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NUMERICAL SIMULATION OF SEVERE PLASTIC DEFORMATION OF WORK PIECE FROM ENAW 6082 IN THE ECAP DIE WITH LOW FRICTION

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Abstract: *One of the most used processes of the severe plastic deformation is the cold deformation process in the conventional ECAP die. Since it is a process with low productivity it is mainly used in laboratories for SPD testing. Starting from the severe plastic deformation process in conventional ECAP die, a new method was realized that allows the realization of this process in better conditions, with low friction. The work piece is 10×10 mm square section. The mobile part of the die is in contact with three of the four surfaces of the work piece. Only one surface of the work piece is in direct contact with the fixed part of the ECAP die that leads to reduced friction forces during plastic deformation. The objective of this paper is to perform a thorough analysis based on numerical simulation methods of the SPD process in the ECAP die with low friction applied on a work piece of aluminum alloy ENAW 6082. At the same time, it is aimed the way in which the plastic deformations are produced and the solution obtained analytically is compared with that obtained numerically. Also, the influence of the die geometrical configuration on effective strain, effective stresses (Von Mises), applied force, and influence of the friction coefficient on the applied force for the same geometrical configuration of the die were pursued.*

Key words: *numerical simulation, low friction ECAP die, SPD, aluminum alloy ENAW 6082.*

1. INTRODUCTION

Nomenclature:

ECAP – Equal Channel Angular Pressure;
El. – Tensile elongation;
FEA – Finite Element Analysis;
SPD – Severe Plastic Deformation;
UTS – Ultimate Tensile Strength;
YS – Yield strength.

1.1. Concerns of scientists regarding SPD in conventional ECAP die

Starting from this conventional process, other processes have been developed including: ECAR rolling, ECAP rolling, ECAP incremental process, and the severe plastic deformation in ECAP die with low friction. The friction-reduced ECAP processes were developed in order to produce long bulk bars with square cross-section [6].

The trend in the current worldwide is to introduce severe plastic deformation processes (cold or hot) widespread in order to obtain materials (work pieces) or parts with superior mechanical properties with regard to those obtained by conventional methods.

SPD describes a group of metalworking techniques involving a large plastic deformation, due to the complex tensions or high shear tension in order to obtain ultra-fine grain structure in work piece [6].

The unique mechanical properties of the ECAP-ed material are directly affected by plastic deformation.

For a better understanding of the phenomena of the plastic deformation that occurring in the work piece, to design a functional die, for achieving an optimum friction inside the die, etc. it is necessary to combine experimental research with numerical simulations of inhomogeneous deformation behavior of the work piece during the deformation process [5].

To achieving good numerical simulations of SPD, it is necessary to obtain experimentally (by tensile tests) a correct characteristic curve (stress-strain) of the material of which the work piece is made. This is the best way [5]. Another possibility is to use mechanical characteristics of the material taken from the software databases (stress-strain curves) but, sometimes, this leads to different results of the numerical simulations, because these data do not correspond exactly to those obtained experimentally [5].

Some researchers have submitted in an article SPD effects regarding the properties and structure of materials used in the different tests, for two materials: high purity aluminum (99,999% Al) and Al-Cu-Mg-Zr aluminum alloy [5]. By means of laboratory tests performed, they studied the dependence of the strain level, material strength, micro hardness, plasticity and grain size, according to the number of passes of the work piece through conventional ECAP die. The results obtained after one pass of the work piece from aluminum alloy through ECAP die, in terms of the mechanical characteristics of the material were presented. In this sense, stress-

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strain curves (obtained by laboratory tests) for aluminum alloy processed by different methods of plastic deformation or heat treatment were compared in Fig. 1. Implementation of the SPD by ECAP method caused an increased resistance of the aluminum alloy compared to the two systems in which this process has not been applied [5].

The results of tensile tests on the samples produced by various processing methods are presented in Table 1.

