Investigation of forming of end parts in pipe tension reduction using QForm program

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The paper deals with issues of longitudinal stresses during pipe rolling pipes on a three-roll stretching and reduction mill. Opportunities and problems in pipe reduction under tension are described. A research program aimed on reduction and evaluation of all input parameters that affect the parameters of the end parts of pipes based has been developed on the finite element model (FEM) base. Computer study on the FEM basis of stretching and reduction rolling of pipes using the Qform-3D program was carried out. When setting up the experiment using the FEM, the relative variation of the pipe wall thickness at the end parts of the pipe was chosen as the parameter for examination. Reduction of the pipe in its diameter in the pass, ovality of the pipe, geometric parameters of the initial pipe, front and rear tension of the pipe and friction coefficient were the main factors that determine the studying values. Geometric parameters of the end parts of the simulated pipe were measured after modeling. A statistical analysis of the results of a computational experiment of data on variation of pipe wall thickness was carried out. Regression dependence was built using the MATLAB program, and the most significant factors were selected according to the level of their importance. The model that describes the behavior of wall thickness during rolling in a stand of a stretching and reduction mill has been constructed.

Keywords: seamless pipes, tube reduction, wall thickness deviation, pipe end parts, computer simulation, high-speed modes, full factorial experiment.
DOI: 10.17580/cisisr.2022.02.06

Introduction

At present time, heavy-duty continuous technological lines, providing manufacture of high-quality tubes with minimal expenses, are used in pipe production. Continuous rolling mills of new generation, in particular stretching and reduction mills (SRM), open wide possibilities for improvement of technical and economical production parameters.

Use of stretching and reduction mills leads to increase of equipment productivity and expanding of dimension range of manufactured pipes, provides fabrication of wide range of pipes in diameter and wall thickness from one billet, and also provides achievement of essential total pipe reduction in its diameter and decrease of wall thickness; quality of pipes improves as well [1].

However, this process has its feature: thickened end parts are formed during pipe tension reduction. It is caused by absence of longitudinal stresses during reduction of these end parts, unlike the main parts of pipes [2-6]. Additionally, their forming is conducted in the conditions of filling and release of deformation area. At the same time, rather small amount of research works were devoted to the issues of forming of thickened end parts in the process of pipe reduction. Thereby examination of unsteady stages of reduction process is considered as an actual problem of pipe production.

The aim of this work is to examine the effect of key rolling parameters on wall thickness variation using computer modeling of pipe reduction process and determination of significance of these parameters. Based on the obtained data, the regression equation should be built, which will be used for solving the optimization problems.

Research program

As soon as continuous rolling process is characterized by large amount of the input independent parameters, which influence on thickened pipe end parts, it is difficult to conduct a full factorial experimental research [7]. Thereby the technique of a computational experiment, conducted via an orthogonal plan on the FEM base, was used in this work for complete examination of reduction process and assessment of all parameters having effect on pipe end parts.

Table 1. **Conditions of conducting the experiments for examination of pipe end parts**

Levels of parameters	Reduction in diameter, %	Pass ovality	Geometrical parameters of initial pipe, mm	Speed of a speed block for creating rear tension*, mm/s	Speed of a speed block for creating front tension*, mm/s	Temerature, °C
	ε	θ	$\left(\frac{d_{i-1}}{s_{i-1}}\right)$	z_{i-1}	z_i	T
Code	X_1	X_2	X_3	X_4	X_5	X_6
Top (1)	9	1.07	39.5	825	1225	1050
Main (0)	6	1.06	29.5	925	1125	950
Bottom (-1)	3	1.05	19.5	1025	1025	850
Variation interval	3	0.01	10	100	100	100

*As soon as QForm program complex has not possibility to set the required tension by concrete value, varying is provided using speed blocks (**Fig. 1**).

