Accuracy of Model Force Prediction in Closed Die Coining Process

Zdenka Keran1,* – Živko Kondić2 – Petar Piljek1 – Biserka Runje1
1 University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Croatia
2 University North, Croatia

In micro-forming processes, such as coining, the microstructure of the material and dimension scale of the coined geometry can have a substantial influence on the mechanism of material deformation. The influence of the grain size on the coining force and closed die filling is investigated experimentally, and a mathematical model for result prediction has been created according to the obtained experimental results. The material of the billet is 99.5 % aluminium, and the die geometry is relatively complex.

The presented mathematical model takes into account the influence of size effect on the material flow curve through die cavity geometry and estimates the final coining force and corresponding associated displacement of the tool. This enables a controlled influence of the grain size of the specimen material on forming force and tool displacement in the coining process and a reliable prediction of the final coining force and related tool displacement associated with a completely filled die cavity. To determine the accuracy of model force prediction, the experimental and modelled data were statistically analysed and graphically presented.

Keywords: micro-forming, coining, mathematical modelling, forging force

Highlights
- This paper presents research of the influence of the grain size of the specimen material on the coining force and closed die filling.
- The influence has been investigated experimentally, and a mathematical model for result prediction has been created.
- The mathematical model takes into account the influence of size effect on the material flow curve.
- The experimental and modelled data were statistically analysed and graphically presented.

0 INTRODUCTION

By using closed shallow die forging (coining), it is possible to obtain complex geometry products with fine surface details of very small dimensions. According to [1] to [4], this process enters the micro-forming field. The micro-forming processes are specific. They deviate from the macro deformation processes assumed on the basis of the similarity theory because they are subjected to the so-called “size effects”. The basis of the coining process was initially published by Bocharov et al. [5]. However, the analysis and models of the coining process, observed from the current state of the art, are more appropriate to the analysis of the classic forging processes. One scientific paper [6] deals with deformation of the surface layer and its asperities. These works completely exclude total deformation of the material and observe the effect of surface roughness on the friction coefficient in processes that involve high levels of contact pressure. Surface roughness affects the size of the contact surface between the tool and workpiece and affects the level of friction during the process. Surface roughness is certainly independent of the dimension of the workpiece itself. According to [7], the causes of size effects can be divided into the causes of density (compression), the causes of the part shape and the causes of the structure. If the density of dislocations in the crystal lattice remains unchanged, the size effect is due to the fact that the reduction in the dimensions of the workpiece also reduces the volume of the material, which results in a reduction in the number of dislocations contained in the material. If the workpiece shape remains unchanged, the ratio of the workpiece surface to the volume changes with the reduction of the dimensions of the workpiece. In this case, the effect of the size is because certain properties are related to the surface (surface tension, heat, friction, surface crystalline grain, etc.), and some properties are related to the volume (weight, thermal capacity, the total number of crystalline grains, etc.). In the case of structural causes, surface roughness, geometry, dislocations, crystalline grain orientation, etc. contribute to the size effect.

The work of Ramaekers and Hoogenboom [8] deals with the analysis of the coining process in a fully closed die. The paper explains the determination of the coining force when considering ideal plastic material, which neglects the elastic properties of the material, and its flow stress is constant, i.e. does not depend on the true strain of the material. The paper published by Brekelmans et al. [9] examines the hardening of material. Although the material elastic properties of such material are neglected, the flow stress is no longer constant but depends on the true strain of the material.
The work of Ike and Plančak [10] classifies the coining process into the micro-forming area. In their paper, the analysis of the micro-geometry forming was done in the closed coining die with the assumed plane state of strain. Many papers are concerned with the study of the size effects in micro-forming, [7] and [11] to [13], and their influence on the various micro-forming processes, such as micro-indentation [14], micro-imprinting [15], micro-extrusion, [16] and [17], and the bulk forming processes of sheet metal, [18] and [19]. However, relatively few works deal with the coining process and the real problems of production, such as residual stress, elastic deformation and incomplete die filling, [1] to [3], [10] and [20] to [22], lubricant residues and surface damage [23], and tool development and manufacturing, [24] and [25]. That is why this process is still not well-researched and well-known, especially from the micro-forming point of view. By defining the crystalline grain size effect on elastic springback, die filling and the coining force, it is possible to control the process parameters, which will greatly contribute to the quality of the product. Some research work found a solution in FEM analysis of a material behaviour that provides very detailed access to stress-strain conditions [26].

