

PAPER • OPEN ACCESS

Analytical and Experimental Investigation of Process Loads on Incremental Severe Plastic Deformation

To cite this article: Mehmet Okan Görtan 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **194** 012046

View the [article online](#) for updates and enhancements.

Related content

- [Incremental ECAP as a novel tool for producing ultrafine grained aluminium plates](#)
L Olejnik, W Chrominski, A Rosochowski et al.
- [Finite element simulation of the T-shaped ECAP processing of round samples](#)
Mehdi Shaban Ghazani, Ali Fardi-Ilkhchy and Behzad Binesh
- [Mechanical properties and structure of AZ61 magnesium alloy processed by equal channel angular pressing](#)
O Hilšer, S Rusz, T Taski et al.

Analytical and Experimental Investigation of Process Loads on Incremental Severe Plastic Deformation

Mehmet Okan Görtan

Mechanical Engineering Department, Hacettepe University, Ankara/Turkey

okangortan@hacettepe.edu.tr

Abstract. From the processing point of view, friction is a major problem in the severe plastic deformation (SPD) using equal channel angular pressing (ECAP) process. Incremental ECAP can be used in order to optimize frictional effects during SPD. A new incremental ECAP has been proposed recently. This new process called as equal channel angular swaging (ECAS) combines the conventional ECAP and the incremental bulk metal forming method rotary swaging. ECAS tool system consists of two dies with an angled channel that contains two shear zones. During ECAS process, two forming tool halves, which are concentrically arranged around the workpiece, perform high frequency radial movements with short strokes, while samples are pushed through these. The oscillation direction nearly coincides with the shearing direction in the workpiece. The most important advantages in comparison to conventional ECAP are a significant reduction in the forces in material feeding direction plus the potential to be extended to continuous processing. In the current study, the mechanics of the ECAS process is investigated using slip line field approach. An analytical model is developed to predict process loads. The proposed model is validated using experiments and FE simulations.

1. Introduction

Ultrafine grained (UFG) materials produced by severe plastic deformation processes (SPD) are known for their unusual properties such as a combination of high strength and ductility or improved fatigue behavior [1, 2]. Among the SPD processes, Equal Channel Angular Pressing (ECAP) is the most investigated and developed one due to its ease of use and scalability [3]. However, ECAP involves several drawbacks in its basis form which are mostly related to the high frictional losses in the production system. Firstly, friction generates an additional resistance against the punch movement in ECAP tool systems and hence increases the axial loads. Increased loads enlarge the buckling risk of punch and limit the ECAP workpiece lengths. Therefore, conventional ECAP is seen as a discontinuous process. Moreover, high friction forces results in a poor surface appearance.

In order to overcome these disadvantages, an incremental ECAP (I-ECAP) process has been proposed [4-6]. I-ECAP tool system is split into three major parts; a stationary body and a moveable wall as well as a feeding unit. During I-ECAP, the moveable die wall is opened before forming so the material can be fed freely. After clamping the sample in the forming position, the moveable wall pushes the material into the groove of the stationary die body. Hence, the workpiece is formed gradually. Since the relative movement between I-ECAP tool walls and the specimen is relatively small for every stroke, the friction is minimized by this process.

A similar incremental SPD process, called as Equal Channel Angular Swaging (ECAS) has been proposed by the author [7-9]. ECAS combines the conventional ECAP and the incremental bulk metal



forming process of rotary swaging. Since this process optimizes friction forces during forming, it has a great potential for a continuous production. However, in its first variant, ECAS tool system had channels with a high angle. Therefore, plastic deformation was limited. In order to improve the efficiency of ECAS, channel angle should be reduced. In the current study, the mechanics of ECAS process has been investigated using slip line field theory. An analytical model has been developed to predict process forces during SPD with ECAS. Afterwards, a tool system has been designed with the aid of the proposed analytical model and it is validated with experiments and FE simulations.

