of materials during processing. In all these analyses, it is assumed that the material moves at a constant speed across the whole cross-section. In this paper we examine the strain experienced by materials when they are extruded through a bent channel under the assumption that cross-sectional planes remain planar, as in elastic bending, which does not permit constant speed of movement of the material across the cross-section. Finite element analysis (FEA) of extrusion through bent channel led to discovery of a new mechanism by which shear is induced in the material apart from the expected tensile and compressive strains.

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1. Introduction

Over the last few decades working of materials by forcing them across a sharp corner at the intersection of two straight channels of equal cross-section is being studied as a possibility to impart significant amount of strain in order to achieve fine grain structure without causing reduction in section size [1–5]. As the cross-section of the material remains unaltered it can be processed over and over again to impart uniform large plastic strains. In spite of its invention in the early 1980s, the process did not progress as much as one would desire and is still confined to the laboratory scale experiments. Experimental work in this area has been confined to easy to work metals like pure Al [6–10], Cu [11] and their alloys. Very few have worked on difficult to deform materials such as gamma titanium aluminides [12], Ti alloys [13–16] and other materials. Even in the lab scale processing, problems are encountered when different metals and alloys are processed using the same ECAP die set. In general, all materials tend to take a curved shape at the corner of the intersecting channels which is a part of the deformation zone. Over the years, dies and channels of various designs [11,17] have been proposed to accommodate the actual behaviour of materials.

In theories of ECAP, various analytical equations have been presented to calculate the average strain imparted to a material when processed through an angular channel, i.e., channel with a certain channel angle (ϕ) and corner angle (ψ) [4,5,18,19]. Luis Pérez [20]

proposed a channel with a radius of curvature at the outer and inner channel surface and provided equations for calculating the average strain imparted to the work piece when processed through a channel with equal radius of curvature at both inner and outer channel surfaces and unequal radius of curvature at channel surfaces. In all these theories/analyses, it is invariably assumed that the material moves in a streamlined manner at a constant speed maintaining their relative distance from the channel walls throughout their course of flow across the deformation zone. Consequently all theories predict homogeneously distributed simple shear, the extent of which depends on the channel angle (ϕ) and the corner angle or the arc (ψ) over which the material lifts itself from the corner with outer surface taking a curved shape [10,18]. However, we have not been able to find an explanation/justification for these assumptions based on which the shear strain and equivalent strain are being calculated. FEM analyses have always shown deviations from uniform shear especially near the outer channel surface and there is always a strain gradient from top to bottom and end-to-end in the deforming work piece [21–23]. Kim [22] has stated that the lower strain near the outer channel surface (bottom surface of the deforming work piece) is due to faster flow of material compared to the inner part (top surface of the deforming work piece) which would be natural consequence if one were to adopt assumptions of bending. Luis Pérez [20] indicated that when the fillet radii at the junction where the two straight channels meet are modified beyond a limit, the material experiences bending instead of shear.

In this paper, we examine the strain distribution across the cross-section when a rigid plastic material is extruded through a channel with a bent region at the junction of two straight channels as shown in Fig. 1A, under the assumption that the cross-sectional

