

## A Review on Equal Channel Angular Extrusion as a Deformation and Grain Refinement Process

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### Abstract

Equal channel angular extrusion (ECAE) has been known over some years now as a deformation and grain refinement process for materials when pushed more than a couple of times through a die formed from two channels of equal cross-section, intersecting to form a 'sharp' corner. Since its invention in 1977 by V. M. Segal, it has been an essential tool by engineers and scientists for imparting various properties on the extruded material. It should be noted also that its usage gained more prominence in the early 80's. A lot of publications and articles have come up as reports after the use of ECAE on various materials. Various factors have been known to affect the properties and the microstructures of ECAEed materials. Some of these factors include temperature, die corner angle and type of route. This paper gives a concise summary of what ECAE entails as a deformation and grain refinement process. This was achieved after reviewing various articles in refereed journals published worldwide

**Keywords:** equal channel angular extrusion, routes, deformation, grain refinement

### INTRODUCTION

Vladimir Segal invented Equal Channel Angular Extrusion (ECAE) in the former Soviet Union (USSR) in 1977. It is an exciting method for inducing large plastic deformation to materials without changing the size or general shape or dimensions of the billet. A die is formed from two channels of equal cross-section, intersecting to form a 'sharp' corner. Deformation occurs at the die corner as the billet is pressed. If the sample is punched through the die, the process is called ECAE and if the specimen is drawn, then the process will be ECAD (Equal Channel Angular Drawing). The ECAE is better known than the ECAD. Effective strain per pass is dependent on the angle of intersection of the die channels and to a lesser extent on the fillet radius at the die corner. ECAE has been used for uniform plastic deformation, increase material strength, and produce ultrafine-equiaxed grains (UFG), complex microstructures and for powder consolidation/compaction.

Parameters that have been used in the course of carrying out experiments include the following:

- Temperatures ranging from  $-200^{\circ}\text{C}$  to  $1330^{\circ}\text{C}$  depending on the test material.
- Corners of  $90^{\circ}$  and  $120^{\circ}$  are more common.  $60^{\circ}$  and  $135^{\circ}$  have also been reported. Different corners provide varied amount of strains.
- Multiple extrusion or passes.
- Change in the orientation of the billet between successive extrusions. This is also known as different routes A, B, C, and D or A, BA, C and BC respectively. These

designations have been accepted universally as description of the routes.

- Dies of circular or square cross-sections (2 mm to 150 mm square/circular x-sections) have been used.

ECAE is also called ECAP – Equal Channel Angular Press/Pressing and ECSLE – Equal Crosssection Lateral Extrusion. However, the most popular name is ECAE.

Figure 1 shows a Schematic Diagram of the ECAE process.

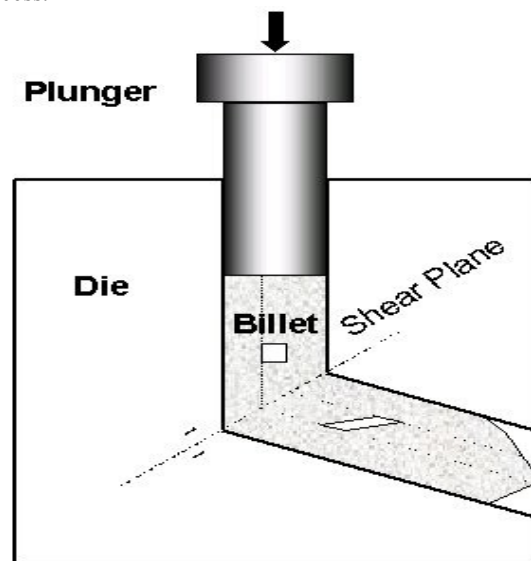


Fig. 1 Schematic Diagram of the ECAE process (www.tamu.edu, 2007)

**ADVANTAGES/USES**

Advantages and uses of ECAE include:

