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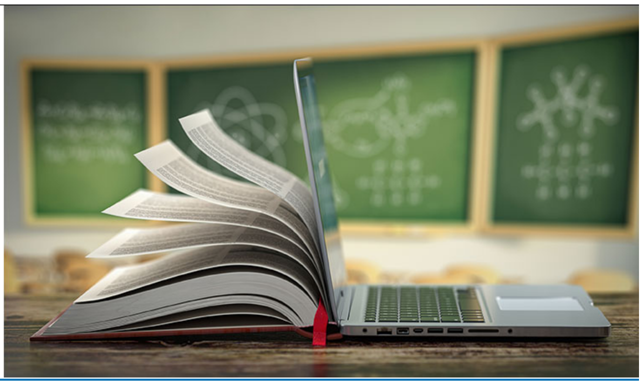

Simulaling the Faceted Tube Drawing

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Abstract. The paper studies cold-sinking of four-, six-, and eight-faceted steel tubes from round billets in a single pass. The built mathematical model of the process objectively describes the drawing and allows forecasting the geometric and deformation parameters of the pipes processed, as well as the power parameters of the process. The model accuracy has been confirmed by a series of parallel calculations and a comparative calculation in two software packages. The results have shown satisfactory convergence. The theoretical experiment results have been verified by performing a full-scale one. The results have also been consistent. The research results are of practical use to the process equipment manufacturers and consumers.

1. Introduction

The manufacture of shaped tubes with high dimensional accuracy while reducing production costs is a relevant scientific and technical problem. Cold sinking is one of the widespread ways to produce shaped precision tubes. The modern packages implementing the finite element technique have proven themselves as a reliable tool in searching for the production problem solutions. Mathematical models allow forecasting the processing result with high accuracy. The process equipment developers and consumers need recommendations allowing them to forecast the processing results at the process equipment design stage and improve it during operation. The research objective is to build a mathematical model objectively describing the shaping, the analysis of which allows developing recommendations for improving this process. The study has been supported by the Russian Foundation for Basic Research (project No. 20-21-00063/20 Rosatom) according to the State Assignment of IMET UB RAS under the Program of Fundamental Research of State Academies. Works on the simulation of form drawing of shaped tubes using the finite element technique are known. In [1–4], the stress-strain state was studied based on a numerical method for the form drawing of shaped tubes. In the work [5], two simulation techniques were applied to study the tube wall deformations. Simulating the effect of friction and the lubricant behavior is described in detail in [6]; a full-scale experiment has been performed. The work [7] studies the drawing of heat-exchange tubes using a mathematical model. In [8], the stress-strain state was analyzed using the *ANSYS* software package for the form drawing of oval tubes. In [9], the cold drawing of precision seamless tubes was considered using the *DEFORM* software package. The work [10] is devoted to studying the tube drawing accuracy using finite element simulation. In [11], a similar process was considered for thin-walled steel tubes. In [12], a numerical method was applied to improve the shape of the working tool used in the tube drawing. A similar problem for square tubes was solved in [13]. In the listed and similar works, the problem raised herein has not been solved; this determines the scientific novelty of the study.

2. Description of the Mathematical Model and Discussion of the Numerical Experiment Results

The finite element technique was chosen as a tool to solve the problem raised herein. The *DEFORM* software package was chosen to generate a solution using the finite element technique. When choosing the size of the finite element mesh partition elements, a series of preliminary calculations were made, and the accuracy of their results analyzed. The rationale for choosing the element size and the estimation of its impact on the calculation accuracy is described in [14–16]. To improve the calculation accuracy, five parallel computer experiments were conducted, and the results averaged. To estimate the accuracy of the theoretical numerical experiment results, a comparative calculation has been performed in the *ANSYS* software package. The results have shown satisfactory convergence.

For the tubular product consumers, the section shape is of particular importance. Figure 1 shows a tube cross-section diagram specifying the dimensions. Under this research, the change of the below parameters depending on the face number of the tubes being processed has been studied: the wall deflection in the face center *L*, the actual wall thickness *Sa*, the radii of the face conjugation on the outer and inner surfaces *R* and *r*, and the elongation μ.