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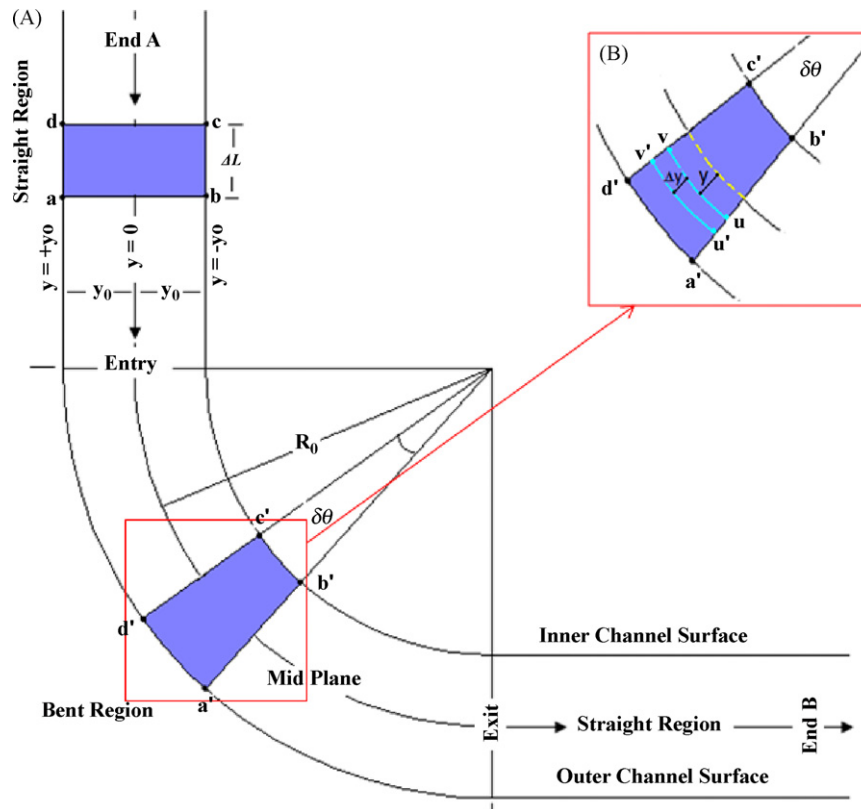


Fig. 1. Bent channel with equal cross-section.

planes remain planar during their passage through the bent portion of the channel as in elastic bending. Thus the mechanism of deformation is distinctly different from the one considered in earlier ECAP theories.

2. Channel design

The channel with a bent region at the junction where the two straight channels of width ' $2y_0$ ' and thickness ' t ' meet at 90° is shown in Fig. 1A. Thus, unlike a channel for equal channel angular extrusion process which does not have a constant cross-section at the junction where the two straight channels meet, the current channel was designed to maintain the channel cross-sectional width throughout the channel. The channel has a mid plane radius ' $R = R_0$ ', outer and inner channel surfaces with radii ' $R_0 + y_0$ ' and ' $R_0 - y_0$ ', respectively thus maintaining a constant cross-sectional width of ' $2y_0$ ' throughout the channel. It can also be noted that as we move along the mid plane of the channel, the value of radius of curvature changes abruptly from zero to a finite value ($\approx 1/R_0$) at the entry plane and remains constant in the bent region and then changes back to zero at the exit plane.

When a material is forced across a bent channel with planar end surfaces as shown in Fig. 1A, the material undergoes bending at entry and unbending at the exit. As the material moves into the bent region, the material experiences bending and the deformation propagates along the length of the material. Under ideal conditions (no effects of friction), the deformation in the channel can be considered analogous to that occurring in conventional bending, where the whole length of material is bent simultaneously by applying a moment at the ends. For the same reason, it appears reasonable to assume that the cross-sectional planes remain planar as in elastic bending. Therefore the distribution and the extent of deformation

in extrusion through a bent channel are analysed under these assumptions. Under these assumptions, the material closer to inner channel surface moves slower while that closer to the outer channel surface moves faster than the material at mid plane in order to maintain planarity of cross-sectional planes. Therefore, there is no analogy between the analysis made here and that reported for angular extrusion process in which the material is assumed to move with a constant speed.

3. Analysis of deformation

Consider a slice of material with width ' $2y_0$ ' and length ' ΔL ' initially above the entry plane in the straight channel. As the slice enters the bent region it undergoes deformation. The slice initially having parallel end planes (ab and cd) become wedge like with the end planes ($a'b'$ and $c'd'$) inclined at angle ' $\delta\theta$ ' to each other as shown in Fig. 1A. Conservation of volume requires that the length at the mid plane remains unaltered. Therefore

$$\Delta L = \delta\theta R_0 \quad (1)$$

In the process of deformation to wedge shape, the material between the mid plane and the inner channel surface is compressed while the material between the mid plane and outer channel surface is elongated. In order to maintain the volume constant in the slice, the material must undergo bulk displacement radially away from the centre of curvature towards the outer channel surface as shown in Fig. 1B. Complete solution to this problem was given by Marciniak et al [24] in the context of sheet metal forming for small radius bends, where plane strain conditions prevail naturally. Following the same approach and applying conservation of volume for a plane (uv) at a distance ' y ' from the mid plane, the displacement (Δy) of the plane

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