Kinematics of ultrasonic processing

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Abstract. The paper considers the kinematics of ultrasonic finishing processing with implementing the vibrations tangentially to the surface machined. The investigations are conducted on determining the main kinematic parameters of the method mentioned and their influence on the character of the tool trace on the machined part surface. The mathematical description of the motion trajectory of the deforming tool on the processed surface is presented. Its analysis allows us to find out the main principles of the formed trajectories and their relative location as well as the possibilities of increasing the processing efficiency.

1. Introduction

Because of the constant development of technology the requirements to the parts working under friction increase, which leads to making the conditions of contact interaction of rubbing surfaces difficult. Therefore, improving the properties of contact surfaces is a vital task. The character of the contact interaction significantly depends on the micro-geometrical and physicochemical state of the part surface layer and influences such performance properties as the wear resistance, the cycle and contact fatigue.

To increase the quality of the surface layer, the methods of surface plastic deforming are used. The ultrasonic processing is considered to be one of such methods. Kinematic parameters of this processing significantly differ from static methods of surface plastic deforming, such as diamond smoothening and ball rolling. The quality of the processed layer is determined by the kinematic and dynamic parameters of the tool influence on the part. In this case, the micro-geometry is determined, to a large extent, by the character of the tool motion relative to the part and by the relative location of the processing traces [1 – 3].

At present, the ultrasonic surface deforming with introducing the ultrasonic vibrations normally to the processed surface is most widely used. The kinematic parameters of such a deforming and their influence on forming the micro-geometry are studied well [4 – 6]. In this scheme, the tool makes an impact and high frequency influence on the processed surface. This influence provides the intensive development of the plastic deformation in the local area of deforming, which defines the use of this scheme for items made from high-strength materials and makes its use for the processing of low and medium hardness metals and alloys as well as thin-walled parts difficult. The possible solution to the problem mentioned is the use of the scheme with introducing vibrations tangentially to the processed surface, kinematic and dynamic peculiarities of
which are not well studied. As the micro-geometrical state of the surface is mainly determined by kinematic parameters of processing, their study is of great interest.

Therefore, the goal of the paper is to determine the kinematic parameters of ultrasonic processing with introducing vibrations tangentially to the processed surface and their relation to the technological modes of ultrasonic surface deforming.

2. Experimental and theoretical studies
Nowadays, a lot of investigations are devoted to describing the ultrasonic surface deforming with introducing the vibrations normally to the processed surface. Its use allows obtaining the maximum deformation effect (Fig. 1, a). Such a scheme belongs to the impact methods of plastic surface deforming and is applied for processing the metals and alloys of high hardness. Processing soft metals and alloys as well as thin-walled parts by this scheme has certain limitations. Therefore, it is necessary to use the scheme of introducing the vibrations with other conditions of contact interaction. Such a condition can be presented by the scheme with introducing ultrasonic vibrations tangentially to the processed surface (Fig. 1, b). In processing according to this scheme, there is a constant contact of the indenter with the processed surface, which significantly changes the stressed state in the contact area [7 – 9].

Figure 1. Scheme of introducing the vibrations: a - processing normal, b – processing tangentially; \( V_s \) – speed of the tool delivery, \( \text{Vv} \) – speed of the part rotation, \( \text{Vk} \) – tool vibration speed, \( F_{st} \) - static force.

In introducing vibrations tangentially the processed surface, the tool displaces relative to it at a speed \( \overrightarrow{V_{REL}} \), the value of which is determined by the equation:

\[
\overrightarrow{V_{REL}} = \overrightarrow{V_v} + \overrightarrow{V_s} + \overrightarrow{V_k}
\]

(1)

where \( \overrightarrow{V_v} \) - vector of the pert periphery speed, \( \overrightarrow{V_s} \) - vector of the delivery speed, \( \overrightarrow{V_k} \) - vector of the tool vibration speed.