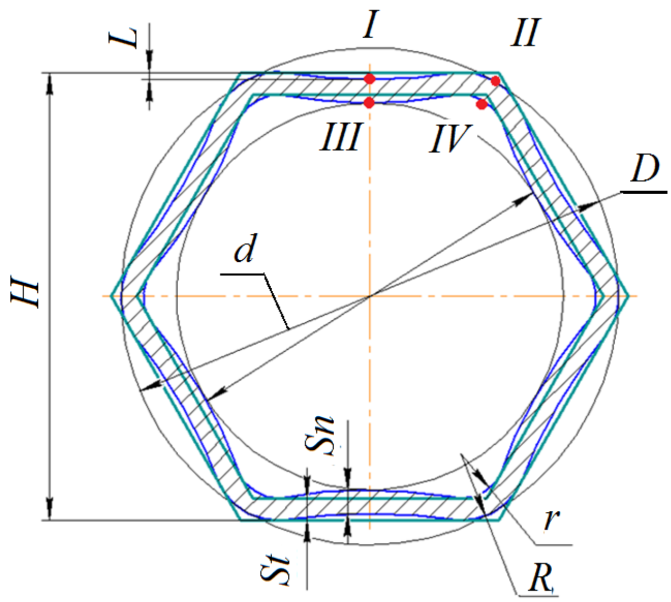

Figure 1. Six-Faceted Tube Cross-Section Diagram: *L* – the wall deflection in the face center; *D* and *d* – the diameters of the circumscribed and inscribed circles; *St* and *Sa* – theoretical and actual wall thickness; *R* and *r* – radii of the face conjugation on the outer and inner surfaces; *H* – the polyhedron height. Characteristic points: A, B, C, and D.

When implementing the drawing, the tubular product manufacturers consider the power indicators [17], i.e. the drawing force *P*, the drawing force work *W*, the energy consumption of the process *E*, and the displaced material amount *q*. Herein, changes in these parameters depending on the face number of the tubes shaped have been determined.

To estimate the quality of deformation parameters, the deformation intensity has been studied. The changes in the deformation intensity at the characteristic points depending on the product face number have been studied. 4 characteristic points were chosen: A, B, C, and D located at the conjunctions of the outer and inner surfaces of the tubes shaped. The characteristic point locations are specified in Figure 1.

As part of a theoretical study, three shaping cases have been considered: four-, six- and eight-faceted tubes. The cross-sectional profile on the outer contour of the tubes under consideration is set by the diameter of the circumscribed circle of the calibrating die section Dsc, which is the same for all three faceted tube processing cases considered.

The shaping has been performed on a die, the cross-section of which is shown in Figure 2. The inner die channel has a crimping section in the form of a truncated pyramid with flat faces. The calibrating section size is 16.4 mm. The working tool shape is described in detail in [18]. The crimping section to the die axis inclination angle is 10^0; there was no rounding radius between the crimping and calibrating working tool sections. Steel 20 GOST 1050 was chosen as the billet material. The billet was a round tube with a wall thickness of 1.5 mm and a diameter of 19 mm. The Amontons-Coulomb friction coefficient was taken equal to 0.15.

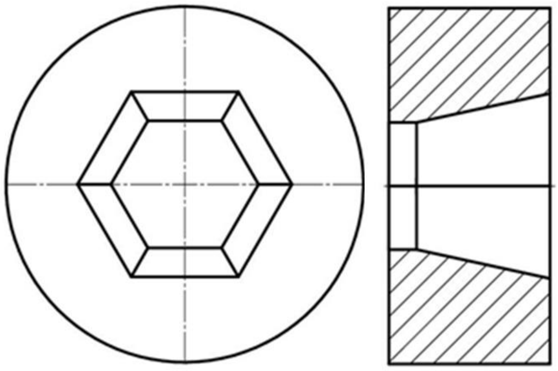

Figure 2. Working Tool Shape Diagram.

Based on the numerical experiment results, a comparative analysis of the parameters studied has been performed for the cases of shaping tubes with a different face number. The data are given in Table 1.

Table 1. Numerical Experiment Data.

