# FORMALIZATION OF THE VIRTUAL EVALUATION OF STRAIN INTENSITY IN SPDed COMMERCIALLY PURE COPPER BILLET

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**Abstract**
This work presented the results of solution of the strain intensity evolution in a commercially pure copper billet in the process of severe plastic deformation (SPD) by equal channel angular pressing (ECAP) technique. At the stage of the modeling task preparation, the most significant factors affecting the strain intensity at ECAP are suggested to be the friction coefficient, as well as the deformation velocity. A computer virtual full factorial experiment (FFE) was conducted accompanied with the application program package "DEFORM-3D" by using two-level model with two unknown varied parameters, followed by the formalization of the results in the form of the regression equation, as well as the optimization of the selected factors. The deformation velocity which coincides with the punch displacement velocity and the friction factor were chosen as independent variables in the ECAP process of characterizing the processing and its effectiveness, which are in terms of strain intensity; whereas the strain intensity of the material was selected as a response variable (dependent variable). Based on the results of the friction coefficient (f.) determination and the strain intensity estimated value of 1.155, a friction coefficient priori was determined to be 0.10. Therefore, the deformation velocity (V) of 1.5 mm/s was obtained by solving the regression equation.

**Keywords:** Commercially pure copper, Severe plastic deformation, Equal channel angular pressing, Virtual full factorial experiment

## 1 Introduction

At the present time, investigations of increasing metal strength by refining their microstructure to the sub micro crystalline (SMC) size via treatment of severe plastic deformation (SPD) arouse certain interest [1]. One of the SPD methods is equal channel angular pressing (ECAP) [2-7], and its development is ECAP-Conform [8] developed to produce long-length billets with bulk SMC structure. The technique enables creating the preconditions for practical implementation of the SPD process.

Development of industrial processes of SPD is held back, particularly, because of the lack of systematic research dealing with billet surface preparation before SPD, which includes formation of a sub lubricant layer and technological lubricant material.

The characteristic feature of the SPD processed by ECAP-Conform is that strongly marked tension zones and compression zones along with stick zones and sliding zones are

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simultaneously observed in the deformation zone. The term "stick zone" does not imply adhesive bond of surfaces, but has a purely kinematic sense as a marker of absence of sliding [9]. This zone is needed to feed the billet in the deformation zone using active friction forces. Thus, two mutually exclusive requirements have to be fulfilled: a more efficient process of strain hardening of metals by ECAP-Conform and fabrication of quality high-strength semi-finished products. A low friction coefficient is required in the sliding zones while retaining the billet integrity in the tension zones, and a high friction coefficient in the zones where the forces of active friction are required, but without the adhesive interaction of the materials of the billet and the tool.

## 2 Virtual full factorial experiment

In metal forming processes, friction plays an important role. The quality of the final product depends on effective control of friction, and an accurate modeling of the friction effect is essential for a good description of the phenomenon [10]. Modern tribology has a number of fundamental theoretical and experimental regularities allowing solving applied problems with regard to dry and boundary friction, gas-dynamic, hydrodynamic and elasto hydrodynamic lubrication, which are implemented in the conditions of metal processing [11-14]. Illustrative examples are mentioned to show the utilization of the commercial computer in industry, as a very flexible tool to design metal forming sequences [15].

### 2.1 Set up of the problem and assumptions

The fundamental mechanical formulation is recalled for simulation of metal forming processes. The basic principles of 3-dimensional finite element discretization and of time integration are summarized. Several important numerical developments for efficient computation of large plastic deformation are briefly described. Various fields of applications to real processes are reviewed. At the stage of preparation of the modeling task, it is believed that the most significant factors affecting the strain intensity at ECAP are the tribological parameters of the contact between the billet and the tool, as well as the deformation velocity. A computer virtual full factorial experiment (FFE) was conducted accompanied with the application program package "DEFORM-3D" by using two-level model with two unknown varied parameters, followed by the formalization of the results in the form of the regression equation, as well as the optimization of the selected factors. In this case, the experience of solving such a task presented in our previous work [16] was used.

Thus, the deformation velocity, that coincides with the punch displacement velocity $V$ ($X_1$), and friction factor $f_{fr.}$ ($X_2$) were chosen as independent variables in the process of drawing with shear characterizing the processing and its effectiveness, which all were expressed in terms of strain intensity. The strain intensity $\varepsilon$ ($Y$) of the material was chosen as a response variable (or a dependent variable).

Each factor was varied on two levels. Variability intervals of variable factors and their real-scale values are given in **Table 1**.