The significant increase of yield strength for the studied aluminum alloy was caused by SPD in its passage through ECAP die. It was also observed a decrease in ductility of the material. It was performed, a FEA analysis to simulate the plastic deformation occurring in a single pass of the work piece through conventional ECAP die in two cases: *a* − mechanical characteristics taken from the database of the software and *b* − mechanical characteristics obtained on experimentally way Fig. 2. In the maximum area of the stress-strain curves, acceptable differences were observed (7%) in terms of the plastic strain values: 1.12 for the mechanical characteristics taken from the database and 1.2 for those experimentally obtained [5].

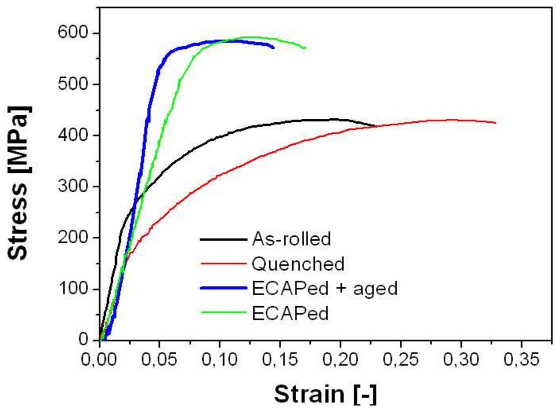


Fig. 1. Stress-strain curves for alloy Al-Cu-Mg-Zn-Zr, subjected to various processes aimed to improve its mechanical characteristics [5].

Table 1

Mechanical properties of investigated aluminum alloy Al-Cu-Mg-Zr [5]

Processing	Mechanical properties		
	YS [MPa]	UTS [MPa]	El. [%]
As-rolled	235	381	22.3
Quenched	157	394	32.8
ECAPed	511	593	17.1
ECAPed+aged	515	541	14.4

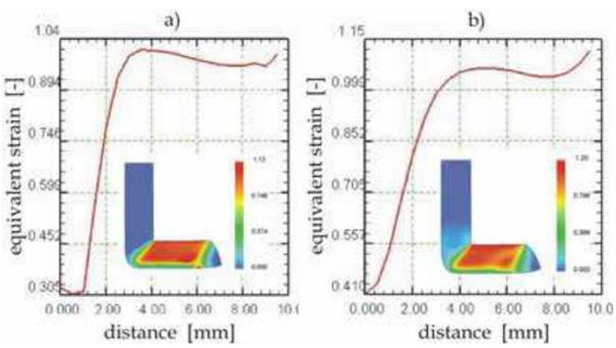


Fig. 2. Distribution of equivalent strain: *a* − characteristics from databases; *b* − characteristics from experimental tests [5].

1.1. Objectives of the paper

The objective of this paper is to perform a thorough analysis based on numerical simulation methods of the SPD process, in ECAP die, with low friction, applied on a work piece. At the same time, it is aimed the way in which the plastic deformations are produced and the solution analytically obtained is compared with that resulted by numerically path.

Equivalent plastic deformation of the work piece after one pass by the ECAP die (φ = 90°) is obtained by the analytical relation [6]:

$$\varepsilon = \frac{2}{\sqrt{3}}\cot\varphi = 1.15 \qquad (1)$$

Also, the influence of the die geometrical configuration on effective strain, effective stresses (Von Mises), application force and the influence of the friction coefficient for the same geometrical configuration of the die on the applied force were pursued.

1.2. Numerical simulation steps

Currently, numerical simulation has become important tool engineering. Numerical simulations follow a similar procedure for all scientific approaches, which consists of passing through several stages. Starting from a phenomenon or process a physical model is created. A mathematical model expresses the quantitative physical laws by means of the governing equations. The next step is the creation of the meshing model. After meshing, the boundary conditions of the problem are inserted and the pre-processing is completed. The last two steps are: solving the problem with the software solver and respectively the post-processing.

2. THE PHYSICAL MODEL

The principle of this process is shown schematically in Fig. 3. By moving the mobile part of the die, the frictional forces of the three areas of contact with the work piece becomes zero. The only area where friction is achieved is between the fixed part of the die and the work piece. Thus, the required load in extrusion process decreases.

