

Ultrasonic Assisted Equal Channel Angular Extrusion Process (UAECAE)

H. Razavi *

Department of Mechanical Engineering,
Golpayegan University of Technology, Golpayegan, Iran
E-mail: razavi@gut.ac.ir
*Corresponding author

Y. Tadi Beni & M. Baharvand

Faculty of Engineering,
Shahrekord University, Shahrekord, Iran
E-mail: tadi@eng.sku.ac.ir, baharvnd@eng.sku.ac.ir

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Abstract: Equal channel angular extrusion (ECAE) is one of the most powerful processes for manufacturing microstructure and nanostructure materials. This process is a kind of severe plastic deformation technique, which requires large extrusion force. In this study, the numerical and experimental investigation of extrusion force in ultrasonic assisted equal channel angular extrusion process (UAECAE) is carried out. ABAQUS Software is used for 2D finite element analysis of the process considering superimposed ultrasonic vibrations to the round billet work material. Experimentally, the conventional and ultrasonic assisted ECAE are performed with copper material to validate simulation results. The reduction in extrusion force is observed due to ultrasonic vibrations. In order to achieve more average force reduction, it is recommended that the extrusion speed decreases and (or) vibrations amplitude increases. Stress and strain distributions are numerically investigated in various vibrational conditions and die angles. The best die angle to obtain optimum force reduction is 120°. In other die angles, vibrations amplitudes of 15 μm and higher is necessary. Ultrasonic vibrations lead to oscillatory stresses with reduced average value, but do not influence the amount of plastic strain distribution. Achieving the beneficial products in ECAE requires heavy special equipment, whereas using UAECAE will lead to more accessible equipment. Finally, some optimal process parameters such as die angle, vibrations amplitude, for the proper application of these vibrations are proposed.

Keywords: Equal channel angular extrusion, Extrusion force, FE Simulation, Ultrasonic vibrations

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Biographical notes: **H. Razavi** received his PhD in Mechanical Engineering from Tarbiat Modares University in 2012. He is currently Assistant Professor of Mechanical Engineering at Golpayegan University of Technology, Iran. His current research interest includes Ultrasonic Engineering, Mechanical Vibrations and Waves, Metal Forming and Non-Traditional Manufacturing Processes. **Y. Tadi Beni** is Associate Professor of Mechanical engineering at the University of Shahrekord, Iran. He received his PhD in Mechanical engineering from Sharif University of Technology, Iran. His current research focuses on elasticity, mechanical vibrations and nano-mechanics.

1 INTRODUCTION

Manufacturing micro or nanomaterials satisfying desired mechanical properties has been the main subject of many researches carried out in the field of material sciences. These materials, known as super metals, exhibit special characteristics such as high stiffness in ambient temperature, superplasticity in high temperature as well as excellent resistance against corrosion [1], [2]. The methods for manufacturing nanomaterials can be divided into two general categories. The first, introduced as the bottom-up procedure, includes processes such as mechanical alloying, chemical vapor-deposition, and rapid solidification [2], [3].

The second, known as the top-down procedure, involves several processes, which reduce the particle size to nanoscale by applying severe plastic strains [2], [3]. Segal [4] firstly introduced the equal channels angular extrusion (ECAE) in 1977, which is identified as one of the proposed methods for structure miniaturization [5]. In this process, the metal sample is pressed through a die with two cross-section channels intersecting at a die channel angle and starts to be sheared when it reaches the angle changing section.

It should be noted that during the procedure, since the work material is constrained inside the die and is under the influence of upper compressive hydrostatic stress, the potential of cracking and material breakdown is considerably reduced. Output materials from ECAE have displayed desired mechanical properties such as high hardness and increased tensile yield strength [6], [7]. One of the most important difficulties beside process unique features is the intensity of the required force and the stresses applied to the die walls. Thus, any change or contraction in ECAE, which leads to the facilitating of its procedure due to its reducing of the extrusion force and its corresponding stresses, will be promising.

In recent years, researchers have focused on the influence of ultrasonic energy on the plastic deformation of metals and subsequently forming processes, which have been improved by ultrasonic vibrations and its subsequent effects such as [8], [9]: reduction in forming force, flow stress, friction between die and work material, generation of structural defects, and improvement in surface quality. Blaha (1955) and Langenecker (1966), first studied the effects of ultrasonic vibrations on the tension test of a zinc metal sample and observed considerable decrease in the yield stress [10], [11]. This is described by acoustic softening phenomenon (analogical with thermal softening), which is proportional to the applied ultrasonic power [12]. Experimental observations showed that the ultrasonic energy required to produce the same amount of softening is 10^7 times less than the

required thermal energy, because the ultrasonic energy is only absorbed in localized regions, such as vacancies, dislocations and grain boundaries, whereas thermal energy is absorbed uniformly in the material [12], [13].

