# Comparative study of the influence of friction forces on cold forming processes in conventional ECAP die and ECAP die with low friction, by numerical simulation methods

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**Abstract.** In the process of severe plastic deformation in the ECAP dies, the frictional forces between the blank and the walls of the dies play a determinant role on forming technologies. Due to the great length of the workpiece subjected to forming (in die), high frictional forces are developing, which can lead to blocking the forming process or even to the cracking of the dies. Two sets of numerical simulations were carried out for two coefficients of friction $\mu = 0.08$ and $\mu = 0.10$. There were analysed the following elements comparatively: the structure of the deformed mesh of the finished piece; the effective plastic strain fields; the Von Misses effective stress fields; the actuation forces on the die punch. The results of the numerical simulations showed: uniform structure of slipped layers in central areas of the finished parts, obtained by the two processes; the effective plastic strain field is uniformly at the process with low friction Von Misses effective stresses were significantly lower at the numerical simulation for the process with low friction; the application forces occurring in the processes carried out in the ECAP die with low friction are significantly lower than those obtained in conventional ECAP die.

## 1. Introduction

Processing and manufacture of fine and ultra-fine granular structure have preserved over the years a strong interest from both the scientific communities as well as from producers, as a result of obtaining attractive mechanical properties of these materials. Materials with fine and ultra-fine grain structure have very good mechanical properties including very high yield strength, high hardness, mechanical strength and ductility improved [1]. Severe plastic deformation (SPD) is defined by a generic term that describes a group of processing techniques for metals that involve extreme stresses to achieve very high shearing deformations in metallic materials [2]. One of the most common and simplest methods to achieve SPD is the conventional ECAP process. Conventional ECAP die has two channels with sections of same dimensions and circular or square shape, at a right angle of 90 degrees usually, figure 1. The blank (workpiece) is forced to pass through these channels by pressing with a punch located on a press ram. After the cold forming, the shape of the finished piece is changed insignificantly in relation to the shape of workpiece from which it was made, but the most important is that the ultra-fine structure of the grains obtained lead to superior mechanical characteristics of finished pieces compared to those obtained by conventional processes (rolling, extrusion, forging etc.). By improving the conventional ECAP process it results ECAP with low friction process, developed in order to produce

finished pieces in the form of long bars with square cross sections. The principle of this process is shown schematically in figure 2. The workpiece is inserted into the movable part of the die in the corresponding channel, realizing contacts on three sides thereof. The friction forces on the three contact interfaces become zero and the necessary force of the cold forming process decreases because the friction force occurs on one surface, namely the surface of contact between the workpiece and the fixed part of the die [3].
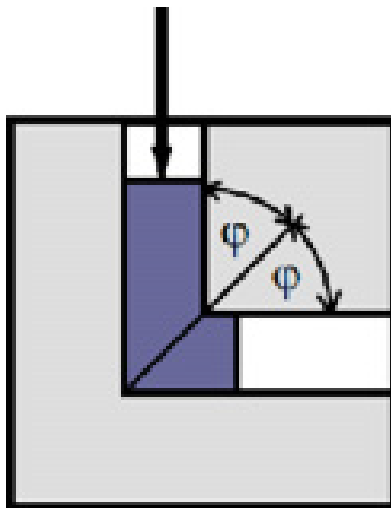


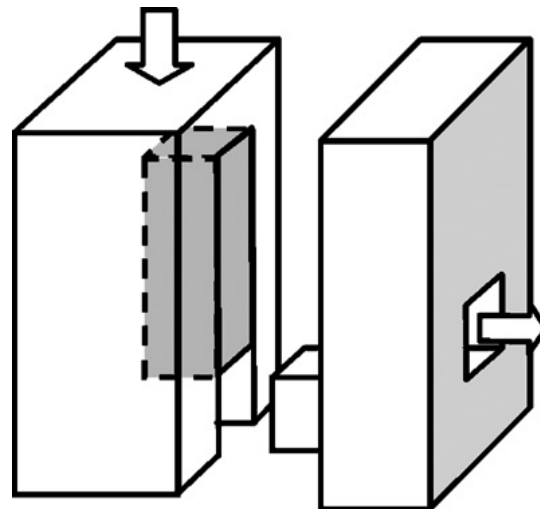**Figure 1.** Cold forming in the conventional ECAP die - schematic representation [3].