- Impartation of tremendous increase in material strength (Semenova et al., 2004; Amol et al., 2005).
- Production of Ultrafine-equiaxed grained (UFG) materials has been achieved e.g. grain size less than 1 μm (Máthis et al., 2004)
- Unusual properties appear such as high tensile strength, ductility and the possibility to get superplasticity at low temperatures (Horital et al., 2000; Komura et al., 2001; Xu et al., 2004).
- Ability to control crystallographic and mechanical texture during multi-pass ECAE by judicious rotation of the workpiece between passes (Tóth et al., 2004).
- Uniform and unidirectional deformations can be produced under relatively low pressure and load for massive products (Park et al., 2005).
- Formation of complex microstructures: equiaxed, laminar and fibrous textures (Ferrasse et al., 2004; Li et al., 2004).
- Increase in hardness (Yu et al., 2005).
- Achievement of powder consolidation/compaction (Senkov et al., 2005; Máthis et al., 2004).

**SHORTCOMINGS**

- Buckling instability of the extruding ram.
- The cross-section of the billet becomes smaller with the number of passes.
- Surface defects such as cracks, pores are also common.

**DEFINITION OF VARIOUS ROUTES USED IN ECAE**

Routes here mean the directions followed by the billet or test sample.

- ROUTE A: 0°, all passes; the billet is not rotated between successive passes.
- ROUTE B or BA: 90°, N even, 270° N odd; the billet is rotated 90° clockwise and counterclockwise alternatively.
- ROUTE C: 180°, all passes; the billet is rotated 180°.
- ROUTE D or BC: 90°, all passes; the billet is rotated 90° clockwise.

Schematic representation for the routes as diagrammatically presented by Stolyarov et al., 2005 is shown in Figure 2.

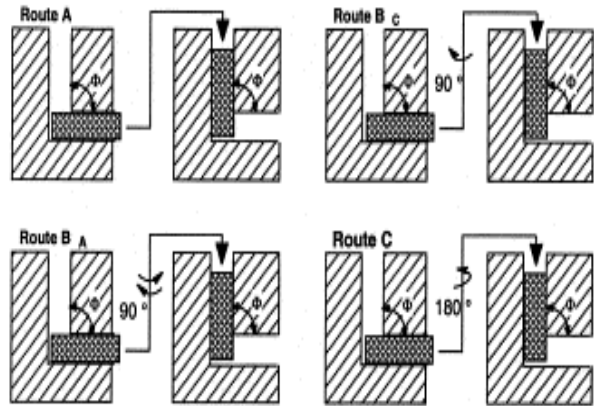


Fig. 2. Rotation schemes of the four ECAP routes

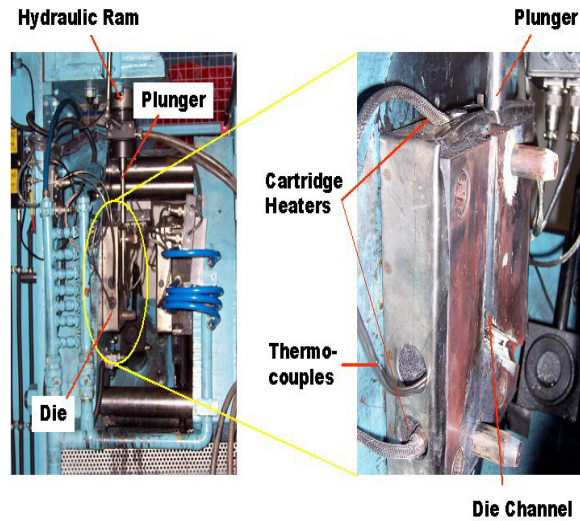


Fig. 3 Photograph of an ECAE die used by the Materials Department at the University of Manchester in the United Kingdom ([www.manchester.ac.uk](http://www.manchester.ac.uk), 2007)

**MODELS AND FORCE EQUATIONS**

Segal, 1995; Gholinia et al., 1998 and Iwahashi, et al., 1996 have proposed different models for the shear strain of the deformed material in terms of some variables. Definitions of various notations/variables used in the model equations are given in Fig. 4.

