Development of algorithmization bases for jet treatment evaluation modes of product curvilinear surfaces

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ABSTRACT

A method and algorithm for evaluating the angular and linear velocities of jet nozzles or products are proposed to ensure uniform jet treatment for the curvilinear surfaces of products. This is considered for two cases such as maintaining a constant distance from the nozzle end to the surface and maintaining a constant attack angle. Uniform processing is achieved by adjusting these velocities. This approach can be used in jet processing for ensuring a surface's quality, which will have different applications in the future.

Keywords: jet treatment, technological equipment, mechanical movement, process modes, curvilinear surface

1. Introduction

Any machine-building production requires productive and cheap methods for processing the metal parts of technological equipment. Such methods include a group of methods that are collectively known as "jet processing" in which multiphase jets are used as a tool. Depending on the physical nature and number of phases, there are methods of treatment with dry abrasives (or shots), those with wet abrasives (or shots), those that use cavitation in the liquid phase (or flooded jets), and so on. These methods can be used in both final technological operations (for example, to strengthen or decorate the surfaces of products) and in the preparation of surfaces for further processing (in particular, for coating operations). The advantages of jet processing are especially evident with the increases in size and complexity of a product's shape, making it a sometimes non-alternative method for achieving the desired quality characteristics of product surfaces. One of the basic requirements for any method of treatment is the predictability of the accuracy and quality of the products that are obtained after applying this method. The proper choice of technological modes can guarantee perfect results of any jet treatment. However, the need to take a significant amount of input data into account (namely, the parameters of the equipment, the jet, the working medium, the physical and mechanical properties of the material, the shape of the treated surfaces, and the lack of clear recommendations) significantly complicate this process – especially in the case of processing curved surfaces. Therefore, an urgent task is the mathematical modeling of a jet treatment for curved surfaces of products by utilizing automated computing systems. The results of mathematical modeling will form the basis of design and technological solutions for those industries in which jet treatment is implemented or used.

An analysis of the literature revealed a significant number of experimental studies for different methods of jet processing. The purpose of these studies was to solve specific tasks that are related to the processing of certain grades of materials (Li, Jiang 2020; Liu, Liao 2010; Slat et al. 2018; Wang et al. 2015). In Ukraine, the basics of the theoretical research of jet processing were developed in Salenko O.F. et al. (2005) and Salenko A.F. et al. (2016). The mathematical modeling of jet processing that uses the energy concept is discussed in detail in Stotsko and Stefanovych (2011a, 2011b). The energy concept is based on the energy conservation law, according to which the energy that is provided by the working medium of a jet (except for losses at different processing stages) is converted into work to change the shape and stress state of a product's surface. Determining the mass distribution of the working medium along a treated surface trajectory with variable processing modes for the case of jet movement along a flat stationary surface and for the case of jet movement along the radius of a rotating faceplate surface was described in Stotsko and Stefanovych (2013). Analytical dependencies for determining a jet's attack angle of the working medium for any point of a surface during treatment by a stationary jet were obtained in Stotsko and Stefanovych (2013). The change of an attack angle is simulated for flat-surface treatment with shock and sliding jets, for spherical and cylindrical surface cross-sections, and curvilinear surfaces of arbitrary shapes that are given by the corresponding analytical equations.

The literature analysis allowed to determine those problems that required further theoretical research. One such task is developing an approach for determining the modes of jet treatment for curvilinear surfaces in order to ensure uniform processing. This can be achieved by maintaining a constant distance from the nozzle end to the surface and maintaining the perpendicularity of the nozzle axis to the curved surface generatrix at the process point by moving the treated surface and changing the nozzle inclination.

To achieve this aim, the following tasks need to be solved:

- formalize jet treatment for curvilinear surfaces of product;
- developing mathematical models to determine processing modes;
- performing quantitative assessment of processing modes that provide uniformity of treatment over entire curved surface in its movement relative to jet apparatus nozzle.