Several investigations regarding conventional ECAE process have been conducted which demonstrate that the process is strongly dependent on the friction [14]-[16]. Luis-Pérez's et al. [17], demonstrated that the friction and the die channel angle are critical factors in pressing force. Eivani et al., using upper-bound analysis, developed a relation to predict forming force in ECAE [18] and observed that the pressing force strongly increases by increasing the friction coefficient [19], [20]. Kumar et al., [21] conducted an experimental research on the influence of applying ultrasonic vibrations both parallel and perpendicular to the sliding direction between aluminum work material and steel die. They observed that the reduction in friction force by longitudinal vibrations was greater than that by transverse vibration.

FEM is a useful tool for the analysis of forming processes, especially the processes in which deformation is incremental [22], [23] or where the dynamic force such as ultrasonic loading is applied [24], [25]. Hayashi studied ultrasonic assisted wire drawing process using FE analysis [26]. Huang carried out other analyses on hot upsetting process under ultrasonic vibrations [27]. In all of these studies, an average forming force reduction was reported. Lucas et al., [28] studied numerically the effects of friction coefficient on forming force in ultrasonic assisted cold extrusion process and two kinds of radially and axially work material excitation. Akbari et al., [29] carried out some simulations with different vibrations frequencies and amplitudes for the extrusion of annealed steel. They showed that while the vibrations are applied perpendicularly to the extrusion flow direction, the maximum stress does not show any change. Whereas the axial excitation of the extrusion flow results in 14 percent decrease in stress values.

Djavanroodi et al., [13] considered the effect of ultrasonic vibrations on deformation behavior of commercial pure aluminum in the ECAE process using three-dimensional finite element analysis. They observed the reduction of 13% in average force when ultrasonic vibrations with 2.5 μm amplitude and 20 kHz frequency are applied. However, regarding the UAECAE, few studies have hitherto been carried out. Ahmadi et al., [30] investigated the effect of superimposed ultrasonic vibrations on the punch during the equal channel angular pressing process. They simulated the process as two different 2D axisymmetric models. In the first model, the die and the punch were considered rigid bodies and in the second, the punch was considered an elastic body. Both models indicated

acceptable reduction in forming forces depending on vibrations amplitude.

Since the forming processes accompanied by ultrasonic-vibrations occur in complicated mechanical conditions, it is difficult to accurately analyze and comprehend the mechanism of improvement based on experimental findings and observations. Finite element simulations were performed in this research to study the frictional effects of ultrasonic vibrations in UAECAE process, as well as illustrating the stress-strain distribution in work material during the process. The main objective is to investigate the beneficial effects of ultrasonic vibrations in facilitating the forming process; in addition to obtain the optimal combination of ultrasonics and ECAE parameters, in which the maximum effectiveness of ultrasonic vibrations occur.

A 2D finite element modeling of UAECAE process was created with ABAQUS/CAE explicit. Round billets of copper material were pushed into dies with two cross-section channels intersecting at several die channel angles, whereas the ultrasonic vibrations were applied axially to the upper end of the work material. The Hydraulic press and an ECAE die were used for the experiments. Longitudinal ultrasonic vibrations with several amplitudes were applied to the specimen and experimental data of average forming force were obtained for validating the FE model, also compensating the friction coefficient in the simulations. The material softening phenomenon due to ultrasonic vibrations is ignored in the current study.

2 THE ECAE PROCEDURE

Fig. 1 illustrates the die geometry as well as its parameters in which two channels intersect with angle ϕ , the angle of curvature at the outside corner ψ and outer corner radius R .

This can be repeated to achieve the required strain in various routes [4]. The meaning of the route here is how the workpiece is placed in consecutive passes. Common routes are as follows (Fig. 2):

1. Route A: In this route, the billet is not rotated between successive passes.
2. Route B: The billet is rotated 90° clockwise and counterclockwise alternatively.
3. Route C: The billet is rotated 180° . The purpose of this workpiece rotation between different passes is to obtain maximum strain as well as more homogenous strain distribution.

