Computer simulation of the SPD process of a low-alloyed chromium bronze using a virtual full factorial experiment

V I Semenov\textsuperscript{1}, N T Tontchev\textsuperscript{2}, L Sh Shuster\textsuperscript{3}, G I Raab\textsuperscript{1} and V V Kamburov\textsuperscript{3}

\textsuperscript{1}Ufa State Aviation Technical University, Ufa, Russia
\textsuperscript{2}Todor Kableshkov Higher School of Transport, Sofia, Bulgaria
\textsuperscript{3}Technical University of Sofia, Bulgaria

E-mail: semenov-vi@rambler.ru

Abstract. Using computer simulation in the DEFORM-3D software package, we performed a virtual full factorial experiment for the ECAP-Conform processing of the low-alloyed chromium bronze Cu-0.14\%Cr. In the course of the experiment we evaluated the effect of independent parameters (the rotation speed of the working wheel, the friction factor at the lateral surfaces of the working wheel and the friction factor between a billet and the die). As a result of the experiment, we obtained a regression equation and determined the most important individual factors and their combinations that influence the response parameter – the deformation force.

1. Introduction
At present, there is interest in the studies of the strength enhancement of metals due to structure refinement to the submicrocrystalline (SMC) range through severe plastic deformation (SPD) processing [1]. Among the SPD techniques is equal-channel angular pressing (ECAP) [2, 3] and its modification – the ECAP-Conform technique [4] developed for the processing of long-length billets with a bulk SMC structure and creating prerequisites for the practical implementation of SPD processing.

However, to produce long-length semi-products, it is necessary to solve the task related to the found contradiction. To feed a billet to the deformation site, it is necessary to use the active friction forces at the lateral surfaces of the working wheel, i.e. to have the maximum friction factor ($f_i$). In contrast, to realize the deformation process and produce a high-quality semi-product with a defect-free surface, it is necessary to provide the lowest value of the friction factor ($f_i$) in the deformation site.

The fragmentary application of a lubricant only on those surfaces where a low friction factor is required leads to a decline in the productivity and mechanization of SPD processing. This makes the processing, which is already not cheap, even more expensive. In order to increase the efficiency of SPD processing by ECAP-Conform, it is necessary to find a compromise solution that involves one variant of billet surface preparation prior to deformation processing, enabling the feeding of the billet to the deformation site and producing semi-products of the required quality.

In the analysis of tribological systems, an important place is held by the numerical methods for the study of complex processes, including computer simulation with the use of the state-of-the-art software [5, 6]. Therefore, it seems reasonable to perform numerical simulation using a virtual full factorial experiment (FFE) [7].
The aim of the simulation is to perform virtual SPD processing by ECAP-Conform using a FFE, and to identify the rational speed regime of the processing, combined with a universal surface preparation of a billet, in the conditions of the fabrication of long-length SMC semi-products under the minimum possible deformation force.

2. Experimental procedure
In order to obtain the fullest possible information about the dependencies under study, the authors used an FFE in their simulation. The design of experiments is a procedure of selecting the number and conditions of experiments, necessary and sufficient to obtain a mathematical model of the process [8]. It is important to consider the following: the striving for the minimization of the number of experiments; the simultaneous variation of all variables defining the process; the selection of a clear strategy that enables making grounded decisions after each series of experiments [9].

The design of the experiment was carried out based on the simulation of the process of the fabrication of long-length semi-products from the low-alloyed chromium bronze Cu-0.14%Cr by ECAP-Conform. The principle of the facility is presented in figure 1.

![Figure 1. Principle of the SPD technique of ECAP-Conform: 1 – stationary die; 2 – billet; 3 – working wheel.](image)

The object of study is the low-alloyed chromium bronze Cu-0.14%Cr, its rheological properties were taken from [10] when designing the numerical model.

To perform the numerical simulation, we used the standard software package DEFORM-3D. With a view to perform the simulation and factorial experiment in the DEFORM-3D software package, we had previously created three-dimensional models in the Kompas-3D software.

2.1. Assumptions
1) The material in the billet in the initial state is isotropic and has no initial stresses and strains;
2) The deformation temperature is taken as 200 °C;
3) The channels intersection angle is taken as 120°;
4) The tool is absolutely rigid, and the tool's geometry is taken into account automatically;
5) The material of the initial billet is taken to be ductile;
6) For the simulation we selected 100 steps taking into account the complete passage of the billet through the dies and getting a stable result;
7) The billet is divided into 43553 trapezoidal elements.

At the stage of preparation of the simulation task, we believed that the most important factors influencing the fabrication of defect-free semi-products are the factors of friction (parameters of contact) between the billet and different parts of the tool, and the deformation speed conditioned by the rotation speed of the working wheel. Therefore, we decided to perform the virtual FFE using a two-tier model with three unknowns corresponding to three variable factors, and then formalize the obtained results in the form of a regression equation and optimize the selected factors.

Thus, we selected the following as the independent variables in the process of drawing with shear, characterizing the running of the process and its efficiency in terms of the deformation force: the friction factor \( f_i (X_i) \) at the upper and lower surfaces of the working wheel determining the efficiency of billet feeding to the deformation site, the friction factor \( f_i (X_i) \) at the shape-forming parts of the tool, and the deformation speed (the rotation speed of the working wheel) \( V (X_i) \). The deformation force \( P (Y) \) was taken as the response parameter (dependent parameter).
3. Experiment results and discussion

It is necessary to find such values of \( f_1, f_2, V \) that will provide the minimum deformation force \( P \). After completing the full factorial experiment, the mathematical model has the following form:

\[
y = b_0 + b_1x_1 + b_2x_2 + ... + b_{12}x_1x_2x_3 + b_{23}x_2x_3 + ... + b_{123}x_1x_2x_3, \tag{1}\n\]

where \( b_i \) is the regression coefficient.