2. Principles of ECAS

The ECAS process bases upon the combination of conventional ECAP and the incremental bulk metal forming method of rotary swaging. During the proposed ECAS process, two forming tool halves, which are concentrically arranged around the workpiece, perform high frequency radial movements with short strokes, while samples are pushed through these. Due to this oscillation motion, the contact time and the relative movement between the tool and the workpiece are very small within a stroke cycle. This feature enables the feeding of the material while the tools are open. Moreover, the discontinuous contact enables the permanent lubrication of the tools and the workpiece. Furthermore, ECAS tool systems contain multiple forming sections to ensure that the material exits the process in the same direction as the entry. In the current study, a tool with two forming sections is investigated. Another important aspect of ECAS is that the samples are not pushed against stationary tool walls. Since the oscillation direction nearly coincides with the pushing direction, the workpiece is pulled by the tools during forming. ECAS tool system is shown in 'figure 1' schematically.

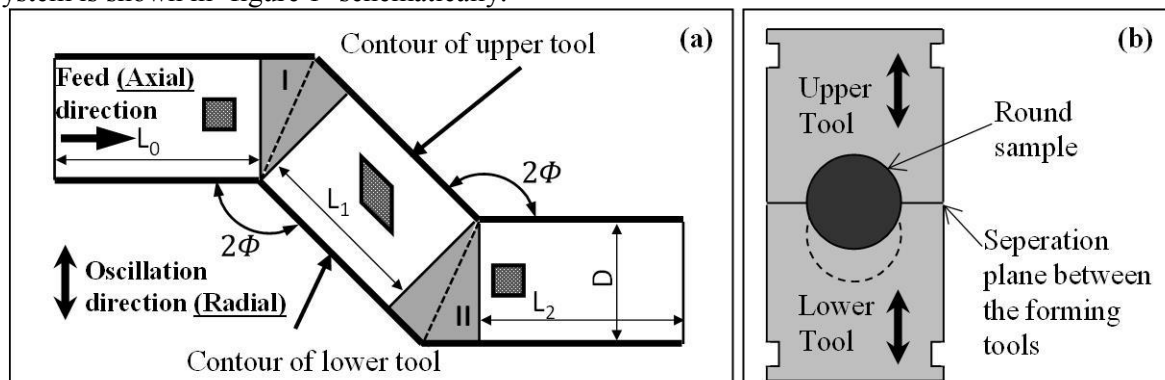


Figure 1. Schematic illustration of ECAS tool (a) cross-section (b) front-view.

In the first studies about ECAS process, a tool system with high channel angles (150°) was used. Although it was possible to refine grain structure of metals with that tool configuration, it required multiple passes [7, 8]. The efficiency of ECAS can be increased by decreasing the channel angle and thus increasing the strain induced in every pass. However, a decrease in the channel angle will cause a significant increase in the forming forces. In such a case, it should be assured that the required force in feeding direction doesn't cause a yielding in the material outside the tool in axial direction. In order to prevent such a failure, first of all, process loads are investigated analytically in the current study.

3. Mechanics of ECAS

Process loads of conventional ECAP has been investigated analytically in many studies [10, 11]. The only force source in conventional ECAP is the punch, which loads workpieces in axial direction. Analytical formulas developed for conventional ECAP process predict the punch force. On the other hand, workpieces are loaded in oscillation direction of the tools during ECAS process. These radial forces in oscillation direction cause the deformation in the material. Forces in feeding direction (axial forces) only compensate the redundant force components in the feeding direction. Therefore, analytical formulas developed for conventional ECAP can't be used for ECAS process.

The forces acting during ECAS process are shown in ‘figure 2’ schematically. ECAS tool system involves two forming sections. Angles in every channel intersection is the same. Therefore, the workpiece leaves the process in the same direction as it enters. Hence, forming follows the Route A. Radial forces are applied to the workpiece by the tool in oscillation direction. Axial forces are applied in feed direction.

