FINITE ELEMENT ANALYSIS OF TWIST CHANNEL ANGULAR PRESSING

ONDREJ HILSER[1], MARTIN PASTRNAK[1], STANISLAV RUSZ[1], HANA KRUPOVA[1], PRZEMYSLAW SNOPINSKI[2]

[1]Department of Mechanical Technology, Faculty of Mechanical Engineering, VSB – Technical University of Ostrava, Ostrava, Czech Republic

[2]Department of Engineering Materials and Biomaterials, Faculty of Mechanical Engineering, Silesian University of Technology, Gliwice, Poland

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ondrej.hilser@vsb.cz

The article deals with the analysis of the unconventional pressing process of metallic materials by twist channel angular pressing (TCAP) method. TCAP process is a modification of the equal channel angular pressing (ECAP) forming method, which can be used to prepare bulk materials with an ultra fine-grained structure. Simulation of the TCAP process is an important source of information on the effect of design and technological parameters on the grain refinement efficiency. The TCAP process was simulated using 3D finite element method (FEM).

KEYWORDS

Severe Plastic Deformation, ECAP, TCAP, FEM analysis.

1 INTRODUCTION

The current trend in the material production is to achieve superior utility properties (tensile strength, corrosion resistance, low and high cyclic fatigue, etc.) [Bucko 2022]**.** One way to achieve these superior properties in crystalline materials is grain refinement. The Hall-Petch relation, which describes the dependence between grain size and the resulting strength of the material, is given in Equation 1 [Olsovska 2021]**.** Based on the validity of the Hall-Petch relation, it can be stated that the yield strength or strength increases with decreasing grain size of a polycrystalline material.

$$\sigma_y = \sigma_0 + \mathrm{k} \cdot \frac{1}{\sqrt{d}} \tag{1}$$

where σ_y is yield stress (MPa), σ_0 is Peirels-Nabarr friction stress when dislocation glide on the slip plane (MPa), k is stress concentration factor (MPa·µm$^{1/2}$) and d is average grain size (µm).

One of the technologies used to achieve a fine-grained structure is severe plastic deformation (SPD) technology. The principle of all SPD technologies is to achieve specific deformation conditions (shear stress/deformation and low homologous temperature) that lead to the transformation of the original coarse-grained structure into a very fine-grained to nano-grained [Cada 2021]**.** By virtue of the validity (Equation 1), such materials exhibit increased yield strength, ultimate strength, hardness, low cycle fatigue, corrosion resistance, etc.) [Sternadelova 2021]**.**

2 PRINCIPLE OF SEVERE PLASTIC DEFORMATION

As already mentioned above, SPD methods use forming of the material by intense shear stress, which induces shear deformation in the material. As the strain value increases, lattice failures (especially dislocations) accumulate in the formed material. Their subsequent rearrangement (formation of subgrains during polygonisation or nucleation and grain growth during recrystallisation) leads to fragmentation of the original grain [Sternadelova 2019].

2.1 Principle of ECAP method

The ECAP method, Equal Channel Angular Pressing, is the basic and one of the most widely used SPD methods.

The principle of the ECAP method is to extrude a sample (circular or square cross-section) with an L-shaped channel tool. As the sample passes from the vertical to the horizontal part of the channel, the shear stress is initiated, causing shear deformation in the extruded sample. There is no change in the cross-sectional dimensions during extrusion.

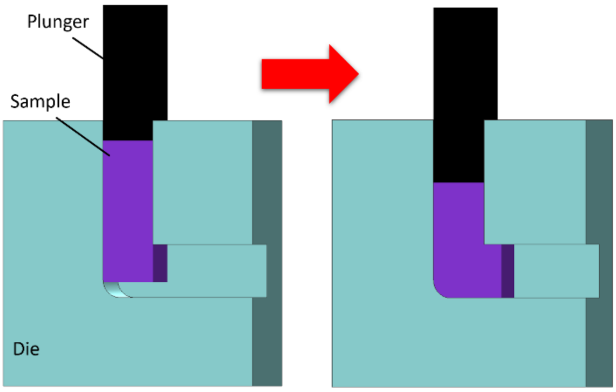

Figure 1. Schematic illustration of the ECAP process

For the die shown in illustration (Fig. 2), the internal channel is bent through an abrupt angle ϕ and there is an additional angle Ψ, which represents the outer arc of curvature where the two channels intersect [Tomasek 2018].

