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Modeling of Pipe-Drawing Tool for Drawing the Multifaceted Pipes of Nonferrous Metals on an Immediate Arbor

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Abstract—A method of mathematical modeling of a pipe-drawing tool for drawing the multifaceted pipes of nonferrous metals and alloys using the vector-matrix apparatus, which can be applied for the analytical description of the bulk deformation region, is presented. Arbors with various geometries of the reduction zone are considered. As a result of modeling the deformation region, which appears when manufacturing the profiled multifaceted pipes by arbor drawing using all types of considered arbors, it is established that the best result with the smallest rounding radii is attained for arbors with a pyramidal input into the reduction zone.

Keywords: pipe-drawing tool, multifaceted pipes, modeling of the surface
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Currently, profiled pipes of nonferrous metals can be produced at plants of nonferrous metallurgy both by arborless drawing and by drawing using an arbor. However, there are still no generalized procedures of calculating the main production parameters of the profiling process of pipes including the drawing process. The calibration of the production tool and the sizes of the starting billet are selected experimentally for each concrete profile. When drawing the multifaceted pipes, a bulk deformation region appears which is rather complex to be described by conventional analytical mathematical models [1, 2].

This study is aimed at the mathematical modeling of the pipe-drawing tool for drawing multifaceted pipes made of nonferrous metals and alloys using the vector-matrix tool.

The simplest model of the metal flow in producing pipes is the theory of weakly conical flows developed by Gun [3]. It recommended itself well when analyzing the mode of deformation in the deformation region when fabricating the pipes by the drawing method as well as when evaluating the energy-power parameters of pipe production. As for applying this theory for the description of profiling multifaceted pipes by the drawing method, there are additional difficulties in this since the deformation of metal is axially asymmetric in this case. The axial symmetry of the nth order occurs in the deformation region considered in this process (n is the number of pipe facets) since the profiling process includes n symmetry planes. When modeling this process, the volume schematic of the deformation region should be used.

One way to optimize the fabrication process of shaped pipes with a simultaneous possibility to fulfill the natural generalization of the Gun theory is the application of a tool, which is modeled using a linear surface specified by a kinematic method. The kinematic method of specifying the linear surface is performed by the motion of the straight-linear generatrix, which intersects two arbitrary directional lines and, depending on the form of lines and certain additional conditions, these surfaces are either cylindroids or conoids. This method can be particularly implemented to construct the simplest surfaces (pyramidal, conical, and other), which are used when designing the pipe-drawing tool.

If two arbitrary parametrized directional lines are specified

$$\vec{r}_1(u) = \begin{pmatrix} x_1(u) \\ y_1(u) \\ z_1(u) \end{pmatrix} \text{ and } \vec{r}_2(u) = \begin{pmatrix} x_2(u) \\ y_2(u) \\ z_2(u) \end{pmatrix},$$

then, according to [4], the vector equation of the linear surface constructed on these lines can be written as follows (Fig. 1):

$$\vec{R}(\nu, u) = \nu\vec{r}_1(u) + (1-\nu)\vec{r}_2(u), \tag{1}$$

where $0 \le \nu \le 1$, $u_1 \le u \le u_2$.

When drawing multifaceted pipes with a constant cross section and controllable inner sizes, the output section of the die channel corresponds to the profile of the ready article. The configuration of the reducing part of the die can be fulfilled in various variants.

Let us consider the die with the inlet shaped like a truncated pyramid with a base shaped like a regular polygon (Fig. 2).

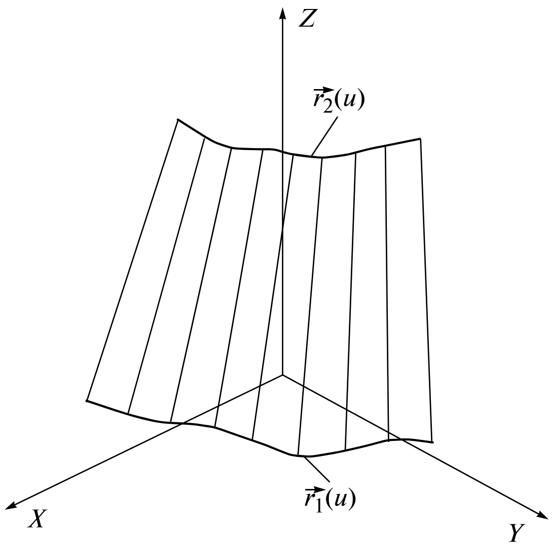

Fig. 1. Ruled surface constructed on two arbitrary directional lines.

