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COMPUTER SIMULATION OF CONTINUOUS SPD PROCESSING OF COMMERCIALLY PURE TITANIUM USING A VIRTUAL FULL FACTORIAL EXPERIMENT WITH ACCOUNT OF THE INFLUENCE OF FRICTION FACTORS

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Abstract: *With the use of computer modeling in the environment of the DEFORM-3D software, a virtual full factorial experiment has been conducted for the processing of commercially pure titanium by equal-channel angular pressing (ECAP) via the Conform scheme. In the course of the modeling, the effect of independent parameters (the rotation velocity of the working wheel, the friction factor on the lateral surfaces of the working wheel and the friction factor between the billet and the die) has been evaluated. As a result of the experiment, a regression equation has been obtained and the most important individual factors and their mutual combinations that influence the response parameter (strain intensity) have been identified.*

Keywords: *computer modeling, commercially pure titanium, virtual full factorial experiment, friction factor, strain intensity.*

1. INTRODUCTION

Currently, there is interest in research aimed at enhancement of the strength of metals by microstructure refinement to a submicrocrystalline (SMC) size using severe plastic deformation (SPD) processing [1]. One of the SPD processing techniques is equal-channel angular pressing (ECAP) [2,3] and its advanced modification – ECAP-Conform [4], which was developed to produce long-length billets with a bulk SMC structure and enables creating preconditions for practical implementation of SPD processing. Figure 1 illustrates the principle of the ECAP-Conform process.

This process, based on structure refinement by SPD processing and implemented on an ECAP-Conform setup, is an effective way to increase the strength of metals and alloys. However, to produce long-length semi-products using this process, it is necessary to solve the problem caused by a revealed contradiction. This contradiction lies in the fact that to feed the billet in the deformation zone, it is necessary to use active friction force on the lateral surfaces of the working wheel, i.e. to have the maximum friction coefficient (f_1). At the same time, to implement directly the deformation process and produce high-quality semi-products with a defect-free surface, it is required to ensure the lowest value of the friction coefficient (f_2) in the deformation zone.

The use of fragmentary application of a lubricant only on those surfaces where it is necessary to have a low friction coefficient leads to lower productivity and mechanization of SPD processing. The processing, which is already not cheap, becomes even more expensive. Thus, to improve the efficiency of SPD processing by the ECAP-Conform technique is necessary to find a compromise solution, which would enable the use of one option of preparation of the billet surface prior to deformation processing, able to ensure the feeding of the billet in the deformation zone and fabrication of semi-products of the required quality in the deformation process.

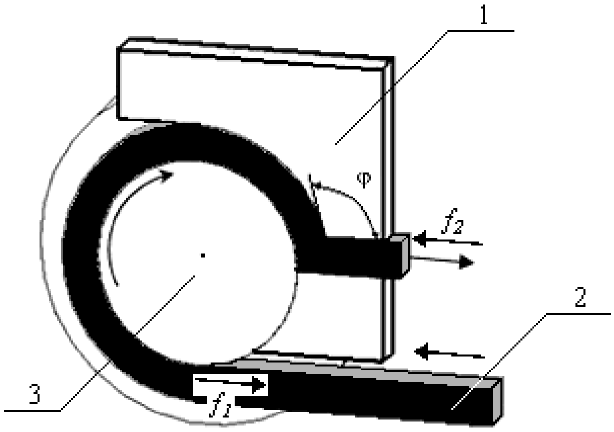

Figure 1. Principle of an SPD technique – equal-channel angular pressing – Conform (ECAP-Conform): 1 – stationary die; 2 - billet; 3 – working wheel-punch

In scientific and practical activities, in particular, in the analysis of tribological systems, of significant importance are numerical methods for the study of complex processes, including computer modeling using the latest software products [5,6]. The efficiency of the methods applied for modeling and solving of engineering problems grows significantly, if at the stage preceding the design of the actual manufacturing process, conditions are created to assess the influence of the most important independent parameters.

The application of mathematical methods is one of the most rational approaches to solving problems related to assessing the effectiveness of non-standard metal forming processes. In this regard, it seems reasonable to conduct numerical simulation using the planning of a virtual full factorial experiment (FFE) [7].