The character of the relative position of these speeds in ultrasonic surface deforming is presented in figure 2.
Figure 2. Direction of velocity vectors in Cartesian coordinate system: \( \vec{V} \) - vector of the part periphery speed, \( \vec{V_S} \) - vector of the delivery speed, \( \vec{V_K} \) - vector of the tool vibration speed, \( \beta \) - angle between the directions of the part speed and the tool vibration speed.

The speed (m/sec) in processing the cylindrical parts is determined by the equation:

\[
V_v = \frac{\pi D n}{1000 \cdot 60}
\]

where \( D \) - diameter of the processed part (mm), \( n \) – number of the part rotations per minute.

The delivery speed (m/sec) is determined by the following equation:

\[
V_s = \frac{Sn}{1000 \cdot 60}
\]

where \( S \) - tool delivery (mm/rev).

The tool vibration speed is presented by the equation:

\[
A = A_0 \sin(\omega t)
\]

where \( A_0 \) - amplitude of ultrasonic vibrations, \( \omega \) - radiant frequency \((\omega = 2\pi f)\), \( f \) – vibration frequency, (sec\(^{-1}\)), \( t \) - time (sec)

The speed of the tool vibration motion will be equal to

\[
V_K = -A \omega \cos(\omega t)
\]

Let us consider that in processing there is a tool point contact with the part surface, and the trace width, which is left by the tool on the part surface, is the width stipulated by this contact.

The tool motion relative to the part surface in the Cartesian coordinate system ZOX is presented by the equation system:

\[
\begin{align*}
Z &= Vst + A_0 \sin(2\pi ft) \sin \beta \\
X &= Vvt + A_0 \sin(2\pi ft) \cos \beta
\end{align*}
\]

The graphical presentations of equations (6) and (7) is shown in figure 3.
As seen in figure 3, there is a trace as a sinusoidal wave on the part surface, the centre line of which is presented by the equations:

\[ Z_{l1} = V_5 t \] (8)
\[ X_{l1} = V_4 t \] (9)

The centre line has a slope at an angle \( \alpha \) to an axis \( Z \), the value of which is determined:

\[ \tan \alpha = \frac{S}{\pi D} \] (10)
\[ \alpha = \arctan \left( \frac{S}{\pi D} \right) \] (11)

where \( \alpha \) – slope angle of the centre line (Fig. 3)

While processing the cylindrical parts, the trace matrix will be formed on the surface. The location of these traces relative to one another will be determined by the technological parameters of processing.

As the surface micro-geometry significantly depends on the shape of the traces left and the character of their relative position, it is necessary to know the factors, which influence the trajectory position after every rotation of the part.

To describe the trace location, the unfolded cylindrical surface is used with a variety of plane coordinates, (which) the trace location obey the following rules – the direction of all the axes of coordinates coincides with the direction \( V_4 \), and the direction of the axis of abscissa (\( X \)) – with the direction of the delivery speed vector (Fig. 4). The zero points of the systems chosen are located in \( O_1, O_2, O_3, \ldots \) \( O_n \), which have the following coordinates \((0, 0); (S, 0); (2S, 0); \ldots ((N-1)S, 0)\). They are obtained by the parallel displacement of the initial system of coordinates \((0, 0)\) by the multiple value \( S \). Forming the trace in each system of coordinates will be accomplished at \( 0 \ldots 60/n \) seconds, i.e. for one cycle, revolution of the part.
In a general case, the initial point of the trace, left by the tool on the part surface at a second revolution, will have a phase shift relative to the beginning of its system of coordinates [9]. It is connected with the fact that not the integral number of the period of vibrations can be located on the trace length for one revolution of the part:

\[ M + m = \frac{60}{n} \frac{f}{M, m} \]  

where \( M, m \) - the integer and decimal parts of the vibration periods, taking place for one revolution of the part.

The value of the phase shift depends on the decimal part of the equation (12).

Taking into consideration the above said, the trajectories of the tool trace in the traditional systems of coordinates will be describes by the equations:

\[ Z_i = S n \left( t + \frac{60}{n} (N_i - 1) \right) + A \sin \left( 2\pi f \left( t + \frac{60}{n} (N_i - 1) \right) \right) \sin \beta \]  

\[ X_i = \pi D n t + A \sin (2\pi f t) \cos \beta \]  

where \( N_i \) - the number of the part cycle revolution, \( 60/n \) - the time of one revolution of the part.

