



I S A V

**Journal of Theoretical and Applied  
Vibration and Acoustics**

journal homepage: <http://tava.isav.ir>



## Numerical and analytical investigation of an ultrasonic assisted ECAP process

Mehdi Eskandarzade, Abolfazl Masoumi, Ghader Faraji \*

*School of Mechanical Engineering, College of Engineering, University of Tehran, 14395515 Tehran, Iran*

### ARTICLE INFO

*Article history:*

Received 27 March 2016

Received in revised form  
1 August 2016

Accepted 14 August 2016

Available online 2 November  
2016

*Keywords:*

ECAP process

Ultrasonic vibrations

Forming forces

Friction

### ABSTRACT

One of the great challenges in the processing of materials using Equal Channel Angular Pressing (ECAP) is the high forming forces required to produce large shear deformation in the material. Researchers show that the friction forces between the die and the sample constitute a great part of the total forming forces. Recently, ultrasonic vibrations are successfully implemented into the ECAP process with the aim of reducing the friction forces. However, there is still need to optimize the parameters of ultrasonic vibrations in the ECAP process using numerical methods. FE simulation of the ultrasonic assisted ECAP process is very time-consuming and during simulation, the constant ram speed has interaction with the vibration speed. A virtual increase in the ram speed for simulation of ultrasonic assisted ECAP process will affect the results. By using Coulomb and Dahl friction models, it is analytically shown how vibration speed and constant ram speed interact with each other during FE simulation. The results clearly suggest against using virtually higher speeds in numerical modelling of the vibrated ECAP process. The conclusion is reached through comparing several simulations, as well as an analytical formulation, with experimental data from literature. The required friction coefficient values to be used in FE simulation at high contact forces are measured experimentally. An alternative strategy is then offered to speed up FE simulation of the vibrated ECAP process without the need for a virtual increase in the ram speed. The proposed strategy can increase the simulation speed of the ultrasonic assisted ECAP process up to ten times.

©2016 Iranian Society of Acoustics and Vibration, All rights reserved.

## 1. Introduction

Equal Channel Angular Pressing (ECAP) is a kind of processing method in material science that produces metal and non-metal parts with ultra-fine grains. The unique properties of the ECAP

\* Corresponding Author.

*E-mail address:* [ghfaraji@ut.ac.ir](mailto:ghfaraji@ut.ac.ir) (Gh. Faraji)

processed materials are restricted by the many practical difficulties in this process. Two main problems in using the ECAP method are the high forming forces for some metallic materials and the low velocity of the process. Several research works are dedicated to study the forming force in an ECAP process (Khan et al., 2003; Son et al., 2007 [1, 2]). One possible method to reduce the forming force is to reduce friction forces. Friction forces not only constitute an important part of the forming forces but also influence the material flow and strain inhomogeneity in the equal channel angular pressing process (Patil, 2008 [3]). It is theoretically proved that using ultrasound reduces the forming forces up to several times (Faraji et al., 2014 [4]). However, the high friction coefficient is also useful to reduce the corner gaps and to achieve a uniform strain behavior in a sample (Djavanroodi and Ebrahimi, 2010 [5]). Based on the material strength and our expectations from the final part, the friction coefficient should be compromised at a moderate level.

Ultrasonic vibrations affect the material deformation in two ways. Firstly, at the presence of ultrasonic vibrations, metals show significant temporary softening which is sometimes referred to as the acoustoplastic effect (Malygin, 2000; Lee et al., 2003 [6, 7]). Secondly, ultrasonic vibrations can reduce the friction coefficient between the die and the specimen (Pohlman and Lehfeldt, 1966; Kumar and Hutchings, 2004 [8, 9]). Moreover, investigations show that the acoustoplastic effect is of secondary importance in comparison with the effect that ultrasonic vibration has on the friction coefficient rate (Ahmadi and Farzin, 2013 [10]).

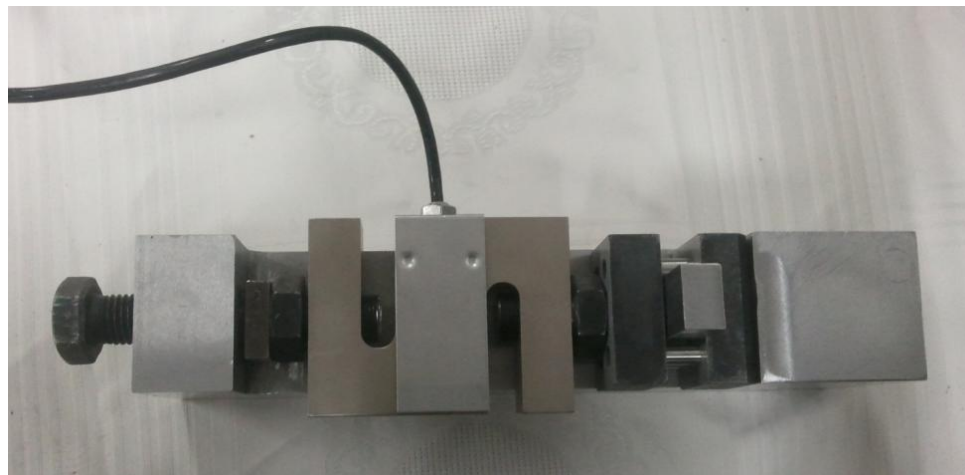
Djavanroodi et al. (2013 [11]) applied ultrasonic vibrations into the ECAP process and reported a considerable reduction in forming forces. Theoretical study of the effect of ultrasonic vibrations in friction reduction is offered in several researches (Pohlman and Lehfeldt, 1966; Kumar and Hutchings, 2004; Littmann et al., 2001; Tsai and Tseng, 2006; Siegert and Ulmer, 2001 [8, 9], [12-14]). There exist several reports which investigated the ECAP parameters numerically (Djavanroodi and Ebrahimi, 2010; Lu et al., 2011; Mahallawy et al., 2010 [5, 15, 16]). Numerical modelling of the ECAP process using the actual ram speed will cause very high computation time. Hence, researchers normally prefer to use virtually higher speeds in their FEM simulations. It means that the ram speed in simulations is normally higher than the ram speed in a real experiment. This is acceptable in a non-ultrasonic assisted ECAP process because it is reported that a pressing speed has no significant influence on the forming forces in the absence of ultrasonic vibrations. However, this is not the case for ultrasonic assisted processes. In this kind of process, the ram speed has interaction with ultrasonic vibrations which substantially affects the final results. The current study investigates the influence of using virtually higher ram speeds in simulation of ultrasonic assisted ECAP process on the results' accuracy. The accuracy of FEM analysis mainly depends on the accuracy of the friction coefficient value employed. The coefficient of friction considerably changes by changes in the contact force. Therefore, in this study, the coefficient of friction for an aluminium alloy and steel system is measured experimentally to be used in simulations. The experimentally measured friction coefficient is employed in the following FEM analysis. According to FEM results, when ultrasonic vibrations is a concern in simulation, the assigned ram velocity significantly influences the friction rate and using unreal higher speeds to the aim of reducing computational time will result in a great discrepancy from experimental data. In the current study, this issue is analytically discussed using Coulomb and Dahl friction models. It is presented how ram speed and ultrasonic vibrations interact with each other during simulation. Also, a novel procedure is recommended to avoid virtual ram speed error and benefit from a rapid simulation.