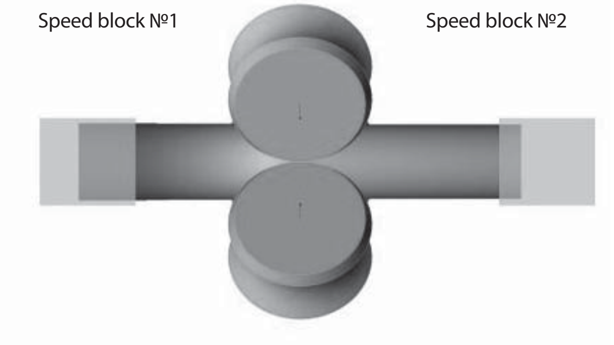

Fig. 1. Parameters of setting up speed conditions

Table 2. **Parameters of roll pass design**

No.	H, mm	B, mm	θ	ε, %
1	83.66	89.1	1.07	6
2		88.57	1.06	
3		87.74	1.05	
4	80.99	89.1	1.07	9
5		88.57	1.06	
6		87.74	1.05	
7	86.33	89.1	1.07	3
8		88.57	1.06	
9		87.74	1.05	

When setting up the computational experiment using FEM, relative variation of pipe wall thickness in its end parts was chosen as the examined parameter. The main factors which determine the value of wall thickness variation were the following ones: pipe reduction in its diameter ($\varepsilon = d_{i-1}-d / d_{i-1}$), ovality of the pipe ($\theta$) (which depends on the relationship between pass height h and width b, geometric parameters of the initial pipe wall thinness d_{i-1} / s_{i-1} relative longitudinal front z_i and rear z_{i-1} tension of the pipe and temperature of initial billet (T).

The index i in these relationships means the parameter of rolled pipe, while i–1 – the parameter of initial pipe. Capital notes are related to a pass, and lowercase notes are related to a billet.

Large amount of factors stipulates difficulties during examination of reduction process, because it is rather difficult to take into account the influence of each of the a.m. factors and to provide permanent experimental conditions [8, 9]. That's why it is necessary to choose such experimental plans for revealing the multi-factorial relationship of reduction process parameters, which allow to minimize the experimental mistake on the base of distinct formalized rules, and to assess the influence of managing factors.

The review of scientific and technical information displayed that the factors having the effect on pipe end parts provide non-linear influence [10-12]. However, this fact should be checked, thereby it is necessary to analyze the factors having more than 2 levels. It is suggested that influence of the factors on the related variable is non-linear, so at least three levels for checking the linear and quadratic effects are required. Moreover, some factors can be categorial with more than two categories.

Methodology of conducting the full factorial experiment during setting up the problem is presented in the **Table 1**.

It should be mentioned also that the original 3D model was developed for decrease of machine time; it consists of one stand of a stretching and reduction mill and allows to examine completely deformation and speed conditions of reduction process.

Varying of reduction in diameter and ovality was conducted via variation of roll pass design (pass height H and width B – see the **Table 2**) as well as geometric parameters of initial pipe (wall thickness 4.5 mm, 7.5 mm and 9.0 mm).

The set of parameters presented in the Table 1 requires conducting of $3^6 = 729$ experiments (three levels of varying the six factors). But such large amount of experiments is