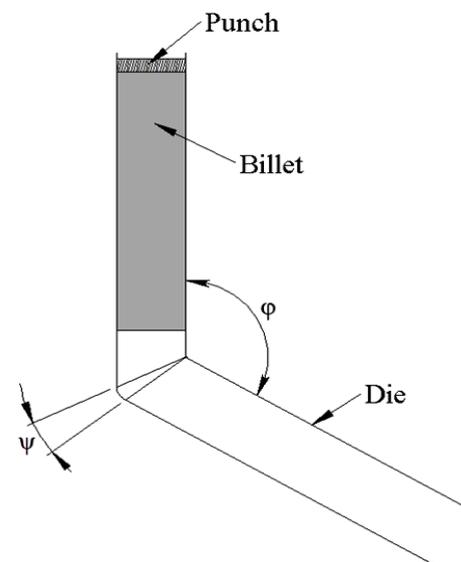


Fig. 1 Schematic illustration of ECAE process

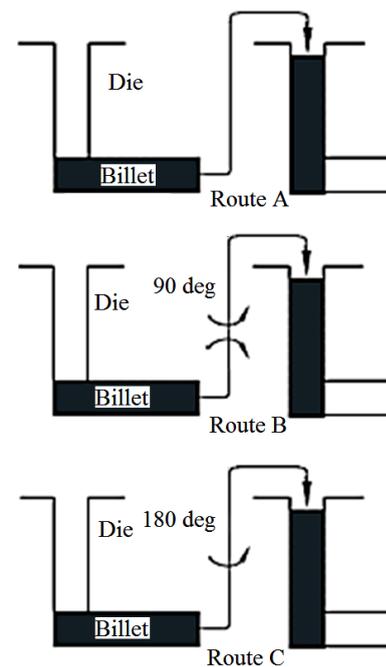


Fig. 2 Common routes in ECAE process

3 FINITE ELEMENT MODELLING

At first, the conventional ECAE process was modeled according to the assumptions of Krishnaiah [31], using ABAQUS/CAE explicit Software and the same results obtained (Fig. 3).

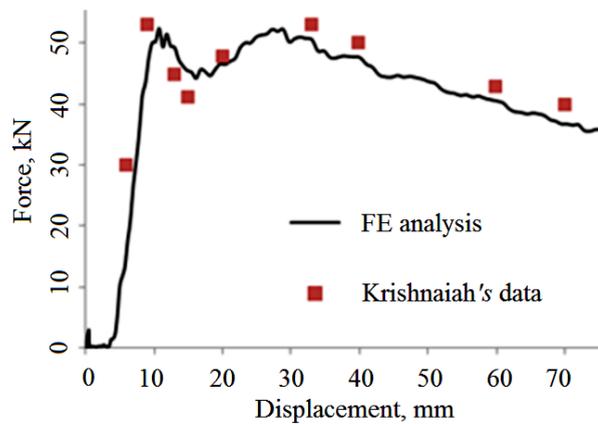


Fig. 3 Comparison between current modeling results and that of Krishnaiah (die with angles of $\phi=120^\circ$ and $\psi=0^\circ$, square billet of 15 mm \times 15 mm, friction coefficient of 0.08) [31]

As for the current research work, a round billet of pure commercial copper with the flow rule of $\sigma=359\varepsilon^{0.3114}$, 15 mm diameter and 108 mm long is subjected to the simulations. Young's modulus and Poisson's ratio are incorporated 69GPa and 0.34, respectively [31] and the temperature effects during plastic deformation are neglected. Considering axisymmetric conditions, 2D modeling of one pass process was performed at die angles of $\phi=90^\circ$, 120° , 135° and $\psi=36^\circ$. The sample was meshed by four-noded first order continuum (CPE4R) elements with reduced integration. To avoid possible convergence problems arising from die sharp corners, fillet radius of 2 mm is considered. The friction coefficient was considered 0.08 [31] and 0.12 [32], [33] for all contact surfaces. The punch is assumed as a rigid body and ultrasonic vibrations were applied longitudinally to the moving punch with 100 mm/sec speed.

4 EXPERIMENTAL WORK

First a hydraulic press of 10ton capacity and an ECAE circular cross section die of $\phi=120^\circ$ and $\psi=36^\circ$ are used for the experiments as shown in Fig. 4. Then a longitudinal ultrasonic vibrator (an ultrasonic transducer and horn) is clamped at its nodal point to the moving ram of the press and the UAECAE process is carried out.

An auto tune 3kW ultrasonic generator of 20 kHz frequency, a Langewin half-wave piezoelectric transducer of 3kW, and several full-wave horns (the length of the horn equals to the wave length of the transmitted wave) are employed (according to previously used equipment [34-36]) for the experiments (Fig. 5). In addition, the vibrations amplitude is measured by Eddy current sensor.

