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RESEARCH

Computer Simulation of Continuous SPD Process Commercially Pure Titanium Using Virtual Full Factorial Experiment with the Influence of Friction Factors

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A B S T R A C T

With the use of computer modeling in the environment of the software DEFORM-3D virtual conducted a full factorial experiment process, equal channel angular pressing (ECAP) by method "Conform" of commercially pure titanium, which evaluated the effect of independent parameters (speed of rotation of the impeller, the friction factor on the side surfaces of the impeller and the factor of friction between the billet and the matrix). As a result of the experiment obtained the regression equation and identified the most important individual factors and their mutual combinations that affect the response parameter are the deformation forces.

1. INTRODUCTION

Currently, there is interest in research in the field of increasing the strength of metals by shredding patterns to submicrocrystalline (SMC) size by processing under conditions of severe plastic deformation (SPD) [1]. One of the SPD methods is equal channel angular pressing (ECAP) [2,3] and its development - ECAP-Conform [4], was developed to obtain long length billets with bulk SMC structure and allows you to create preconditions for the implementation of the SPD process. In Fig. 1 is a diagram of the process for the implementation of the ECAP-Conform.

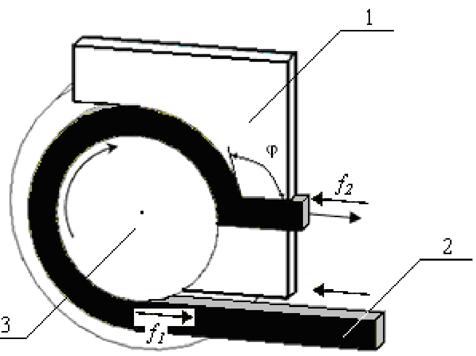

Fig. 1. Scheme one of the methods SPD - equal channel angular pressing - Conform (ECAP - Conform): 1 - stationary matrix; 2 - billet; 3 - impeller-punch.

Process technology is based on the refinement of the structure by the method of SPD and implemented on the installation of the ECAP-Conform is an effective way to increase the strength of metals and alloys. However, for the manufacture of long length semi-finished products according to the above scheme, it is necessary to solve the problem caused by identified by contradiction. It is that for feeding the billet in the deformation zone, you must use active friction force on the side surfaces of the impeller, i.e. have a maximum friction coefficient (f_1). At the same time to implement directly the deformation process and ensure high-quality semi-finished product with a defect-free surface in the deformation zone is required to ensure the lowest value of the friction coefficient (f_2).

The use of fragmentary coating of lubricant only on those surfaces where it is necessary to have a low friction coefficient leads to lower productivity and mechanization of the process of SPD. It is more expensive and not so cheap for the whole process. Thus, to improve the efficiency of the process SPD method ECAP-Conform is necessary to find a compromise solution, which would enable the use of one variant of the preparation of the billet surface before deformation processing, allowing ensuring the supply of billet in the deformation zone and obtaining semi-finished products of the required quality in the deformation process.

In scientific and practical activities, in particular, in the analysis of tribological systems, a significant numerical methods for the study of complex processes, including computer modeling using the latest software products [5-7]. The efficiency of methods for modeling and solving of engineering problems increase significantly, if at the stage preceding the design of the actual manufacturing process to create conditions to assess the impact of the most important independent parameters.

The application of mathematical methods is one of the most rational approaches to solving problems in assessing the effectiveness of non-standard processing pressure. In this regard, it seems reasonable to conduct numerical simulation using virtual planning of a full factorial experiment (FFE) [8].

The advantage of FFE is the ability to describe the process in full compliance with the algorithm of physical experiment, based on established assumptions. FFE is the most easy to implement numerous methods of physical experiment. When using FFE purpose is to obtain a linear mathematical model of the process, which will allow defining future strategy for conducting a real experiment.

Thus, the purpose of modeling is holding a virtual process SPD by ECAP-Conform method with the use of FFE, and the identification of rational speed processing mode in combination with the universal training of the billet surface in the condition of receiving lengthy SMC semi-finished product.

2. RESEARCH METHODOLOGY

It is possible to obtain more complete information about the investigated dependencies when you run the simulation, the authors have used FFE. Experiment planning is the procedure of choice in the number and conditions of the experiments, a necessary and sufficient to obtain a mathematical model of the process [9]. It is important to consider the following: a desire to minimize the number of experiments; the simultaneous variation of all the variables that define the process; the choice of a clear strategy that allows you to make informed decisions after each series of experiments. Prior planning of the experiment it is necessary to gather additional information about the test object, which uses the skills and knowledge obtained in previous studies, or described in the literature [10].