## **2. Friction coefficient measurement**

The friction between two materials is a characteristic of a system consisting of the types of the base and sliding materials as well as the condition at their interface. The friction coefficient can be determined only through experimental measurement. In the ECAP process, a sample experiences variable loads while sliding inside two channels. The coefficient of friction changes drastically by changes in the normal load. Thereupon, in the current study, the friction coefficient of the Al-1070-Steel system is obtained for different contact pressures. Samples with different surface roughness values are fed as initial input to the ECAP die. Then, in addition to applied normal load, the effect of surface roughness on a friction coefficient has been investigated.

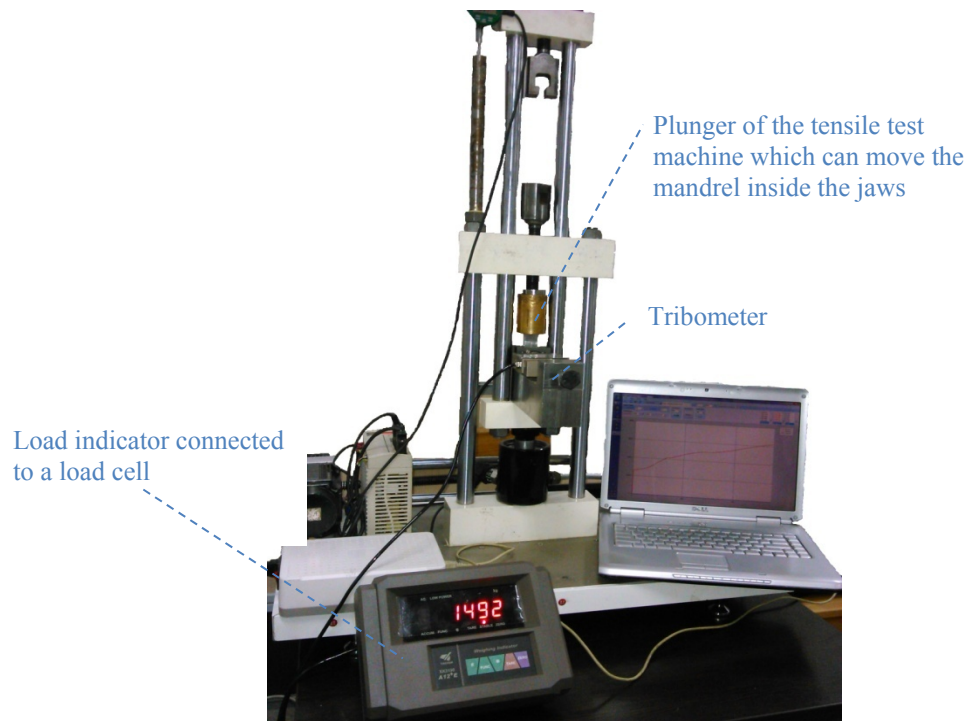
For empirical measurement of the friction coefficient in a real working condition of the system, many tribometer devices have been designed and are in use. Severe Plastic Deformation (SPD) is a special process which involves very high contact pressures (about several times the sample's yield strength) (Malygin, 2000 [6]). In this process, friction is the most influencing parameter on the magnitude of the required force. However, for many material pairs, there are no reliable friction coefficient values in the literature. Lai et al. (2012 [17]) have developed a friction test apparatus for measuring the friction coefficient between sheet metals in a crash test. They have designed their device to be used in the measurement of friction coefficient values at relatively high contact pressures (up to 100 MPa). However, this amount of pressure is still too low as compared with the pressures involved in some metal forming methods like SPD. Recently, Pougis et al. (2013 [18]) suggested a suitable method for measuring the friction coefficient value at very high contact pressures and low speeds. In the current study, the apparatus proposed by Pougis et al. (2013 [18]) is redesigned and used for friction coefficient measurement.

Figure (1) shows a photograph of the tribometer fabricated for this study. It consists of the main body, mandrel, two jaws and a load cell for measuring an applied force. Material type of the jaws is chosen the same as the real SPD die's material, steel. The mandrel holds a sample and moves it between the two jaws. To guarantee that only sample tips will be in contact with the jaws' surface, the length of the specimen is set about 0.1 mm longer than the mandrel wide length on both sides.



**Fig. 1.** The tribometer used in the current study

One of the jaws can move easily in one direction which helps to locate the mandrel and specimen between the jaws. Its motion is limited in other directions by four guide rods. A moveable jaw, connected to a fastening screw, can be pushed by a load cell. By tightening the screw, it is possible to create compression stress at the specimen between the two jaws and inside the mandrel. The whole system is attached to a tensile test machine as shown in Fig. (2).



**Fig. 2.** Experimental setup for friction coefficient measurement

In fact, the plunger of the tensile test machine is connected to the mandrel of the tribometer. An indicator shows the applied load on the specimen measured by a load cell. After setting the desired applied hydrostatic load on a specimen by fastening a screw and checking the load in the indicator, the plunger moves the specimen down on the jaw's face. The displacement speed of the plunger can be controlled via a computer program. The load and displacement values of the plunger are recorded by an electronic data acquisition system available on the machine.

This system is a new arrangement of the friction test apparatus offered by Pougis et al. (2013 [18]). However, the efficiency of the tribometer is improved in few ways.

The friction coefficient of the Al-1070-Steel system is calculated using Eq. (1). In this equation,  $\mu$  stands for the friction coefficient,  $F_T$  is the tangential force and  $F_N$  shows the normal force. It should be noted that the factor 2 in Eq. (1) is due to the presence of two sliding surfaces.

$$\mu = \frac{F_T}{2F_N} \tag{1}$$

### 3. Finite element modelling

Three-dimensional finite element modelling is carried out to investigate the ECAP process using the ABAQUS/Explicit software. The model is firstly designed in a CAD software and then exported to the FEM code. The material properties were selected as for 1070 Aluminium alloy. The plastic deformation behavior of the material follows the relation  $\sigma(MPa) = 104.3\epsilon^{0.168}$  where  $\sigma$  is the effective von-misses stress and  $\epsilon$  is the effective plastic strain. The material and other parameters are selected such that the simulation results can be validated with experimental data from literature (Djavanroodi et al., 2013 [11]). The contact between the surface of the rigid die and the specimen is modelled as surface-to-surface contact where a finite amount of sliding between the surfaces is allowed. The dry frictional behavior of the contact pair is assumed to follow the Coulomb's law. Table 1 shows the values of the parameters used in modelling. The specimen is modeled as a deformable member and the die is considered as a rigid body.