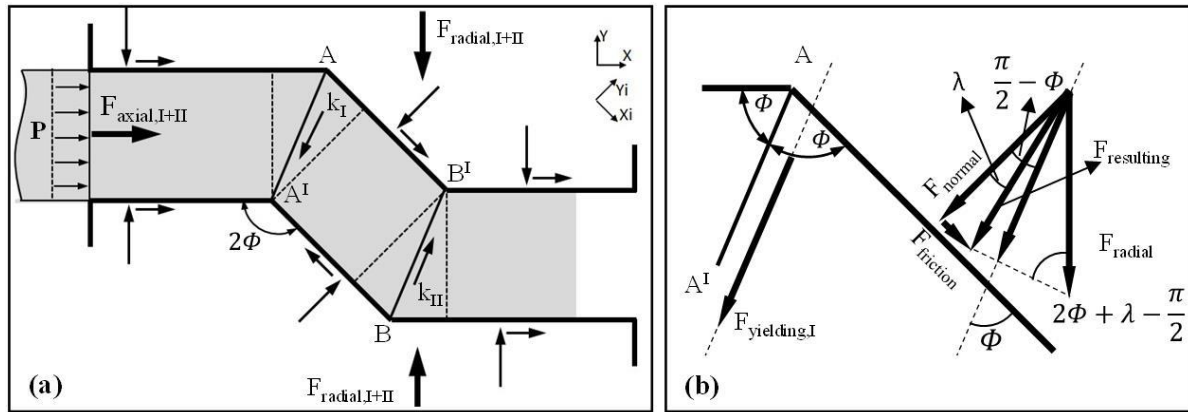


Figure 2. (a) Forces during ECAS process and (b) detail of force distribution.

Unlike conventional ECAP, due to the kinematics of the tools, friction is acting on the sample's feeding direction in ECAS, not on the opposite direction. Thus, as shown in ‘figure 2’ it eases the feeding and reduces the axial forces. This aspect is seen as the most significant advantage of ECAS process over ECAP concerning the force requirement.

For the analytical calculation of the process forces, it is assumed that the deformation takes place along single lines. As a result, force required to form the material along the first yielding line can be expressed as follows:

$$F_{yielding,I} = \frac{k_I}{\sin \phi} \cdot A \quad (1)$$

where, k_I is the shear strength of the material in the first deformation zone, Φ is the half channel angle and A is the area of the workpiece. In order to be able to form the material, the component of the resulting force in the yielding direction should be equal to the yielding force. The resulting force can be represented as follows:

$$F_{resulting,I} = \frac{k_I}{\sin \phi \cdot \sin(\phi + \lambda)} \cdot A \quad (2)$$

where λ is the friction angle. Moreover, this resulting force is a consequence of the radial force. After making the trigonometrical calculations, the radial force required to form the material in the first and second deformation zone can be calculated using the following equation:

$$F_{radial,I+II} = \frac{(k_I + k_{II})}{\sin \phi \cdot \sin(\phi + \lambda) \cdot (-\cos(2\phi + \lambda))} \cdot A \quad (3)$$

where, k_{II} is the shear strength of the material in the second deformation zone. Additionally, the component of the resulting force in the feeding direction should be compensated by the axial force. However, part of that force is compensated by the friction acting on the tool walls. By doing the trigonometrical calculations, the following formula can be derived to predict axial force in the investigated ECAS process, which contains two forming sections:

$$F_{axial,I+II} = \left[\frac{(k_I + k_{II}) \cdot \sin(\phi + \lambda)}{\sin \phi \cdot \sin(\phi + \lambda)} - \frac{(k_I + k_{II}) \cdot (-\cos(2\phi + \lambda))}{\sin \phi \cdot \sin(\phi + \lambda)} \cdot \mu \right] \cdot A \quad (4)$$

where, μ is the friction coefficient. A common method to demonstrate forces on such a system is to use the dimensionless $P/2k$ value. Assuming that the shear strength of the material is the same in both deformation zones, the change in $P/2k$ value in axial and radial directions dependent on friction coefficient and half channel angle is shown in 'figure 3'.