The advantage of FFE is the ability to describe the process in full compliance with the algorithm of physical experiment, taking into account the established assumptions. FFE is the most easily implementable method among the numerous methods of physical experiment. The aim of conducting the FFE is to obtain a linear mathematical model of the process, which will allow defining the future strategy for conducting a real experiment.

Thus, the purpose of modeling is to perform a virtual SPD processing by ECAP-Conform with the use of FFE, and to identify the rational processing velocity in combination with a universal preparation of the billet surface in the conditions of fabrication of long-length SMC semi-products.

2. RESEARCH PROCEDURE

In order to obtain more complete information about the studied dependencies, the authors used FFE when performing modeling. Experiment planning is a procedure of selecting the number and conditions of the experiments, which are necessary and sufficient to obtain a mathematical model of the process [8]. It is important to consider the following: a tendency to minimize the number of experiments; simultaneous variation of all variables that determine the process; the choice of a clear strategy that allows to make grounded decisions after each series of experiments. Prior to planning a full-scale experiment, it is necessary to gather additional information about the object under study, employing the skills and knowledge obtained in previous studies, or described in literature [9].

The planning of the experiment was conducted on the basis of the modeling of the processing of long-length semi-products from commercially pure titanium, using the ECAP-Conform technique. The principle of the device for ECAP-Conform is presented in Figure 1.

The object of study is commercially pure titanium VT1-0, the rheological properties of which were entered when developing the numerical model [10].

For the purposes of numerical simulation, the standard application software package (ASP) *DEFORM-3D* was applied.

To perform the simulation and factorial experiment with the *DEFORM-3D* software, three-dimensional models were preliminarily created with the *Kompas-3D* software.

2.1 Assumptions

1) The material of the billet in the initial state is isotropic and has no initial stresses and strains;
2) The temperature of deformation is assumed to be 200 °C;
3) The angle of the channels intersection is 120°;
4) The tool is absolutely rigid, and the geometry of the tool is taken into account automatically;
5) The initial billet material is assumed ductile;
6) The selected number of modeling steps is 100, taking into account a full passage of the billet through the die and obtaining a stable result;
7) The billet is divided into 43553 trapezoidal elements.

We believe that at the stage of preparation of the modeling task, the most significant factors influencing the fabrication of defect-free semi-products in the conditions of severe deformation at a temperature of 200 °C are factors of friction (contact parameters) of the billet with different parts of the tool and the deformation velocity, conditioned by the rotation velocity of the working wheel. In this connection, it was decided to perform a virtual FFE using a two-level model with three unknown variable factors, followed by the formalization of the results in the form of a regression equation and the optimization of the selected factors.

Thus, as independent variables in the process of drawing with shear, characterizing the running of the process and its effectiveness from the point of view of the deformation force, we chose the friction factor from the upper and lower surfaces of the working wheel, which determines the efficiency of feeding of the billet in the deformation zone, f_1 (X_1), the friction factor from the forming tool parts, f_2 (X_2), the deformation velocity (the rotation velocity of the working wheel) V (X_3). The deformation force P (Y) was determined as the response parameter (dependent parameter).

The factors were varied at two levels. The variation intervals of the variable factors and their real-scale values are shown in Table 1.

The number of experiments N was determined from the number of factors k in accordance with the formula:

$$N = 2^k = 2^3 = 8 \tag{1}$$

It is required to determine such values of f_1, f_2, V, at which the lowest deformation force P is ensured.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The mathematical model after the implementation of the full factorial experiments takes the following form:

$$y = b_0+b_1x_1+b_2x_2+\ldots+b_{12}x_1x_2+b_{13}x_1x_3+ \\ +b_{23}x_2x_3\ldots+b_{123}x_1x_2x_3, \tag{2}$$

where b_i is the regression coefficient.

For calculating the coefficients of this model, the extended matrix of experiment planning and results has been used (Table 2).

Figure 2 illustrates the solution of the problem of numerical simulation of the ECAP-Conform process, as a result of which the minimum deformation force has been obtained.

The regression coefficients were calculated using the formula:

$$\mathrm{b_i} = \frac{\sum_{\mathrm{i=1}}^{N} x_i y_i}{N}, \tag{3}$$

where i = 0, 1, 2, ..., 8.