**Table 1.** Parameters used in simulation (Djavanroodi et al., 2013 [11])

Billet diameter (mm)	Billet length (mm)	Die angle $\varphi$	Channel arc $\psi$
20	150	90°	15°

A linear C3D8R element type from the explicit library of ABAQUS software is chosen for meshing the specimen. C3D8R is an eight-node brick element with reduced integration. Thanks to the reduced integration characteristic of the C3D8R type element, not only the locking phenomenon eliminates, but also the computation time is reduced considerably. The latter is vital in modelling of the ECAP process. About the precision, this element is preferred as compared with the full integrated element (C3D8) in plasticity and problems involving high strains. The integration point of the C3D8R element is located at the center of the element and then stress and strain values are most accurate at integration points. Hence, small elements are required to capture a stress concentration at the weak points of the model. Hourglassing is the main issue in using this element. To ensure hourglassing will not affect the results, the hourglass control is set in the enhanced mode. High concentrated stress and strain values cause element distortion during the modeling procedure. To overcome these interruptions, the ALE adaptive remeshing technique was used in simulations. However, despite all measures, it is observed that there exist some elements with very high undesired strains. It is found through several trial and error efforts that by changing the incremental time from the step module, this problem can be fixed. The R3D4 element type is employed for meshing the rigid bodies. The specimen and rigid bodies were constituted from 27323 and 13748 elements respectively. It is found that further refinement in the element size does not result into any considerable change in the output force. It is thus concluded that the selected number of elements is enough for modeling the ECAP process.

## 4. Analytical modelling

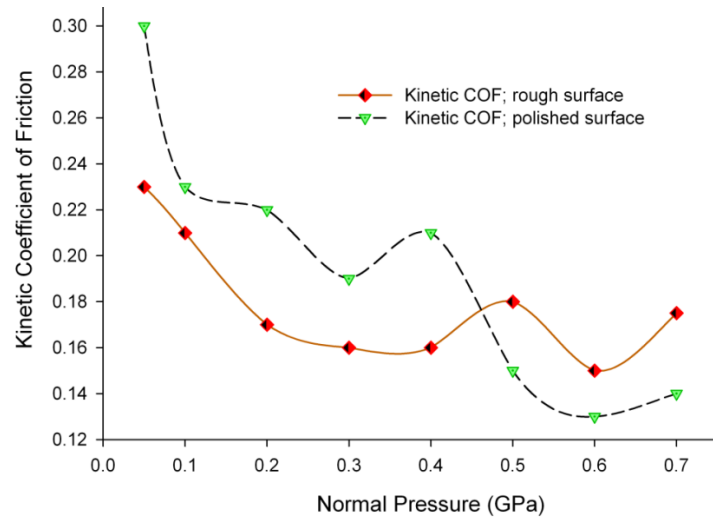
Although the application of ultrasonic vibration has no considerable effect on the equivalent plastic strain of the material (Faraji et al., 2014 [4]), it causes a considerable reduction in the forming forces. For simplicity of the numerical methods used in modelling the ECAP process, researchers prefer to use constant friction coefficient between the die and the specimen. However, in practice, the specimen experiences variable frictional behavior while sliding at different locations of the die. Generally, the total force required in the ECAP process to push the specimen can be described as  $F_e = F_{id} + F_{sh} + F_{en} + F_{ex} + F_r$  where  $F_e$  is the total forming force,  $F_{id}$  is the ideal forming force (no friction state),  $F_{sh}$  is the force required to overcome the shearing strain,  $F_{en}$  is the force needed to overcome the friction in the entrance area of the die,  $F_{ex}$  is the force to overcome the friction in the exit section of the die and  $F_r$  is the force to overcome the friction in the arc section of the die. According to the separation and contact mechanism proposed by Mousavi et al. [19], it is the friction force in the die entrance channel ( $F_{en}$ ) that is mostly affected by the ultrasonic vibrations because of the decreased actual contact time between the die wall and the material flow.

Nevertheless, there is no doubt that ultrasonic vibrations have a considerable effect on the frictional forces. The real mechanism behind this phenomenon is relatively opaque. The separation and contact mechanism proposed by Mousavi et al. [19] are not useful for quantitative evaluation of the influence that ultrasonic vibrations have on the ECAP process. A theoretical investigation about the friction forces under ultrasonic vibrations is done by Littmann et al. (2001, [12]) for an ultrasonic machining process. It is reported (Tsai and Tseng, 2006 [13]) that vibrations can reduce the friction coefficient only if the vibration velocity amplitude is higher than the relative velocity between the die and the specimen as a base motion. In this study, the Coulomb and Dahl friction models are employed to show why using virtually high speeds in FE modelling of the ultrasonic assisted ECAP process affects the final results. The following discussions clearly indicate that the analyses with both friction models anticipate almost the same amount of interaction between the constant ram speed and vibration speed.

## 5. Results and discussion

### 5.1. Friction coefficient measurement results

Figure (3) shows the kinetic friction coefficient value for polished and machined samples. It can be simply concluded that the effect of normal pressure is much greater than the surface roughness for the range under study. The effect of surface roughness is shown more significant at small normal pressures (lower than the softer material's yield strength). The friction coefficient becomes independent of the surface roughness at high normal pressure values (higher than the material's yield strength as it is the case in the ECAP process).



**Fig. 3.** Comparison of the kinetic friction coefficient in polished and rough surfaces

As shown in Fig. (3), the curve of the friction coefficient becomes approximately flat at pressure values higher than 0.6 GPa. It can be interpreted that at very high contact pressure values, the dry friction coefficient for Aluminium alloy and Steel system is about 0.14. This value is used in all contact surfaces between the Aluminium alloy specimen and a steel die.

### 5.2. FE results

Fig. (4) shows the configuration used for FE modelling in the current study. To calibrate the model, initial modelling is performed for conventional and ultrasonic assisted ECAP processes and the results are compared with experimental data from literature. As shown in Figs. (5) and (6), the results of analysis for the pressing forces are in good agreement with experimental data [11] for the conventional and ultrasonic assisted ECAP processes. This assures that the selected number of elements and contact conditions are properly set.

