SELECTING THE OPTIMUM VARIANT OF THE SHEAR DRAWING PROCESS FOR LOW-CARBON STEEL

ВЫБОР ОПТИМАЛЬНОГО ВАРИАНТА ПРОЦЕССА ВОЛОЧЕНИЯ СО СДВИГОМ НИЗКОУГЛЕРОДИСТОЙ СТАЛИ

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Abstract. *With the help of computer simulation in the DEFORM-3D software, there was performed a virtual full factorial experiment of the process of shear drawing. In the course of the experiment, the effect of independent parameters (drawing speed, die rotation rate, die angle and friction factor) on the strain intensity was evaluated. As a result of the experiment, a regression equation was derived and the most significant individual factors and their combinations, influencing the response parameters, were determined. Also, comparative results were presented for the processes of regular drawing and shear drawing. It was demonstrated that the process of shear drawing has a higher efficiency from the point of view of strain intensity.*

KEY WORDS. SIMULATION, SHEAR DRAWING, VIRTUAL FULL FACTORIAL EXPERIMENT, PLANNING MATRIX, STRAIN INTENSITY.

1. Introduction

At present, there is interest in studies in the area of enhancement of metals' strength due to structure refinement down to the submicrocrystalline (SMC) size through severe plastic deformation (SPD) processing [1]. Among the SPD techniques are equal-channel angular pressing (ECAP) [2, 3] and its advanced variation – ECAP-Conform [4], which was designed for the fabrication of long-length billets with a bulk SMC structure and enables creating prerequisites for the practical implementation of SPD processing.

The technical process based on structure refinement through SPD processing and implemented with the use of an ECAP-Conform facility is an efficient method to increase the strength of metals and alloys. However, it has several drawbacks:

1) muti-cycle processing is required to produce high levels of accumulated strain in the processed material;

2) long-length rods with a square section are produced;

3) additional post-deformation treatment, e.g. drawing, is required to produce rods with a round section.

To eliminate the above-mentioned drawbacks, the method of shear drawing was proposed. Deformation accompanied by a change in the mechanical properties of a metal is effected due to drawing and rotation of an eccentric drawing die, which provides additional shear deformation [5].

It is difficult to describe the behavior and prediction of the process of shear drawing due to the lack of sufficient full-scale experiments, since work at a physical experiment is rather time-consuming and costly in terms of capital investments.

In research and practical activity, a prominent place is held by numerical methods for the study of complex processes, inculding simulation with the use of cutting-edge software products. The efficiency of the use of simulation methods and solution of engineering tasks grows substantially, if at the stage preceding the design of actual technological processes, conditions are created for the evaluation of the most important parameters.

Application of mathematical methods is one of the most rational approaches to the solution of tasks related to the efficiency of evaluation of non-conventional metal forming processes. In this connection, it is reasonable to perform numerical simulation with the use of planning of a virtual full-factorial experiment (FFE) [6].

The advantage of a FFE is the ability to describe a process with full observation of the physical experiment's alogorythm, taking into account the set assumptions. FFE is the most easily implementable method among the numerous methods of physical experiment. The aim of applying FFE is to produce a linear mathematical model of a process, which will help to define further strategy in performing a real experiment.

Thus, the aim of simulation is to perform a virtual process of shear drawing with the use of FFE, and to reveal the most efficient conditions for producing long-length SMC semi-products.

2. Experimental procedure

In order to obtain the fullest information about the studied dependencies, the authors used FFE when performing the simulation. Experiment planning is a procedure of selecting the number and conditions of tests that are necessary and sufficient for producing the mathematical model of a process [7]. Here, it is important to consider the following: tendency for the minimization of the number of tests; simultaneous variation of all variables defining the process; selection of a clear strategy that enables making grounded decisions after each series of experiments. Prior to planning a full-scale experiment, it is necessary to collect additional information about the studied object, using the skills and knowledge obtained earlier in previous investigations or described in literature [8].

The experiment planning was performed for the method of processing of long-length rods with a round section from low-carbon steel. The facility for shear drawing consists of two eccentric drawing dies, one of which rotates [5]. Its schematic illustration is presented in fig.1.