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

$$y = 15.33X_0 - 0.15X_1+2.88X_2-2.03X_3+ \\ 0.20X_1X_2-1.15X_1X_3 - 1.28X_2X_3 - 0.50X_1X_2X_3 \tag{4}$$

Table 1. Factor levels

Factors	X_1	X_2	X_3 (V, [m/min])
Basic level (X_i)	0.50	0.50	20
Variability interval (ΔX_i)	0.25	0.25	10
Upper level ($x_i = 1$)	1	1	30
Lower level ($x_i = -1$)	0	0	10

Table 2. Extended matrix of plan 2^3 and results of experiments

Experiment No.	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	y [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

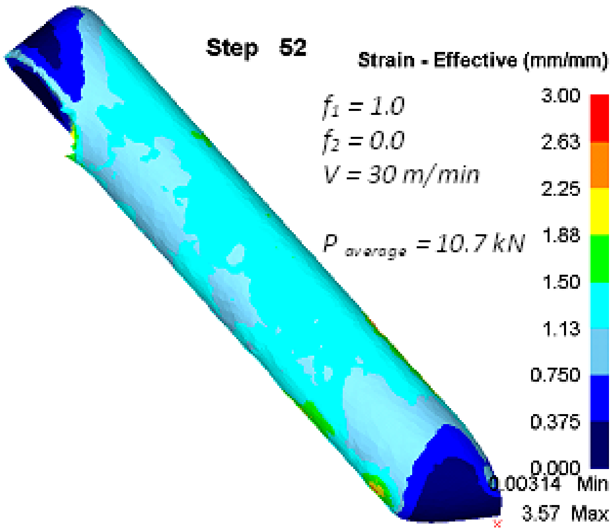

Figure 2. The result of the simulation of the ECAP-Conform process: distribution fields of accumulated strain; Deformation force $P_{average}$ = 10.7 kN

Equation (4) shows that the most significant influence on the deformation force is exerted by the friction factor in the sliding contact between the billet and the tool f_2 (X_2) and the deformation velocity V (X_3). Moreover, it can be seen from the coefficients of the regression equation that the deformation force will decrease with an increase of both factors. A much smaller influence on the deformation force is exerted by the active friction factor f_1 (X_1) from the upper and lower surfaces of the working wheel which feeds the billet in the deformation zone. While the greatest and unidirectional influence is extered by the factors X_2 and X_3, it becomes possible to select the option of universal preparation of the billet surface. It should be noted that double and triple mutual interactions have ambiguous interpretations, and therefore complex interactions should be analyzed separately and with reference to the specific operating conditions of a multicomponent system.

A priori, it can be stated that in the considered conditions the minimum value of the deformation force can be obtained at the optimal combination of the independent parameters adopted in this study.

It is of practical interest to solve the optimization problem dealing with defining the actual values of the independent parameters considered in the virtual experiment of numerical simulation and providing the minimum value of the deformation force when implementing ECAP-

Conform. This task is solved by the “steepest ascent” method [6].

Steps in the variation of the factors were calculated in the real scale. For this purpose, we first identified the product of the coefficients with the corresponding intervals of factor variation, i.e. $b_i\Delta X_i$, then in proportion to these products steps were assigned. Using the values of $b_i\Delta X_i$, the steps in the variation of the factors were determined as follows. From the technological considerations, the step in the variation of the factor of friction from the upper and lower surfaces of the working wheel was selected (Δ_1 = 0.05). The steps for the other factors were derived from the following proportions:

$$\frac{b_1\Delta X_1}{b_2\Delta X_2} = \frac{\Delta_1}{\Delta_2}; \frac{b_1\Delta X_1}{b_3\Delta X_3} = \frac{\Delta_1}{\Delta_3}, \quad (5)$$

The sequence of the stages of the steepest ascent is presented in Table 3.