Experiment planning was conducted on the basis of modeling the process of obtaining long length semi-finished products of commercially pure titanium method ECAP-Conform. Diagram of the device represented in Fig. 1. The object of study is commercially pure titanium VT1-0 flow characteristics of which were laid during the development of the numerical model [11].

For the purposes of numerical simulation used a standard software package (SP) *"DEFORM-3D"*. The purpose of the simulation and factorial experiment in SP *"DEFORM-3D"* were pregenerated three-dimensional model in the software product *"Kompas-3D"*.

Assumptions

1) Material of the billet in the initial state is isotropic and there are no initial stress and strain;
2) The temperature of deformation is assumed to be 200 °C;
3) The angle of intersection of the channels 120°;
4) The tool is absolutely rigid, and accounting for the geometry of the tool is performed automatically;
5) The material of the billet took plastic;
6) For the simulation was chosen 100 steps, taking into account the full passage of the billet in spinnerets and obtaining a stable result;
7) The billet is divided into 43553 trapezoidal elements.

In preparation for the task of modeling believe that the most significant factors affecting the production of defect-free products in the conditions of intensive deformation at a temperature of 200 °C are factors of friction (contact options) billets with different parts of the tool and the rate of deformation, due to the speed of rotation of the impeller. In this regard, it was decided to hold a virtual FFE using a two-level model with three variables on a number of variables, followed by the formalization of the results in the form of the regression equation and the optimization of the selected factors.

Thus, as independent variables during the drawing process with a shift to describing the execution of the process and its effectiveness from the point of view of the deformation forces chose the friction factor from the upper and lower surfaces of the impeller, which determines the efficiency of feed of the billet in the deformation zone f_1 (X_1), the friction factor from the forming tool f_2 (X_2), the strain rate (the speed of rotation of the impeller) V (X_3). Parameter response (dependent parameter) determined the effect of strain rate P (Y).

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

Table 1. Factor levels.

Factors	X_1	X_2	X_3 (V, m/min.)
Datum level (X_i)	0,50	0,50	20
Variability interval (ΔX_i)	0,25	0,25	10
Higher level ($x_i = 1$)	1	1	30
Lower level ($x_i = -1$)	0	0	10

3. EXPERIMENTAL RESULTS AND DISCUSSION

The number of experiments N was determined by the number of factors k in accordance with the expression:

$$N = 2^k = 2^3 = 8 \qquad (1)$$

It is required to determine such values f_1, f_2, V, which will ensure the lowest force deformation P.

The mathematical model after the implementation of experiments full factorial experiment is:

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

where b_i – regression coefficient.

For calculating the coefficients of this model using the extended planning matrix and results of the experiments (Table 2).

Table 2. Extended matrix of plan 2^3 and the results of tests.

№ test	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	У(кН)
1	+	+	+	+	+	+	+	+	13,3
2	+	-	+	+	-	-	+	-	16,5
3	+	+	-	+	-	+	-	-	10,7
4	+	-	-	+	+	-	-	+	12,7
5	+	+	+	-	+	-	-	-	23,2
6	+	-	+	-	-	+	-	+	19,8
7	+	+	-	-	-	-	+	+	13,5
8	+	-	-	-	+	+	+	-	12,9

In Fig. 2 the problem of numerical simulation of the process of ECAP-Conform, this resulted in the minimum of the strain rate.

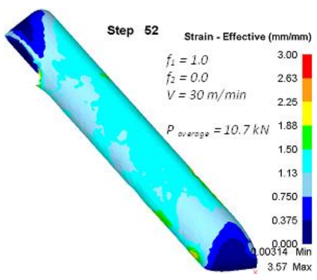

Fig. 2. The result of the simulation process, the ECAP-Conform: field distribution of the accumulated plastic deformation. Strain rate $P_{average}$ = *10,7 kN.*

The regression coefficients were calculated by the formula:

$$b_i = \frac{\sum_{i=1}^{N} x_i y_i}{N}, \quad (3)$$

where i = 0, 1, 2, …, 8.

On the basis of calculations received the following General form of linear regression equation:

$$y=15{,}33X_0 - 0{,}15X_1+2{,}88X_2-2{,}03X_3+0{,}20X_1X_2-1{,}15X_1X_3 - 1{,}28X_2X_3 - 0{,}50X_1X_2X_3 \quad (4)$$

From equation (4) shows that the most significant influence on the strength of deformation have the factor of friction in sliding contact of the billet and tool f_2 (X_2) and the rate of deformation V (X_3). Moreover, from the coefficients of the regression equation shows that the force of deformation will decrease with the increase of both factors. A much smaller impact on deformation force has an active factor of friction f_1 (X_1) from the upper and lower surfaces of the impeller, which is supplied to the billet in the deformation zone. Despite the fact that the greatest and unidirectional influenced by factors X_2 and X_3 can select variants universal preparation of the surface of the billet. It should be noted that double and triple interaction have multiple interpretations and therefore a complex interaction should be analyzed separately, and with reference to specific operating conditions of a multicomponent system.