3. MATERIAL MODELS FOR WORK PIECE AND DIE

To achieve a good simulation of the deformation process of the work piece in the ECAP die with low friction, it is necessary to correctly determine the material properties, for all states of deformation up to failure. More tests of tensile and compression was performed to get a plastic feature for the aluminum alloy studied. To extend the real characteristic diagram up to fracture, for the aluminum alloy, was required a FEA analysis, which also used experimental data. In this analysis, control parameters that describe the phenomenon, were: necking diameter

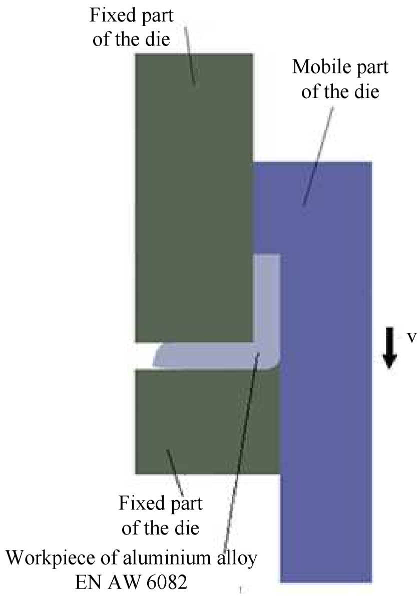


Fig. 3. The physical model of ECAP dies with low friction.

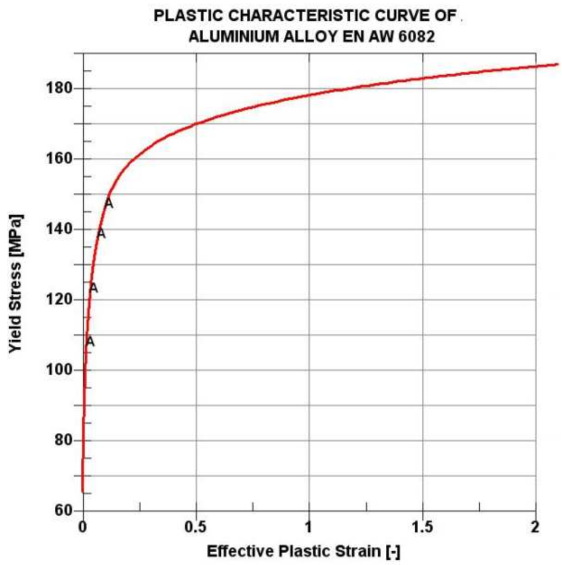


Fig. 4. Plastic characteristic curve of aluminium alloy EN AW 6082.

in the final stage, final elongation and final load. Using data obtained from laboratory tests and with the numerical simulation of tensile sample, the plasticity curve for aluminum alloy studied was built (Fig. 4) [7].

The work piece used in the numerical simulation of plastic strain is considered from square bar, with 10×10×80 mm dimensions and it have been assigned the mechanical properties and chemical composition of the aluminum alloy EN AW 6082 presented in Tables 2 and 3. To achieve numerical simulations, the work piece was considered in its natural state "0" as Table 2 shows.

A plastic characteristic according to the stress-strain curve given in Fig. 4 was attributed to a sample from aluminum alloy EN AW 6082. For the material of the die tools (the fixed part and the mobile part of the die) have been attributed to the elastic features of the material which correspond with the tool steels. The mechanical characteristics of material for the tools of the die are superior in comparison with the material of the work piece.

Table 2

Aluminum alloy EN AW 6082. Mechanical properties

Material state	0	T4	T6
Yield strength 0.2%[MPa]	60	170	310
Tensile strength [MPa]	130	260	340
Shear strength [MPa]	85	170	210
Elongation A5 [%]	27	19	11
Vikers hardness [HV]	35	75	100

Table 3

Chemical Properties

Element	Percentage [%]
Si	0.7 ...1.3
Mg	0.6 ... 1.2
Mn	0.4 ... 1.0
Fl	0.50
Cr	0.25
Zn	0.20
Cu	0.10
Ti	0.10
Al	balance

4. MESHING DIE AND WORK PIECE

The die geometry was designed directly in LS-DYNA 2D. The geometrical parameters of the die are: the die channels are for 10 × 10 mm square section; R – outer fillet radius; r − inner fillet radius; the angle between channels is 90 °.

