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EXPERIMENTAL AND NUMERICAL ANALYSIS OF COINING PROCESS USING MICROFORMING APPROACH

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Original scientific paper

This study concerns the analysis of significant changes of process parameters in a coining process when dealing with different grain sizes. A reason for these changes can be found if the coining process is understood as a microforming process. Using that approach a few problems are explained and solved: large elastic springback, insufficient die filling, significant enlargement of total forming force, changes in friction factor. An experimental research provided data about percentage of elastic springback in total high reduction during coining process of Al 99,5 in three grain sizes. An experiment also included microscopic observation of gravure filling. The final result is a correlation between grain sizes and elastic springback, and also a correlation between grain sizes and gravure filling for different forming forces. Using experimental data in the creation of numerical FE (finite element) model, the dependence of contact friction changes in correlation to the change of the grain size is presented. Physical interpretation of the results is given by the theory of Bowden and Tabor.

Keywords: *coining process, die filling, microforming, process parameters*

Eksperimentalna i numerička analiza plitkog gravurnog kovanja kao procesa mikrooblikovanja

Izvorni znanstveni članak

Istraživanje obuhvaća analizu značajnih promjena parametara procesa plitkog gravurnog kovanja pri promjeni dimenzije kristalnog zrna materijala. Razlog ovih promjena može se pronaći ako spomenuti proces promatramo kao proces mikrooblikovanja. Korištenjem ovog pristupa nekoliko problema može biti objašnjeno i riješeno: veliki elastični povrat, nedostatno ispunjavanje gravure, značajno povećanje sile oblikovanja, promjene faktora trenja. Eksperimentalno istraživanja dalo je podatke o udjelu elastične deformacije u ukupnoj deformaciji tijekom plitkog gravurnog kovanja Al 99,5 u tri dimenzije zrna. Eksperiment je uključio i mikroskopsko promatranje ispunjavanja gravure. Konačni rezultat jest međuzavisnost dimenzije zrna i elastičnog povrata te dimenzije zrna i popunjenosti gravure za različite sile oblikovanja. Korištenjem eksperimentalnih podataka kreiran je numerički model kojim je dobivena ovisnost promjene faktora trenja o promjeni dimenzije kristalnog zrna. Fizikalna interpretacija ovih rezultata načinjena je prema Bowden Taborovoj teoriji.

Ključne riječi: *popunjavanje gravure, mikrooblikovanje, plitko gravurno kovanje, parametri procesa*

1
Introduction

Coining is a deformation processing of metallic materials. It is usually a closed die forging (but that is not a rule) where only the surface topography of a blank is modified without significant bulk metal flow in a large scale. In such a way, coining is widely used for giving a functional and/or decorative surface geometry. The main characteristic of coining process is threedimensional traceabillity of surface microgeometry. The most common product of coining are money coins. This fact puts a tabu on accessibility of data about the process.

Apparently, the process of coining seems very simple: it is nothing but geometrical matching of die and workpiece by plastic deformation. However, the following factors hinder even micrometer scale precision: surface damage, insufficient filling, foreign substance, excess lubricant, deformation during unloading and large elastic springback [1].

This paper is going to deal with the last mentioned problem: elastic springback of the material and also with the forming force that is needed for correct die filling. These problems are experimentaly analysed. Changes in friction factor are going to be numerically analysed using experimental data and finite element method.

In settling the problem microforming approach is used. This approach takes into consideration grain size influence on the process parameters. It is a new approach to coining analysis that still has no wide application.

The goal of the performed experimental research is to solve some of the most common problems that occur in coining process and are confirmed through available data from practice:

- Insufficient filling of very small parts of the die.
- Significant changes of forming force and elastic springback for different grain sizes in open and closed die coining.

The hypothesis of the performed research is that blank material, because of the size influence, acts according to microforming postulates. Furthermore, it is assumed that material will show significantly different behaviour in open and closed die coining processes and will also demand significantly different forming force for different grain sizes.

Grain size is expected to be optimized according to the smallest forming force and the best die filling. Another recommendation for optimisation should come from numerical analysis of friction factor.

2
Basis of classical forming approach

While external forces influence a working part, dimension and shape changes occur. These changes consist of elastic and plastic deformations. If external forces overcome elastic limit, atoms are moved to new positions where cohesive forces try to place them in a new steady state. Once atoms reach a new steady state, the deformation becomes permanent – plastic deformation [2].