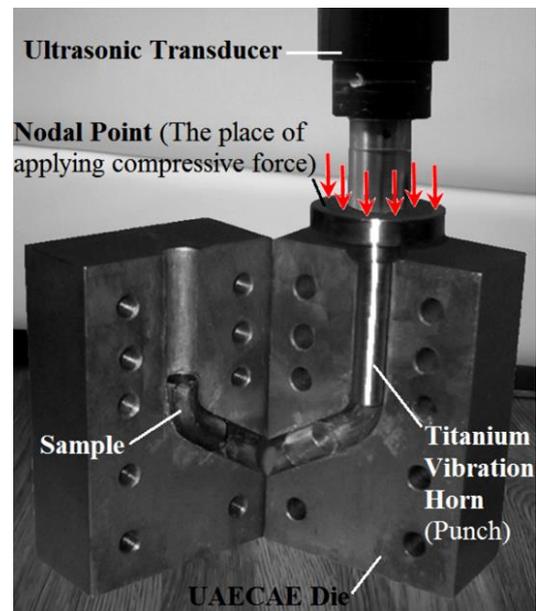


Fig. 4 Experimental setup (ECAE die with $\phi=120^\circ$ and $\psi=36^\circ$, ultrasonic transducer and vibrational horn as punch)



Fig. 5 Ultrasonic generator, Force and amplitude measurement equipment (load cell, data acquisition setup, eddy current and oscilloscope)

To investigate the extrusion force during ECAE and UAECAE processes, also validating the numerical results, a 120° ECAE die is used for both ECAE and UAECAE experiments. The maximum forming force in the experiments is a very important factor to select the suitable hydraulic press in ECAE setup. The work material was pushed to the die channel while the ram

speed was 100 mm/sec. The simulations were carried out using the both 0.08 [31] and 0.12 [32], [33] as friction coefficient between all contact surfaces. Fig. 6 shows a good agreement between the numerical and experimental results.

According to this figure, if acoustic softening of the work material and any other ultrasonic effects are ignored in numerical analyses, the best conformity of simulations and the experiments will be achieved by the friction coefficient of 0.09, whereas it is 0.12 for ECAE process. The reduction of the extrusion force due to applying ultrasonic vibrations is quite visible.

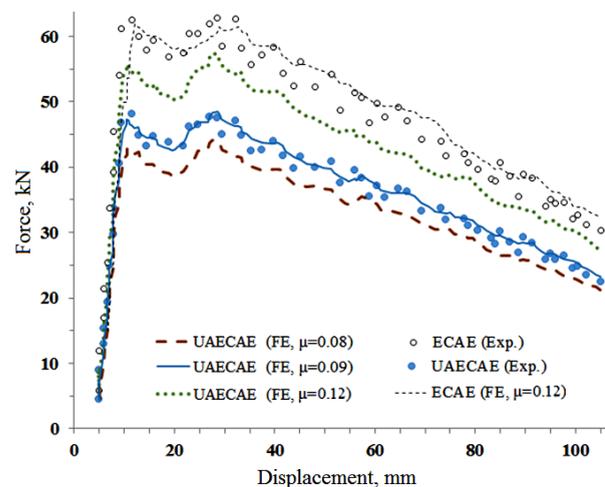


Fig. 6 Comparison between experimental and numerical force in ECAE and UAECAE (a=15 μm, f=20 kHz)

It can be seen that the ECAE and UAECAE forces increase rapidly to the maximum punch pressure when the sample starts to be sheared at the die two-channel intersecting area. Then the pressing force decreases continuously with a slow rate to the end of the process; which is due to a reduction in the billet length and friction force [13].

5 RESULTS

5.1. The Effect of Extrusion Speed on the Extrusion Force

Decreasing the forming force in all ultrasonic assisted forming processes is only possible in velocities less than the critical velocity. This velocity is described by $V_C=2\pi.a.f$ in which a and f are the amplitude and frequency of the vibrations, respectively. Fig. 7 shows the average extrusion force against extrusion speed in ECAE process and in that of UAECAE with respect to parameters a=5 μm, f=20 kHz. The critical velocity for this case is $V_C=628$ mm/s. The results demonstrate that in ECAE, the average extrusion force is independent of

the extrusion speed. Whereas in the UAECAE process, only if the extrusion speed is less than the V_C , the extrusion force reduction will be observable. Greater difference between the two speeds leads to further reduction in the extrusion force.

The results refer to 120° angle die, with an inner angle of 36°. It should be noted that the analysis for container angles of 90 and 135 degrees yields such results.