Nodal mesh density for the die component parts was different compared to nodal mesh density of the work piece. So, the step used to achieve the nodal mesh for all component parts of the die was 1 mm. For the work piece that represents the area of interest, a step of 0.2 mm was adopted. The total number of finite elements for work piece and for die was 33 954 from which 20 000 were distributed only to work piece (Fig. 5).

5. THE MATHEMATICAL MODEL

Simulation of SPD that occurs when passing the work piece through the ECAP die with low-friction is based on

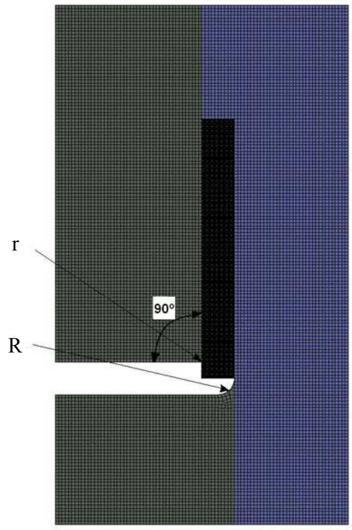


Fig. 5. The meshing models for the component parts of the die and work piece.

theory of plastic flow that establishes incremental relations between the strain, stress and other parameters that characterize the plastic state. Assumptions plastic flow theory is [1]:

- The work piece is isotropic.
- Changing unit volume is infinitesimal, elastic and proportional to the mean stress,

$$d\varepsilon = \frac{1}{K} d\sigma \,. \tag{2}$$

- Total increments $d\varepsilon_{ij}$ of the strain consists of elastic strain increments $d\varepsilon_{ij}^{e}$ and plastic strain increments $d\varepsilon_{ij}^{p}$,

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} \,. \tag{3}$$

- The elastic strain increments are obtained with Hooke's law,

$$d\varepsilon_{ij}^{e} = \frac{1}{2G}\left(d\sigma_{ij} - \frac{3v}{1+v}\delta_{ij} d\sigma \right). \tag{4}$$

- The plastic strain increment deviator is proportional to stress deviator,

$$d\varepsilon_{ij}^{p} = d\lambda\, S_{ij} \,, \tag{5}$$

where $d\lambda$ is an infinitesimal scalar factor. It concludes that the state of stress determines the instantaneous increment of plastic strain. Infinitesimal term $d\lambda$ depends on the incremental plastic strain work and the yield stress on flow surface. The flow surface in von Misses equation is accepted as cylindrical shape around the hydrostatic axis. Because the effort required for work piece strain in ECAP die with low friction is uniaxial, the flow condition for von Mises equation is: $\sigma_1 \neq 0$, $\sigma_2 = \sigma_3 = 0$ and equation became:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_y^2 \,. \tag{6}$$

6. CONDITIONS OF NUMERICAL SIMULATION

After meshing models, the boundary conditions on component parts of the die and the work piece subjected to SPD process were put. SPD of the work piece in the die takes place only in the *X*-*Y* plane. This process presents a great advantage in terms of files size work. This is explained by the fact that the number of finite elements of the component parts of the die and work piece are reduced due to the lack of size along *Z*-axis.

2D numerical simulation conditions are:

- fixed part of the die shows no displacement on *X* or *Y* axes;
- mobile part of the die (which is playing the role of punch) moves only on *Y* axis;
- time needed acheving the plastic deformation in the die − 10 s;
- speed of the mobile part of the die is constant and depends on the geometrical configuration of the die; this speed has values between 7.2 mm/s and 7.5 mm/s;
- due the deformation to which it is subjected in the ECAP die, work piece practically is moving on both directions *X* and *Y*.

7. NUMERICAL SIMULATION

After putting the boundary conditions, the preprocessing phase is completed and the solver of LS-DYNA software takes over fully the solving of problems.

The influence of the geometric parameters of the die was pursued in terms of: effective plastic strains field; effective stresses (Von Mises) and the applied forces on the mobile part of the die. Also, in the case of the same geometrical configuration of the die, the influence of friction coefficient on the applied force on the mobile part of the die was pursued.