Using the polar coordinate system, we describe the surface of one element of a pyramidal die, which is restricted by the inlet plane into the die on one side and by the plane of the passage to a parallel land at distance l, by the equation

$$\bar{R}_1(\nu, \varphi) = \nu\begin{pmatrix} H_f \\ H_f \tan\varphi \\ l_{fin} \end{pmatrix} + (1-\nu)\begin{pmatrix} H_d \\ H_d \tan\varphi \\ l_{fin} + l_d \end{pmatrix},$$

where $0 \le \nu \le 1$, $-\frac{\pi}{n} \le \varphi\ \frac{\pi}{n}$, H_f is the width of the facet of the die parallel land, H_d is the facet width at the die inlet, l_{fin} is the length of the calibrating die segment, and l_d is the length of the reducing die segment.

Other elements of a multifaceted die (for any configuration of the reducing part) are determined by the linear transformation of the rotation around the axial line

$$\vec{R}_{i+1}(\nu, \varphi) = \begin{pmatrix} \cos\frac{2\pi i}{n} & -\sin\frac{2\pi i}{n} & 0 \\ \sin\frac{2\pi i}{n} & \cos\frac{2\pi i}{n} & 0 \\ 0 & 0 & 1 \end{pmatrix}\vec{R}_1(\nu, \varphi), \ldots \quad (2)$$

$$i = 1, 2, \ldots, n-1,$$

where $\vec{R}_1(\nu, \varphi)$ is the equation which describes the first facet of the die and n is the number of its facets.

Let us consider another variant of the reducing die segment. In this case, the die inlet is a truncated cone

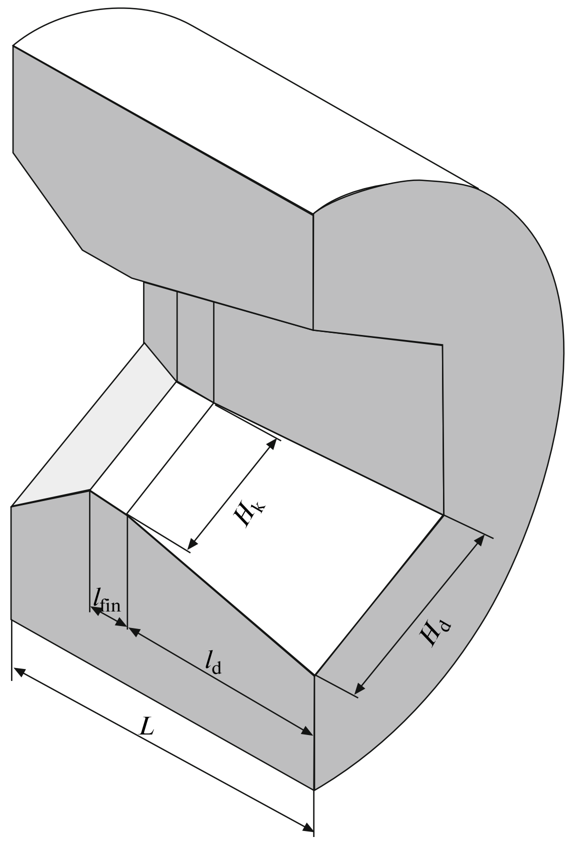

Fig. 2. Die with inlet into the reduction zone shaped like a truncated pyramid.

into which a multifaceted calibrating segment is incorporated (Fig. 3). In this case one part of the die surface can be described by the finishing segment facet and the corresponding segment of the cone surface.