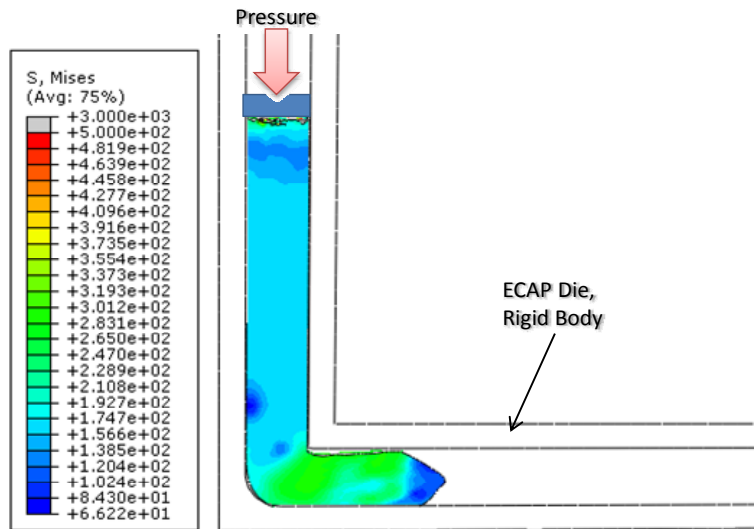


Fig. 4. FE modelling of the ECAP process

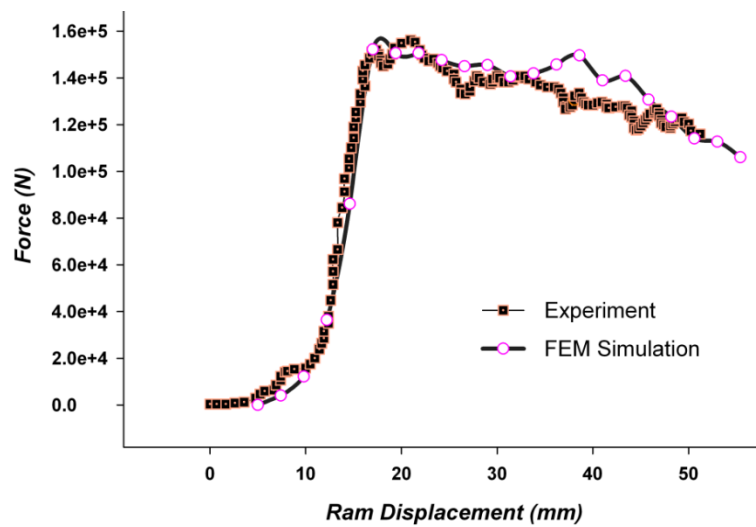
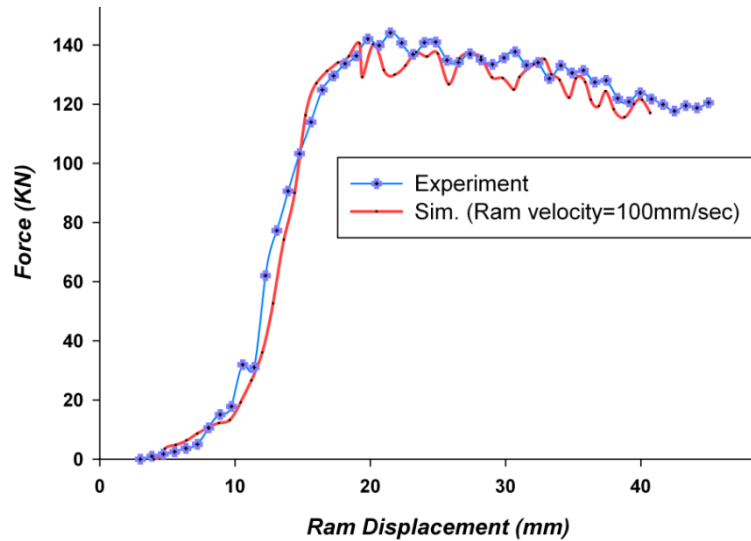


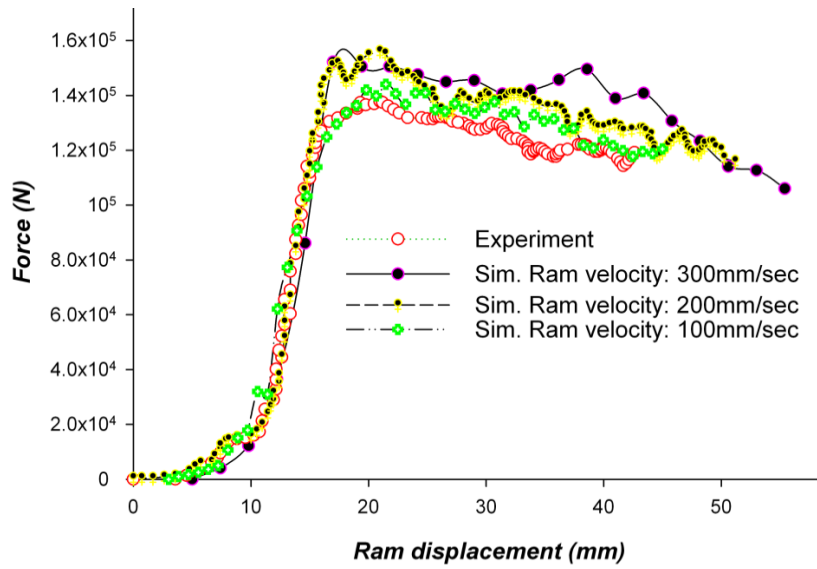
Fig. 5. Comparison between FE simulation of the conventional ECAP process and experimental data (Djavanroodi et al., 2013 [11])





**Fig. 6.** Comparison between FE simulation of the ultrasonic assisted ECAP process and experimental data (Djavanroodi et al., 2013 [11])

In practice, a high amount of heat is produced due to friction forces and thereupon, the ram speed is usually kept low (at about 2 mm/s). However, it is experimentally proved by Gurau et al. (2014 [20]) that if the effect of heat production is negligible, the stress values on the elements will not differ by changing the ram speed in the conventional ECAP process (Chung et al., 2003 [21]). Investigations show that the pressing speed has no significant influence on the equilibrium size of the ultrafine grains formed by the ECAP process and the forming force. However, lower speeds help to obtain an easier recovery. In addition, these lower speeds produce more equilibrated microstructures (Valiev and Langdon, 2006 [22]). In modelling of non-vibrated ECAP process, for time saving reasons, the simulation is run with ram speed of about 100 mm/s or higher which is much greater than the ram speed in the related experiment. However, as it is obvious from Fig. (7), using virtually higher ram speeds in FE simulations affects the results considerably. According to Fig. (7), as the difference between the real ram speed and the virtually used ram speed in simulations increases, the discrepancy between the results from simulation and experiments increases as well. For the purpose of modelling ram vibrations in the ultrasonic assisted ECAP process, a sinusoidal vibrating boundary condition is employed.