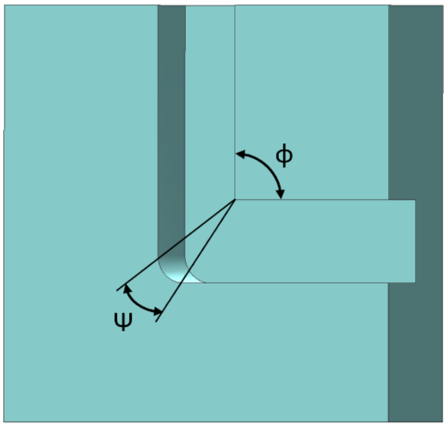

Figure 2. ECAP die geometry

The magnitude of the introduced deformation plays a key role in the subsequent grain refinement process [Sipova 2020]. It is therefore very important to accurately and quantitatively describe the deformation during extrusion using the ECAP method.

Based on the analytical and numerical analyses of the ECAP process, a formula (Equation 2) was proposed for the general calculation of the magnitude of sample deformation during extrusion by the tool with the values of the angles ϕ and Ψ ≠ 0°.

$$\varepsilon_{ECAP} = \frac{1}{\sqrt{3}} \cdot \left[2.\,\mathrm{cotg}\left(\frac{\Phi}{2} + \frac{\Psi}{2}\right) + \Psi \cdot \mathrm{cosec}\left(\frac{\Phi}{2} + \frac{\Psi}{2}\right)\right] \tag{2}$$

where ε_{ECAP} is total ECAP, von Misses, induced strain (-), ϕ is channel angle (°) and Ψ is corner angle (°).

According to equation (2), it is clear that as the value of ϕ and Ψ angles decreases, a higher strain value is initiated. To achieve the maximum deformation value, it is good to choose the values of the design angles of the extrusion tool ϕ=90° and Ψ=0°. In this case, the maximum deformation value calculated according to equation (2) is 1.15 [Valiev 2006]. According to [Frint 2019], it is necessary to achieve a strain value ≈ 5 for effective grain refinement. The number of repetitions of the passes through the tool must therefore be included in the calculation of the cumulative strain value. The effect of the number of passes can be implemented into the equation (2) and after modifying it we obtain equation (3).

$$\varepsilon_{ECAP} = \frac{n}{\sqrt{3}} \cdot \left[2.\operatorname{cotg}\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right) + \Psi \cdot \operatorname{cosec}\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)\right] \qquad (3)$$

where *n* is a number of passes.

2.2 Principle of TCAP method

The TCAP method, Twist Channel Angular Pressing, was developed to increase the value of the cumulative strain in the extruded sample [Machackova 2020]. This method combines conventional ECAP extrusion with an added deformation zone in the form of a helical section in the extrusion channel. The TCAP extrusion concept combines the ECAP and the forward extrusion method through a helical channel, twist extrusion (TE) [Ozbeyaz 2022]. The TE method was developed and is being refined primarily by Professor Beygelzimer's working group [Beygelzimer 2009] and [Beygelzimer 2017].

Pushing the sample through the helical part of the channel leads to an increase in the total value of the accumulated deformation. Thus, it is clear that high strain values per pass through the extrusion tool can be achieved due to the combination of two or more SPD methods [Nouri 2018]. This leads to an increase in the efficiency of the ECAP process, i.e. achieving a UFG structure with a minimum number of repeated passes. The amount of deformation during extrusion through the helical part of the channel can be calculated according to the equation (4).

$$\varepsilon_{TE} = \frac{[\operatorname{tg}\gamma + (0.4 + 0.1 \cdot \operatorname{tg}\gamma)]}{2} \qquad (4)$$

where ε_{TE} is total TE, von Misses, induced strain (-) γ is a twist angle of helical part of channel.

According to the equation (4), the total value of the cumulative deformation increases with increasing value of the twist angle γ, which can be calculated according to the equation (5).

$$\varepsilon_{TOTAL} = \varepsilon_{ECAP} + \varepsilon_{TE} \qquad (5)$$

The design of the forming tool for TCAP extrusion is shown in Fig. 3. The geometry of the extrusion tool with the pitch angle of the helical part of the horizontal channel γ=30° is given as an example.