**Table 1** Factor levels

| **Factors** | $X_1$ **(V, m/s.)** | $X_2$ **($f_{fr.}$)** |
|---|---|---|
| Basic level ($X_i$) | 5 | 0.50 |
| Variability interval ($\Delta X_i$) | 2.5 | 0.25 |
| Upper level ($x_i = 1$) | 10 | 1 |
| Lower level ($x_i = -1$) | 0.1 | 0 |

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Coded values of quantitative factors ($x_i$) are connected with natural ($X_i$) equations.

$$x_1 = \frac{X_1 - 5}{2.5};\ x_2 = \frac{X_2 - 0,5}{0.25} \qquad (1.)$$

It is required to determine such values of *V, f,* which would provide strain intensity $\varepsilon$ in the range from *1 to 1.5 (1 ≤ ε ≤ 1.5).*
The number of experiments *N* was determined by the number of factors *k* in accordance with the formula:

$$N = 2^k = 2^2 = 4 \qquad (2.)$$

Conditions and assumptions for the modeling are shown below:

- The billet material in the initial condition (before straining) is isotropic and has no initial stresses and strains;
- The temperature is constant $T = 20\ °C$ , strain heating of the billet is neglected;
- The tool is an absolutely rigid body. The geometric shapes of the 3D model tool are preliminarily created in *KOMPAS 3D* 11V and saved with the file extension stl.;
- The initial billet material is ductile. The material taken for modeling is copper Cu (counterpart of M0, M1);
- The friction coefficient (shear) between the die-set and the billet is equal to 0 and 1, between the punch and the billet it is 0;
- The number of finite elements is 52762…57233;
- The number of modeling steps is 50…500, with a step 1 s;
- The punch speed is constant and equal to 0.1 and 10 mm/s. In the course of modeling the punch moved by 50 mm.

The initial billet size: the diameter is 10 mm, the height is 60 mm.

### 2.2 Results of the virtual experiment

After the performance of full factorial experiment, the mathematical model takes the following form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 \qquad (3.)$$

where $b_i$ – the regression coefficients.
**Fig. 1** shows the results of computer FFE in the process of SPD of commercially pure copper M1 by ECAP.
To calculate these model coefficients, a matrix of planning and experiment results was drawn (**Table 2**).
Regression coefficients were calculated according to the formula:

$$b_i = \frac{\sum_{i=1}^{N} x_i y_i}{N}, \qquad (4.)$$

where *i* = 0, 1, 2, …, 4.
As a result of virtual implementation of the two-level, two-factor FFE model and performed calculations, we obtained the following general form of linear regression equation (5):

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$$Y_{Cu} = 2.155X_0 + 0.935X_1 - 0.711X_2 - 0.265X_1X_2 \quad (5.)$$

After determining the statistical significance of each of the four coefficients [17], the regression equation (5) has the following form:

$$Y_{Cu} = 2.155X_0 + 0.935X_1 - 0.711X_2 \quad (6.)$$

The statistically insignificant coefficient $b_{12}$ was excluded from the equation (5).

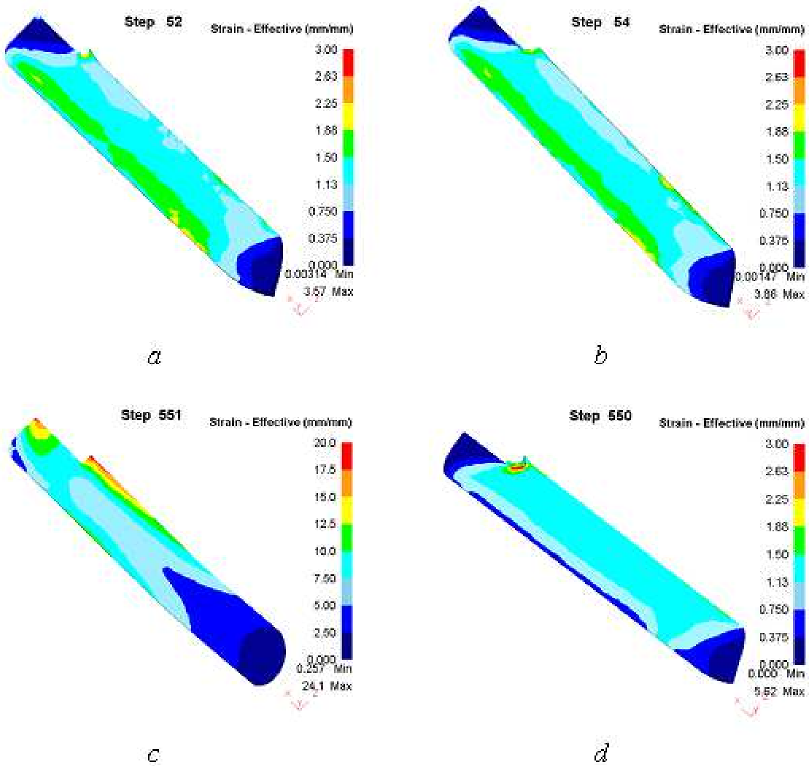


**Fig. 1** Strain intensity distribution fields in each variant of FFE according to the design matrix in Table 2.

**Table 2** Extended matrix of planning $2^2$ and experiment results

| **Experiment No** | **Marking on the Fig. 1** | **For commercially pure copper** | | | | $Y_{Cu}$ |
|---|---|---|---|---|---|---|
| | | $x_0$ | $x_1$ | $x_2$ | $x_1x_2$ | |
| 1 | *a* | + | + | + | + | 1.42 |
| 2 | *b* | + | - | + | - | 1.51 |
| 3 | *c* | + | + | - | - | 4.78 |
| 4 | *d* | + | - | - | + | 0.94 |

In this case, the hypothesis of the mathematical model adequacy (5) by Fisher's criterion [16] at 5% significance level is not rejected.