**Fig. 7.** Virtually increasing the ram speed in FE simulation of the ultrasonic assisted ECAP process affects the obtained results as compared with experimental measurements

### 5.3. Comparison between Coulomb and Dahl friction models

The amount of friction coefficient reduction anticipated by analytical models is investigated for the Coulomb's and Dahls' friction laws. It is assumed that a high power piezoelectric crystal (device for imposing vibrations to the specimen in the ECAP process) is used to vibrate the specimen based on the following equation:

$$x = a_0 \sin(2\pi ft) \quad (2)$$

The vibrating velocity at the surface of the sample will then be:

$$v_v = a_0 \times 2\pi f \times \cos(2\pi ft) \quad (3)$$

The total velocity  $v_t$  of a particle in the sample is the superposition of vibration velocity induced by the ultrasonic device  $v_v$  and the constant velocity due to constant speed of the hydraulic ram  $v_c$  as shown by Eq. (4).

$$v_t = v_c + a_0 \times 2\pi f \times \cos(2\pi ft) \quad (4)$$

According to Eq. (4), if the oscillating term is high enough, the sign of the term for total velocity  $v_t$  changes periodically. It is clear that the changes drastically depend on vibration frequency.

In the Coulomb friction model, a rigid behavior is assumed for both contact surfaces. According to Eq. (5), in this model, the magnitude of friction force is affected only by the normal contact force  $F_N$  and the friction coefficient. In addition, the direction of total velocity  $v_t$  determines the sign of the friction force.

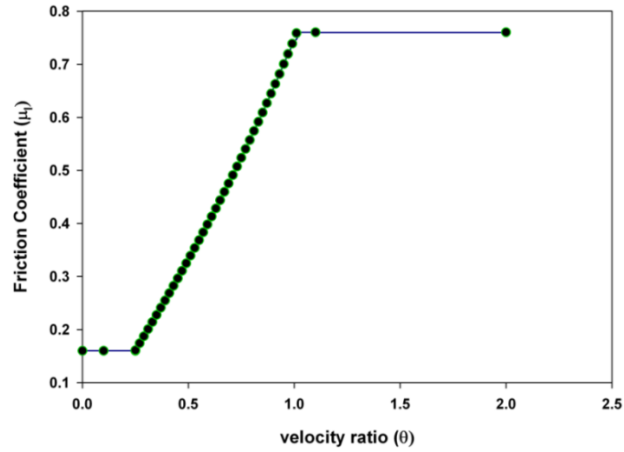
$$F_f = \mu F_N \cdot \text{sgn}(v_t) \quad (5)$$

However, in the Dahl friction model, it is assumed that the asperities of the rough surfaces act like a spring and sliding occurs when the spring breaks out. The friction reduction value  $\mu_l$  based on the Dahl model and due to ultrasonic vibrations can be calculated based on Littmann et al. (2001, [12]) as:

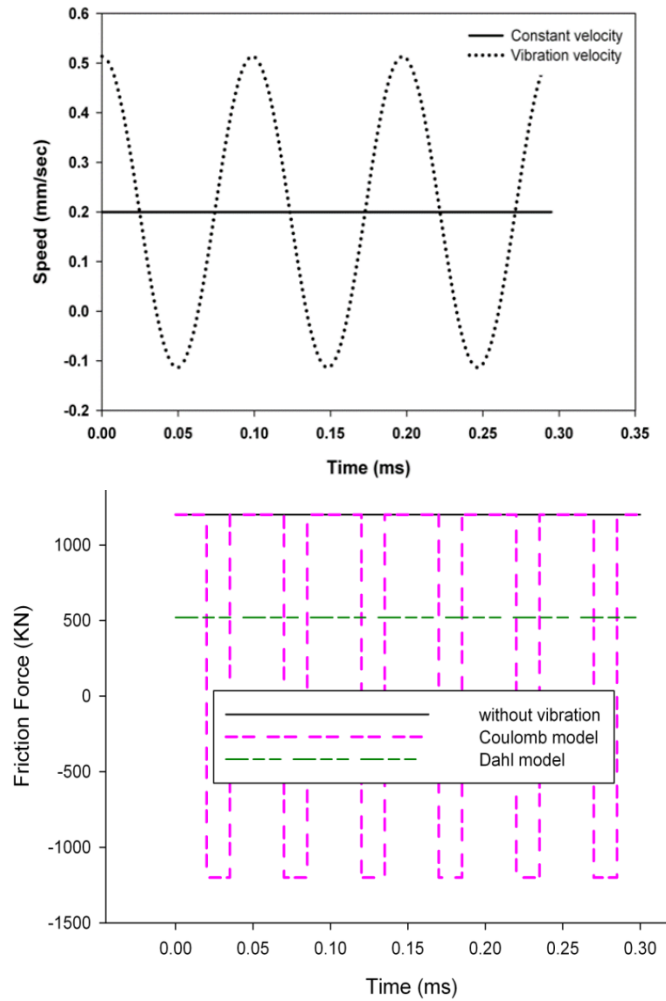
$$\mu_l = \begin{cases} 1 & \text{if } \vartheta \geq 1 \\ \frac{2}{\pi} \sin^{-1} \vartheta & \text{if } -1 \leq \vartheta \leq 1 \\ -1 & \text{if } \vartheta \leq -1 \end{cases} ; \quad \vartheta = \frac{v_c}{v_v} \quad (6)$$

in where  $v_c$  is the constant ram speed and  $v_v$  is the amplitude of ultrasonic vibration speed in the ultrasonic assisted ECAP process. This formula is in good agreement with experimental results offered by Littmann et al. (2001 [12]) when  $\vartheta > 0.25$ . For  $\vartheta < 0.25$ , experimental results show that  $\mu_l$  must be considered as 0.25. In other words, there exists a limit for friction reduction using ultrasound vibrations in experiments and it is not possible to remove the total friction effect ultrasonically. Then, Eq. (6) can be modified to give Eq. (7) by taking into account the experimental findings (see Fig. (8)).

$$\mu_l = \begin{cases} 1 & \text{if } \vartheta \geq 1 \\ \frac{2}{\pi} \sin^{-1} \vartheta & \text{if } 0.25 \leq \vartheta \leq 1; \\ 0.25 & \text{if } \vartheta \leq 0.25 \end{cases} \quad \vartheta = \left| \frac{v_c}{v_v} \right| \quad (7)$$



**Fig. 8.** The relation between the friction coefficient and amplitude of ultrasonic vibrations using the Dahl model



**Fig. 9.** Comparison between the Coulomb and Dahl friction models in predicting the total friction force when using ultrasonic vibrations