The surface, which describes one facet of the finishing segment, can be expressed as follows:

$$\vec{R}_{finish}(\nu, \varphi) = \nu\vec{r}_1(\varphi) + (1-\nu)\vec{r}_2(\varphi),$$

while the surface which describes one part of the conical reducing die segment can be described by the equation

$$\vec{R}_{reduction}(\nu, \varphi) = \nu\vec{r}_2(\varphi) + (1+\nu)\vec{r}_3(\varphi),$$

where $0 \le \nu \le 1$, $-\frac{\pi}{n} \le \varphi \le \frac{\pi}{n}$; n is the number of die facets; $\vec{r}_1(\varphi)$ is the radius-vector, which describes the intersection of the conical and finishing parts of the die; and $\vec{r}_3(\varphi)$ is the radius-vector, which describes the section of the conical die part at the input into the deformation region (Fig. 4).

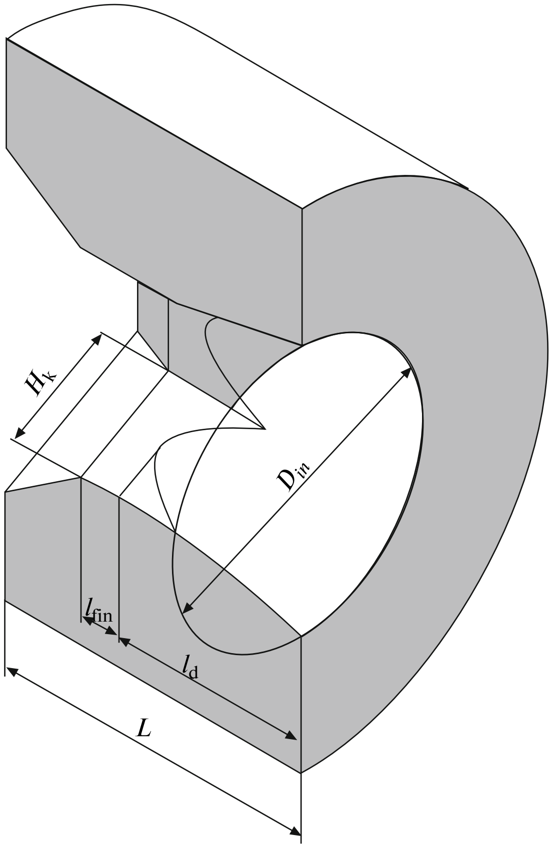

Fig. 3. Die with a conical inlet into the reduction zone.

Correspondingly, expressions for radius vectors will take the following form:

$$\vec{r}_1(\varphi) = \begin{pmatrix} H_f \\ H_f \tan\varphi \\ 0 \end{pmatrix},$$

$$\vec{r}_2(\varphi) = \begin{pmatrix} H_f \\ H_f \tan\varphi \\ l_{fin} + l_d + \dfrac{2(H_f - D_{in}\cos\varphi)}{2\tan\alpha} \end{pmatrix},$$

$$\vec{r}_3(\varphi) = \begin{pmatrix} 1/2 D_{in}\cos\varphi \\ 1/2 D_{in}\sin\varphi \\ l_{fin} + l_d \end{pmatrix},$$

where H_f is the facet width for the finishing die segment, D_{in} is the inlet die diameter, l_{fin} is the length of the finishing die segment, l_d is the die length from the inlet to the finishing segment, and α is the die conicity angle.

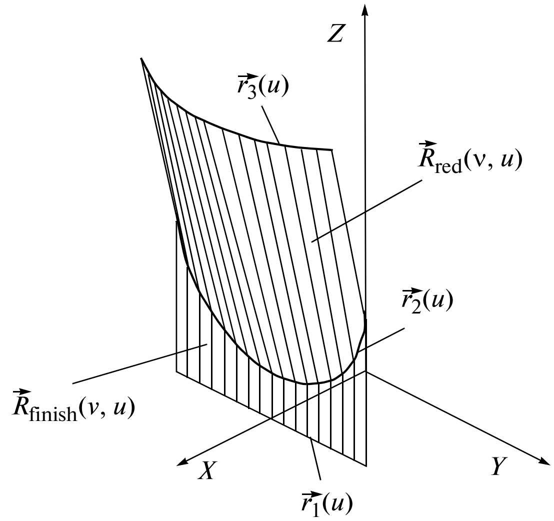

Fig. 4. Surfaces describing one facet of the die with a conical reducing segment.

Other elements of the conical-inlet die are determined by the linear rotational transformation around axial line (2).