Table 3. **Box-Behnken planning matrix (36-2)**

№	ε	θ	$\frac{s_{i-1}}{d_{i-1}}$	z_{i-1}	z_i	T	№	ε	θ	$\frac{s_{i-1}}{d_{i-1}}$	z_{i-1}	z_i	T	№	ε	θ	$\frac{s_{i-1}}{d_{i-1}}$	z_{i-1}	z_i	T
1	-1	-1	-1	-1	-1	-1	28	0	-1	-1	-1	1	1	55	1	-1	-1	-1	0	0
2	-1	-1	-1	0	1	0	29	0	-1	-1	0	0	-1	56	1	-1	-1	0	-1	1
3	-1	-1	-1	1	0	1	30	0	-1	-1	1	-1	0	57	1	-1	-1	1	1	-1
4	-1	-1	0	-1	1	-1	31	0	-1	0	-1	0	1	58	1	-1	0	-1	-1	0
5	-1	-1	0	0	0	0	32	0	-1	0	0	-1	-1	59	1	-1	0	0	1	1
6	-1	-1	0	1	-1	-1	33	0	-1	0	1	1	0	60	1	-1	0	1	0	-1
7	-1	-1	1	-1	0	-1	34	0	-1	1	-1	-1	1	61	1	-1	1	-1	1	0
8	-1	-1	1	0	-1	0	35	0	-1	1	0	1	-1	62	1	-1	1	0	0	1
9	-1	-1	1	1	1	1	36	0	-1	1	1	0	0	63	1	-1	1	1	-1	-1
10	-1	0	-1	-1	-1	1	37	0	0	-1	-1	1	0	64	1	0	-1	-1	0	-1
11	-1	0	-1	0	1	-1	38	0	0	-1	0	0	1	65	1	0	-1	0	-1	0
12	-1	0	-1	1	0	0	39	0	0	-1	1	-1	-1	66	1	0	-1	1	1	1
13	-1	0	0	-1	1	1	40	0	0	0	-1	0	0	67	1	0	0	-1	-1	-1
14	-1	0	0	0	0	-1	41	0	0	0	0	-1	1	68	1	0	0	0	1	0
15	-1	0	0	1	-1	0	42	0	0	0	1	1	-1	69	1	0	0	1	0	1
16	-1	0	1	-1	0	1	43	0	0	1	-1	-1	0	70	1	0	1	-1	1	-1
17	-1	0	1	0	-1	-1	44	0	0	1	0	1	1	71	1	0	1	0	0	0
18	-1	0	1	1	1	0	45	0	0	1	1	0	-1	72	1	0	1	1	-1	1
19	-1	1	-1	-1	-1	0	46	0	1	-1	-1	1	-1	73	1	1	-1	-1	0	1
20	-1	1	-1	0	1	1	47	0	1	-1	0	0	0	74	1	1	-1	0	-1	-1
21	-1	1	-1	1	0	-1	48	0	1	-1	1	-1	1	75	1	1	-1	0	-1	-1
22	-1	1	0	-1	1	0	49	0	1	0	-1	0	-1	76	1	1	0	-1	-1	1
23	-1	1	0	0	0	1	50	0	1	0	0	-1	0	77	1	1	0	-1	-1	1
24	-1	1	0	1	-1	-1	51	0	1	0	1	1	1	78	1	1	0	1	0	0
25	-1	1	1	-1	0	0	52	0	1	1	-1	-1	-1	79	1	1	1	-1	1	1
26	-1	1	1	0	-1	1	53	0	1	1	0	1	0	80	1	1	1	-1	1	1
27	-1	1	1	1	1	-1	54	0	1	1	1	0	1	81	1	1	1	1	-1	0

difficult owing to large expenses of machine time for FEM modeling.

The method for elimination of maximal amount of the main effects during the most possible small amount of experiments was developed for the plans 3^{k-p} (where k is the amount of factors; p is the amount characterizing decrease of the amount of required experiments) — so-called Box-Behnken plans [13]. These plans have not simple generators, they are constructed via combining of two-level factorial plans and plans of incomplete blocks and are characterized by complicated correlation of interactions. The experimental plan 3^{6-2} in accordance with the Box-Behnken method, needs conduction of 81 experiments [14]. This plan is presented in the **Table 3**.

Results and discussion

Geometrical parameters of simulated pipe end parts (ΔS / d_i) were carried out after modeling using special program [15], which allows to determine geometrical parameters of a pipe after modeling quickly and with required accuracy. Statistical analysis of the results of the calculating experiment for wall thickness variation data was conducted.

To reveal statistically important variable factors, which are included in the signature of approximating polynom, it is necessary to analyze the pair correlation matrix of factorial space as well as response function (pipe wall thickness variation). The vector of relative variation of pipe wall thickness for experimental planning matrix s presented in the corresponding column of the **Table 4**.

Using the MATLAB[1] program, the regression relationship was built and the most important factors were chosen. They were added in their turn, from the most importance to the most suitable one, which meets the requirements of the criterion of significance [16]. The determination coefficient increases during each step and was finally equal to $R^2 = 0.8650$, what testifies about confidence of this relationship (**Fig. 2**).

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[1] High level interpreted software language together with the package of applied programs and integrated medium for development and conduction of engineering and mathematical calculations as well as operations with matrix data bases and visualization.