Fig. (9) shows the comparison between the amount of friction forces calculated using Dahl and Coulombs friction models for the state that both constant and vibration speeds have been applied on the ram. The friction reduction value  $\mu_l$  as per the Dahl friction model for the condition of the current experiment can be calculated as follows:

The displacement field of ultrasonic vibrations in the experiment is:

$$X = 2.5 \times 10^{-6} \sin(40,000\pi t) \quad mm \quad (8)$$

The vibration velocity will then be:

$$v_v = 0.314 \cos(40,000\pi t) \quad mm/s \quad (9)$$

The constant ram speed in the experiment is about  $0.2 \text{ mm/s}$ . Therefore, it is concluded that  $\vartheta = 0.2 / 0.314 = 0.64$ . Hence, for this experiment condition, the friction reduction value  $\mu_l$  is theoretically calculated as:

$$\mu_l = \frac{2}{\pi} \sin^{-1} \vartheta = 0.44 \quad (10)$$

This means that by applying ultrasonic vibrations, the friction coefficient is reduced to about half its value. Because the vibration velocity changes by time, the  $\mu_l$  calculated here is the time averaged friction reduction value for one oscillation period. For the special case where there is no constant motion of the ram ( $v_R = 0$ ), the variable  $\vartheta$  will be zero and hence, the theoretically calculated average friction coefficient for a vibrating die/ram system will be zero as well. It should be noted that despite the zero averaged friction coefficient, some energy will be dissipated during such vibrations. For  $0 \leq \vartheta < 1$ , the value of dissipated energy can be calculated using Eq. (11) (Littmann et al., 2001 [12]):

$$w = \int_0^T F_R(t) \times v(t) dt = \frac{4F_R v(t)}{2\pi f} (\vartheta \sin^{-1} \vartheta + \sqrt{1 - \vartheta^2}) \quad (11)$$

where in this equation  $F_R(t)$  is the transient Coulomb's friction force and  $T$  is the time period of oscillations. This energy is too low in comparison with the strong friction reduction effect of ultrasonic vibrations. It means that by adding ultrasonic vibrations and spending a little energy for ultrasonic excitations, considerable reduction in friction is achievable.

In practice, the friction coefficient will not be zero even by adding ultrasonic vibrations, and as mentioned previously, there exists a limit for the friction reduction factor  $\mu_l = 0.25$ . There are two main reasons for this fact. Firstly, the longitudinal ultrasonic vibrations cannot follow the changes in the direction of the billet easily and thus, these vibrations are effective only at the straight section of the entrance channel of the die. Secondly, ultrasonic vibrations naturally decay on an exponential trend by distance from the source (top of the billet) due to wave absorption and scattering.

As discussed, using the Dahl friction model, the friction coefficient in the ECAP process gets halved by adding ultrasonic vibrations. Furthermore, using the Coulomb friction model (Eq. (5)), the average friction coefficient for the same vibration condition will be 0.45 times the actual

friction value. This is almost the same with the results from the Dahl model for this oscillation condition. The average friction coefficient reduction ratio in one vibration period is calculated using Eq. (12).

$$\bar{\mu}_l = \frac{1}{\bar{F}_N n} \sum_{i=1}^n F_{f(t+i\Delta t)} \cdot \text{sgn}(v_t) \quad (12)$$

where  $n$  is the number of time steps in one vibration period:

$$n = \frac{2\pi}{\omega\Delta t} \quad (13)$$

#### 5.4. A strategy to speed up FE simulation of the vibrated ECAP process

Figure (10) illustrates the amount of friction reduction rate by changing the frequency and at constant ram speed. These results are extracted based on the Dahl friction model (Eq. (7)). These curves indicate that it is necessary to employ high-frequency vibrations for higher constant ram speeds. For example, vibrations with frequencies lower than 120 KHZ do not reduce the friction coefficient at all. Another useful application of such calculation can be in FE analysis of the ultrasonic assisted ECAP process. As discussed above, virtually soaring the ram speed in simulations will result in discrepancy from experimental data for the ultrasonic assisted ECAP process. A plausible strategy is to calculate an effective friction value based on Eq. (7) and to use this value in oscillating surfaces to the worth of removing ultrasonic vibrations from simulation and consequently, increase the simulation speed. In fact, by knowing the amplitude of the constant ram speed and the vibrating speed of the ram, it is possible to calculate a friction reduction factor using Eq. (7). In this way, FE simulations can be run in lower times (orders of five to ten times) with the benefit of considering the effect of ultrasonic vibrations.

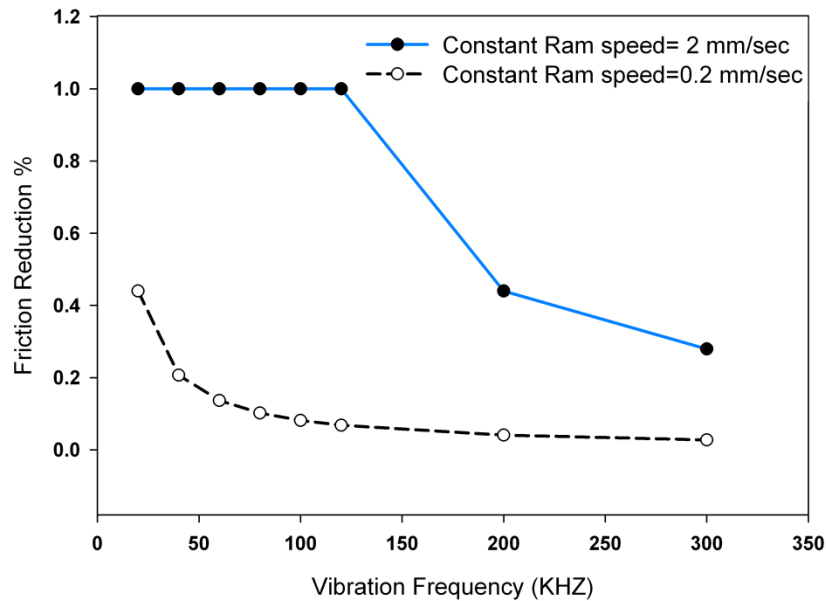


Fig. 10. The relation between constant ram speed, vibration frequency and a friction reduction rate

This strategy is implemented to the ultrasonic assisted ECAP modelling system presented in Djavanroodi et al. (2013 [11]). The results are compared in Fig. (11). In the simulation procedure, ultrasonic vibrations are included and the value of 0.12 is used as the coefficient of friction for all surfaces. However, in the suggested strategy of the current work, Eq. (7) is used to calculate a correction factor (0.44 for current calculations (Eq. 10)) which is then multiplied with a real coefficient of friction (0.12) for the affected surfaces ( $0.44 \times 0.12 = 0.053$ ).