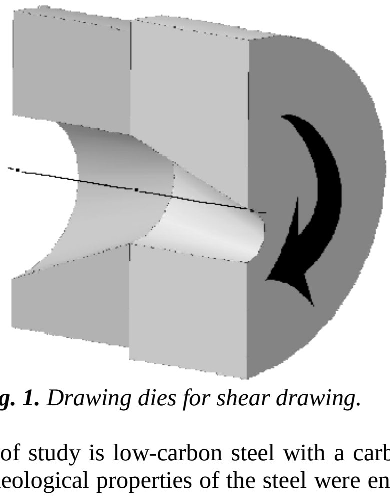


Fig. 1. *Drawing dies for shear drawing.*

The object of study is low-carbon steel with a carbon content of 0.1 %. The rheological properties of the steel were entered when developing the numerical model [9].

To perform the numercial simulation, the standard application software package (ASP) DEFORM-3D was used.

With a view to perform modeling and factorial experiment in the DEFORM-3D ASP, three-dimensional models of dies with different angles of the working part were designed in advance in the KOMPAS-3D software.

Accepted assumptions

1) The billet material in the initial state is isotropic and has no initial stresses and strain;

2) The temperature of the deformation environment is accepted as 20ºC;

3) The tool is absolutely rigid, and the tool's geometry is taken into account automatically;

4) The initial billet's material is accepted as ductile;

5) For the simulation, 100 steps are selected, taking into account the full passage of a billet in the dies and the generation of a stable result;

6) The billet is divided into 43553 trapezoidal elements.

At the stage of the simulation task preparation, the most significant factors influencing strain intensity in the process of shear drawing at room temperature are the die angle, the drawing speed, the rate of the die's rotation around its axis and the tribological parameters of the billet's contact with the tool. In this connection, it was decided to perform a virtual FFE using a two-level model with four unknown variable factors with subsequent formalization of the obtained results in the form of regression equation and optimization of the selected factors.

Thus, as independent variables in the process of shear drawing, characterizing the execution of the process and its efficiency, from the point of view of strain intensity we selected the wire drawing speed V (X_1), the die rotation rate ω (X_2), the die angle α (X_3) and the friction factor $f_{mp.}$ (X_4). The parameter of response (or dependent variable) determined the material's strain intensity (Y).

The factors were varied at two levels. The variation intervals of variable factors and their values in full scale are presented in table 1.

Table 1. *Levels of factors*

Factors	X_1 (*V, m/min.*)	X_2 (ω, *min*$^{-1}$)	X_3 (α, *grad.*)	X_4 (f_{mp})
Basic level (X_i)	20	350	15	0.50
Variation interval (ΔX_i)	10	50	5	0.25
Upper level (x_i = 1)	30	600	20	1
Lower level (x_i = – 1)	10	100	10	0

The number of tests N was determined from the number of factors k in accordance with the expression:

$$N = 2^k = 2^4 = 16 \qquad (1)$$

It is necessary to determine such values of V, ω, α, $f_{mp.}$, under which the strain intensity ε in the range of 1 to 3 ($1 \le \varepsilon \le 3$) will be provided.

The mathematical model after running tests of full factorial experiment has the following form:

$$y=b_0+b_1x_1+b_2x_2+\ldots+b_{12}x_1x_2+b_{13}x_1x_3+\ldots+b_{123}x_1x_2x_3+b_{124}x_1x_2x_4 + \ldots+b_{1234}x_1x_2x_3x_4, \qquad (2)$$

where b_i is regression coefficients.

To calculate the coefficients of this model, we constructed an expanding matrix of planning and test results (table 2).