2. Developing mathematical models

2.1. Formalize jet treatment for curvilinear surfaces of product

The essence of jet treatment affects a treated surface with a multiphase jet. While interacting with a surface, a jet changes its state, modifying and removing the surface layers of a material or having a combined effect.

The jet-treatment scheme of a curved surface is shown in Figure 1. The jet apparatus' nozzle (1) forms a multiphase jet (2). The working medium of the jet moves to the curved surface (3) at a high speed. The treatment is performed in the area of the contact of the jet's working medium (2) with the surface (3).

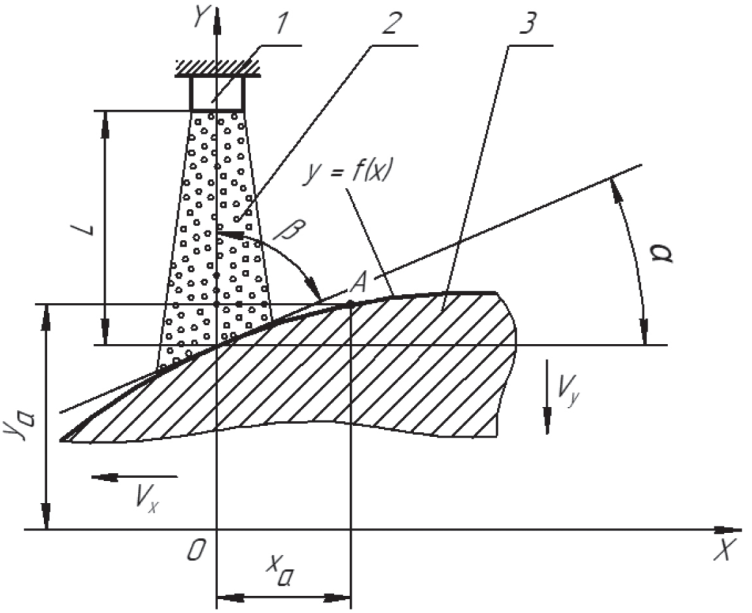

Fig. 1. Scheme of jet treatment of curved surface for L = const, $\alpha \neq$ const, and $\beta \neq$ const: 1 – nozzle; 2 – jet; 3 – surface; L – distance from nozzle to surface; α – angle of surface inclination; β – impingement angle; V_x, V_y – velocities of surface

During the treatment of a product with a curved surface, however, both distance L from the nozzle to the surface and jet attack angle β will change if the product moves relative to the nozzle. This causes a change in the treatment mode and, accordingly, the instability of the quality parameters of the treated surface. The stability of the surface-processing modes can be ensured if the nozzle axis of the jet apparatus (1) will remain permanently perpendicular to the generatrix of the treated surface; i.e., the attack angle of the jet must be equal to $\beta = 90°$ (Fig. 2), and the distance from the nozzle end to the surface must be constant (L = const). Depending on the treated surface profile, the jet apparatus nozzle must oscillate with an angular velocity ù along an arc trajectory in order to fulfill these conditions. The position of the nozzle axis is determined by the angle of generatrix inclination α to the OX axis. The cross-section of the curved surface (3) is given in the plane by the equation $y = f(x)$. During the treatment, the cross-section performs a plane-parallel motion that consists of translational motions along the OX and OY axes. The velocity as related to the OX axis is denoted as V_x, and that as related to the OY axis is denoted as V_y.