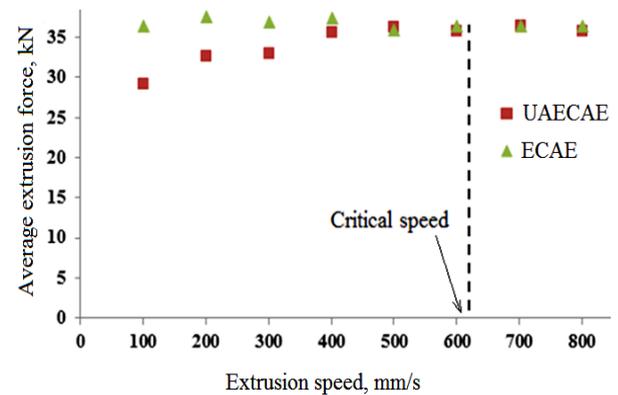


Fig. 7 The relationship between extrusion speed and average extrusion force

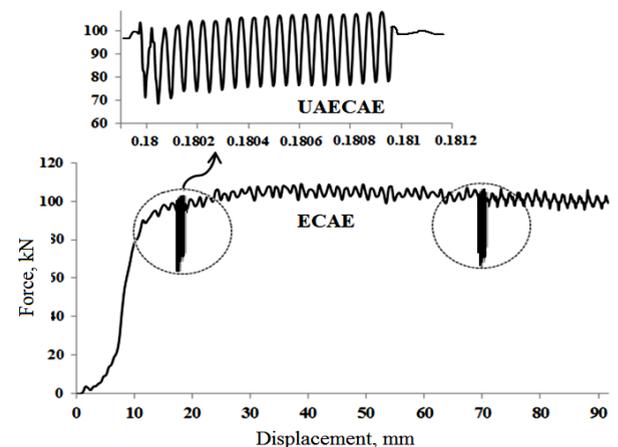


Fig. 8 Oscillation of the extrusion force during the application of ultrasonic vibrations

5.2. The Relation between Ultrasonic vibrations Amplitude, Extrusion Force and Die Angle

Simultaneously, in order to investigate the effects of die angle and superimposed ultrasonic vibrations (vibrations amplitude) on the average extrusion force, an analysis was performed for common angles of 90, 120 and 135 degrees and amplitudes of 5, 10 and 15 μm. In all analyses, the inner corner angle of the two-channel interface was considered 36 degrees.

Furthermore, the extrusion speed was considered 100 mm/sec [13], the friction coefficient was 0.09 and vibrations frequency was 20 kHz. In Fig. 8, the force-displacement diagram has been illustrated for both the normal state and oscillating section corresponding to the application of ultrasonic vibrations in a 90° die. It should be noted that any change in vibrations amplitude and investigating its effects is much simpler than that of the vibrations frequency due to the characteristics of vibrations devices (transducers and vibrational horns). Figs. 9, 10 and 11 demonstrate the results for various die angles in different amplitudes.

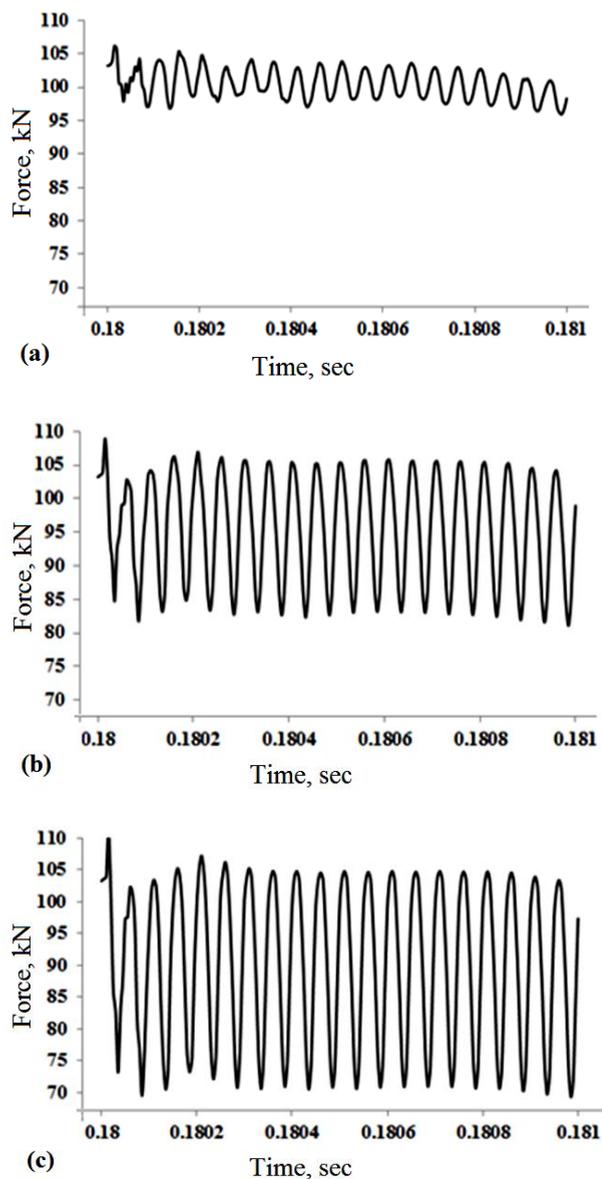


Fig. 9 Extrusion force against time in UAECAE with die angle of $\varphi=90^\circ$, a) $a=5 \mu\text{m}$, b) $a=10 \mu\text{m}$ and c) $a=15 \mu\text{m}$