3. Experiment results and discussion

Table 2. *Expanded matrix of the plan* 2^4 *and test results*

Test No.	x_0	x_1	x_2	x_3	x_4	x_1x_2	x_1x_3	x_1x_4	x_2x_3	x_2x_4	x_3x_4	$x_1x_2x_3$	$x_1x_2x_4$	$x_1x_3x_4$	$x_2x_3x_4$	$x_1x_2x_3x_4$	y
1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	0.30
2	+	-	+	+	+	-	-	-	+	+	+	-	-	-	+	-	0.70
3	+	+	-	+	+	-	+	+	-	-	+	-	-	+	-	-	0.90
4	+	-	-	+	+	+	-	-	-	-	+	+	+	-	-	+	0.50
5	+	+	+	-	+	+	-	+	-	+	-	-	+	-	-	-	0.50
6	+	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	0.90
7	+	+	-	-	+	-	-	+	+	-	-	+	-	-	+	+	0.60
8	+	-	-	-	+	+	+	-	+	-	-	-	+	+	+	-	0.70
9	+	+	+	+	-	+	+	-	+	-	-	+	-	-	-	-	0.40
10	+	-	+	+	-	-	-	+	+	-	-	-	+	+	-	+	1.50
11	+	+	-	+	-	-	+	-	-	+	-	-	+	-	+	+	1.10
12	+	-	-	+	-	+	-	+	-	+	-	+	-	+	+	-	1.20
13	+	+	+	-	-	+	-	-	-	-	+	-	-	+	+	+	0.70
14	+	-	+	-	-	-	+	+	-	-	+	+	+	-	+	-	0.90
15	+	+	-	-	-	-	-	-	+	+	+	+	+	+	-	-	1.30
16	+	-	-	-	-	+	+	+	+	+	+	-	-	-	-	+	1.00

The regression coefficients were calculated according to the formula:

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

where i = 0, 1, 2, …, 16.

From the calculations, the following general form of the linear regression equation was obtained:

$$y=0.825X_0+0.0125X_1+0.2X_2–0.1125X_3–0.075X_4–0.1625X_1X_2–0.05X_1X_3+0.175X_1X_4– 0.0125X_2X_3+0.05X_2X_4–0.0375X_3X_4+0.05X_1X_2X_3– 0.0875X_1X_2X_4 +0.0X_1X_3X_4+0.0625X_2X_3X_4+0.0X_1X_2X_3X_4 \qquad (4)$$

As a result of implementation of the two-level four-factor model of FFE and identification of the statistical significance of each of the 16 coefficients [10], regression equation (4) assumed the following form:

$$y=0.825X_0+0.2X_2-0.1125X_3-0.075X_4+0.1025X_1X_2+0.175X_1X_4-0.0875X_1X_2X_4+0.0625X_2X_3X_4 \quad (5)$$

Here, the hypothesis of the adequacy of mathematical model (5) in terms of the F-test [6] at a 5% significance level is not discarded.

It can be seen from equation (5) that the strain value is most significantly influenced by the die rotation angle, the die angle and the friction factor, as well as the combined interaction of the drawing speed and the die rotation rate; drawing speed and friction factor; drawing speed, die rotation rate and friction factor; die rotation rate, die angle and friction factor. A combined interaction of the rest of the factors has an insignificant influence on the strain intensity value. It is established that strain intensity increases with increasing die rotation rate and decreasing die angle and friction factor. Also, the response parameter grows as the drawing speed and the die rotation rate are simultaneously increased. A combined increase in the drawing speed and friction factor has a more significant effect on strain intensity. What can be predicted to a lesser degree is the effect on strain intensity of simultaneously three independent variables from the variables considered in this setting: the drawing speed, the die rotation rate and the friction factor, as well as the die rotation rate, the die angle and the friction factor. Also, their cumulative effect is multidirectional. Therefore, complex interactions should be analyzed separately and and in connection with the specific operation conditions of the multi-component system.

It can be seen from equation (5) that the drawing speed on its own has a small effect on strain intensity, but in combination with the die rotation rate, the die angle and the contact conditions in the plastic tribocoupling it can efficiently increase strain intensity.

Thus, it follows that the maximum strain intensity value can be attained under the optimum combination of the drawing rate with other independent parameters considered in this study.

For a more illustrative analysis of the obtained mathematical model, a diagram was built showing the effect of different factors on strain intensity (fig. 2).

It is visible from fig. 2 that the increase in strain intensity grows with increasing die rotation rate. The combination of deformation speed with the die rotation rate has a substantial effect on the response parameter.