The real monocrystal incorporates discontinuities that can be places with missing atom, with inserted atom in inter atomic space, or edge discontinuities. Surface discontinuities appear on crystal boundaries. All these discontinuities are called dislocations. Dislocation makes a low strength area because of irregular inter atomic distance which disturbs inter atomic forces. In the case of loading, even a lower force can be enough to make dislocation move through the crystal. Consequently: plastic deformation is the moving of dislocations through the crystal induced by shear stresses [2].

Because of the shear stress activity, gradually dislocation moving takes effect until dislocation comes to the crystal surface. Dislocations move through the crystal and pile up on its surfaces. Inhibited dislocation moving and need to "break away" from the obstacle of any kind demands increasing of shear stress. Plastic deformation progress requires constant increase of shear stress which means that crystal more and more resists dislocation moving. After a large number of dislocations pile up on the crystal boundaries, material ductility is considerably reduced. When force works on polycrystalline material and reaches its critical value, sliding occurs in the most favourable oriented planes until deformation reaches critical level. Rotation of other crystals that follows this process settles them into a good position for further deformation.

Once when crystal boundaries become the places of dislocation concentration, under the same force, the deformation on the crystal boundaries will become lower than the deformation inside the crystal body. The consequence is that real polycrystalline material resists plastic deformation more than real monocrystal. That is the reason for enlargement of shear stresses needed to provide plastic deformation; hence the result is increased flow stress.

Grain size of polycrystalline material also influences the flow stress. The smaller the grain size is, the larger is the flow stress, consequently, formability is lower [3].

3
Microforming approach

When the dimension of the workpiece (or even a part of the workpiece) decreases to the same order as is the magnitude of the grain size (i.e. 5-10 times of the grain size), individual grains will dominate the properties of that workpiece. This change in properties directly influences the changes in process parameters. The classical plasto-mechanics theory could not be used to explain the phenomena directly.

The surface grains are less restricted than volume grains. Dislocations, moving through the grains during deformation, accumulate at grain boundaries but not at the free surface. This leads to less hardening and lower resistance to the deformation of the surface grains.

The specific conditions of orientation and size of every single grain are now reflected in the forming result as it is no longer averaged by a huge number of grains. For example, the micro size tensile tests at room temperature have shown that the yield strength and the tensile strength decrease with scale decreasing, as well as with grain size increasing [4].

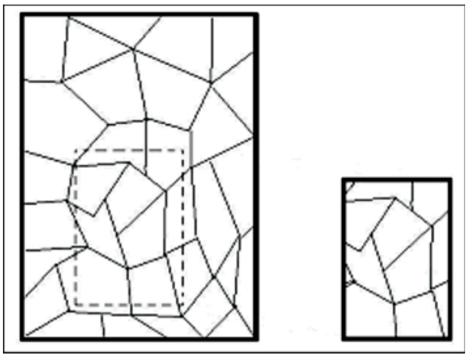

Figure 1 Size influence to the ratio of surface and inner grains: larger part – surface grains/inner grains = 17/16, smaller part - surface grains/inner grains = 9/2 [5]

In a closed die, grains will not have free surfaces (they will be surrounded by the die) and influence of the part size will go off because there will be no free material flow. That is why there is no reduction of forming force.

Size influence to the ratio of surface and inner grains is presented in Fig. 1.

4
Experimental research

Because of dealing with a part with relatively small dimensions (1-2 mm high, and 0,06 mm - the smallest die parts), it is assumed that this forming technology completely turns into microforming technology. Working part is observed as a group of crystal grains with defined shape and dimensions.

Because of that, it is expected that blank material will follow microforming assumptions in a way that the amounts of elastic springback will have the opposite values whether the coining process is performed in open or closed die. This way of material behaviour would confirm the assumption that coining, in complete, belongs to the group of microforming processes, and should be treated like one of them. In such a way many problems could be avoided.

An experiment should prove all these assumptions. Blanks made of Al 99,5, initial height 2 mm, and diameter 20 mm will be deformed with different reduction coefficient in open and closed die. Measured values will be: forming force, total high reduction, elastic springback and die filling. The results of annealing are three different grain sizes: 76 μm, 47 μm and 39 μm. All three grain sizes are analyzed by observation of the same process parameters and their interference. The heat treatment regime is given in Tab. 1.