**Figure 2.** Cold forming in the ECAP die with low friction – schematic representation [3].

## 2. The objective of the numerical simulations
The objective of the numerical simulations presented in this paper is the highlighting by comparison of the influence of friction forces on severe plastic deformation processes, by realizing two sets of numerical simulations: one for conventional ECAP die and the other for ECAP die with low friction. Both dies have channels with the external radius R = 4 mm and the numerical simulations were carried out for the coefficients of friction $\mu$ = 0.08 and $\mu$ = 0.10. The finite element method with Lagrange mesh was used to achieve the numerical simulations. The following were analysed comparatively: structure of the deformed mesh for the finished piece; effective plastic strain field; Von Misses effective stress field; the actuation forces on the die punch for the two cases.

## 3. Simulation procedure
The numerical simulations follow a procedure similar to all scientific approaches, which consists of the following steps:
- Stage 1 - The achievement of the physical model;
- Stage 2 - Mathematical model;
- Stage 3 - The achievement of the discretized model;
- Stage 4 - Coding;
- Stage 5 – Numerical solving.

### 3.1. Achievement of the physical model
One physical model for each case is built for the analysed phenomenon (SPD in the two dies).
Physical models should highlight the main laws that govern them. To reduce the computational effort of the numerical simulation processes from the solving stage, 3D physical models were made as follows: for the conventional ECAP die, the model was realised on half; for ECAP die with low friction, the model was achieved on quarter. For the simulations in continuum mechanics, an important

moment in the development of the stage of building the physical model refers to the formulation of the material model. A material model correctly formulated ensures from the start the success of the numerical simulation. For die body and for the die punch, in both cases there were assigned models made of rigid material. The workpiece used in the numerical simulations has the dimensions (L x l x h) 20x20x105 mm and is made of aluminium alloy EN AW 6082. The material for the workpiece is poly-linear plastic and was built using the own experimental data [4]. Sensitivity to the speed of deformation is introduced by the multiplier model Cowper-Symond [5], whose material parameters appear in the executable file of LS-DYNA software.

### 3.2. Mathematical model
The mathematical model is established based on laws that govern the physical model using some simplifications and assumptions. The mathematical model is expressed in general under the form of governing equations, boundary and initial conditions; this model is based on the theory of plasticity [6].

### 3.3. The achievement of the discretized model
In the case of the methods with mesh, the definition domain is divided into sub-domains of simple shapes, polygonal or polyhedral ones, with straight or curved sides, so that the nodes should occupy the peaks arranged on the sides, or the faces from the interior of these sub-domains. Such a sub-domain, corresponding to Lagrange mesh, is called finite element. Meshing under both its aspects, geometric and mathematical, refers to the transformation of the continuous domain of definition of the problem into a discreet domain and of the governing differential or integral equations into algebraic equations. Figures 3 and 4 present the discretized models for conventional ECAP die and ECAP die with low friction, respectively.
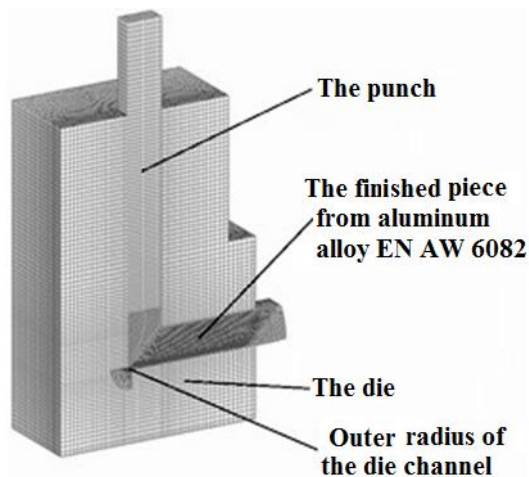


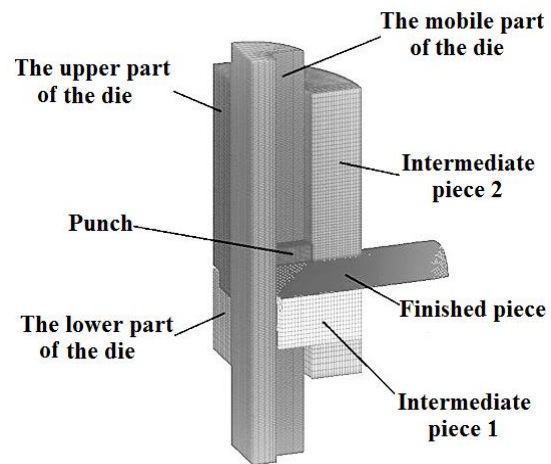**Figure 3.** The discretized model of the conventional ECAP die.