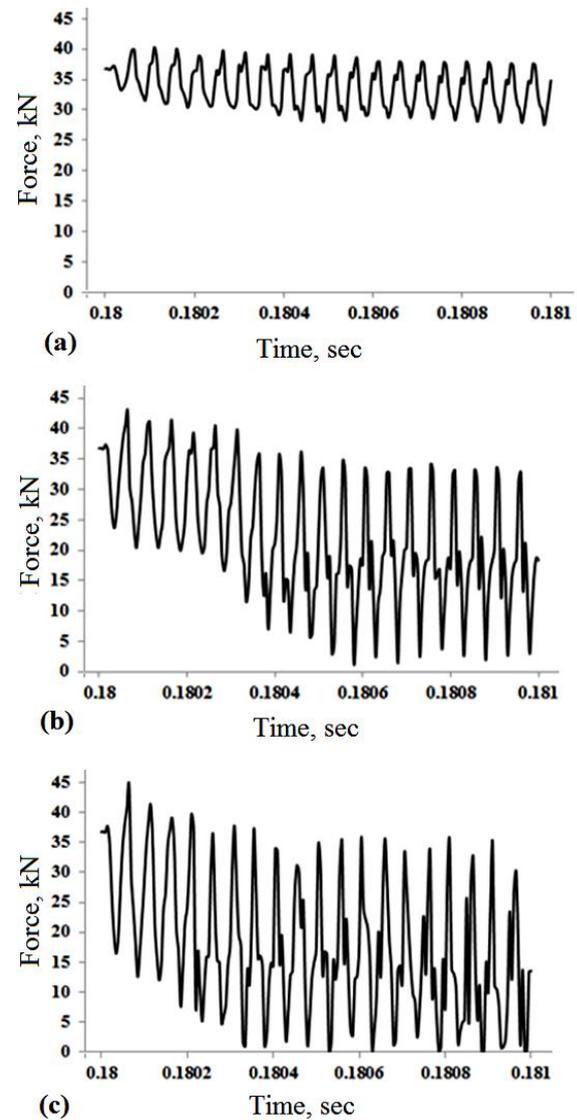


Fig. 10 Extrusion force against time in UAECAE with die angle of $\varphi=120^\circ$, a) $a=5 \mu\text{m}$, b) $a=10 \mu\text{m}$ and c) $a=15 \mu\text{m}$

The findings in this research represent the fact that the effect of ultrasonic vibrations on the extrusion force reduction for $\varphi=90^\circ$ or $\varphi=135^\circ$ is less than that of $\varphi=120^\circ$. The maximum force reduction percentage belongs to the die angle of 120° , whereas in 90° angle, the minimum force reduction occurs.

For the case of $\varphi=135^\circ$, by increasing the vibrations amplitude from 10 to 15 μm , an average force reduction of 20.7 to 19.5 kN occurs which leads to a 5 percent reduction improvement. Whereas, for the $\varphi=120^\circ$ case, the similar improvement is more than 11 percent. All in all, in 90° and 135° angles, vibrations amplitudes of more than 10 μm would be used in order to achieve better results.