Table 1 Grain sizes achieved by different heat treatment regime

Heat treatment regime	Grain size / μm
350 °C – 2 h / air cooling	39
450 °C – ½ h / air cooling	47
450 °C – 2 h / air cooling	76

4.1
Experiment – the first step

Aluminium blanks of three different grain sizes have been coined in an open die. This means they have been pressured between two plane parallel parts of a tool. The controlled variable was the forming force. It was changed from 50 kN to 400 kN in a step of 50 kN. The measured values were total high reduction and elastic springback. Deformation speed was 0,012 mm/s. Tool position was measured by linear variable differential transformer and tracked by a computer. Obtained results are presented by diagrams in Figs. 2, 3 and 4.

It is noticeable that there exists a significant difference between relevant variables for different grain sizes. Total displacement grows up along with the grain size. On the opposite, elastic springback rises as the grain size declines.

Using measured experimental values, the relation between flow stress and obtained true strain has been calculated for each grain size. These curves were gained from standard equations as follows:

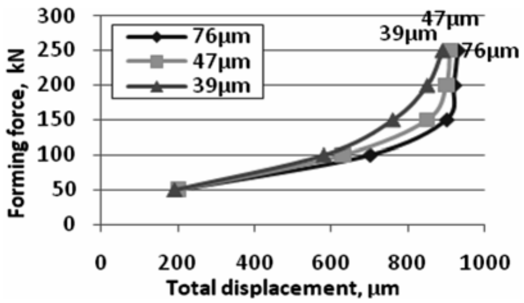

Figure 2 Relation between forming force and total displacement - open die coining

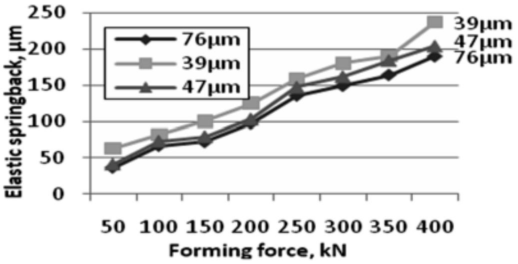

Figure 3 Relation between elastic springback and forming force – open die coining

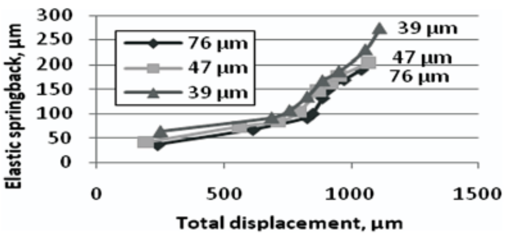

Figure 4 Relation between elastic springback and total tool displacement – open die coining

$$k_{\mathrm{f}} = \frac{F}{A}, \tag{1}$$

where k_{f} presents flow stress, F is a momentary forming force, and A is a momentary contact pressurized surface area.

True strain can be calculated from the following expression:

$$\varphi = \ln \frac{h_0}{h_0 - \Delta h}. \tag{2}$$

Where φ is a true strain, h_0 is an initial blank high; Δh is a total tool displacement for the specific forming force. Calculated curves are presented in Fig. 5.

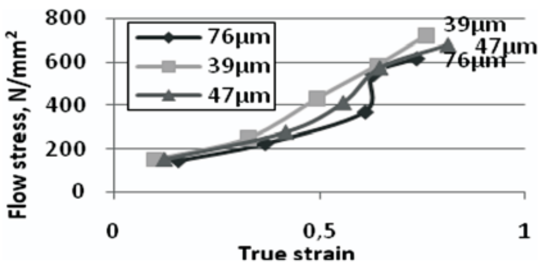

Figure 5 Experimentally obtained true strain – flow stress dependence

Although there are some irregularities in the shape of the curves, the tendency of flow curve decreasing as the grain size grows up is obvious.

It is important to notice the reason of certain imperfections in curve shapes on presented diagrams. Each point that defines certain diagram is calculated from the experimental results. It presents an average of numerous measurements. Because of great dissipation of measured values, the calculated average cannot form a perfect shape of diagrams.

4.2
Experiment – the second step

The second step of the experiment leads to exploration of closed die coining of identical blanks as they were in the first step of the experiment. Because of die influence, the metal flow has been restricted and steered to die filling. Material behaviour in such changed conditions has been examined. In this case 'material behaviour' means elastic springback after the action of forming force. Greater elastic springback can cause insufficient die filling. Furthermore, the quality of coined surface after the influence of different forming forces and for three different grain sizes is going to be considered.