**Figure 4.** The discretized model of the ECAP die with low friction.

### 3.4. The coding
Coding of the numerical simulation consists of passing the meshing model and the calculation algorithms in the computer code using a programming language.

### 3.5. Numerical solving
The numerical solution is obtained in the solving module - SOLVER - by the set of output data.
Besides the output data, the solution of the problem can be also presented in graphical form as colour fields (maps) or as diagrams. The numerical simulation of cold forming processes for metals uses, in

most cases, the finite element methods. The characteristic of these methods is a material mesh Lagrange type, a mesh that is linked to bodies and that deforms together with them.

## 4. Numerical simulations

### 4.1. Conditions for numerical simulations
After meshing of the dies physical models and of the utilized workpieces and after assigning the mathematical model [6] there were put the conditions for the numerical simulations:

- The punch (the mobile part of the die) moves according to a linear time law;
- The working speed of the punch (the mobile part of the die) ~ 50 mm/s;
- Duration of the cold forming process in the conventional ECAP die – 1.75 s;
- Duration of the cold forming in the ECAP die with low friction -1.79 s;
- The increment imposed $\Delta t = 5 \times 10^{-6}$ s, in quasi-static conditions [5].

### 4.2. Results obtained at the numerical simulations

### 4.2.1. Deformed structure of the nodal mesh
Two sets of numerical simulations of cold forming processes were made in the conventional ECAP die and in ECAP die with low friction, respectively. Afterwards, cut outs with the deformed mesh structure have been extracted from the central areas of the finished pieces during the post-processing phase for the two cases $\mu = 0.08$ and $\mu = 0.10$. In figures 5 and 6 are comparatively shown the shear angles resulted from the slipping of the material layers from the workpiece. It can be noted that the values of shear angles in the central area of the finished piece are very close for the both simulations carried out in conventional ECAP die and in the ECAP die with low friction as well.
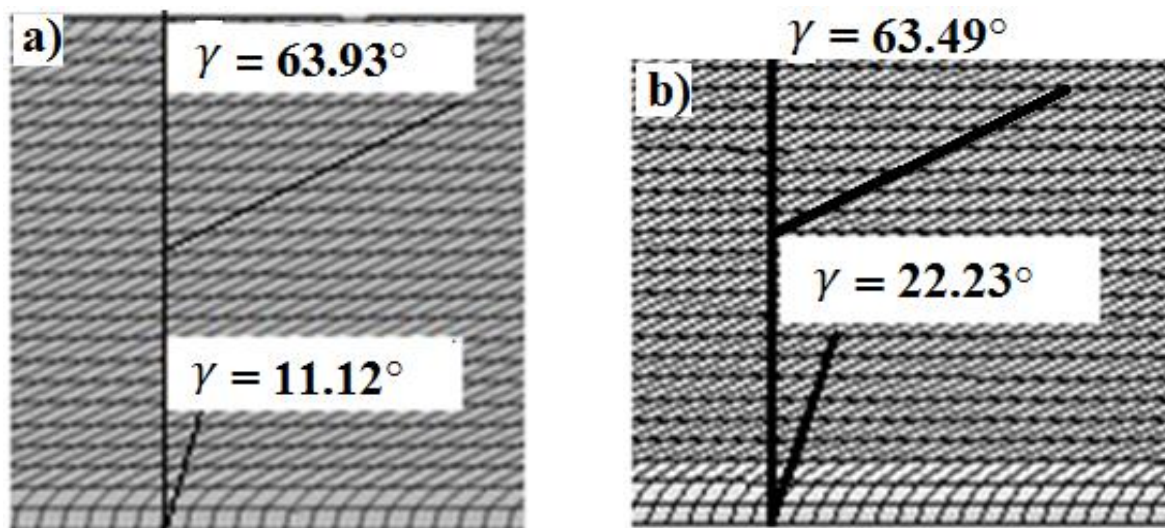


**Figure 5.** Share angle for friction coefficient $\mu = 0.08$ – a) Conventional ECAP die b) ECAP die with low friction.