Table 4. **Measurement results for wall thickness variation along the complete pipe cross section**

Experiment	$\frac{\Delta S}{d_i}$, mm	Experiment	$\frac{\Delta S}{d_i}$, mm	Experiment	$\frac{\Delta S}{d_i}$, mm	Experiment	$\frac{\Delta S}{d_i}$, mm	Experiment	$\frac{\Delta S}{d_i}$, mm	Experiment	$\frac{\Delta S}{d_i}$, mm
1	0.1478	16	-0.0332	31	0.0034	46	0.0868	61	-0.1065	76	-0.0676
2	0.4738	17	-0.0354	32	-0.0070	47	0.2895	62	-0.0239	77	0.1603
3	0.5088	18	0.1847	33	0.3199	48	0.0613	63	-0.1147	78	0.1917
4	0.0553	19	0.1495	34	-0.0779	49	0.0008	64	-0.0743	79	0.0414
5	0.1955	20	0.4611	35	0.0929	50	-0.0062	65	0.0475	80	-0.1060
6	0.0486	21	0.4908	36	0.1125	51	0.3204	66	0.1751	81	-0.1156
7	-0.0352	22	0.0575	37	0.0866	52	-0.0782	67	-0.0708		
8	-0.0382	23	0.1964	38	0.2891	53	0.0931	68	0.0736		
9	0.1855	24	0.0491	39	0.0637	54	0.1131	69	0.1880		
10	0.1513	25	-0.0337	40	0.0011	55	-0.0705	70	-0.1040		
11	0.4691	26	-0.0374	41	-0.0064	56	0.0356	71	-0.0181		
12	0.4938	27	0.1800	42	0.1434	57	0.4734	72	-0.1139		
13	0.0593	28	0.0863	43	-0.0768	58	-0.0710	73	-0.0729		
14	0.1974	29	0.2844	44	0.0919	59	0.1562	74	0.0407		
15	0.0504	30	0.0592	45	0.1116	60	0.1853	75	0.3440		

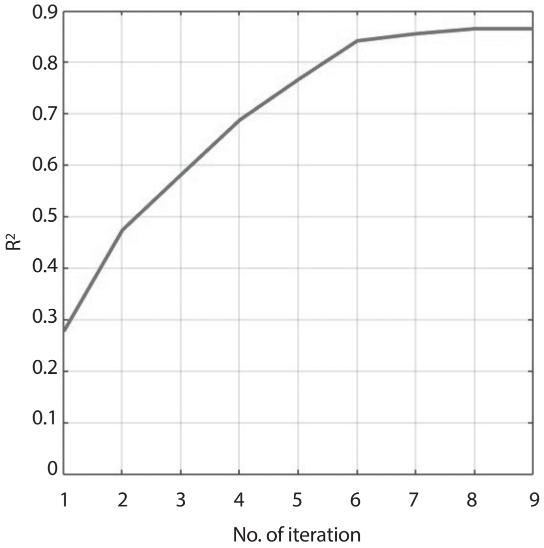

Fig. 2. Variation of the determination coefficient after adding the important factors

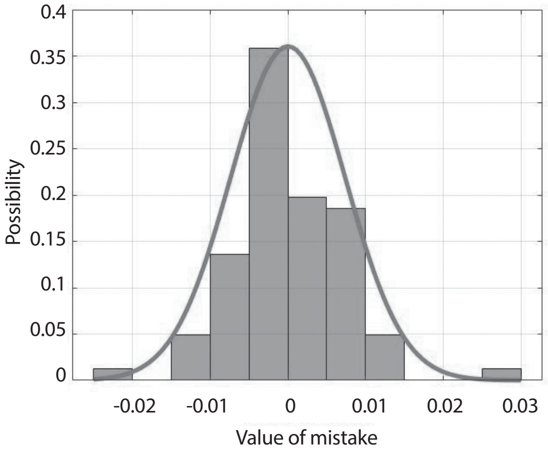

Fig. 3. Histogram of distribution of dispersion reminders

Thereby, the following regression equation should be accepted:

$$\frac{\Delta S}{d_i} = -0.399 - 0.256 \cdot \varepsilon_i - 0.336\left(\frac{d_{i-1}}{s_{i-1}}\right) - \\ - 0.212 \cdot z_{i-1} + 0.271\varepsilon_i \cdot \frac{d_{i-1}}{s_{i-1}} - 0.108\varepsilon_i \cdot z_i + \\ + 0.78\frac{d_{i-1}}{s_{i-1}} \cdot z_{i-1} - 0.209 z_{i-14} \cdot z_{i5} \quad (3)$$

where ε_i – deformation degree; d_{i-1} / s_{i-1} – degree of pipe wall thinness; z_{i-1} – rear tension; z_i – front tension.