Numerical simulations on three geometrical configurations of the die were performed: 1) R = 5mm; r = 0 mm; 2) R = 2.5 mm, r = 1 mm and 3) R = 0, r = 0 mm (instead of the radius chamfers 1 × 45° and 0.5 × 45° were made) for the same coefficient of friction $\mu = 0.1$. In case of the die having the configuration (R = 0, r = 0) three numerical simulations with different friction coefficients ($\mu = 0.05$, $\mu = 0.1$ and $\mu = 0.12$) were performed.

8. OBTAINED RESULTS BY FEM METHOD

After achievement of the simulations, post-processing phase followed, in which the colored maps with effective stresses, strains and the graphs with applied forces needed for the plastic deformation process were made.

Numerical simulation of the mesh deformation after the first pass through the ECAP die with low friction was made using LS-DYNA 2D software. The largest plastic strains of the mesh are located in the area in which the work piece exceeded the right angle between the two channels of the die (horizontal channel area). It can be also notivced that in the immediate area of the small fillet radius r of the die, the first layer of finite elements remained almost unaltered, unlike the second layer of elements that is remaining behind (displaced with respect to each other.).

This can be explained by the occurrence of a large friction force between the work piece and fixed part of the die during the SPD that causes a sliding (shearing) of the material layers (Fig. 6). Approximate value of this shearing strain angle is $\gamma = 60°$. In the large fillet radius area of the die, it is noted that the friction is much smaller and this has resulted in a much smaller plastic deformation for the layers of the finite elements. Approximate value of the shearing strain angle in this area is $\gamma = 10°$. These two values are very close to those obtained by finite element analysis ($\gamma = 60°$ and $\gamma = 8°$) by the authors of the article [5].

Two comparative analyzes of the simulation results were conducted:

- A comparative analysis of the simulations results for the three geometrical configurations of the die (at the same coefficient of friction $\mu = 0.1$) in which the evolution of the effective stresses $\sigma_{\text{Von Mises}}$, effective plastic strains ε_p, and applied force exerted by the moving part of the die on the work piece were pursued.

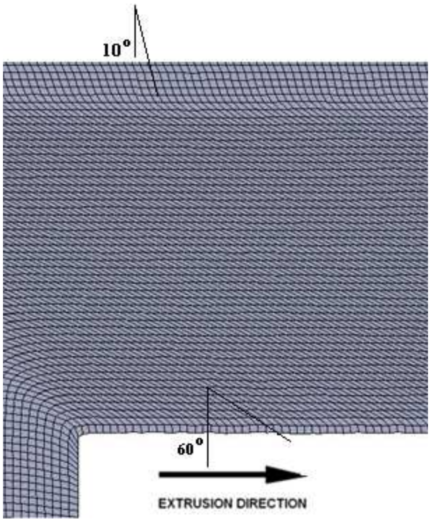


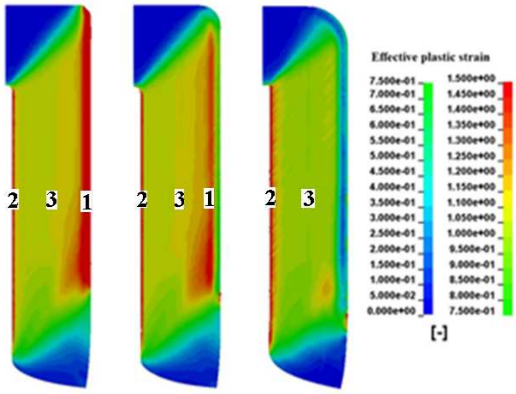
Fig. 6. Evolution of the nodal mesh, during work piece plastic deformations (R = 5 mm, r = 0 mm, μ = 0.1).

- A comparative analysis of the simulations results for the geometrical configuration of the die R = 5 mm, r = 0 mm for different coefficients of friction (μ = 0.05, μ = 0.1 and μ = 0.12) in terms of the evolution of the application forces on the moving part of the die was pursued.

In Fig. 7, the effective plastic strains for the three geometrical configurations of the die are presented.