In the area of the contact between the finished work piece and the die channel, the measured shear angles have higher values in case of the simulations carried out on the model of ECAP die with low friction than in case of the simulations carried out on the model of conventional ECAP die(~ 22° compared to ~ 11°). This can be explained by the fact that the friction forces are distributed relatively uniformly on the four walls of the die channel at the conventional ECAP die while the entire friction force is distributed on a single wall at the ECAP die with low friction.
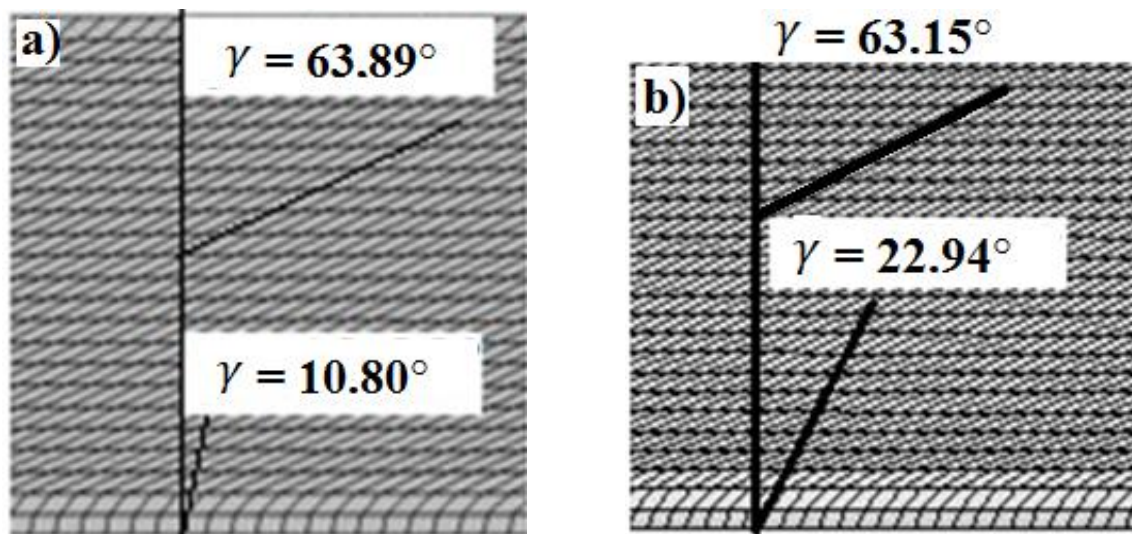
**Figure 6.** Share angle for friction coefficient μ = 0.10 – a) Conventional ECAP die; b) ECAP die with low friction.

*4.2.2. Effective plastic strain field*
In Figures 7 and 8 are presented, by comparison, the effective plastic strain fields of the finished pieces for the two cases μ = 0.08 and μ= 0.10.
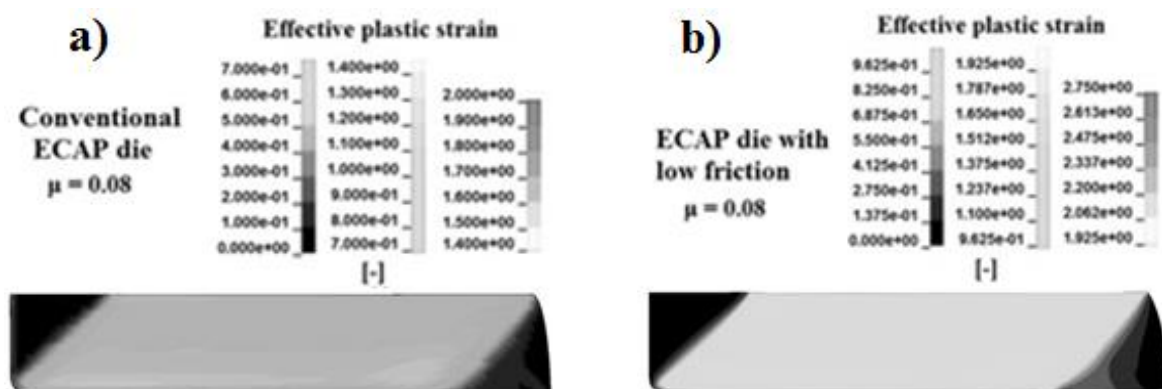


**Figure 7.** Effective plastic strain field for friction coefficient μ = 0.08 – a) Conventional ECAP die; b) ECAP die with low friction.