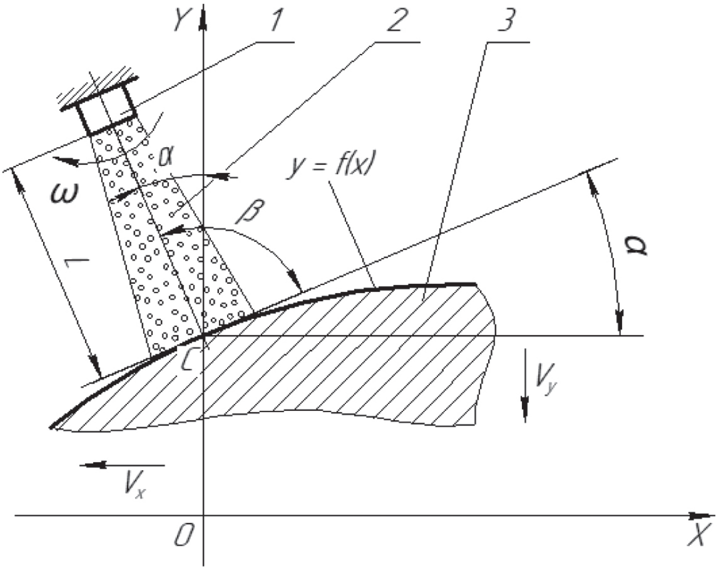

Fig. 2. Scheme of jet treatment of curved surface for L = const, $\alpha \neq$ const, and $\beta = 90°$: α – nozzle angular velocity; C – center of jet treatment

2.2. Developing mathematical models to determine processing modes

A case of treating a curved surface is under consideration according to the scheme in Figure 1. The treated surface moves at a constant velocity V_x. It is necessary to determine the velocity of surface movement V_y, provided a constant distance L from the nozzle end to the surface.

According to the geometric constructions (Fig. 1), it will be discovered how V_x and V_y relate to each other with reference to the curved surface shape.

The shape of the curved surface can be set by the angle of surface generatrix inclination α to the OX axis. The value of α is defined as $\mathrm{tg}\alpha = dy/dx$. Linear velocity V_x is given as a derivative of coordinate x from time t; namely, $V_x = dx/dt$ (where $dx = V_x dt$). Substitute dx into the formula for determining $\mathrm{tg}\alpha$ and we get $\mathrm{tg}\alpha = dy/V_x dt$ or $\mathrm{tg}\alpha = V_y/V_x$. Thus, the ratio between the V_x and V_y linear velocities will be $V_y = V_x \mathrm{tg}\alpha$:

$$V_y = V_x \frac{df(x)}{dx} \tag{1}$$

For the partial case when the product surface is a plane ($\alpha = 0$), velocity V_y will be equal to zero – this is true when the product does not move in the transverse direction.

It is possible to determine surface velocity V_y under a predetermined V_x and provided a constant distance L from the nozzle end to the surface using Formula (1).

Consider how to mathematically describe a curved surface in an XOY fixed-coordinate system depending on its shape and nature of motion. When $V_x = 0$ and $V_y = 0$, the equation of the surface in the cross-section will look like $y = f(x)$ for a stationary surface. The equation takes the form of $y = f(x, t)$ if the surface moves and V_x and $V_y \neq 0$. For an arbitrary Point A (Fig. 1) that lies on a curved surface and moves translationally along the OX and OY axes, the equation of its motion can be written as follows:

$$\begin{aligned} x &= x_a + V_x t \\ y &= y_a + V_y t \end{aligned} \tag{2}$$

Assume as a partial case that the surface cross-section is a straight line – the equation of which can be given by analytical dependence:

$$y = a + bx \tag{3}$$

Substituting Formulas (2) into Equation (3) and given the motion of Point A, $y_a + V_y t = a + b(x_a + V_x t)$ or $y_a = a + b(x_a + V_x t) - V_y t$ is obtained.

In the general case, the line equation for its displacement with velocities V_x and V_y is obtained:

$$y = a + b\left[x + (V_x - V_y)t\right] \tag{4}$$

At the initial moment of time $t = 0$ and under the conditions of $V_x = 0$ and $V_y = 0$, Equation (4) will turn into Equation (3); this confirms the correctness of its derivation. Thus, the surface that is given in the cross-section as the line can be described using Equation (4), which takes its shape and nature of motion into account.

Suppose as a partial case that the surface cross-section is a cubic parabola that is given by the following analytical dependence:

$$y = x^3 \tag{5}$$

Substituting Formulas (2) into Equation (5) given the motion of Point A, $y_a + V_y t = (x_a + V_x t)^3$ or $y_a = x_a^3 + 3x_a{}^2 V_x t + 3x_a V_x^2 t^2 + V_x^3 t^3 - V_y t$ is obtained.