Results of measurements are given in Figs. 6 and 7. Fig. 6 shows the relation of forming force and total high reduction for its two sizes – 800 μm and 850 μm. Measurements have been made on five samples (blanks) for each size of total high reduction and also for each grain size. Fig. 7 shows the relation between total high reduction and elastic springback for two sizes of reduction – 800 μm and 850 μm. It can be noticed that forming force rises with greater high reduction and also at coarse grain. Elastic springback also rises together with grain size.

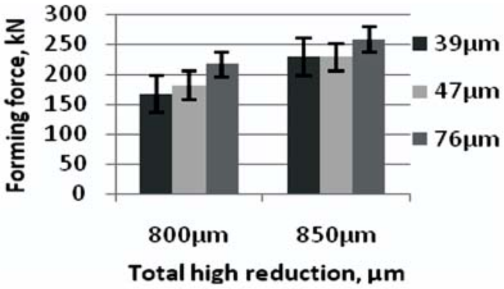

Figure 6 A correlation of total high reduction and forming forces for three different grain sizes in closed die coining

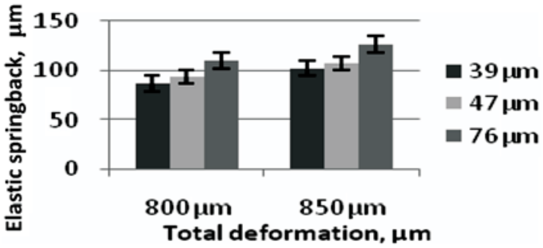

Figure 7 A correlation of total high reduction and elastic springback for three different grain sizes in closed die coining

The influence of grain size on die filling has also been monitored during the second part of the experiment. Specimens of different grain sizes with high reduction of 800 μm have been snapshot by microscope. Lower high reduction has been chosen because it demands lower forming force and lower forming force is always more acceptable in industrial conditions. Difference in die filling is very obvious. Specimens with grain size of 76 μm have much worse die filling than those whose grain size is 39 µm. The most obvious parts are marked in Fig. 8.

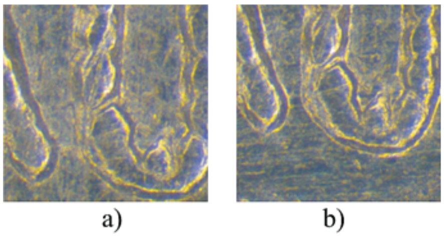
a) b)

Figure 8 Photos of one segment of the coin surface, specimens with two grain sizes, (a) 76 µm and (b) 39 µm, produced with the same high reduction

4.3
Resume of the experiment

Experimental results very clearly put the coining process into a microforming category. As it is presented, an open die coining designates that finer grains cause greater elastic springback and greater forming force. Also enlargement of the grain size causes decrease in flow stress. All these differences in process variables are significant and reach even 20 % between specimens of two different grain sizes (39 µm and 76 µm). Such behaviour is typical for microforming processes. On the contrary, when the coining process is performed in a closed die, and material flow is restricted and steered to die filling, the process variables show the opposite behaviour. Now, coarse grains demand greater forming force and cause larger elastic springback. Also, coarse grains cause poor die filling. Such behaviour is also typical for microforming processes. Therefore, the conclusion of this research can be that the coining process belongs to the group of microforming processes. To avoid some specific problems that occur during a coining process, it must be treated as a microforming process. This means that grain size takes a leading part in controlling of process parameters. If the coining process is preformed in a way that material flow is free, or predominantly free, coarse grains are recommended. On the other hand, if material flow is restricted in a closed die, and exact die filling is important, finer grains should be taken.

5
Numerical simulation

This part of the research analyses significant changes in contact friction by changing the grain size. That phenomenon characterizes all microforming processes. Contact friction is analyzed using finite element method (FEM) and the intention of the analysis is a description of grain size – friction factor correlation in a case of open die forging. Although, it would be interesting to make the same analysis in the case of closed die forging, in particular case it is not possible because of very complex and small dimensions of gravure details that cannot be digitalized and prepared for the numeric model.