Parameter	Tube Face Number		
	4	6	8
Actual wall thickness in the face center *Sa* (mm)	1.53	1.61	1.65
Deflection in the face center *L* (mm)	0.71	1.39	1.01
Elongation μ	1.032	1.099	1.131
The radius of face conjugation on the outer surface *R* (mm)	2.50	2.55	2.74
The radius of conjugation of the faces on the inner surface *r* (mm)	1.34	2.02	2.38
Drawing force *P* (H)	8515	15456	18893
Draw force work *W* (J)	8784	16992	21371
Displaced material mass *q* (kg)	2.92	11.40	16.11
Energy consumption of the process *E* (J / kg)	3009	1491	1327
Deformation intensity at point *I*	0.210	0.408	0.467
Deformation intensity at point *II*	0.255	0.184	0.172
Deformation intensity at point *III*	0.163	0.221	0.230
Deformation intensity at point Point *IV*	0.552	0.620	0.546

As can be seen from these data, the wall thickness *Sa* increases with an increase in the face number. The elongation μ and the conjugation radii r and R demonstrate the same behavior, i.e. increase with increasing the face number. The face deflection *L* has divergent dynamics.

In turn, with an increase in the fact number, the drawing force *P* increases, like the drawing force work *W* and the displaced material mass unit *q*, while the processing energy consumption *E* decreases.

The shape of the tubes to be processed also significantly affects the deformation intensity. With an increase in the face number, the deformation intensity at points I and III increases and at point II decreases; at point IV, the tendency to increase first prevails, but when processing tubes with six or more faces, it

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decreases: the deformation intensity changes nonlinearly and shows a divergent tendency when the face number changes. The greatest deformation intensity value is achieved at point IV.

3. Verifying the Theoretical Research Results and Describing the Full-Scale Experiment

To verify the computer experiment results, a full-scale one has been performed exemplified by shaping a six-faceted tube from a billet, the shape and mechanical properties of which, as well as the working tool and process parameters, correspond to those adopted in the theoretical experiment. To reduce the statistical error in processing the results, the full-scale experiment was performed on three groups of specimens. To ensure identical mechanical properties, the specimens were made of the same tube billet.

The tubes were shaped on a tensile testing machine MI-40U, for which tooling was prepared, which allowed reproducing the drawing and measuring the power indicators of the process. Instruments and process equipment are described in [19]. The geometrical parameters of the tube processed were measured using coordinate measuring devices with optomechanical conversion UIM-23 and DIP3 with a measurement accuracy of up to 5 μm using *Global Performance Power SHAPE 7080* software [20]. The deformation intensity was studied according to the technique [21] at characteristic point A. The study is described in more detail in [22, 23].

Comparative analysis of the theoretical and full-scale experiment results is represented in Table 2. The results have shown satisfactory convergence.

Table 2. Theoretical and Full-Scale Experiment Results.

Parameter	Theoretical	Full-scale.
Actual wall thickness in the face center *Sn* (mm)	1.53	1.52
Deflection in the face center *L* (mm)	0.71	0.72
Elongation μ	1.032	1.04
The radius of face conjugation on the outer surface *R* (mm)	2.50	2.47
The radius of face conjugation on the inner surface *r* (mm)	1.34	1.33
Drawing force *P* (H)	8515	8328
Draw force work *W* (J)	8784	895
Displaced material mass *q* (kg)	2.92	3.16
Energy consumption of the process *E* (J / kg)	3009	3295
Strain intensity. Point *I*	0.210	0.21

4. Conclusions and Practical Significance of the Results

As a result of the research, a mathematical model of cold-sinking of four-, six-, and eight-faceted tubes from seamless steel tubes in a single pass has been developed. The model accuracy has been confirmed by a series of parallel calculations and a comparative calculation in two software packages. The results have shown satisfactory convergence. The theoretical experiment results have been verified by performing a full-scale one. The results have also been consistent.

The mathematical model developed objectively describes the process and allows forecasting the shaping result. The model represented allows determining the power indicators of shaping, as well as the geometric and deformation parameters of the tube processed. The data obtained based on this model can be used in developing recommendations for improving the process equipment.

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