From this figure we can draw the following conclusions:

- On the die with geometrical configuration R = 0, r = 0 (chamfers of 1 × 45° and 0.5 × 45°) two fields of plastic strains are observed (see no. 1 and 2 on Fig. 7,*a*), in the contact area of the work piece with the fixed part of die, both in the right of the large chamfer and the small one. This is due to the effect of the larger friction forces that occur in these areas and also that locally they leads to greater deformations than on the entire cross-sectional area of the work piece; it is noted that on approximately 75% of the cross-sectional area of the work piece, the effective plastic strains field is yellow (see no. 3 on the Fig. 7,*a*), which indicates an effective plastic strain between 1.15 and 1.2;
- On the die with geometrical configuration R = 2.5, R = 1 the effective plastic strains field is similar, but less pronounced in the contact areas of the fixed part of the die with the work piece, which suggests lower friction forces (see no. 1 and 2 on the Fig. 7,*b*). Effective plastic strain is situated in the same limits between 1.15 and 1.2 (see no. 3 on the Fig. 7,*b*);
- On the die with the geometrical configuration R = 5, r = 0 it's observed a stronger field of effective plastic strains only in the area of the contact between the fixed part of the die and work piece in the right of the small fillet radius (see no. 2 on the Fig. 7,*c*). Here, the friction forces that occur, leads to the appearance of the local higher effective plastic strains. In rest, (see no. 3 on the Fig. 7,*c*) indicates a field of effective plastic strains slightly lower than the previous configurations, within the range 1.05 and 1.1;



a b c

Fig. 7. Effective plastic strain in the work piece, with different geometries: a − R = 0, r = 0; b − R = 2.5, r = 1 mm; c − R = 5, r = 0 mm (coefficient of friction μ = 0.1).

- from the technological point of view, a die with geometrical configuration R = 0, r = 0 (chamfer) is more easily achieved.

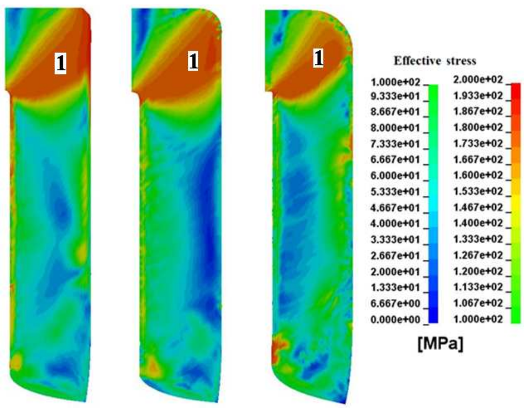
The die with the geometrical configuration R = 5, r = 0 is technologically more difficult to realized, but has the advantage of a more homogeneous distribution of the effective plastic strain field.

In Fig. 8 the distribution fields of the effective stresses (von Mises) are shown for three configurations of the die. From the diagrams of the distribution fields for theeffective stresses (von Mises) a similar distribution in the three cases is observed. The maximum effective stresses for the three geometrical configurations are: R = 0, r = 0 – σ_y = 195 MPa; R = 2.5, r = 1 – σ_y = 185 MPa and R = 5, r = 0 – σ_y = 188 MPa.

In the case of the geometrical configuration of the die R = 5, r = 0, a distribution of effective stresses field, on a lower surface than in the other two configurations (see the areas noted with no. 1 on the Fig. 8,*a*).

The evolution of the applied forces accomplished during the SPD in the three geometrical configurations of the dies is presented in Fig. 8.

The graph from Fig. 9, obtained in post-processing phase, highlights that the internal geometry of the die (fillets, chamfers) does not influence in a large extent the



a b c

Fig. 8. Effective stress (Von Mises) in work piece, with different geometries: a − R = 0, r = 0; b − R = 2.5, r = 1 mm; c − R = 5, r = 0 mm (coefficient of friction μ = 0.1).