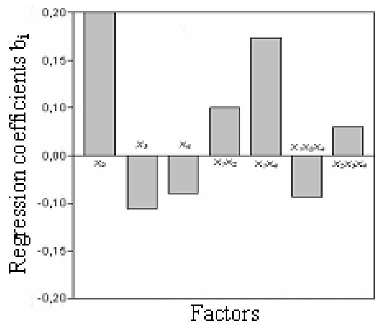


Fig. 2. *Effect of significant factors and their interactions: for the negative values – the response parameter grows as a factor decreases; for the positive values – the response parameter grows as a factor increases*

From this it follows that the efficiency of the shear drawing process depends on the synchronization of these two parameters which need to be considered in combination when designing the technnological process. It can also be seen from fig. 2 that the die angle and the friction factor, as individual parameters, are supposed to decrease for the strain intensity to increase. At the same time, from the analysis of pair and triple interaction effects (X_1X_4, $X_1X_2X_4$, $X_2X_3X_4$) it can be seen that the friction factor and the die angle, in combination with the drawing speed and the die rotation rate, have a significant and ambiguous effect on strain intensity, which should also be taken into account when designing the technological process of shear drawing.

Of practical interest is the solution of the optimization task for determining the actual values of independent parameters considered within the virtual experiment of numerical simulation, ensuring the maximum value of strain intensity in the process of shear drawing. This task was solved using the metod of «the steepest ascent» [6].

The steps in the variation of factors were calculated in full scale. With this aim, at first the products of the coefficients and the corresponding variation intervals of these factors were determined, i. e. $b_i\Delta X_i$, then steps were assigned proportionately to these products. The realization sequence of the steepest ascent stages is shown in table 3.

Table 3 *Steepest ascent*

Factors	**X_1 (drawing speed, m/min)**	**X_2 (die rotation rate, min^{-1})**	**X_3 (die angle, deg.)**	**X_4 (friction factor)**	**y (strain intensity)**
b_i	0.0125	0.20	- 0.1125	- 0.075	
$b_i\Delta X_i$	5*	10.00	- 0.5625	- 0.019	
Step	10	20	- 1.125	- 0.038	
Step after rounding	10	50	- 2.0	- 0.05	
Basic level (X_i)	20	350	15	0.50	
Thought test	15	100	20	0.45	
Implemented test	15	150	18	0.40	0.90
Thought test	15	200	16	0.35	
Thought test	15	250	14	0.30	
Implemented test	15	300	12	0.25	0.70
Thought test	15	350	10	0.20	
Thought test	15	400	20	0.15	
Implemented test	15	300	18	0.10	1.20
Thought test	15	500	16	0.12	1.60
Thought test	15	550	14	0.15	
Implemented test	15	600	12	0.10	0.70
Thought test	15	600	10	005	

* the value of $b_i\Delta X_i$ for X_1 (drawing speed) is set a priori due to the need to synchronize this factor with the other significant independent parameters admitted to consideration. Here, the step is selected randomly for technological reasons

Some of the thought tests were implemented within the computer model (table 4). The experiment planning using the steepest ascent method demonstrated that in the considered conditions the strain intensity will be the largest under a high die rotation rate ($\omega \approx 500$ min^{-1}), a small die angle ($\alpha \approx 16^o$) and a decreasing friction factor ($f_{mp.} \rightarrow min$). Here, the axial drawing rate *(V)*, due to its small effect on strain intensity as an individual parameter, was accepted as constant and equal to *15 m/min*.

In the framework of the task set for the study, we obtained optimized numerical values of the variable parameters, corresponding to the required value of strain intensity ($\varepsilon \geq 1.155$).

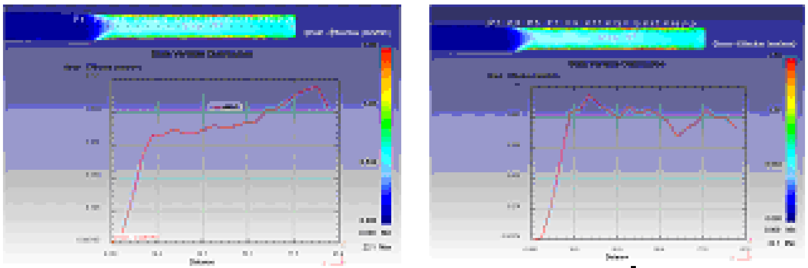
Simulation of the shear drawing process in the DEFORM-3D environment was performed with the following parameters:

Table 4. The source of data for computer models

Friction factor (according to Siebel)	0.12
Die angle, *deg.*	16
Drawing speed, *m/min*	15
Die rotation rate, min^{-1}	500

Given below are the results of numerical simulation according to the optimized values obtained in the process of the virtual FFE.