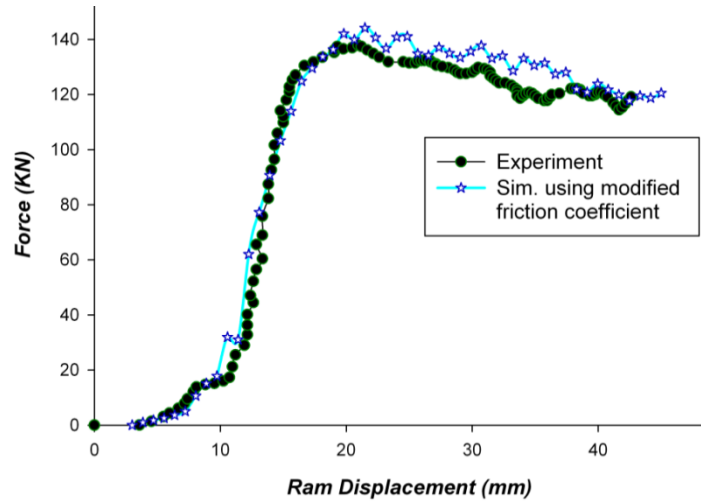


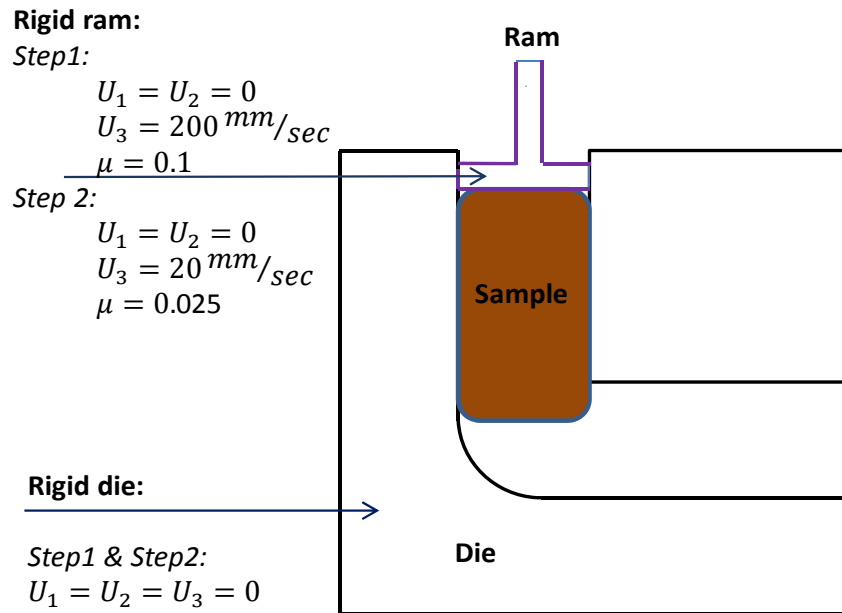
Fig. 11. Simulation of ultrasonic assisted ECAP process based on Eq. (7)

As it can be seen from Fig. (11), by removing ultrasonic vibration from the simulation and adding its effect in simulations, acceptable results are obtained.

In addition to the comparison of the results of FE simulation using the suggested strategy with the data from Djavanroodi et al. (2013 [11]), the proposed method is applied on the data provided by Ahmadi and Farzin (2013 [10]). In this reference, authors have investigated different aspects of FE simulation for the ultrasonic assisted ECAP process. Table 2 indicates the parameter values used in the simulation procedure of the current study and the simulation process from Ahmadi and Farzin (2013 [10]). Ahmadi and Farzin (2013 [10]) simulated the ultrasonic assisted ECAP process in two steps (Fig. (12)).

Table 2. Parameters used in simulation based on reference (Ahmadi and Farzin, 2013 [10])

Billet diameter (mm)	Billet length (mm)	Die angle $\varphi$	$\mu$	Material properties $\sigma$ (MPa)	$v_c$ (mm/s)	$v_v$
10	50	90°	0.1	$124.3e^{0.2}$	20	$1256\cos(125664t)$



**Fig. 12.** Boundary condition of FE simulation using the proposed strategy

In the first step which takes 0.05 s, ultrasonic oscillations are not yet active. For this reason, as shown in Fig. (13), no oscillations are recorded for the forces. Fig. (12) shows the boundary conditions during the steps one and two for a deformable sample and rigid die. In the second step which takes about 0.01 s, vibrations are induced which causes an abrupt reduction in the average required ram force as seen from Figure 13. In this step, the required force shows rapid changes between the maximum and minimum values but the average required force in this condition is considerably lower than the one without vibration (say step one). These results are obtained using the traditional simulation method and by considering vibrations in simulations. In this study, to validate the proposed strategy, a similar two-step simulation process is repeated but this time by removing vibrations from simulations and considering the friction correction factor as discussed above. As it is evident from Fig. (13), the results of simulation using both methods are coinciding at the first step because all parameters are equal in this step for both methods. A little difference at this stage can be referred to the different mesh sizes. However, at the second step using the proposed strategy, a corrected friction coefficient is used and no vibration is included. As a result, although rapid changes at the required ram force are appeared again, no oscillation is recorded in the second step using the proposed strategy. The average of the oscillating ram force in the traditional simulating method is fairly good coinciding with the result of the simulation using the proposed strategy (Fig. (13)). It means that the results of simulations using the two methods support each other.



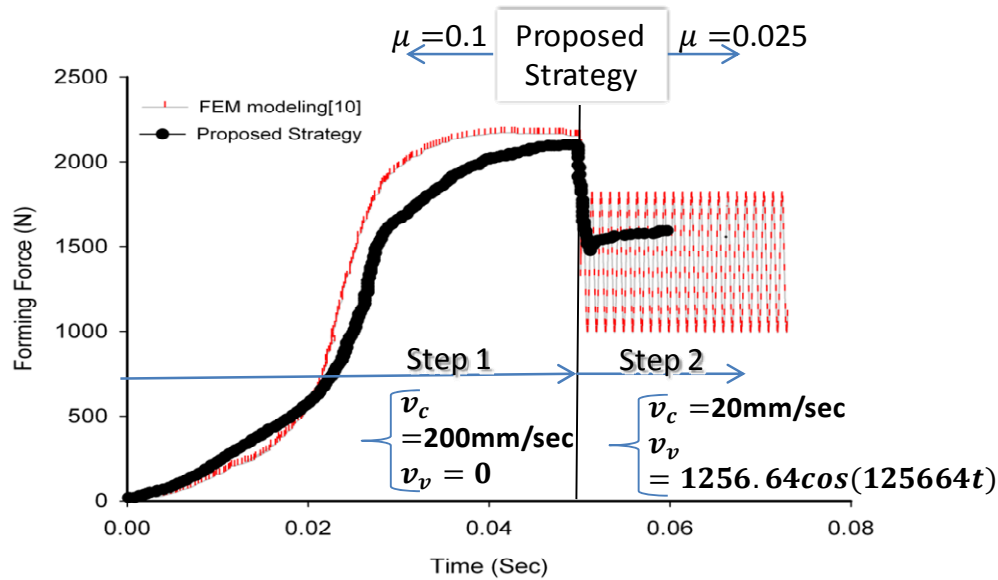


Fig. 13. Comparison between the results of simulation with and without (proposed strategy) adding vibration on a ram

The two comparisons discussed above confirm that the proposed strategy for simulating an ultrasonic assisted ECAP process is reporting acceptable results.