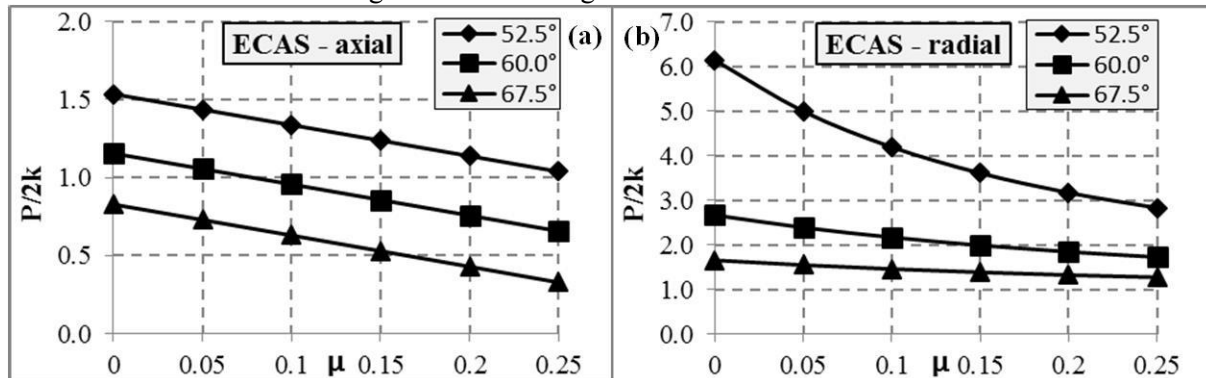


Figure 3. Unitless pressure values of ECAS in (a) axial and (b) radial direction.

The pressures in both axial and radial directions decrease while the friction coefficient increases in ECAS process. Besides the fact that the radial pressures are extremely higher than the axial ones and the ECAS process is inefficient in terms of overall pressure requirement compared to ECAP, the axial pressure in the feeding direction is considerably lower. Since a major prerequisite for a continuous forming operation is a low force requirement in the feeding direction, ECAS process has a high potential for the continuous and thus cost efficient production of UFG materials. An important aspect is that the pressures in the axial direction for a channel angle (2Φ) of 120° is lower than the yield strength of the material by friction coefficients higher than 0.07. Thus, in order to prove the validity of the derived formulas, an ECAS tool system with a channel angle of 120° will be used in this study.

4. Experimental Results

4.1. Process parameters

For the experimental investigations of ECAS process and validation of the derived analytical formulas, a tool system as shown in 'figure 4' with two forming sections at an channel angle $2\Phi=120^\circ$ and a channel diameter of 20 mm was used. Other geometrical parameters of the tools are demonstrated in 'figure 4'. The oscillation frequency and amplitude of the tools was 30 Hz and 0.7 mm, respectively. The feed speed was 1 mm/s. Commercially pure copper (Cu 99.9%) round bar samples with a diameter of 20 mm were used in the experiments. Commercial FE code of MSC.Marc has been used for the numerical investigation of the ECAS process.

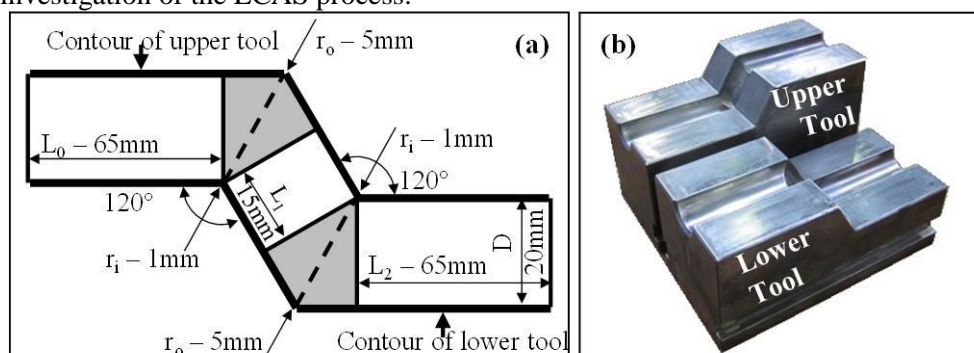


Figure 4. (a) Geometrical parameters and (b) picture of ECAS tool system.