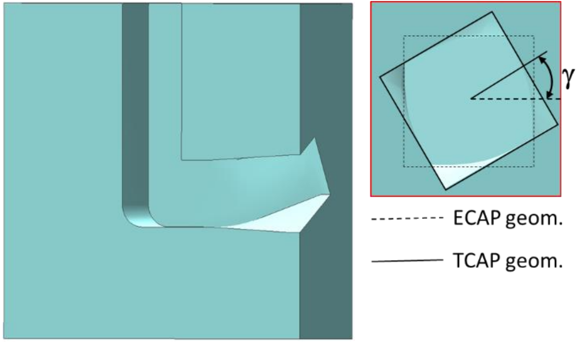

Figure 3. TCAP die geometry and the detail of the helical part of the channel geometry (example, geometry with γ=30°)

The aim of the work is to perform and evaluate the simulation of the extrusion of samples by ECAP and TCAP tools with different pitch angles of the helical part of the channel (γ=0°, 10°, 30° and 45°, respectively).

3 3D FEM ANALYSIS OF ECAP/TCAP PROCESS

The simulation of the extrusion process represents an important basis for the verification of the proposed forming tool modifications and the precise determination of the basic parameters influencing the process of plastic deformation [Vinogradov 2018].

The analysis of the extrusion process by the TCAP method was carried out in the simulation program Simufact.Forming.

To accurately determine the effect of TCAP extrusion, the simulation was set for zero friction conditions. The friction between the extruded specimen and the tool leads to localization of higher strain in the peripheral parts of the extruded specimen and increases the non-uniformity of the strain distribution [Wagner 2020].

The boundary conditions set during the simulation of the extrusion process are shown in Tab. 1.

Conditions	
Material	AlMg3
Ram speed [mm.min^{-1}]	40
Sample dimensions	
Width [mm]	15
Height [mm]	15
Length [mm]	60
Temperature	
T_{Die} [°C]	25
T_{Sample} [°C]	25
Die geometry	
ϕ [°]	90
Ψ [°]	0
γ [°]	0, 10, 30 and 45°
Friction conditions	
Friction coefficient μ [-]	0
Interface friction factor m [-]	0

Table 1. Basic conditions used in the FEM of the ECAP/TCAP process

The progress of the extrusion forces obtained by the simulation is graphically shown in Fig. 4. From the graphical progression, the influence of the built-in helix on the extrusion force increase can be observed. With increasing value of the pitch angle of the helical part, a steep increase is observed (from the displacement value 15 mm, see Fig. 4). This increase is caused by the strengthening of the sample as a result of its pressing into the helical part of the channel. Compared to the classical geometry (γ=0°), an increase in the maximum force value of 4 %, 24.2 % and 43.2 % was found when using a tool with γ=10°, γ=30° and γ=45°, respectively.

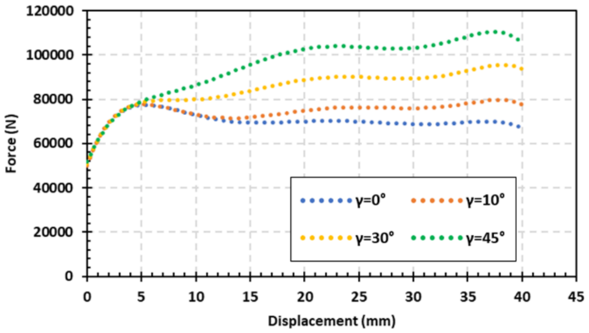

Figure 4. Force – Displacement curves for different value of helix angle

Based on the results of the extrusion forces, it can be determined that the magnitude of the pitch angle of the helical part of the channel has a significant influence on the increase of the deformation resistance of the extruded sample and at the same time a higher deformation must be initiated. The deformation will primarily occur when the sample passes through the ECAP zone (crossing of the vertical and horizontal channel) and in the secondary deformation zone when the extruded sample is intensively torsionally deformed (helical part of channel) [Schrek 2021].

Figure 5 shows the strain distribution along the length of the extruded samples. From these images, the effect of extrusion using a tool with an embedded helix, on reducing the non-uniform strain distribution, can be seen. Non-uniformity of strain distribution occurs when the sample is pressed through the ECAP deformation zone, where the sample does not fully fill the corner part of the channel and the so-called corner gap is formed (Fig. 6). As a result of the corner gap, the stress state changes from pure shear stress to a combination of shear and bending stress, which significantly affects the uniform distribution of the resulting deformation. The corner gap increases the value of the angle Ψ [Dayal 2018]. According to equation 2, in this case the total value of the accumulated strain is reduced and at the same time the inhomogeneity of the strain distribution over the cross-section of the sample increases.