We can see from the formula (3) that those important factors were chosen, which have strong influence indeed on the value of pipe thickened end parts. It should be noted that such factor as wall thinness degree as the most important parameter was added in the equation during the 2nd iteration. Another factor – deformation degree – was added in the equation during the 3rd iteration, and front and rear tension, as well as cross effect of these factors, were added during further iterations. Such factors as temperature and ovality have no essential effect on wall thickness variation.

To analyze the mistakes, it is necessary to build the histogram of mistakes distribution (**Fig. 3**).

The average calculated value of mistakes (reminders) makes $2.2 \cdot 10^{-16}$, while deviation from the expected value $\sigma = 0.007$. Taking these values and the histogram (Fig. 3) into account, it can be concluded that the confidence interval of the equation (3) does not exceed $\pm \sigma$. It can be seen also that the histogram is described by a normal curve. The suggestion about normality of reminders can be considered as realized: there are no stand-out reminders and no regularities in their behaviour were observed.

It is required to build the graph with relation between predicted and initial values, with overlapping by the

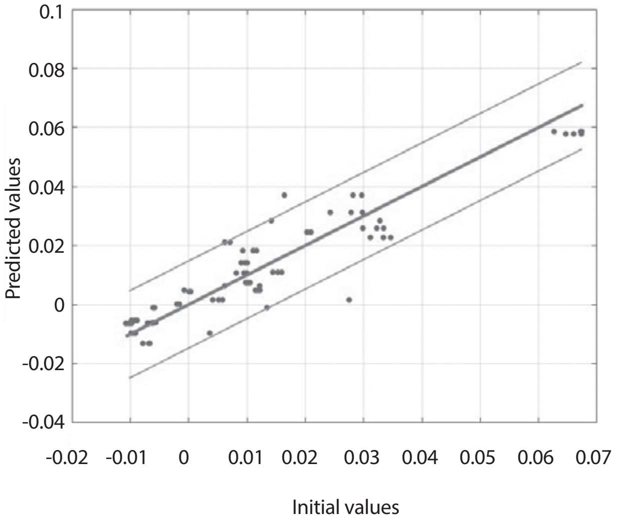

Fig. 4. Distribution of deviations of wall thickness predicted values depending on initial values

confidence interval for checking linearity and reliability (**Fig. 4**).

It can be seen that the graph on the Fig. 4 can be characterized mainly by minimal deviation, the root mean square error (RMSE) makes 0.0078; however, some extremal values testify about more low level of tuning the experimental data to a model. Based on the results of analysis, it can be established that the model (3) provides rather adequate description of experimental data. In such way the model describing behaviour of pipe wall thickness during rolling in a stretching and reduction mill was built; it can be used, in particular, for solving the optimization problem aimed on search of the optimal speed conditions in order to minimize the length of pipe thickened end parts.

The results of calculation according to the relationship (3) are presented on the **Fig. 5**.

Let us assess the obtained results via analysis of the graphs on the Fig. 5. It can be seen that zero values of