This paper presents research on the influence of the grain size on the coining force and closed die filling. The influence has been investigated experimentally, and a mathematical model for result prediction has been created according to obtained experimental results. The mathematical model takes into account the influence of size effect on the material flow curve and estimates the final coining force and corresponding associated displacement of the tool.

To determine the accuracy of model force prediction, the experimental and modelled data were statistically analysed and graphically presented.

1. EMPIRICAL MODEL OF COINING FORCE

Important information in the coining process is knowledge about the forming force or force in which a completely filled die cavity is achieved. In scientific publications, [27] to [29], the coining force was estimated with similar empirical models, which can be reduced to Eq. (1):

$$ F = K_k \cdot k_f \cdot A_1 \cdot k_{f1} = f(\varphi_{p1}). \quad (1) $$

The forging factor $K_k$ is, in this case, a correction factor that includes the impact of the initial dimensions of the workpiece material, inhomogeneous deformation and friction between the contact surfaces of the workpiece and the tool (forging die) [2]. Since the forging factor depends on the type of forging process and the geometry of the die, Eq. (1) can be understood as a general model for calculating the forging force. The empirically determined ranges of the forging factors, for the specific processes and complexity of the die cavity, are adapted from [27] to [29] and given in Table 1, which gives a relatively wide range of forging factors for a specific process. Together with a subjective estimation of the complexity of die cavity geometry this shows that the results are mostly based on the experience of engineers.

| Die type     | Die cavity complexity | Forging factor |
|--------------|-----------------------|----------------|
| Half Closed  | Simple                | 3 to 5         |
|              | Complex               | 5 to 8         |
|              | Very complex          | 8 to 12        |
| Closed       | Simple                | 6 to 8         |
|              | Complex               | 8 to 10        |

Flow stress expresses the mean value of the current flow stress in the workpiece, and it directly depends on the current true strain of the material. Since the coining process involves the impressing of complex die geometry into the workpiece material, the true strain is not uniform and changes depending on the observed working point, which makes it very difficult to determine the adequate value of the current strain and the current flow stress.

In this case, the current stress is estimated approximately on the basis of the upsetting test and the yield stress of the material or, as in the case of a correction factor, is determined by the empirically obtained values from [24], shown in Table 2. Deformation resistance in Table 2 is defined as a product of a forging factor, $K_k$, and flow stress, $k_{f1}$, for the specimen material [2].

| Material     | Tensile strength, $R_m$ [MPa] | Deformation resistance, $K_k \cdot k_{f1}$ |
|--------------|-------------------------------|------------------------------------------|
| Al, 99 %     | 80 to 120                     | 50 to 80                                 |
| Al alloys    | 180 to 320                    | 150                                       |
| Bronze       | 290 to 410                    | 200 to 300                               |
| Copper       | 210 to 240                    | 200 to 300                               |
| Ferrous alloy| 280 to 420                    | 300 to 400                               |
| Steel        | 600 to 750                    | 600 to 800                               |

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1.1 Extended Empirical Model Depending on the Crystalline Grain Size

The empirical model of the coining force, Eq. (1), can be expressed depending on true strain as:

\[ F(\varphi_p) = p(\varphi_p) \cdot A(\varphi_p). \]  

(2)

The required acting pressure can be expressed as:

\[ p(\varphi_p) = K_k(\varphi_p) \cdot k_f(\varphi_p). \]  

(3)

Here \( k_f(\varphi_p) \) expresses the flow stress as a function of a true strain \( \varphi_p \), i.e. the strain determined by the given flow curve, and represents a specific deformation resistance as a material parameter, while the \( K_k(\varphi_p) \) is a strain-dependant forging factor which represents a correction function that corrects the effect of contact friction and the influence of die geometry and workpiece dimensions and shapes.

When coining in identical conditions (equal die, equal workpiece dimensions, equal friction conditions, equal deformation velocity, etc.) for which the only difference is the crystal grain size of the workpiece, the change in the effective coining (forming) pressure depends entirely on the change in material resistance to deformation, i.e. the material flow curve, and is independent of the forging factor:

\[ p(\varphi_p, d) = K_k(\varphi_p) \cdot k_f(\varphi_p, d). \]  

(4)

Therefore, the forging factor \( (K_k) \) can be considered constant for the individual true strain of the material. In the case of true strain at which the die is fully filled, the correction function value corresponds to the empirically determined forging factor (Table 1).