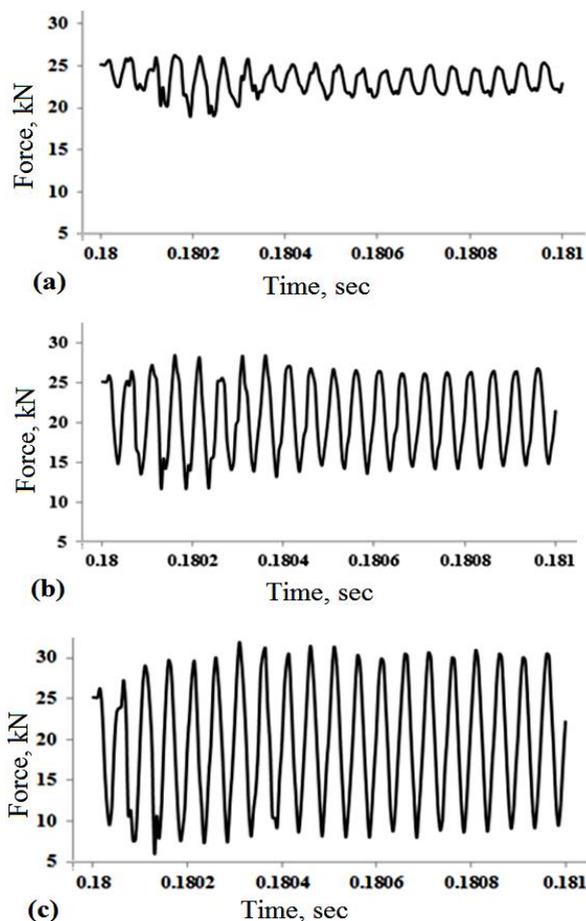


Fig. 11 Extrusion force against time in UAECAE with die angle of $\varphi=135^\circ$, a) $a=5 \mu\text{m}$, b) $a=10 \mu\text{m}$ and c) $a=15 \mu\text{m}$

Table 1 summarizes the average extrusion force in ECAE and UAECAE processes and its reduction percentage compared to that of ECAE. In all numerical studies, by increasing the vibrations amplitude, more reduction is observed in average extrusion force. In addition, an important result is the identification of the 120° UAECAE die to achieve the best-desired profit from ultrasonic vibrations compared to other studied angles in this research.

Srinivasan showed that in ECAE, to obtain greater strains, the smaller die angle should be used and the number of process passes must be increased as well [37]. He concluded that based on the additive nature of strains in this process, in order to achieve strain values of about 4, four passes in 90° dies will be required; equivalently six passes in 120° or nine passes in 135° dies [37]. However, since the application of small angles is limited due to required great extrusion force, ultrasonic vibrations can be used to obtain smaller forces in processes with smaller die angles and low passes by the same large strains.

Table 1 Average extrusion force in ECAE and UAECAE and its reduction percentage compared to that of ECAE

Vibrations amplitude, μm	Average extrusion force, kN ($\varphi=90^\circ$)	Reduction, %
a=0 (ECAE)	101	-
a=5	100.5	0.6
$\alpha=10$	95.6	5.4
a=15	90.3	10.6
$(\varphi=120^\circ)$		
a=0 (ECAE)	36.8	-
a=5	33.7	8.3
a=10	22.3	39.3
a=15	17.9	51
$(\varphi=135^\circ)$		
a=0 (ECAE)	24.7	-
a=5	23.2	6
a=10	20.7	16.2
a=15	19.5	21

Using the optimal die angle of 120° for UAECAE is recommended to achieve large strains as in more than one pass at ECAE process as well as profiting from the advantages of ultrasonic vibrations in reducing the extrusion force. On the other hand, it should be noted that obtained material microstructure in smaller die angles differs from the material microstructure achieved from larger die angles [6]. Thus providing the beneficial finer microstructure related to the smaller angles in a heavier ECAE die would be possible in an UAECAE die by the same angles but with less extrusion forces and therefore more accessible equipment.

5.3. Comparison between Plastic Stress and Strain in ECAE and UAECAE

Fig. 12 demonstrates plastic strain and Von Mises stress distribution for both ECAE and UAECAE processes at 120° die angle. The contours displayed in Fig. 12-a refers to the common process while the contours in Fig. 12-b refers to the UAECAE process. As it can be seen, ultrasonic vibrations have an impact on stress distribution while they do not influence the strain. At the second case, stresses have decreased in comparison with the first one, whereas the strains show no considerable change.

Fig. 13 presents the effect of ultrasonic vibrations on the maximum generated stress in the material. The current findings show that by increasing the ultrasonic vibrations amplitude, all stress oscillations occur around lower values. Similar to the force analysis results, the more desired results are observable for 120° and 135° angles, respectively.

Material approximate separation from the die is observed for the close-to-zero stress values in the 120° die angle and for vibrations amplitude of 15 μm .