To calculate the coefficients, in this model we used an extended matrix for the experiment design and results (table 1).

| Experiment No. | \( x_0 \) | \( x_1 \) | \( x_2 \) | \( x_3 \) | \( x_1x_2 \) | \( x_1x_3 \) | \( x_2x_3 \) | \( x_1x_2x_3 \) | \( Y \text{(kN)} \) |
|----------------|---------|---------|---------|---------|-----------|-----------|-----------|----------------|--------|
| 1              | +       | +       | +       | +       | +         | +         | +         |                 | 13.3   |
| 2              | +       | -       | +       | +       | -         | -         | +         |                 | 16.5   |
| 3              | +       | +       | -       | +       | -         | +         | -         |                 | 10.7   |
| 4              | +       | -       | -       | +       | -         | -         | +         |                 | 12.7   |
| 5              | +       | +       | +       | -       | -         | -         | -         |                 | 23.2   |
| 6              | +       | -       | +       | -       | +         | -         | +         |                 | 19.8   |
| 7              | +       | +       | -       | -       | -         | +         | +         |                 | 13.5   |
| 8              | +       | -       | -       | -       | +         | +         | -         |                 | 12.9   |

Table 1. Extended matrix of the experiment design \(^2^3\) and results.

Figure 2 shows the solution of the task of the numerical simulation of the ECAP-Conform process. As a result, the minimum deformation force was obtained.

Figure 2. Result of the simulation of the ECAP-Conform process – fields of accumulated strain distribution. The deformation force \( P_{\text{average}} = 10.7 \) kN.

On the basis of the calculations, we obtained the following general form of a linear regression equation:

\[
y = 15.33x_0 - 0.15x_1 + 2.88x_2 - 2.03x_3 + 0.20x_1x_2 - 1.15x_1x_3 - 1.28x_2x_3 - 0.50x_1x_2x_3. \tag{2}\n\]

Equation (2) demonstrates that it is the friction factor \( f_2 (X_2) \) in the sliding contact between the billet and the tool, and the deformation speed \( V (X_3) \) that have the greatest influence on the deformation force. It can be seen from the coefficients of the regression equation that the deformation force will decrease as both of these factors increase. The factor \( f_1 (X_1) \) of active friction at the upper and lower surfaces of the working wheel, which provides the feeding of the billet to the deformation site, has a much smaller effect on the deformation force. Since the greatest and unidirectional influence is exerted by the factors \( X_2 \) and \( X_3 \), this makes it possible to select a variant of universal preparation of the billet surface. It should be noted that two-way and three-way mutual interactions have an ambiguous interpretation, and therefore complex interactions should be analyzed separately and with a reference to the specific operation conditions of a multi-component system.

A priori, it can be stated that in the conditions under consideration the minimum value of deformation force can be obtained under the optimum combination of independent parameters taken in this study.

The design of the experiment showed that in the considered conditions the deformation force will be the lowest when there is high friction at the upper and lower surfaces of the working wheel (\( f_1 \approx 1.0 \)), the friction at the shape-forming parts of the tool tends to have the minimum values (\( f_2 \approx 0.00 \),
and the deformation speed is $V \approx 25\text{ m/min}$. When the above-mentioned values of independent parameters are ensured, it is possible to provide the deformation force $P \approx 10.7\text{ kN}$ (figure 2).

However, the task of this study was to provide the SPD processing by ECAP-Conform with the minimum possible deformation force under the condition of a universal preparation of the billet surface.

By solving the reverse task, we managed to select a variant of universal surface preparation and the deformation speed that provide a deformation force of $P \approx 12.5\text{ kN}$. For this purpose, it is necessary to ensure $f_1 = f_2 = 0.3$ and a deformation speed of $V \approx 30\text{ m/min}$.

4. Conclusions

1. As a result of a virtual full factorial experiment, it has been found that it is the friction factor $f_2 (X_3)$ in the sliding contact between the billet and the tool, and the deformation speed $V (X_3)$ that have the greatest effect on the deformation force.

2. For the practical implementation of the ECAP-Conform processing of the low-alloyed chromium bronze Cu-0.14%Cr, a variant of billet surface preparation can be proposed that combines the application of an under-lubricant coating and a processing lubricant.

References

[1] Valiev R Z and Alexandrov I V 2007 Bulk Nanostructured Metallic Materials: Production, Structure and Properties (Moscow: Akademkniga) [in Russian]

[2] Segal V M, Reznikov V I and Kopylov V I 1994 Processes of Plastic Structure Formation in Metals (Minsk: Science and Technology) [in Russian]

[3] Segal V M 2004 Mater. Sci. Eng. A 386 269

[4] Raab G I and Valiev R Z 2000 Izvestiya Vuzov. Tsvetnaya Metallurgiya 5 50 [in Russian]

[5] Abdullah O I and Schlattmann J 2012 Tribology in Industry 34 206

[6] Petrović Savić S, Adamović D, Devedžić G, Ristić B and Matić A 2014 Tribology in Industry 36 354

[7] Belhocine A, Abu Bakar A R and Bouchetara M 2014 Tribology in Industry 36 49

[8] Novick F S and Arsov Y B 1980 Optimization of Technology Processes for Metals by the Methods of Experiment Design (Moscow: Mashinostroenie) [in Russian]

[9] Adler Yu P 1978 Experiment Design (Moscow: Znanie) [in Russian]

[10] Adler Yu P 1969 Introduction to Design of Experiments (Moscow: Metallurgiya) [in Russian]

[11] Frolova N Yu, Zeldovich V I, Khomskaya I V, Kheifets A E and Shorokhov E V 2015 Diagnostics, Resource and Mechanics of Materials and Structures 5 99