Numerical simulation of an open die forging has been supported by MSC Marc Mentat program package. Axisymmetric 2D FEM model has been created. Material is defined as elasto-plastic isotropic. In elastic field constants for Al 99,5 are: Young modulus E = 69000 MPa, Poisson ratio v = 0,33. Isotropic plasticity is modelled using experimentally obtained results – the correlation between true strain and maximal specific stress for three different grain sizes – Fig. 5.

Element type 10, a four-node, isoparametric arbitrary quadrilateral is used. As this element uses bilinear interpolation functions, the strains tend to be constant throughout the element. This element is preferred over higher-order elements when used in a contact analysis. The stiffness of this element is formed using four-point Gaussian integration.

Coulomb friction that is used in modelling is a highly nonlinear phenomenon dependent upon both the normal force and relative velocity. When the stress based friction model is used, the following steps are taken [6]:

1. Extrapolate the physical stress, equivalent stress, and temperature from the integration points to the nodes using the conventional element shape functions.
2. Calculate the normal stress.
3. Calculate the relative sliding velocity. At the beginning of an increment, the previously calculated relative sliding velocity is used as the starting point. When a node first comes into contact, it is assumed that it is first sticking, so the relative sliding velocity is zero.
4. Numerically integrate the friction forces and the stiffness contribution.

The friction calculation is dependent upon the surface normal and tangent. When using the analytical approach, the friction calculation includes the effect of changes in the direction of the normal vector from iteration to iteration. This improves the accuracy and convergence behaviour.

Model has been created from 2000 elements and analyses open die coining up to $\varphi = 0{,}6$ (true strain). Figures 9 and 10 present initial mesh and a deformed one with maximum distortion.

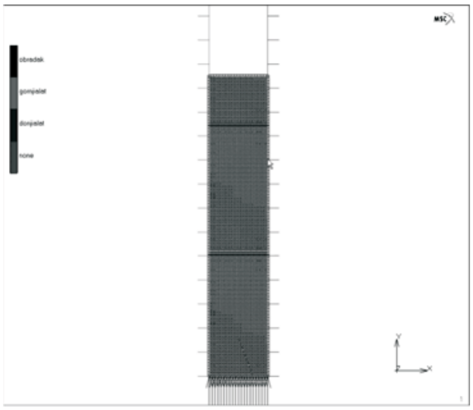

Figure 9 2D Axisymmetric FE model created of 2000 elements

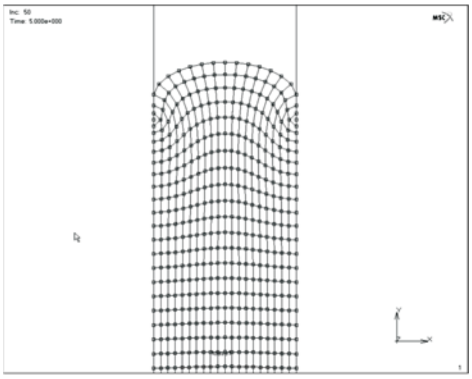

Figure 10 Distorted mesh at the end of coining process

5.1
Algorithm for determination of friction factor

By using well known constants for defining material properties in elastic field, geometry of axisymmetric 2D model, experimentally defined curves (true strain – flow stress dependence for different grain sizes in plastic area), simple boundary conditions and contact definition, the initial base for algorithm developing is set. Another relevant factor for its development is: experimentally obtained maximal forming forces for different grain sizes. These forces should be achieved using numerical simulation (in a range ±10 %), so that numerical model could be relevant, and friction factor valid. Fig. 11 presents that algorithm.