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As it can be seen from equation (6), the punch displacement velocity and the friction factor, as independent of each other parameters, have the most significant influence on the strain intensity value in the proposed formulation of a problem. The interaction of the two analyzed factors has little influence on the strain intensity value, and it is excluded from further consideration. It was established that the strain intensity increases as long as the punch displacement velocity increases. The response parameter increases, when the friction factor (coefficient) decreases.
For a more illustrative analysis of the developed mathematical model, a chart of factors influence on the strain intensity was plotted (**Fig. 2**).

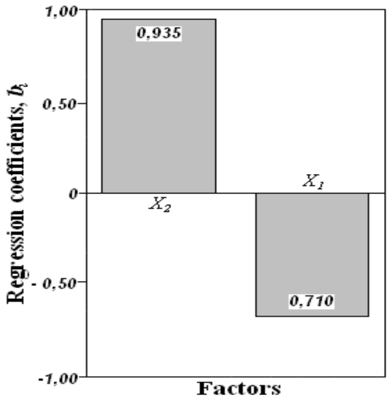


**Fig. 2** Influence of significant factors: negative values – as the factor decreases, the response parameter increases; positive values – as the factor increases, the response parameter increases.

From Fig. 2 we can see, as it was noted before, that the strain intensity increases with the friction coefficient decreasing and the punch displacement velocity increasing.
A solution to the optimization problem of determining the actual values of independent parameters considered in the numerical modeling experiment, which provides the maximum strain intensity value at drawing with shear is of practical interest. This problem is solved by the "steepest ascent" method [18]. As part of the assigned research task, the optimized numerical values of the varied parameters corresponding to the estimated value of strain intensity *($\varepsilon \approx 1.155$)* were obtained. For the calculation of the accumulated strain degree, the formula was used [19, 20]:

$$\varepsilon = N\,\frac{2\cot(\varphi/2)}{\sqrt{3}}, \qquad (7.)$$

where $N$ – number of deformation processing cycles; $\varphi$ – angle of channels intersection.
Based on the strain intensity estimated value ($Y = 1.155$), a priori friction coefficient ($f$) was determined to be 0.10 in the straining processing, which can be provided when using graphite-based lubricant. Thus, by solving the regression equation (6), the deformation velocity ($V$) of 1.5 mm/s was obtained.
**Fig. 3** shows the distribution of strain intensity obtained from the modeling based on the optimization problem solution. It demonstrates that the optimized variable factors (friction

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coefficient and deformation velocity) provide basically homogeneous strain intensity in terms of the volume of the processed billet, which is approximately 1.2 and is slightly different from the estimated value (1.155) calculated by formula (7). This is illustrated by the applicable graphic chart.

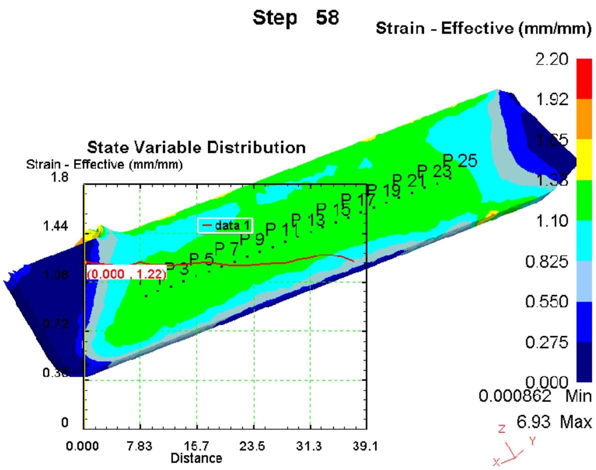


**Fig. 3** Results of solving the optimization problem of modeling

According to the results of the virtual FFE, an interim conclusion can be made on the practicability of the actual SPD process by ECAP: the friction coefficient of about 0.1 and the punch displacement velocity of about 1.5 mm/s were suggested. Such deformation velocity is a working velocity in any hydraulic press practically, and this friction coefficient can be achieved when using oil-graphite lubricant.

## 3 Conclusion

The regression equation was derived on the basis of the virtual full factorial experiment. The regression equation allows determining the influence of variable factors (friction coefficient and deformation velocity) on the response variable (strain intensity). As a result of optimization of variable factors, it was established that in order to provide the calculated value of strain intensity at 1.155 and maximal uniformity of deformation of copper and copper-bearing alloy, the coefficient friction should be about 0.1, and the punch displacement velocity should equal to about 1.5 mm/s.

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