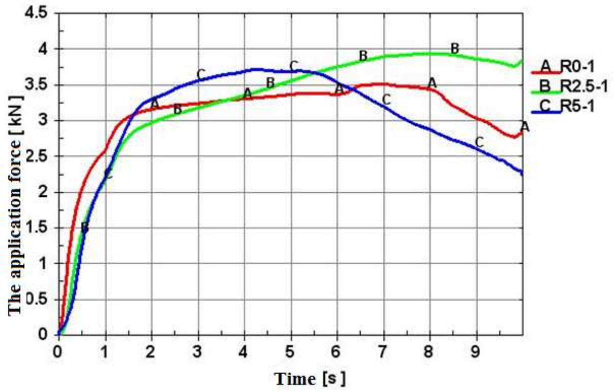


Fig. 9. Forces applied on the moving parts of the die, for various geometries: *a* − *R* = 0, *r* = 0; *b* − *R* = 2.5, *r* = 1 mm; *c* − *R* = 5, *r* = 0 mm (coefficient of friction μ = 0.1).

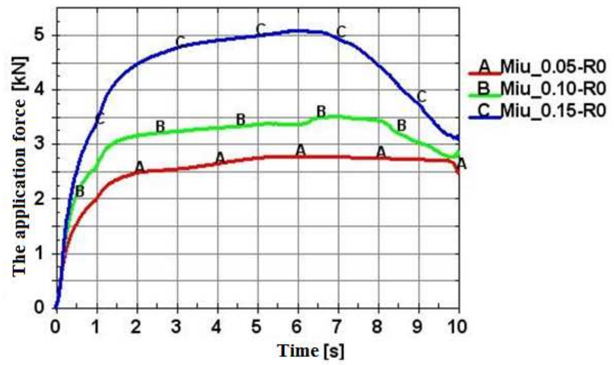


Fig. 10. Forces applied on the moving parts of the die, for various friction coefficients: *a* – μ = 0.05, *b* – μ = 0.1; *c* – μ = 0.15 (geometrical configuration of the die *R* = 0, *r* = 0).

size of applied forces. It should be noted that the applied force is exclusively the result of the forces inside the die: the forces consumed for the plastic strains and those of friction between the work piece and the die. The geometrical simplicity of the die without fillets (*R* = 0, *r* = 0, with chamfers) it recommends for the use in the technological processes of achieving for materials with enhanced mechanical properties.

The evolution of the application forces achieved during the SPD in the ECAP die with low friction (obtained also in the post-processing phase), for the geometrical configuration *R* = 0, *r* = 0 for three coefficients of friction: *a* − μ = 0.05, *b* − μ = 0.1 and *c* − μ = 0.15, is shown in Fig. 10.

As expected, the higher coefficients of friction mean larger forces. For the coefficient μ = 0.15 an applied force of around 5 kN is obtained, that is about two times higher than the force resulting for the coefficient of friction μ = 0.05, while the applied force achieved for the coefficient of friction μ = 0.1 is located between these two values (≈ 3.5 kN).

9. CONCLUSIONS

Following the completion of numerical simulations concerning the study of the SPD, in the ECAP die with low friction, we can draw the following general conclusions:

- the value of the application force on the mobile part of the die, grows once with increasing friction coefficient;
- the fields of the effective plastic strains for the die configurations, from Fig. 8 a and b, are local the most prominent (see the no. 1 and 2) in the areas of the contact High coefficients of friction can lead to depositions material on the walls of the die, that prevents plastic deformation process and may ultimately lead to its blocking;
- inner geometry of the die (fillets) does not much influence the application forces that working on the moving part of the die;
- even if the friction forces developed are less than in conventional ECAP die however to achieve plastic deformation with less effort is necessary to use a special anti-friction oil;
- after the analyze by numerical simulation, need to achieve a inclined areas (chamfer or fillet) at the contact between the die and the work piece has resulted, for its engaging, without blocking the process of plastic deformation;
- the goal of this process is the obtaining of an ultrafine grain structure of the material, that means superior mechanical properties to those by conventional processes achieved;
- numerical simulation presented in this work has in addition to the one realized in the article [5] from the references, 2 studies: the influence of the friction coefficient as well as the internal geometry of the die, on the application forces;
- the numerical simulation provides an alternative tool for scientific investigation, substituting costly laboratory experiments, time consuming and funds.

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