4.2. Strain distribution

In order to verify the feasibility of the developed ECAS tool system, model experiments are conducted with marked copper samples. Therefore, 320 mm long round copper bars are split in the middle surface and then marked with a square grid of 2 mm. Afterwards, these two parts are put together and processed by ECAS. The results of the experiments together with the numerically simulated mesh are demonstrated in 'figure 5'. The entry channel is not fully shown in this figure for a better visualization. The regularly distributed markings in the middle channel indicate a homogeneous shearing of the material along the first yielding line. However, as the sample reaches the second yielding line, the lower section of the workpiece tend to be bent rather than simply sheared. Although in an insignificant manner, a similar effect is also observed on the upper section of the material. Nevertheless, the regular mesh in the middle section of the sample in the exit channel indicates that the deformation is mostly recovered along the second yielding line. The square shape of the grid is preserved after the forming with a little deviation. The deformation in the experiments resembles the one from FE simulations

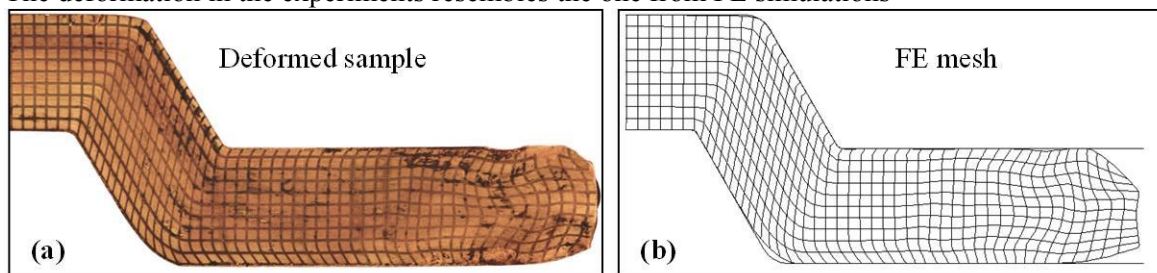


Figure 5. Deformation patterns obtained from (a) experiment and (b) FE simulation.

4.3. Force requirement

In 'figure 6', measured forces are shown with light gray lines, FE results are demonstrated with black lines, analytically predicted ones are displayed with broken lines and their values are written on these. A strain gage based force measurement system was used to measure axial and radial loads during ECAS process. The forming starts with a sudden increase in axial forces and stabilizes shortly after. A similar distribution is observed also when the sample reaches the second forming section. Stabilized forces after the first and second forming sections are 45 kN and 77 kN, respectively. Forces in radial direction after first and second forming section are 74 kN and 143 kN, respectively. It is clear that FE simulations can predict process loads more accurately than the developed analytical formula. It can be explained by investigating the material flow demonstrated in 'figure 5'. By the derivation of the analytical model, it was assumed that the tool geometry is completely filled and the deformation is simple shear along a single line. However, especially along the second deformation section, the samples are rather bent than sheared. Accordingly, an unfilled corner section is present at the second deformation zone.

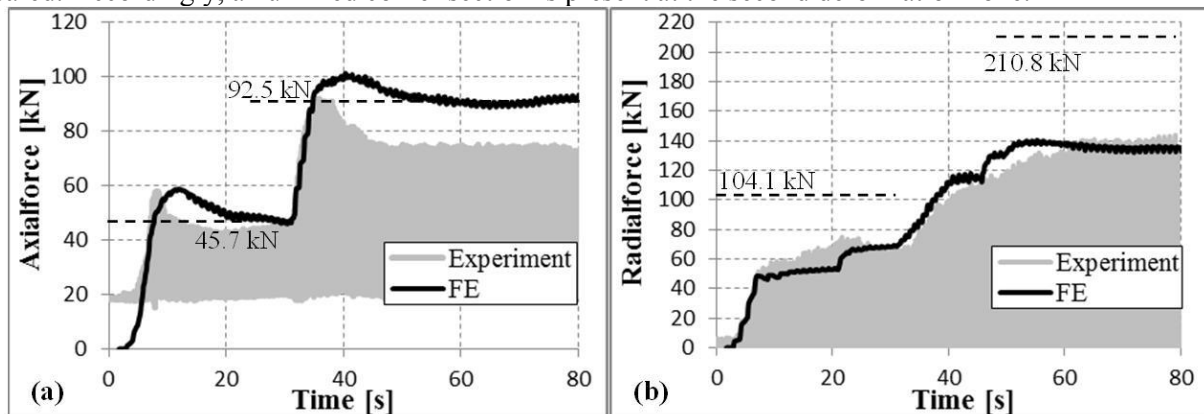


Figure 6. Measured, FE simulated and analytically calculated (a) axial and (b) radial forces.