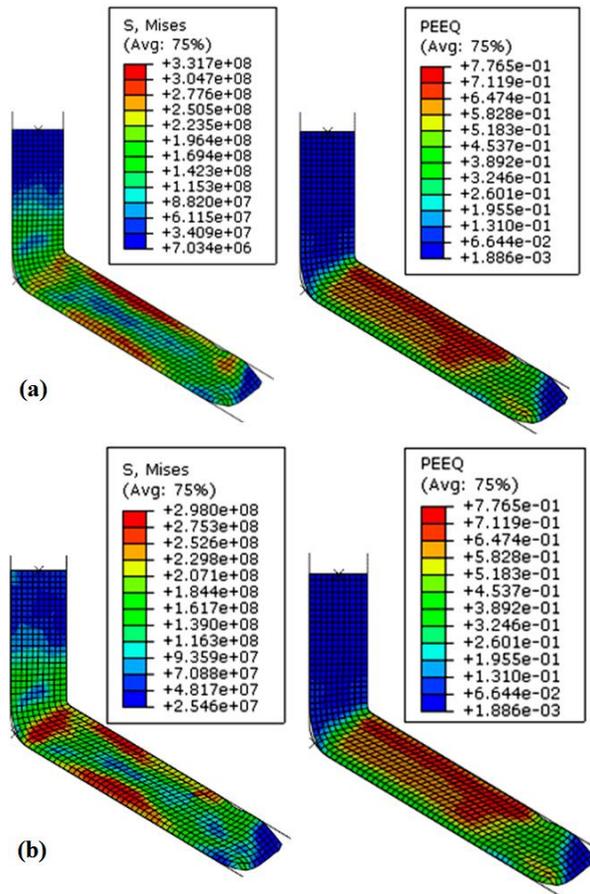


Fig. 12 Stress and strain contours in a) ECAE and b) UAECAE

This is observable in earlier force against time diagrams as well. No complete separation of the material from die walls occurs probably due to the spring back phenomenon (elastic resiliency) of the work material. In addition, it would be due to the higher values of material recovery rate after unloading than the vibrant punch speed. Further investigation would be necessary in future studies.

6 CONCLUSION

In this paper, the conventional ECAE process along with the process with the application of ultrasonic vibrations, UAECAE, were modeled.

The current research findings are as follows:

1) Ultrasonic vibrations result in the extrusion force reduction at ECAE process. This type of vibrations is only effective in velocities less than the critical velocity

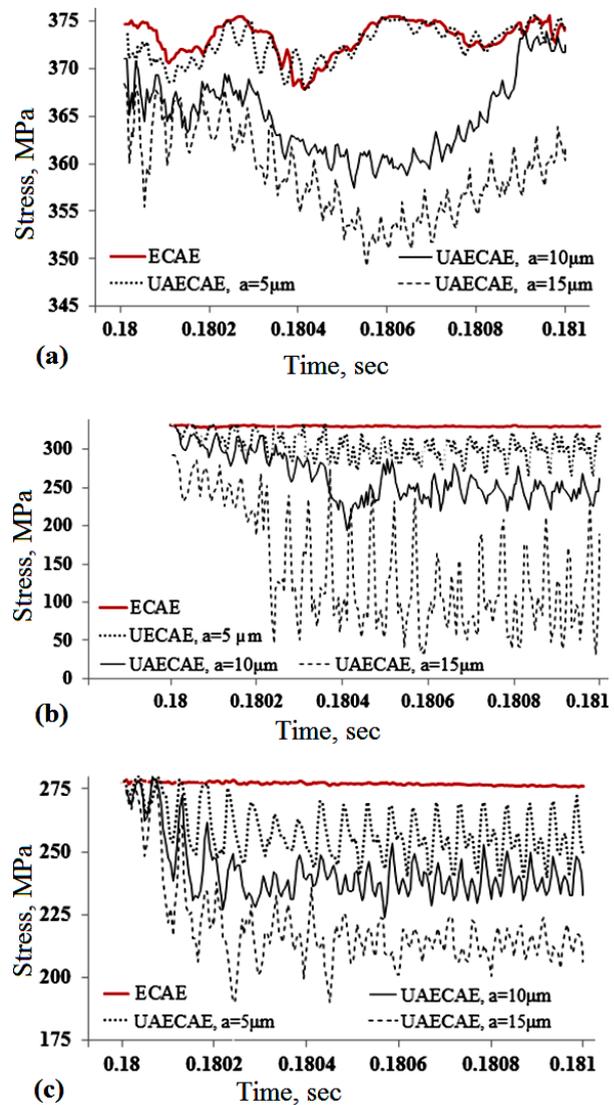


Fig. 13 The Von Mises stress in ECAE and UAECAE with different amplitudes, a) $\phi=90^\circ$, b) $\phi=120^\circ$ and c) $\phi=135^\circ$

and the more difference between extrusion speed and V_C ; the more force reduction will be resulted. In order to achieve more average force reduction, it is recommended that the extrusion speed decreases and (or) vibrations amplitude increases.

2) The die angle is an effective parameter in the reduction percentage of average extrusion force. The best angle (out of the common angles) for obtaining optimum force reduction is 120° angles.

3) For better results in 90° and 135° angles, vibrations amplitudes of 15 μm and higher should be used.

4) Ultrasonic vibrations are effective on Von Mises stress distribution and lead to oscillatory stresses with reduced average value. In addition, it is evident that ultrasonic vibrations do not influence the amount of plastic strain distribution.

5) Achieving the beneficial finer microstructure of the output material corresponding to the smaller die angles in ECAE, requires heavy special equipment, whereas using the same die geometry in UAECAE leads to the same output material but more accessible equipment due to reduced extrusion force.

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