(a) V. M. Segal

$$\gamma_N = \frac{2N}{\sqrt{3}} \cot \frac{\Phi}{2} = 1.16 N \cot \Phi \quad 1$$

(b) Goforth et al

$$\gamma_N = \frac{N}{\sqrt{3}} \left[ 2 \cot \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right) + \Psi \right] \quad 2$$

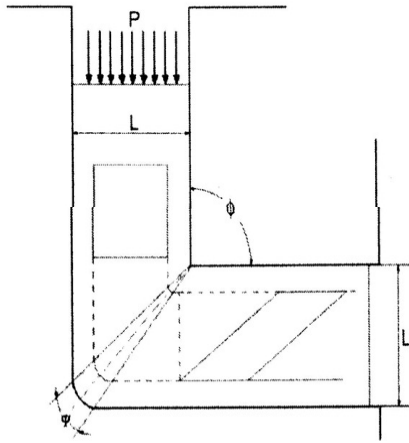
(c) Iwahashi et al

$$\gamma_N = \frac{N}{\sqrt{3}} \left[ 2 \cot \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right) + \Psi \operatorname{cosec} \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right) \right] \quad 3$$

(d) von Mises effective strain equation: von Mises define the effective strain as follows

$$\varepsilon = \frac{\gamma_N}{\sqrt{3}}$$

4



$N$  = number of passes,  $\gamma N$  = equivalent plastic shear strain,  $\phi$  = angle between the channels (inner arc angle),  $\psi$  = outer arc angle,  $\varepsilon$  = effective strain.

Fig. 4 Definitions of the various notations.

(e) Extrusion stress or pressure

Using V. M Segal Model, we have

$$P = \frac{2}{\sqrt{3}} \sigma_o \cot \frac{\Phi}{2} \quad 5$$

For  $\Phi = 90^\circ$ ,  $P = \frac{2}{\sqrt{3}} \sigma_o$ ,

For  $\Phi = 120^\circ$ ,  $P = \frac{2}{3} \sigma_o$ .

$P$  = Required Stress or Plunger Pressure required to push the test material through the die.  $\sigma_o$  = the yield strength of material under test. Pressure for deformation mostly depends on the ECAE angle and the yield strength of the material. Variations occur with the inclusion of  $\psi$  in the pressure formula.

**MATERIALS TESTED**

Below are some of the materials that have been deformed using ECAE processes.

**Metals and Alloy**

- Aluminum alloys
- Chromium
- Copper
- Intermetallics
- Iron/Steel
- Magnesium
- Silver
- Tantalum
- Titanium

**Powders**

- WC-Co
- Ti-6Al-4V
- $Al_{8.5}Ni_{10}Y_{2.5}La_{2.5}$
- P-type  $Bi_2Te_3-Sb_2Te_3$

**Polymers**

**Composites**

**CONCLUSIONS**

(a) Various materials have been tested over the years using ECAE. These materials include metals, composites, polymers and ceramics.

(b) There has been reported significant occurrence of superplastic flow in materials after ECAE pressing (Horita et al., 2000; Komura et al., 2001).

(c) Nano-grained materials of grain size less than 1  $\mu m$  have been produced with the use of ECAE (Cao et al., 2003; Khan et al., 2003). Most interesting is the one reported by Berbon et al., 1999 where refinement occurred from 500  $\mu m$  to 0.6  $\mu m$  after four passes through a 90° die for an Al-1%Mg alloy.

(d) The various routes have been found to be of significant importance in the properties of the ECAPed products. It has been concluded (Komura et al., 2001) that a microstructure of equiaxed grains separated by high angle boundaries is a prerequisite for achieving high tensile ductilities and this is attained most readily when processing using route BC.

(e) Mechanical properties of ECAEed samples (Horita et al., 2000; Chakkingal et al., 1998) depend on factors such as strain rate and temperature as the case with other processes. Strength (UTS and YS) and ductility usually increase with the first couple of passes. However, Hopkinson pressure bar method has not been used to test ECAPed materials. Hopkinson pressure bar technique is commonly used to demonstrate how stress and strain within the deforming specimen are related to displacements in the pressure bars.

(f) Increase in extrusion temperature (Ferrasse et al., 2004; Chen et al., 2003) resulted in the development of equiaxed-like grains in AA5052.

(g) Compacted powder (Senkov et al., 2004) has been found to increase in density up till about the fourth pass for  $Al_{8.5}Ni_{10}Y_{2.5}La_{2.5}$ .

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