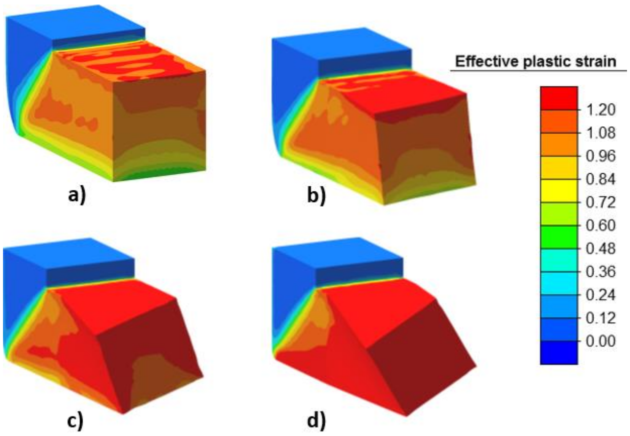

Figure 5. Effective strain distribution in the extruded sample: a) γ=0°, b) γ=10°, c) γ=30° and γ=45°

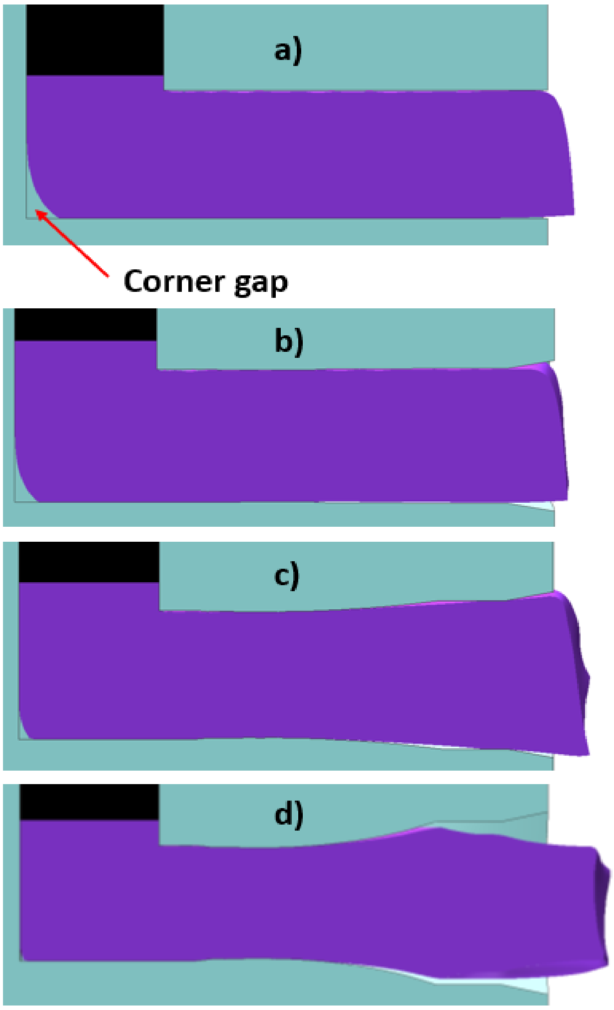

Figure 6. Corner gap formation during ECAP process: a) γ=0°, b) γ=10°, c) γ=30° and γ=45°

To quantify the deformation inhomogeneity [Patil Basavaraj 2017] a deformation inhomogeneity index C_i is calculated using Eq. (6).

$$C_i = \frac{Max\varepsilon_p - Min\varepsilon_p}{Avg\varepsilon_p} \tag{6}$$

where C_i is inhomogeneity index (-), $Max\varepsilon_p$ is maximum equivalent plastic strain (-), $Min\varepsilon_p$ is minimum equivalent plastic strain (-) and $Avg\varepsilon_p$ is average equivalent plastic strain (-).

The evolution of the C_i coefficient value as a function of the helix pitch angle is shown in Fig. 7. As the angle γ increases, the C_i value decreases, i.e., the uniformity of the strain distribution in the extruded specimen increases.