By incorporating the expanded Hall-Petch expression from [20] and [30] into Eq. (4), the next formulation for forging force is obtained, in which the forging force depends on true strain and the crystalline grain size:

\[ F(\varphi_p, d) = K_k(\varphi_p) \cdot A(\varphi_p) \cdot \left[ M_{\alpha} \cdot \tau_G(\varphi_p) + K_{hp}(\varphi_p) \cdot d^{\frac{1}{2}} \cdot \beta \right]. \]  

(5)

In Eq. (5), \( M_{\alpha} \) is the average orientation of the crystalline grid of all grains. Lorentzen et al. [31] have experimentally demonstrated that the metal with the FCC structural grid orientation factor has \( M_{\alpha} \) about 2.6. \( \tau_G \) is the critical shear stress of a crystalline grain [31]. \( K_{hp} \) is interpreted as the resistance of the grain boundary to deformation (parameter from a Hall-Petch model), and \( d \) is the size of the crystalline grain. Parameters \( \alpha_{SE} \) and \( \beta_{SE} \) are determined on the basis of the findings of [20] and [30]. The size factor \( (\lambda) \) is obtained from the diagram on Fig. 1, in which size factor is defined as:

\[ \lambda^2 = A_D / A_f. \]  

(6)

The true strain is determined by the volume of the impressed die or volume of squeezed out material as:

\[ p(\varphi_p) = V / \left( V - V_{\text{int/SG}} \right). \]  

(7)

The shear flow stress \( \tau_G \) and the grain boundary resistance \( K_{hp} \) are the parameters of the classical Hall-Petch model and can be determined by using a classical experiment of flow curves recording with samples of different crystalline grain size. It is necessary to know the size of crystalline grain samples and to use samples of at least two different crystalline grain sizes.

Dependence of the current (contact) surface and the size factor on true strain can be estimated by knowing the geometry of the die cavity. By knowing the size factor, it is possible to determine the effect parameters of the size \( (\alpha_{SE} \) and \( \beta_{SE} \).
of the forehead of the die. Filling the tool cavity and forming the geometry of the product are done. During the forming process, it is desirable to achieve the same deformation of the material in all segments of the die cavity, and it is necessary to provide free separation of the workpiece from the tool cavity after the deformation process is completed. Therefore, to obtain the final product shape, it is necessary to find a compromise between the design and the imposed geometric constraints. The final geometry of the die cavity comes from the experience and the trial-and-error method.

Because of the use of a hydraulic press with a continuous force measurement, the forming force was selected as the first input variable of the experiment, i.e. the first influencing factor. The final force levels are 55 kN, 100 kN, 150 kN, and 200 kN. The second input variable was the crystal grain size of the test sample. The output variables are total tool displacements. The plan of the experiment is given in Table 3. After metallographic sample preparation (cutting, polishing and etching), the workpiece grain size is determined using an optical microscope (Olympus GX51) and chart comparison methods according to the ASTM standard. The average grain size is obtained as a mean value of at least five grain size measurements on the radial and axial planes of the workpiece. Samples of microstructures, on workpiece radial and axial sections, for different grain sizes are shown on Fig. 3.

Table 3. Plan of the experiment (number of samples for specific grain size and final forming force)

| Grain size [μm] | 25 | 50 | 90 |
|----------------|----|----|----|
| Final force [kN] |    |    |    |
| 55             | 5  | 5  | 5  |
| 100            | 5  | 5  | 5  |
| 150            | 5  | 5  | 5  |
| 200            | 5  | 5  | 5  |

Fig. 3. Workpiece microstructures a) and b) 25 μm, c) and d) 50 μm, e) and f) 90 μm, for radial and axial sections, respectively.

2.1 Experimental and Model Results

Fig. 4 shows a comparison of model results and experimental results. There is a noticeable increase in model deviations and experimental results in small tool displacements, which can be attributed to the simplified determination of the contact surface and the true strain of the workpiece. However, in the case of total displacement and total deformation, when the die cavity is nearly filled, and the contact surface is
very close to the maximum contact surface, the results obtained through Eqs. (1) to (7) and experimental measurements are very well matched.

Although the experimental and model results are very well matched, the point at which the engraving cavity is completely filled can be determined only with the visual evaluation of the forged geometry at a certain forging (coining) force. Therefore, Figs. 5 and 6 show a parallel view of the geometry of the coin detail for different crystalline grain size that is obtained with the force of 150 kN and 200 kN.