It can be noted a higher degree of the effective plastic strain (strain rate $\varepsilon_{max}$ = 2.75) in the case of ECAP die with low-friction than in the case of conventional ECAP die (strain rate $\varepsilon_{max}$ = 2). The effective plastic strain fields are more uniform for the pieces realized in the ECAP die with low friction than those made in the conventional ECAP die. At the conventional ECAP die the effective plastic strain field is more uniform for the lower friction coefficient (μ = 0.08) and, by comparison, insignificant differences of the effective plastic strain fields for the two coefficients of friction are observed at the ECAP die with low friction.

*4.2.3. Von Misses effective stress field*
Figures 9 and 10 highlight by comparison the fields of Von Misses effective stresses of the finished pieces for the friction coefficients μ= 0.08 and μ = 0.10.

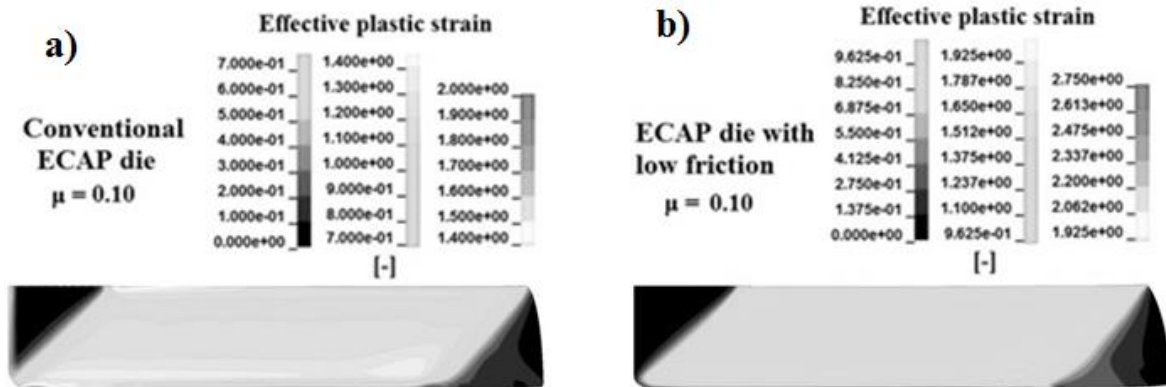**Figure 8.** Effective plastic strain field for friction coefficient μ = 0.10 – a) Conventional ECAP die; b) ECAP die with low friction.
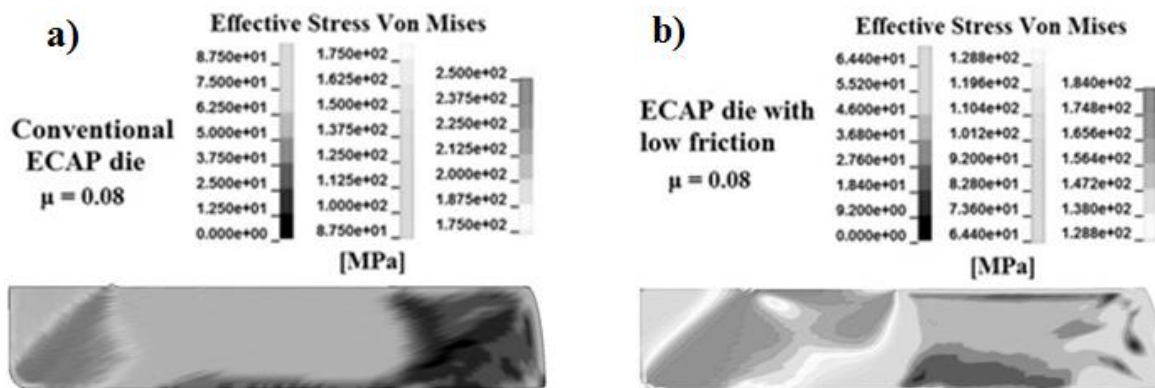