A priori, we can say that in the considered conditions the minimum value of the deformation forces can be obtained when the optimal combination adopted in this study, the independent parameters.

Is of practical interest, the solution of the optimization problem for determining the actual values of the independent parameters considered in the virtual experiment, numerical simulation and provides minimum value of the deformation forces to implement the ECAP-Conform. This task is solved by the method of "steep ascent" [8].

Steps in the change factors were calculated in the natural scale. For this, we first identified the product of the coefficients on the corresponding intervals of varying factors, i.e. $b_i\Delta X_i$, then in proportion to these works prescribed steps. Using the values $b_i\Delta X_i$, identified the steps in changing the factors as follows. From technological considerations chose a step change in the friction factor from the upper and lower surfaces of the impeller (Δ_1 = 0.05). Steps for the other factors received from the proportions of:

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

The sequence of stages steep ascent is presented in Table 3. Some mental experiments implemented in a computer model (Tab. 3). Experiment planning using the steep ascent showed that under these conditions the strength of the deformation will be minimal at high friction from the upper and lower surfaces of the impeller (f_1 ≈ *1.00*), the friction tending to the minimum values from the forming tool (f_2 ≈ *0.00*), as well as at high strain rate (V ≈ *25 m/min*).

Table 3. Steep ascent.

Factors	X_1 (the friction factor from the upper and lower surfaces of the impeller, f_1)	X_2 (the friction factor from the forming tool, f_2)	X_3 (the rate of deformation, V *m/min*)	Y (the force of deformation P, *kN*)
b_i	-0.15	2,875	-2,025	
$b_i\Delta X_i$	-0.15	1.44	- 40.5	
Step	-0.05	0.05	- 5.0	
Step after rounding	-0.05	0.05	- 5,0	
Basic level (X_i)	0,5	0,5	20	
Mental experience	0,45	0,3	15	
Implemented experience	0,45	0,3	20	0,70
Mental experience	0,55	0,7	15	
Mental experience	0,55	0,3	25	
Implemented experience	0,55	0,7	15	0,90
Mental experience	0,45	0,7	25	
Mental experience	0,55	0,3	15	
Implemented experience	0,55	0,3	20	1,20
Implemented experience	0,55	0,3	15	1,50

If all these values of independent parameters it is possible to ensure the strength of the deformation *P ≈ 10.7 kN* (Fig. 2). However, the objective of the study was to provide a process SPD processing method ECAP-Conform with the minimum possible force deformation at the universal condition of preparation of the surface of the billet.

By solving the inverse problem were able to choose the option of a universal surface preparation and rate of deformation, which achieved a value of the deformation forces *P ≈ 12.5 kN*, which is quite acceptable.

Herewith want to ensure $f_1 = f_2 = 0.3$ and the rate of deformation of *V ≈ 30 m/min*.

In Fig. 3 shows the simulation results for the above values of variables in the context of the stated objectives of the study.

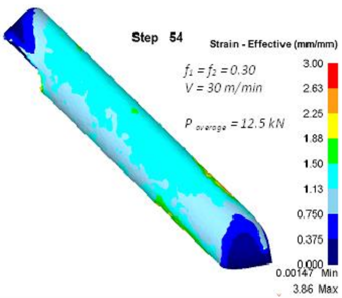

Fig. 3. The result of the simulation process, the ECAP-Conform after solving the inverse problem: the field distribution of the accumulated plastic deformation. Force deformation $P_{average}$ *= 12,5 kN.*

Thus, universal preparation of the surface of the billet with minimum value of the force of deformation. On this basis, for the practical implementation process of ECAP-Conform commercially pure titanium can offer the option of preparing the surface of the billet, combining under lubricating coating and technological lubricant. Thus the rheological properties of such combination must match the material with high shear stress in the area of sliding contact. This assumption requires further research.

CONCLUSIONS

The result is a virtual full factorial experiment was established that the most significant influence on the strength of deformation have the factor of friction in sliding contact of the billet and tool f_2 (X_2) and the rate of deformation V (X_3). It was found that the active factor of friction f_1 (X_1) from the upper and lower surfaces of the impeller, which is supplied to the billet in the deformation zone, has a much smaller impact.

Virtual full factorial design method a steep ascent in the process of numerical simulation allowed us to determine the numerical values of friction factors from the upper and lower surfaces of the impeller, f_1 and forming parts of the instrument, f_2, which are universal for the SPD process of commercially pure titanium by method ECAP-Conform.

For the practical implementation process of ECAP-Conform commercially pure titanium can offer the option of preparing the surface of the billet, which combines the application of under lubricating coating and technological lubricant.

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