In the general case, the cubic parabola equation for its displacement with velocities V_x and V_y can be written as follows:

$$y = x^3 + (3x^2 V_x - V_y)t + 3x V_x^2 t^2 + V_x^3 t^3 \tag{6}$$

At the initial moment of time $t = 0$ and under the conditions of $V_x = 0$ and $V_y = 0$, Equation (6) will turn into Equation (5); this confirms the correctness of its derivation. Thus, the surface that is given in the cross-section as the cubic parabola can be described using Equation (6), which takes its shape and nature of motion into account.

Consider the case according to Figure 2 for determining nozzle angular velocity ω. The nozzle must oscillate with angular velocity ω along an arc trajectory for ensuring uniform processing. Angular velocity ω is given as the derivative of angle α over time t; i.e., $\omega = d\alpha/dt$. In turn, angle α depends on the curved surface shape, which is $\mathrm{tg}\alpha = df(x, t)/dx$; whence:

$$\alpha = \mathrm{arctg}\frac{df(x,t)}{dx} \tag{7}$$

Residually, nozzle angular velocity ω along the arc trajectory is as follows:

$$\omega = \frac{d\left(\mathrm{arctg}\dfrac{df(x,t)}{dx}\right)}{dt} \tag{8}$$

2.3. Recommendations for ensuring uniform jet treatment

Therefore, to comply with the conditions of uniform treating (namely, providing a constant distance from the nozzle end to treated surface L = const and providing a constant attack angle of the jet to treated surface $\beta = 90°$; in other words, the perpendicularity of the nozzle axis of the jet apparatus to the curved surface generatrix), it is necessary to set the following processing modes:

- product must carry out translational motion that is described in Formulas (2);
- linear velocities of product or nozzle of jet apparatus must correspond to Relationship (1);
- nozzle angular velocity must comply with Equation (8).

Based on the above theoretical approach, an algorithm can be proposed for determining the V_x, V_y, ω modes:

1) determine curve equation $y = f(x)$ as line of intersection of XOY plane and curved surface of product;
2) choose Point C with coordinates $(0, y_c)$ in which curve $y = f(x)$ intersects with OY axis and in which center of jet treatment is located;
3) set L (i.e., distance from Point C to nozzle end of jet apparatus);

4) set surface velocity V_x relative to OX axis as constant value;
5) define time function for curve as $f(x, t)$;
6) determine surface velocity $V_y(x, t)$ relative to OY axis;
7) determine angle of surface inclination α at Point C as $f(x, t)$;
8) determine nozzle angular velocity ω as derivative of α in time t (namely, $\omega = d\alpha/dt$).

This algorithm can be used to obtain the graphical dependencies for the analysis of the jet-processing modes for different surface shapes.

3. Results and discussion

Consider one of the simplest cases for which a curved surface cross-section is a straight line – the general equation of which is given by Formula (3). Take the value of constant term a that is equal to 0 and coefficient b that is equal to 1; then, Formula (3) will be $y = x$. The coordinates of Point C (where the line intersects with the OY axis) are (0, 0). Distance L from C to the nozzle end is set as being equal to 1, as to the surface velocity V_x. If velocity V_x is equal to 1, then $x(t) = t$, and the time function for the curve can be written as $y(t) = t$. Determine surface velocity $V_y(x, t)$ by (1); i.e., $V_y = V_x$. That is, when moving the workpiece surface that is given by cross-sectional equation $y = x$ relative to the OX axis at a constant velocity of 1 to ensure a constant distance from the nozzle end to the workpiece, this surface must be moved relative to the OY axis at a velocity of 1 as well. Obviously, the tangent of the angle of the surface inclination will be equal to 1, and the angle itself will be 45°. For the constant angle, the value of the angular velocity for Equation (8) will be 0; i.e., it is enough to orient the nozzle that is fixed relative to the treated surface providing an attack angle of 90°.