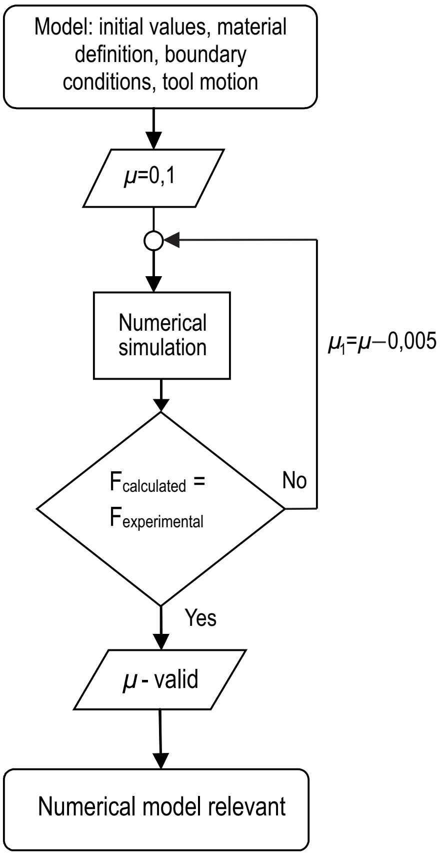

Figure 11 Algorithm used for numerical determination of friction factor

5.2
Results of numerical simulation

By using a described algorithm a numerical simulation is performed. Calculated forming forces achieved predicted confidence interval of ±10 % according to experimental values. Maximal calculated forming forces match different friction factors for different grain sizes. Parallel overview of experimental and calculated results together with associated friction factor is presented in Tab. 2.

5.3
Interpretation of difference in friction factor

For physical interpretation of difference in friction factor, the Bowden and Tabor adhesion model or plastic junction model is used. This model gives an access into friction nature and into friction factor changes in relation to surface roughness and used lubricants. The base of this model (as it is shown in Fig. 12) is that the real area of contact is made up of a large number of small regions of contact, in the literature called *asperities* or junctions of contact, where atom-to-atom contact takes place. When rough surface slides against a softer surface, in adhesive wear, asperity junctions plastically deform above a critical shear strength, which depends on the adhesive forces of the two surfaces in contact. Assuming during a frictional sliding process a fully plastic flow situation of all asperities, friction is found to change linearly with the applied load. This stress regularly reaches 2000-2500 MPa distributed on convex spots. Under such point load micro-welding occurs. In order to achieve sliding, micro welds must be broken. Therefore according to Bowden and Tabor friction force becomes a sum of all shear forces needed for this breaking.

Table 2 Friction factors obtained by numerical simulation

Grain size / μm	Experimental forming force / kN	Calculated forming force / kN	**Friction factor**
39	275	293	0,050
47	225	244	0,040
76	155	167	0,025

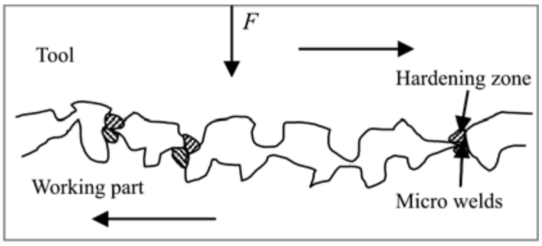

Figure 12 Bowden and Tabor adhesion model [3]

According to the explained model it is possible to make an explanation of friction factor increase by decrease of grain size of the material. It can be assumed that smaller grain size makes larger number of critical convex spots. In this way the number of micro-welds is increased, and also a sum of all shear forces that need to be broken.

6
Conclusion

Through presented research work it becomes clear that the coining process undoubtedly belongs into a group of microforming processes. In the intention to prove this statement the next steps have been done, and they brought clear results:

- Identical experimental samples have been deformed in two ways: open and closed die coining. Open die coining provided free material flow, and closed die restricted its flow.
- Heat treatment resulted in three different grain sizes of the same material – Al 99,5.
- Data processing for open die coining experiment showed significant influence of forming force and grain size on total high reduction and elastic springback in the following way: large grain size and identical forming force result in greater total high reduction and minor elastic springback.
- Data processing for closed die coining experiment showed significant influence of total high reduction and

grain size on elastic springback and forming force, but that influence is reflected in the opposite way: increased grain size and identical forming force resulted in decreased total high reduction and major elastic springback.
- Surface scanning showed better gravure filling, even in case of smaller high reduction, in case of smaller grain size.

With regard to the hypothesis that the coining process belongs to the group of microforming processes these results are expected. Namely, all microforming processes show the opposite behaviour of the previously mentioned parameters in the cases of free and restricted flow of working piece material.

According to the presented results it is possible to give some recommendations to avoid some specific problems that occur during a coining process. Coining must be treated as a microforming process. This means that the grain size takes a leading part in controlling of process parameters. If coining process is preformed in a way that material flow is free, or mostly free, coarse grains are recommended. On the other hand, if material flow is restricted in a closed die, and exact die filling is important, finer grains should be taken.

In favour of that recommendation are the results of numerical simulation which indicates increased friction factor with finer grain. This means that in the case of closed die coining especially in the case of small dimensions of gravure details, very fine grain size is recommended.

Further research work should be directed to the comparison between different materials, and also to numerical simulation of the closed die coining process.

7
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