**Figure 9.** Von Misses effective stress field for friction coefficient μ = 0.08 – a) Conventional ECAP die; b) ECAP die with low friction.
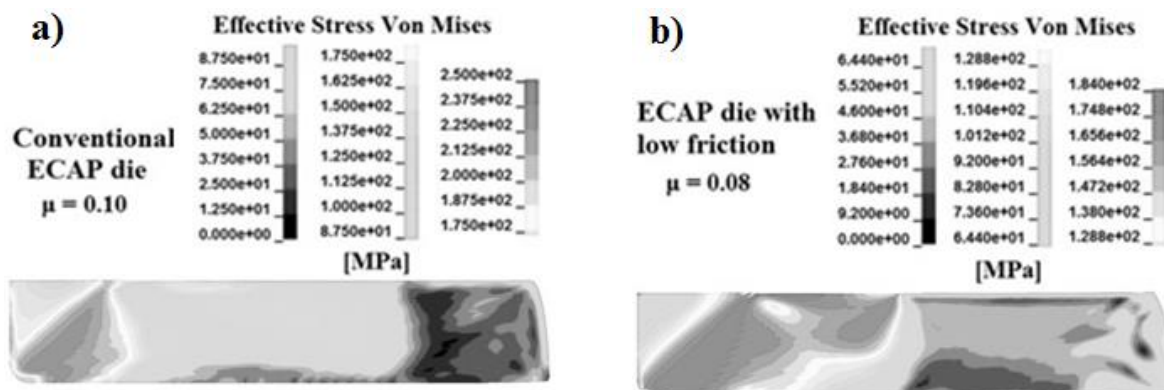


**Figure 10.** Von Misses effective stress field for friction coefficient μ = 0.10 – a) Conventional ECAP die; b) ECAP die with low friction.

As expected, the field values of Von Misses effective stresses fields for the finished piece realized in the conventional ECAP die are significantly higher ($\sigma_{eff}$ = 250 MPa) than the values obtained for the piece realized in the ECAP die with low friction ($\sigma_{eff}$ = 184 MPa). From the data mentioned above, it results a better yield for ECAP die with low friction than for the conventional ECAP die, explained by the fact that it undertakes the same process with smaller efforts, caused by the lower friction forces.

Also, perceivable (but not essential) differences are found out in terms of Von Misses effective stresses fields, obtained at the finished pieces realized in the conventional ECAP die, for two friction coefficients. At the ECAP die with low friction, the differences between the two fields of the Von Misses effective stresses, for the two coefficients of friction, are very small. To highlight in a more categorical way the difference between the two dies, figures 11 and 12 present comparatively the variations in time of the actuation forces on the dies punches, for the two friction coefficients μ = 0.08 and μ = 0.10.
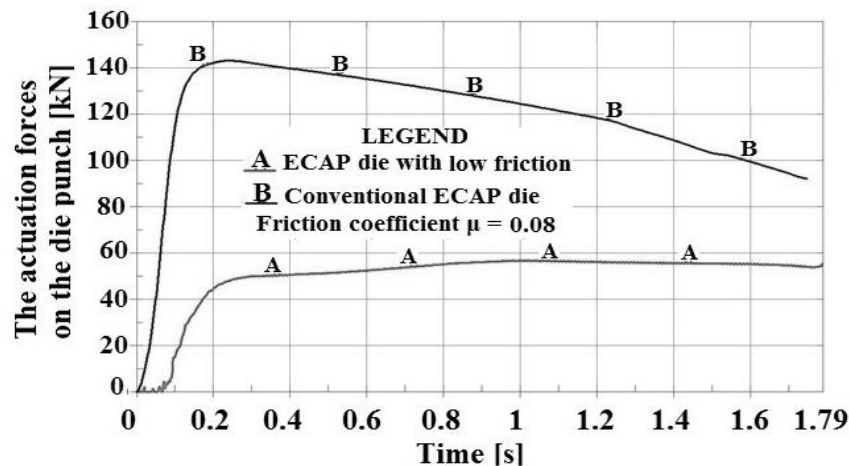


**Figure 11.** The graphic of the actuation forces on the punch: A – for ECAP die with low friction;
B – for the conventional ECAP die (friction coefficient μ = 0.08).