Some of the mental experiments were implemented in a computer model (Table 3). Experiment planning using the steepest ascent showed that under these conditions the deformation force will be minimum at high friction from the upper and lower surfaces of the working wheel ($f_1 \approx 1.00$), at the friction, tending to the minimum values, from the forming tool parts ($f_2 \approx 0.00$), as well as at a high deformation velocity ($V \approx$ 25 m/min). If the indicated values of independent parameters are observed, it is possible to ensure the deformation force $P \approx 10.7$ kN (Fig. 2). However, the objective of the study was to provide 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 inverse problem we were able to choose such an option of universal surface preparation and deformation force, at which the value of the deformation force $P \approx$ 12.5 kN, which is quite acceptable, is achieved.

Here, it is necessary to ensure $f_1 = f_2 = 0.3$ and the deformation velocity $V \approx 30$ m/min.

Figure 3 shows the simulation results for the above values of variable factors in the context of the stated task of the study.

Thus, a universal preparation of the billet surface is possible, ensuring the minimum value of the deformation force. On this basis, for a practical implementation of processing of commercially pure titanium by ECAP-Conform, an option of preparing the billet surface can be proposed, combining a sub-lubricant layer and a technological lubricant. The rheological properties of such a combination should correspond to a material with a high shear stress in the area of the sliding contact. This assumption requires further research.

Table 3. Steepest ascent

Factors	X_1 (the factor of friction from the upper and lower surfaces of the working wheel, f_1)	X_2 (the factor of friction from the forming tool parts, f_2)	X_3 (the deformation velocity V [m/min])	Y (the deformation force P [kN])
b_i	0.25	- 0.8	- 0.2	
$b_i\Delta X_i$	0.125	- 0.4	- 4.0	
Step	0.05	- 0.16	- 1.6	
Step after rounding	0.05	- 0.2	- 5.0	
Basic level (X_i)	0.5	0.5	20	
Mental experiment	0.45	0.3	15	
Practical experiment	0.45	0.3	20	13.20
Mental experiment	0.55	0.7	15	
Mental experiment	0.55	0.3	25	
Practical experiment	0.55	0.7	15	17.90
Mental experiment	0.45	0.7	20	
Mental experiment	0.55	0.3	20	
Practical experiment	0.55	0.3	30	12.20
Practical experiment	0.55	0.3	10	14.50

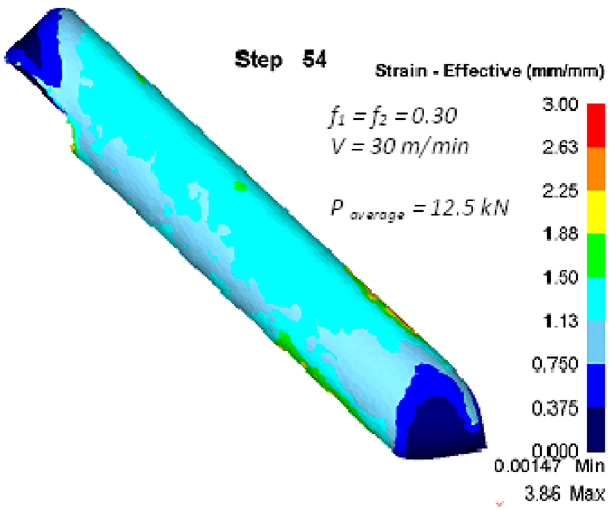

Figure 3. The result of the simulation of the ECAP-Conform process after solving the inverse problem: the distribution field of accumulated strain; Deformation force $P_{average}$ = 12.5 kN

4. CONCLUSIONS

1. As a result of a virtual full factorial experiment, it has been established that the most significant influence on the deformation force is exerted by the friction factor in the sliding contact between the billet and the tool f_2 (X_2) and the deformation velocity V (X_3). It has also been found that the active friction factor f_1 (X_1) from the upper and lower surfaces of the working wheel, which feeds the billet in the deformation zone, has a much smaller influence.

2. The virtual full factorial experiment, conducted using the steepest ascent method in the process of numerical simulation, has allowed us to determine the numerical values of friction factors from the upper and lower surfaces of the working wheel, f_1 and from the forming parts of the tool, f_2, which are universal for the SPD processing of commercially pure titanium by the ECAP-Conform technique.

3. For a practical implementation of processing of commercially pure titanium by ECAP-Conform, an option of preparing the billet surface can be proposed, combining the application of a sub-lubricant layer and a technological lubricant.

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