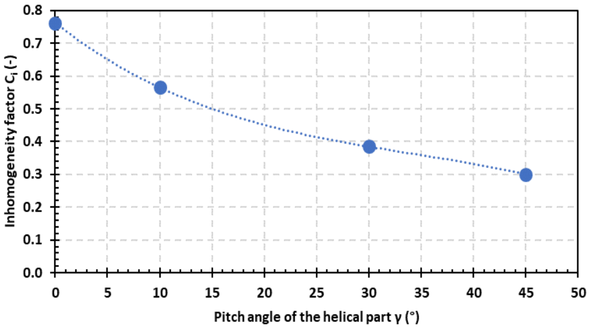

Figure 7. Evolution of C_i depend on the angle γ

The magnitude of the resulting deformation is directly dependent on the values of the tool angles ϕ, Ψ and γ, respectively. In the case of extrusion using the ECAP method (γ=0°), the average value of the accumulated effective deformation is $\varepsilon_p \approx 1.05$. This value does not agree with the calculation of the strain according to the equation (2), where the value of $\varepsilon_p \approx 1.15$ should be achieved. Due to the non-uniform strain distribution, the average value of ε_p is reduced.

In the case of helix implementation, the value of the induced deformation increases. By extruding with a tool with an angle γ=10°, we achieve values of $\varepsilon_p \approx 1.15$. It was determined by simulation that by using a tool with an angle γ=30°, an average strain value $\varepsilon_p \approx 1.3$ can be achieved. The average strain value using a tool with an angle value γ=45° was determined by simulation to be $\varepsilon_p \approx 1.5$. A graphical representation of the prediction of the effective plastic strain average value evolution is shown in Fig. 8.

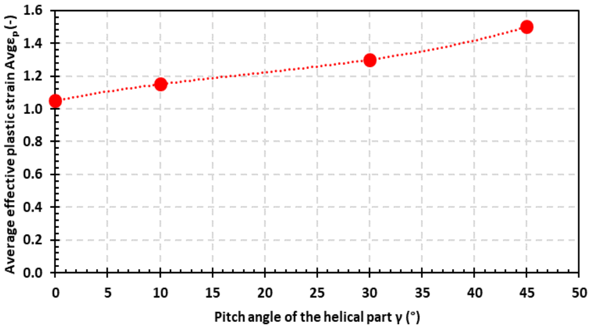

Figure 8. Evolution of average value of ε_p depend on the angle γ

The strain distribution on samples extruded with tools with built-in helix has a positive effect on the strain distribution uniformity. The change in the nature of the strain distribution is due to the back pressure (BP) applied when the sample is pushed into the helical section of the channel. This BP acts over the entire volume and evens out the uneven strain distribution. The BP effect depends on the magnitude of the pitch angle γ. The effect of the helix in the extrusion channel is not only to increase the value of the total deformation, but it has a major effect on the extrusion process itself, where harder to form materials such as metals with hcp crystallographic lattice can be extruded at lower forming temperatures [Nagasekhar 2009]. The extrusion of the helical part generates back pressure (BP), which reduces the risk of crack initiation in these materials [Hruby 2015].

4 CONCLUSIONS

The aim of the work was to perform and evaluate the simulation of extrusion of the sample by ECAP method with modified tool geometry. The modified geometry consists of a combination of the Equal Channel Angular Pressing (ECAP) and Twist Extrusion (TE) methods.

Based on the results obtained, it can be concluded that:

- the use of the TCAP tool leads to the initiation of higher deformations in the extruded sample.
- The helical section of the channel results in back pressure (BP), which directly affects the uniform distribution of deformation and minimizes the negative effect of the corner gap.

Based on the obtained results, it can be concluded that the incorporation of the helical section into the ECAP extrusion tool increase the efficiency of grain refinement per pass through the forming tool.

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CONTACTS:

VSB – Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Mechanical Technology.
17. listopadu 2172/15, 708 00 Ostrava - Poruba, Czech Republic; Website: https://www.fs.vsb.cz/345/cs/

Ing. Ondrej Hilser, Ph.D.
E: ondrej.hilser@vsb.cz
T: +420 596 999 412

Ing. Martin Pastrnak, Ph.D.
E: martin.pastrnak@vsb.cz
T: +420 596 999 412

prof. Ing. Stanislav Rusz, Ph.D.
E: stanislav.rusz@vsb.cz
T: +420 596 993 315

Ing. Hana Krupova
E: hana.krupova@vsb.cz
T: +420 596 993 524

Silesian University of Technology, Faculty of Mechanical Engineering, Department of Engineering Materials and Biomaterials.
Konarskiego 18a, 44-100 Gliwice, Poland; Website: https://www.polsl.pl/rmt1/

Ing. Przemyslaw Snopinski, Ph.D.
E: przemyslaw.snopinski@polsl.pl
T: +48 322 372 603