For the coefficient of friction μ = 0.08 it was found out an actuating force approximately two times higher at the conventional ECAP die compared to the actuation force realized in the ECAP die with low friction. For the friction coefficient μ = 0.10 it is found out a tripling of the actuating force on the die punch in the case of the conventional ECAP die related to the ECAP die with low friction.
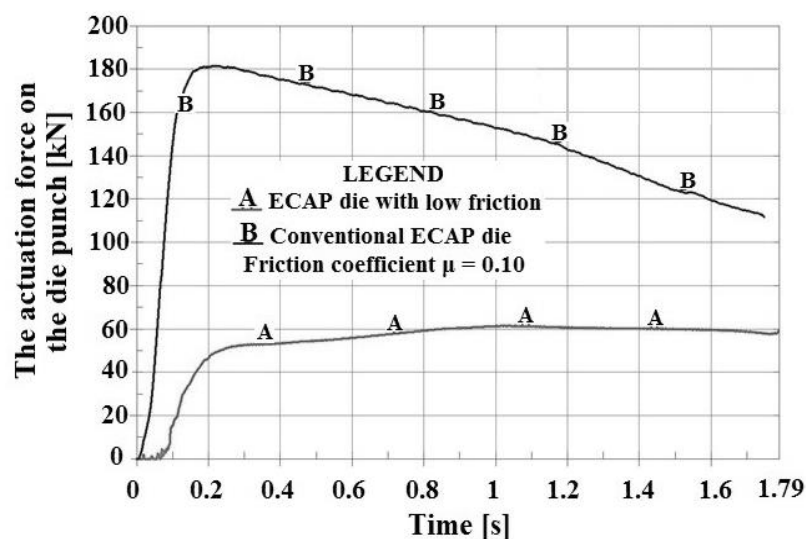


**Figure 12.** The graph of the actuation forces on the punch: A – for ECAP die with low friction; B – for the conventional ECAP die (friction coefficient μ = 0.10).

## 5. Conclusions to the numerical simulations

It should be noted that the comparative study of the results obtained regarding the cold forming processes in the two types of dies were made under the same conditions of the numerical simulations, namely:  the outer channel radius of the dies, R = 4 mm, the same coefficient of friction, the same conditions of displacement for the die punch (the mobile part of the die), the same dimensions of the workpiece. After the comparative analysis made on the basis of the numerical simulations, the following conclusions have resulted:

-the ECAP die with low friction has the advantage of a reduced frictional force, due to the fact that during the process of severe plastic deformation the workpiece is in contact with a single surface of the die channel, namely the one on the fixed side of the die, while at the conventional ECAP die the workpiece is in constant contact with all 4 surfaces of the die channel;

-the deformed structure of the mesh of the finished pieces is similar for the two types of dies; the only difference is that in the contact area between the finished piece and the die channel, the shear angles measured have greater values in the case of the numerical simulations carried out on the model of the ECAP die with low friction than the simulations carried out on the model of conventional ECAP die ($\sim 22$ ° to $\sim 11$ °). This can be explained by the fact that at the conventional ECAP die the friction forces are distributed relatively evenly across the four walls of the die channel while at the ECAP die with low friction, the entire friction force is distributed on a single wall;

-in terms of effective plastic strains field (figures 7 and 8) it can be noted a better uniformity in the case of the finished piece obtained in the ECAP die with low friction;

-Von Misses effective stresses have lower values for the finished piece obtained in the ECAP die with low friction, of 184 [MPa] compared to the value of 250 [MPa] obtained for the finished piece realized in the conventional ECAP die (figures 9 and 10);

-In figures 11 and 12 were presented by comparison the actuation forces that are exerted to achieve the severe plastic deformation process in the ECAP die with low friction respectively in the conventional ECAP die. For the friction coefficient $\mu = 0.08$ it was found out a ratio of approximately 1 / 2.5 of the actuation forces on the die punch for the two dies while for the friction coefficient  $\mu = 0.10$ it was found out a ratio of about 1/3 of the actuation forces on the die punch for the two dies. From these graphics it results the advantage of the ECAP dies with low friction, because they realize the same process of severe plastic deformation with less efforts and which is finally reflected in higher yields. Also, one can notice that in the case of ECAP die with low friction, the difference of the actuation force on the die punch, resulted from the numerical simulations in comparison with the case of the conventional ECAP die, can be used for achieving finished pieces (workpieces) with much greater lengths.

## 6. Appendices

### 6.1. List of abbreviations

ECAP - Equal Channel Angular Pressing; SPD - Severe Plastic Deformation; L - The length of the workpiece; l - The width of the workpiece; h – The height of the workpiece.

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