From the diagram in Fig. 4 and the visual comparison of the geometry in Figs. 5 and 6, it is apparent that the dimensional model satisfactorily describes the coining and gives a very good estimation of the final forging force.

### 3 STATISTICAL ANALYSIS OF EXPERIMENTAL AND MODEL RESULTS

Modelled and experimental data for crystalline grain size $d_{25}$, $d_{50}$, and $d_{90}$ were analysed using Bonnet’s and Levene’s tests. These tests are used to verify the homogeneity of variances. They are more robust than tests when normality is not assumed [32].

The test was performed on a sample of 30 measurement points (forces up to 200 kN) for each grain size. The results are presented in Table 4.

|       | Bonett’s test | Levene’s test |
|-------|---------------|---------------|
| $d_{25}$ | $P = 0.817$   | $P = 0.745$   |
| $d_{50}$ | $P = 0.832$   | $P = 0.846$   |
| $d_{90}$ | $P = 0.805$   | $P = 0.816$   |

Because all the p-values are greater than a reasonable choice of $\alpha$ ($\alpha = 0.05$), there is no significant evidence to reject the null hypothesis stating that the variances are equal. This data does not provide enough evidence to claim that modelled and experimental data for all crystalline grain sizes have unequal variances.

Modelled data and experimental data were also compared using the quantile-quantile plot (q-q plot). Results are presented in Fig. 6. The q-q plot graphical technique shows that modelled and experimental data for all crystalline grain sizes come from populations with a common Weibull distribution.

The high values of coefficients of determination (R-squared) show that the model fits the observed data.

![Graph](image-url)
well, i.e. the relationship between the modelled data and the observed data is fairly strong.

![Graph A](image1)

![Graph B](image2)

![Graph C](image3)

**Fig. 6.** The Quantile-Quantile q-q plot for crystalline grain size a) 25 μm, b) 50 μm, c) 90 μm

4 CONCLUSIONS

Since the coining process is regularly linked to large-scale and mass production and the size of the crystal grain of the workpiece affects the required forging force, it makes possible to achieve the same or satisfactory quality of the final product with significant energy savings if this forging force can somehow be predicted and optimized.

The influence of the size effects on the flow curve, and thus on the flow stress, is determined by the extended Hall-Petch model, which requires the knowledge of the size factor parameters ($\alpha_{SE}$ and $\beta_{SE}$).

The size factor parameters are determined by data based on the die size factor ($\lambda$).

The final results of a model are the forging force and the tool displacement in which the die cavity is completely filled, and the coining process is completed. The model was verified experimentally by the collected data from the force sensor and displacement sensor during the workpiece compression for all three different sizes of the crystalline grain (25 μm, 50 μm, 90 μm) and by visual comparison of the forged details. Collected experimental data and model results are shown in curves in the displacement–force diagram. Statistical analysis shows that modelled and experimental data for each crystalline grain size have unequal standard deviations and come from populations with a common distribution. The high values of coefficients of determination (R-squared) show that the model fits the observed data well, i.e. the relationship between the modelled data and the observed data is fairly strong.

Further research should include a variety of material investigations and model testing on different material types.

5 NOMENCLATURES

- $A$: current contact surface [mm$^2$]
- $A_1$: final workpiece surface [mm$^2$]
- $A_d$: surface of crystalline grain [mm$^2$]
- $A_D$: surface of impressed die [mm$^2$]
- $d$: size of crystalline grain [μm]
- $F$: forging/coining force [kN]
- $k_f$: current flow stress [MPa]
- $k_{f1}$: final flow stress [MPa]
- $K_k$: forging factor (empirically determined)
- $K_{hp}$: resistance of grain boundaries [MPa]
- $M_{or}$: mean crystal orientation factor
- $p$: acting pressure [MPa]
- $P$: statistical probability value [%]
- $V$: workpiece volume [mm$^3$]
- $V_{IM/SQ}$: volume of impressed die [mm$^3$]
- $\alpha$: statistical significance level
- $\alpha_{SE}$, $\beta_{SE}$: size effect parameters
- $\phi_{pl}$: current true strain
- $\phi_{pl1}$: final true strain
- $\lambda$: size factor
- $\tau_c$: critical shear stress [MPa]

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