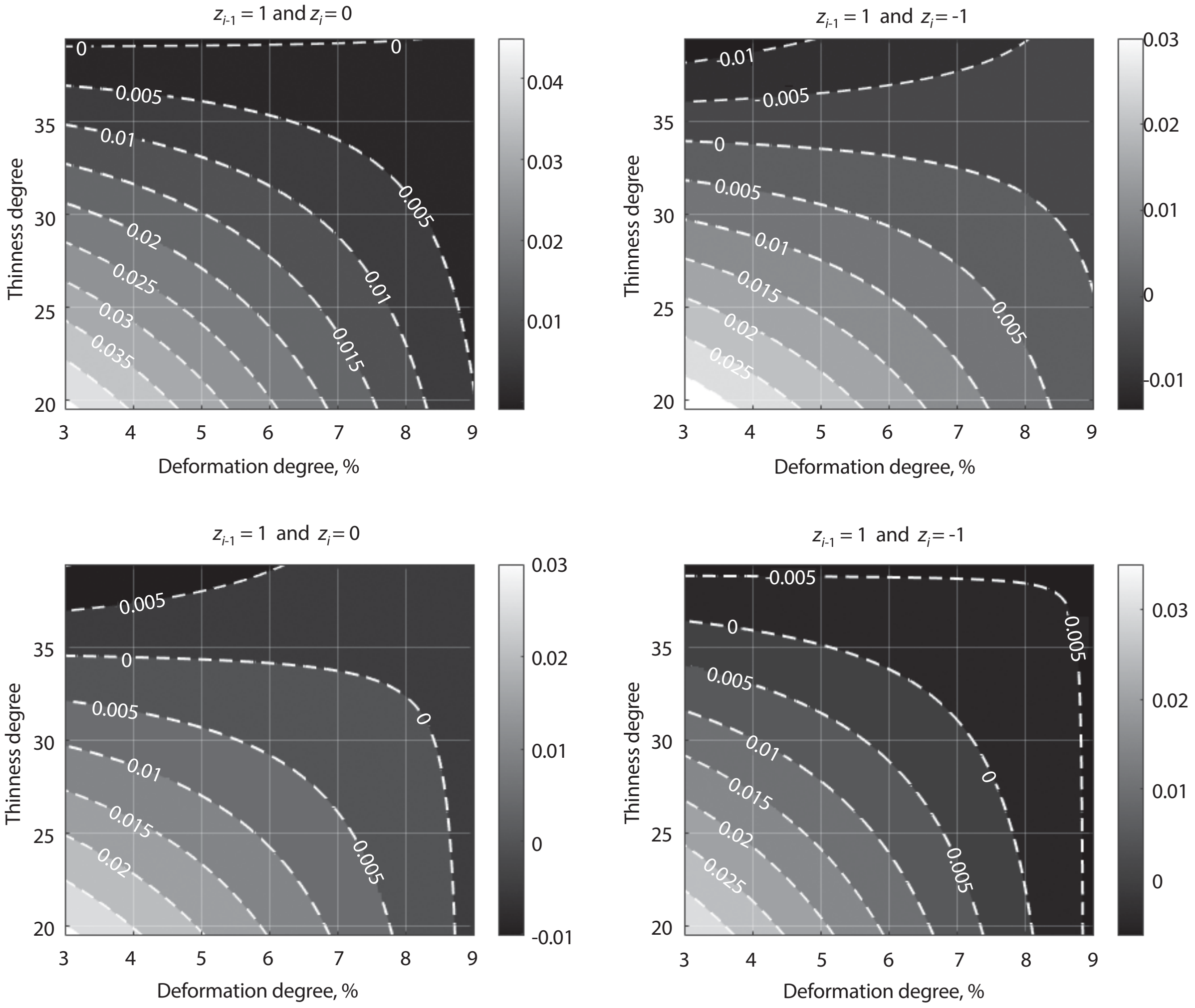

Fig. 5. Relationship of the pipe wall thickness variation at fixed tension parameters[1]

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[1] The tension values are preset by top, bottom and main limits according to the Table 1

specific rear and front tensions the essential influence on wall thickness thickening is provided by thinness degree. When rolling with use only rear or only front tension at the pipe end parts, wall thickness thinning occurs; it confirms necessity of development of such models that can be used just to provide influence on the pipe end parts [5]. Models mean the speed conditions that changes intentionally rotation frequencies of PPC drive motors in order to achieve stress and deformation values at the pipe end parts which are maximally close to steady conditions.

Conclusions

The following conclusions can be made on the base of the results of this conducted research:

1. The original technique for investigation of deformation and speed conditions of pipe reduction process was created with minimal expenses of machine time.

2. Comprehensive calculating experiment for examination of pipe reduction processes and assessment of influence of key input factors on parameters of the pipe end parts using FEM was conducted.

3. The regression relationship, describing pipe wall thickness behaviour during rolling in a stretching and reduction mill, was obtained. It can be used for solving the optimization problem in the field of searching the optimal speed conditions in order to minimize the length of thickened pipe end parts. These optimal speed conditions allow to minimize wastes via decrease of length of cutting pipe end parts by 20-30 %. Such technical solution was checked during pilot-industrial works. Prediction accuracy using this model makes ±14,8 %, what is quite allowable for research of metal forming processes.

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