Consider the case in which the curved surface cross-section is a cubic parabola – the equation of which is given by Formula (5). The cubic parabola equation as it moves with velocities V_x and V_y is described by Expression (6). Similar to the previous case, the coordinates of Point C are (0, 0). Distance L from Point C to the nozzle end is set as being equal to 1, as is surface velocity V_x relative to the OX axis. If velocity V_x is 1, then $x = t$, and the time function for the curve can be written as $y(t) = t^3$. Surface velocity $V_y(x, t)$ by Equation (1) is defined as $V_y(t) = 3t^2$. Graphs of the linear velocities for a curved surface (the cross-section of which is given by a cubic parabola) are shown in Figure 3. The angle of surface inclination α at Point C is determined by Equation (7) as $\alpha(\mathrm{t}) = \mathrm{arctg}(3t^2)$, and angular velocity ω is determined by Formula (8) as $\omega(t) = 6t/(9t^4+1)$. Graphs for the angle of surface inclination α and angular velocity ω are shown in Figure 4.

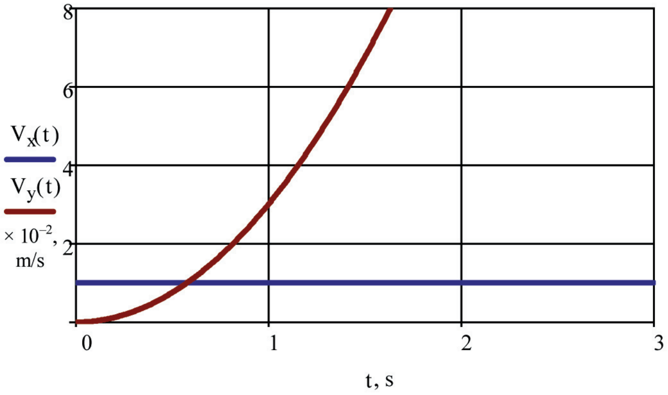

Fig. 3. Linear velocities of treated surface:
V_x – relative to OX axis; V_y – relative to OY axis

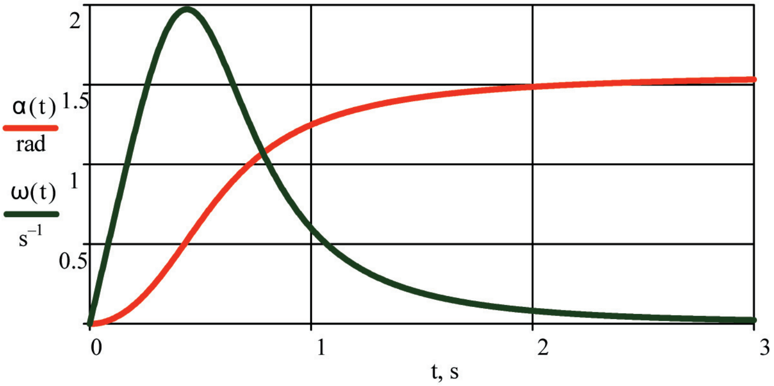

Fig. 4. Jet-processing modes associated with oscillating movement of nozzle:
$\alpha(t)$ – angle of surface inclination; $\omega(t)$ – nozzle angular velocity

4. Conclusions

A mathematical approach that will allow for the uniform jet treatment of curved surfaces by determining the processing modes (namely, the linear and angular velocities of the product or the jet apparatus) is proposed. This is considered for cases for which the uniformity of a curved-surface treatment is achieved by maintaining a constant distance from the nozzle end to the surface or maintaining a constant attack angle of the jet. For these cases, mathematical dependencies were obtained for determining the linear and angular velocities by using a graphical representation of the jet treatment. Based on the developed mathematical approach, an algorithm for determining the jet-treatment modes has been proposed, and the graphs of the linear and angular velocities for different surface shapes over time have been obtained. In further research, it is planned to evaluate the quality characteristics of a product's curvilinear surfaces that can be obtained by jet treatment.

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