4.4. Microstructural evolution

In order to investigate the ability of ECAS process to refine grain size, the microstructure of the processed copper samples was analyzed with EBSD in a high resolution SEM after four times ECAS processing using route E. The grain distribution is shown in ‘figure 7’ as an Image Quality Picture. The dark lines between the grains represent the grain boundaries in this figure. Here, the fine grains dominate the microstructure. The average grain size is slightly less than 0.7 μm . If all grain boundaries are taken into account including the ones in the grains, the proportion of HAGBs is approximately 20 %. On the other hand the proportion of the HAGBs, which separates the grains from each other, is over 80 %.

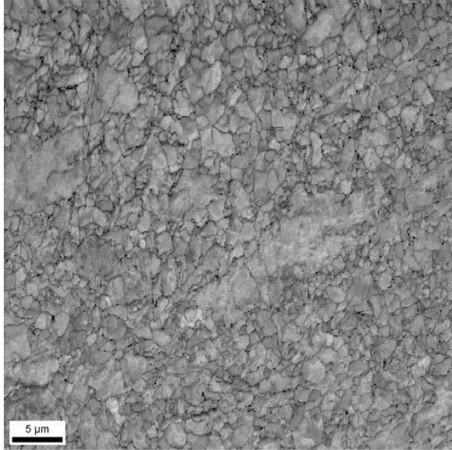


Figure 7. Microstructure of the copper sample after four ECAS steps.

5. Conclusion and Outlook

A new SPD process called as equal channel angular swaging (ECAS) has been proposed recently which combines the conventional ECAP and the incremental bulk metal forming method of rotary swaging. The most important advantages of ECAS process in comparison to conventional ECAP are a significant reduction in the forces in material feeding direction plus the potential to be extended to continuous processing. In the current study, the mechanics of the ECAS process is investigated using slip line field approach. An analytical model is developed to predict process loads. The proposed model is used to design a new set of ECAS die with low channel angles. Model experiments and FE simulations validated that ECAS process with a low channel angle is feasible. In future, other materials should be tested.

Acknowledgments

This work was supported by Research Fund of the Hacettepe University. Project Number: 13661. The author wishes to thank Dr. Enrico Bruder for his support in the microstructure analysis.

References

- [1] Valiev R Z, Islamgaliev R K and Alexandrov I V 2000 *Prog. Mater. Sci.* **45** 103
- [2] Valiev R Z, Estrin Y, Horita Z, Langdon T G, Zehetbauer M J and Zhu Y T 2006 *JOM* **58/4** 33
- [3] Azushima A, Kopp R, Korhonen A, Yang D Y, Micari F, Lahoti G D, Groche P, Yanagimoto J, Tsuji N, Rosochowski A and Yanagida A 2008 *CIRP Annals* **57/2** 716-735
- [4] Rosochowski A and Olejnik L 2007 *Proc. 10th ESAFORM Conf. on Material Forming (Zaragoza, Spain)* 653-658
- [5] Rosochowski A and Olejnik L 2008 *Int. J. Mater. Form.* **1** 483-486.
- [6] Rosochowski A, Rosochowska M, Olejnik L and Verlinden B 2010 *steel res. int.* **81** 470-473.
- [7] Görtan, M O, Bruder E, Groche, P and Müller C 2010 *steel res. int.* **81** 478-481
- [8] Bruder E, Görtan M O, Groche P and Müller C 2011 *Mater. Sci. For.* **667-669** 103-107
- [9] Görtan M O, Bruder E, Groche P and Müller C 2012 *Proc. 18th PLASTICITY'12 (Puerto Rico)* 226-228
- [10] Segal V M 2003 *Mater. Sci. Eng. A* **345** 36-46
- [11] Segal V M 2004 *Mater. Sci. Eng. A* **386** 269-276