Analysis of the billet's strained stated after shear drawing shows that the largest value of ε is attained on the billet's surface (fig. 3b), since this is where the greatest metal deformation takes place, associated with the geometry of the dies and the rotation of one of the dies.

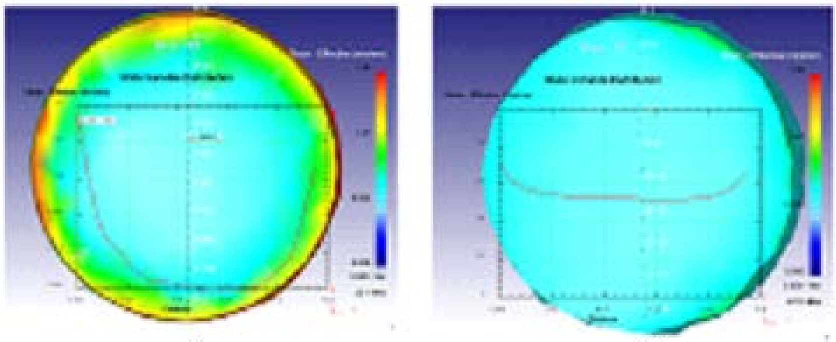


a b

Fig. 3 *Pattern of strain intensity distribution in the process of shear drawing: a – in the longitudinal section on the axis; b – in the longitudinal section on the surface.*

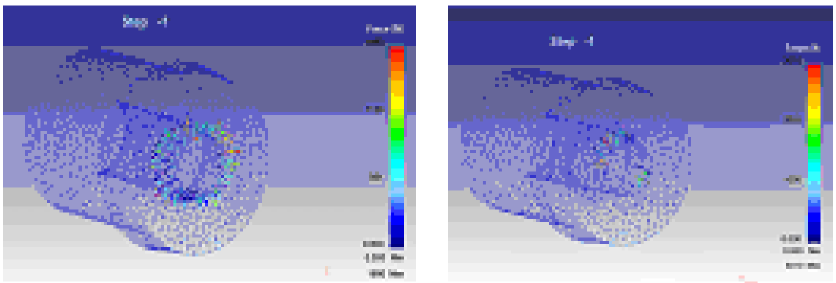
To estimate the values of strain intensity per one processing cycle, analysis of the processes of shear drawing and regular drawing was performed.

From the distribution of strain intensities (fig. 4) it can be seen that per one cycle of shear drawing larger values are obtained than per one cycle of regular drawing.



a b

Fig. 4 *Pattern of strain intensity distribution in the transverse section: a – shear drawing; b – regular drawing.*



a b

Fig. 5 *Distribution of normal forces on the deforming tool. a – shear drawing; b – regular drawing.*

Study of the normal forces on the tool demonstrates that as the die rotates, the forces acting on the tool decrease almost by 2 times, which expands the nomenclature of steels for the production of the tool and thus may facilitate cheapening of the process (fig. 5).

4. Conclusions

1. The virtual FFE using the steepest ascent method in the process of numerical simulation has enabled identifying the optimum numerical values of independent parameters which ensure the maximum strain intensity value at room temperature. To obtain $\varepsilon \approx 1.6$, it is necessary to provide a die rotation rate of $\omega \approx 500\ min^{-1}$, a die angle of $\alpha \approx 16^{o}$ and a friction factor of $f_{mp.} \approx 0.12$ under a rotation speed of $V = 15\ m/min$.

2. Comparative analysis of the processes of shear drawing and regular drawing for steel 10 at room temperature enables reducing the drawing forces almost by 2 times, increasing the maximum values of accumulated strain intensity from 0.5 to 1.6 and, in addition, reducing normal forces on the tool by 1.8 times.

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