Let us consider one more type of dies which were constructed using a special class of linear surfaces called regular conoids [5]. It is known that the conoid is the ruled surface, which is formed by the motion of the straight-linear generatrix, which conserves the parallelism to a certain specified plane (the parallelism plane) in all its locations and intersects two directional lines, one of which is curvilinear and another one is a straight line. The straight-line generatices of the regular conoid intersect similar directional lines, but the parallelism condition is replaced by the uniform distribution condition of the intersection points of the generatrix in all its locations with the curvilinear directional line.

The use of conoidal dies for drawing the profiles made of nonferrous metals and alloys makes it possible to conform the tool (die) geometry with the motion trajectories of metal particles since modeling the conoidal die surface is performed from the condition of coincidence of these trajectories with the straight-linear generatrix of the surface in all its locations (Fig. 5).

Let us consider modeling the conoidal die to fabricate multifaceted pipe. The passage of the reducing segment to the finishing segment is modeled by a regular polygon with the number of sides n, which is inscribed into the circle with radius R. In this case, the first curvilinear facet of the conoidal die, which is restricted by

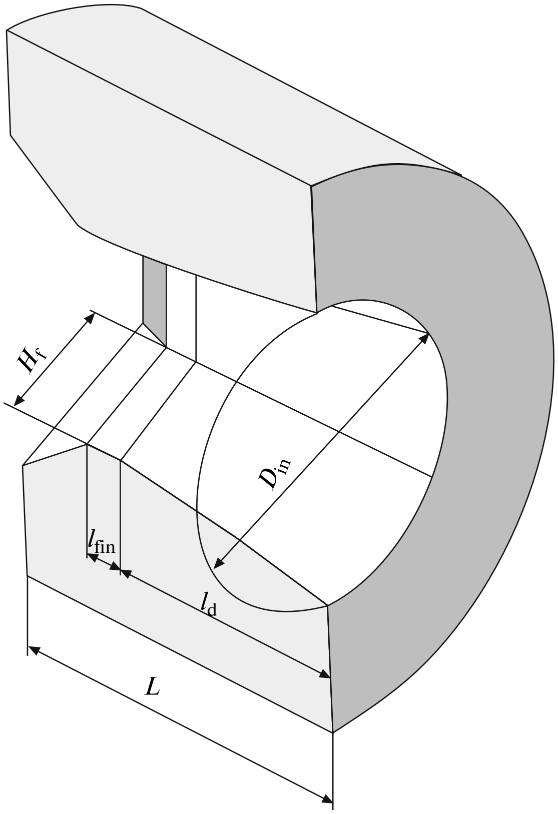

Fig. 5. Conoidal die.

two parallel planes (which are remote at distance l_d from one another), is specified by the equation

$$\vec{R}_{fin}(\nu, \varphi) = \nu\begin{pmatrix} H_f \\ H_f \tan\varphi \\ l_{fin} \end{pmatrix} + (1-\nu)\begin{pmatrix} 1/2 D_{in}\cos\varphi \\ 1/2 D_{in}\sin\varphi \\ l_{fin} + l_d \end{pmatrix},$$

where $0 \le \nu \le 1$, $-\frac{\pi}{n} \le \varphi \le \frac{\pi}{n}$, H_f is the facet width for the finishing die segment, D_{in} is the inlet die diameter, l_{fin} is the length of the finishing die segment, and l_d is the die length from the inlet to the finishing segment.

Other elements of the conoidal die surface are determined by the above-considered linear rotation transformation around axial line (2).

When drawing the multifaceted pipes on the die, one facet of its surface is described by the equation

$$\vec{R}_{arb}(\nu, \varphi) = \nu\begin{pmatrix} h_{arb} \\ h_{arb} \tan\varphi \\ 0 \end{pmatrix} + (1+\nu)\begin{pmatrix} h_{arb} \\ h_{arb}\tan\varphi \\ l_{arb} \end{pmatrix},$$

where $0 \le \nu \le l$, $-\frac{\pi}{n} \le \varphi \le \frac{\pi}{n}$, h_{arb} is the die facet width, and l_{arb} is the die length (Fig. 6).