## 6. Conclusion

3D finite element simulation of the conventional and vibrated ECAP processes are conducted for several ram speeds. An analytical procedure based on the Coulomb and Dahl friction models is also proposed. The following results are obtained:

- Analytical calculations showed that it is the interaction between the constant ram speed and the vibrated speed of the ram which dictates the amount of friction reduction in the ultrasonic assisted ECAP process.
- Unlike the conventional ECAP process, due to the related errors, there is great restriction in virtually increasing the ram speed in FE simulation of the ultrasonic assisted ECAP process. It is highly recommended to use the real ram speed in numerical modelling of the ultrasonic assisted ECAP process.
- A novel strategy is proposed to speed up FE simulation of the vibrated ECAP process. It is shown possible to calculate, theoretically, an ultrasonic correction factor based on the Dahl or Coulomb friction models and use this factor in the FE codes to the worth of removing ultrasonic vibration from simulations. Using such technique, the computation time reduces up to ten times while fairly accurate results can be achieved as well.

## References

- [1] Z.A. Khan, U. Chakkingal, P. Venugopal, Analysis of forming loads, microstructure development and mechanical property evolution during equal channel angular extrusion of a commercial grade aluminum alloy, Journal of Materials Processing Technology, 135 (2003) 59-67.

- [2] I.H. Son, Y.G. Jin, Y.T. Im, S.H. Chon, J.K. Park, Sensitivity of friction condition in finite element investigations of equal channel angular extrusion, *Materials Science and Engineering: A*, 445 (2007) 676-685.
- [3] B.V. Patil, U. Chakkingal, T.S.P. Kumar, Influence of friction in equal channel angular pressing—A study with simulation, in: *Proceedings of the 17th International Conference of Metallurgy and Materials (Metal 2008)*, Czech Rep., 2008.
- [4] G. Faraji, M. Ebrahimi, A.R. Bushroa, Ultrasonic assisted tubular channel angular pressing process, *Materials Science and Engineering: A*, 599 (2014) 10-15.
- [5] F. Djavanroodi, M. Ebrahimi, Effect of die channel angle, friction and back pressure in the equal channel angular pressing using 3D finite element simulation, *Materials Science and Engineering: A*, 527 (2010) 1230-1235.
- [6] G.A. Malygin, Acoustoplastic effect and the stress superimposition mechanism, *Physics of the Solid State*, 42 (2000) 72-78.
- [7] J.-C. Lee, J.-Y. Shu, J.P. Ahn, Work-softening behavior of the ultrafine-grained Al alloy processed by high-strain-rate, dissimilar-channel angular pressing, *Metallurgical and Materials Transactions A*, 34 (2003) 625-632.
- [8] R. Pohlman, E. Lehfeldt, Influence of ultrasonic vibration on metallic friction, *Ultrasonics*, 4 (1966) 178-185.
- [9] V.C. Kumar, I.M. Hutchings, Reduction of the sliding friction of metals by the application of longitudinal or transverse ultrasonic vibration, *Tribology International*, 37 (2004) 833-840.
- [10] F. Ahmadi, M. Farzin, Finite element analysis of ultrasonic-assisted equal channel angular pressing, *Journal of Mechanical Engineering Science*, 228 (2014) 1859-1868.
- [11] F. Djavanroodi, H. Ahmadian, K. Koohkan, R. Naseri, Ultrasonic assisted-ECAP, *Ultrasonics*, 53 (2013) 1089-1096.
- [12] W. Littmann, H. Storck, J. Wallaschek, Reduction of friction using piezoelectrically excited ultrasonic vibrations, in: *SPIE's 8th Annual International Symposium on Smart Structures and Materials*, International Society for Optics and Photonics, 2001, pp. 302-311.
- [13] C.C. Tsai, C.H. Tseng, The effect of friction reduction in the presence of in-plane vibrations, *Archive of Applied Mechanics*, 75 (2006) 164-176.
- [14] K. Siegert, J. Ulmer, Influencing the friction in metal forming processes by superimposing ultrasonic waves, *CIRP Annals-Manufacturing Technology*, 50 (2001) 195-200.
- [15] S.K. Lu, H.Y. Liu, L. Yu, Y.L. Jiang, J.H. Su, 3D FEM simulations for the homogeneity of plastic deformation in aluminum alloy HS6061-T6 during ECAP, *Procedia Engineering*, 12 (2011) 35-40.
- [16] N.E. Mahallawy, F.A. Shehata, M.A. El Hameed, M.I.A. El Aal, H.S. Kim, 3D FEM simulations for the homogeneity of plastic deformation in Al-Cu alloys during ECAP, *Materials Science and Engineering: A*, 527 (2010) 1404-1410.
- [17] X. Lai, Y. Xia, X. Wu, Q. Zhou, An experimental method for characterizing friction properties of sheet metal under high contact pressure, *Wear*, 289 (2012) 82-94.
- [18] A. Pougis, S. Philippon, R. Massion, L. Faure, J.J. Fundenberger, L.S. Toth, Dry friction of steel under high pressure in quasi-static conditions, *Tribology International*, 67 (2013) 27-35.
- [19] S.A.A.A. Mousavi, H. Feizi, R. Madoliat, Investigations on the effects of ultrasonic vibrations in the extrusion process, *Journal of materials processing technology*, 187 (2007) 657-661.
- [20] G. Gurău, C. Gurău, O. Potecașu, P. Alexandru, L.-G. Bujoreanu, Novel high-speed high pressure torsion technology for obtaining Fe-Mn-Si-Cr shape memory alloy active elements, *Journal of Materials Engineering and Performance*, 23 (2014) 2396-2402.
- [21] S.W. Chung, W.-J. Kim, M. Kohzu, K. Higashi, The effect of ram speed on mechanical and thermal properties in ECAE process simulation, *Materials Transactions*, 44 (2003) 973-980.
- [22] R.Z. Valiev, T.G. Langdon, Principles of equal-channel angular pressing as a processing tool for grain refinement, *Progress in Materials Science*, 51 (2006) 881-981.