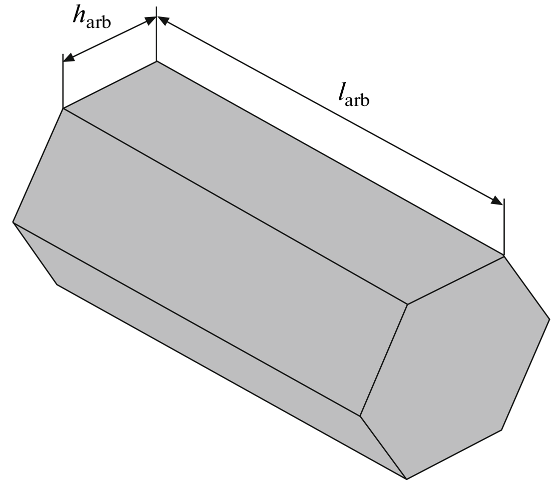

Fig. 6. Short arbor for drawing six-faceted pipes.

Other elements of the die surface are also determined by the linear rotation transformation around axial line (2).

Using the above-considered mathematical models, we designed and prepared the bulk (3D) models with the help of the SolidWorks package for the solid-state modeling to investigate the profiling of the six-faceted pipes using an immobile die. As a billet, we took a round pipe with starting diameter D_0 = 18 mm and wall thickness S_0 = 2.5 mm made of brass L-63. This pipe billet undergoes a radial reduction at the inlet into the six-faceted die. A ready six-faceted pipe has sizes D_{cir} = 16.24 mm (the diameter of the circumscribed circle) and D_k = 14.2 mm (the width across flats), and S_0 = 2.0 mm is the wall thickness of the ready pipe.

The deformation region was further modeled using the DEFORM-3D software complex [6]. In modeling, the deformed pipe material was accepted as elastic-plastic and isotropic and the die and the arbor material was accepted as perfectly rigid. To evaluate the friction at contact surfaces of the tool with the pipe, we used the Coulomb law [7]. The friction coefficient for the tool made of tungsten carbide with subsequent grinding and polishing with the diamond paste, the pipe billet made of brass L-63, and the liquid lubricant of the type of the vegetable oil was accepted to be equal to 0.75.

During modeling, the deformation region applying the above-considered mathematical models, nonflowing of metal into the edge vertexes was revealed, which leads to the appearance of the rounding radii, especially on the outer pipe wall.

Due to modeling the drawing process of a six-faceted pipe by the considered method, it was revealed that the geometry of the reducing die part considerably affects the magnitude of rounding radii. It was established that the smallest magnitude of outer rounding radii (0.9 mm for the ready profile) is observed when drawing using a die with a pyramidal inlet into the reduction zone. When drawing the six-faceted pipe using dies with a conoidal reducing part, the outer rounding radius was 1.3 mm, and that for the dies with the conical reducing part was 2.1 mm.

Due to modeling the deformation region, which appears when drawing the profiled multifaceted pipes using all types of considered dies, it was revealed that the best result with the smallest rounding radii is attained for the dies with a pyramidal inlet into the reduction zone. We can isolate three characteristic features in this case, which promote the formation of the minimal rounding radii:

(i) an increase in the radius of the pipe wall on the die facets, which totally leads to the formation of flat surfaces;

(ii) a decrease in radii of the deformed pipe on flat surfaces, which determines the formation of the edges of the profiled pipe and the better working out of the corners.

CONCLUSIONS

The developed mathematical models of the dies make it possible to evaluate the possibilities to make the profiled multifaceted pipes of ferrous metals and alloys, as well as optimize the shape of the tool to improve the technology of fabricating the mentioned wares.

Due to the further improvement of the mentioned models, we can prospectively determine the following:

(i) the rational geometry of the drawing channel;

(ii) the energy-power process parameters with the purpose of increasing the efficiency of production machines;

(iii) the deformation mode in the deformation region;

(iv) the evaluation of the damage of metal;

(v) the unstable forming modes, which leads to rejection (nonflowing the metal into the vertexes of edges, the appearance of a barrel form and convexity of the profile facets, and in certain cases the appearance of concavity or even loss in stability of the facets).

Thus, modeling of the pipe-drawing tool based on the vector-matrix apparatus can be applied to improve existing and develop new processes of pipe profiling, increase the accuracy of the ready wares for the drawing process with the standard size of the specified tool, and attain higher process efficiency from the viewpoint of its energy-power parameters.

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