These equations allow us to describe the position of the point on the trajectory of the tool displacement at any moment of time.

3. Results and Discussions

To analyze the relative position of the trajectories obtained in processing, let us consider the location of the specific points, which correspond to the beginning of the period of vibrations of the tool. The position of these points on the surface obeys a rule, which can be described by linear (S, l) and angular (\( \varphi \)) parameters of the matrix. The adjacent points are located in the parallelogram apex. The matrix configuration is determined by the angle value \( \varphi \) (Fig. 5). At \( \varphi \) equal to zero, the position of the adjacent points forms the parallelogram similar to the configuration of the rectangle (Fig. 5, a).

The value of the matrix parameters is described by the equations:

\[ l = \frac{V}{f} \]  

\[ \varphi = \arctg \frac{A}{B} = \arctg \frac{(1 - m) \cdot l \cdot \cos \alpha}{S + (1 - m) \cdot l \cdot \sin \alpha} \]  

Figure 4. Development of the additional systems of coordinates

Figure 5. Position of the adjacent points depending on the angle value \( \varphi \): a - \( \varphi = 0 \), b - \( \varphi \neq 0 \)
where $l$ – the path along the centre line passed by the indenter for one period of vibrations.

The relative position of traces depends on the angle variation $\varphi$ (Fig. 6), which value is determined by the technological parameters of the processing: $S, f, V, \alpha$.

**Figure 6.** Influence of the magnitude $m$ on the value of the linear shift $ml$ and the position of the trace matrix: a - $m = 0$; b - $m = 0.25$; c - $m = 0.5$

As seen in figure 6, the change in the value $\varphi$ influences the relative position of the specific points of the processing adjacent traces. In this case, the distance between the adjacent trajectories of the deformer changes in the direction of the part axis, which will affect the character of the formed micro-geometry. As in real conditions of processing the trace width is not a point and has a certain value, the change in the distance between the adjacent traces will influence the overlapping of the processing traces, which, in its turn, will cause the change in the physico-mechanical and micro-geometrical state of the surface.

The influence of the parameter values $l, S$ on the position of the specific points is shown in figures 7 and 8.

**Figure 7.** Position of the adjacent points in changing the processing parameter $l$ ($S =$ const): 1 - $l = l$; 2 - $l_1 = 1.5 \cdot l$; 3 - $l_2 = 2 \cdot l$
Figure 8. Position of the adjacent points in changing the processing parameter $S (l = \text{const})$: 1 - $S = S$; 2 - $S_1 = 1.5 \cdot S$; 3 - $S_2 = 2 \cdot S$

The scheme of the ultrasonic surface deforming considered here allows us to control the character of the trace in changing the technological parameters of processing, which significantly widens the possibilities of the method mentioned. The various positions of the processing traces are presented in figures 9 – 13.

Figure 9. Trajectory of the processing trace position depending on the change in the delivery pitch $S$: a - $S = 0.05 \text{ mm/rev}$; b - $S = 0.1 \text{ mm/rev}$; c - $S = 0.15 \text{ mm/rev} (f = 20 \text{ kHz}, V = 10 \text{ m/min}, \beta = \pi/2, A = 10 \text{ mm})$

Figure 10. Trajectory of the processing trace position depending on the change in the frequency $f$: a - $f = 20 \text{ kHz}$; b - $f = 44 \text{ kHz}$; c - $f = 66 \text{ kHz} (S = 0.05 \text{ mm/rev}, V = 10 \text{ m/min}, \beta = \pi/2, A = 10 \text{ mm})$
Figure 11. Trajectory of the processing trace position depending on the change in the speed $V$:

- $V = 10$ m/min; 
- $V = 100$ m/min; 
- $V = 200$ m/min ($S = 0.05$ mm/rev, $f = 20$ kHz, $\beta = \pi/2$, $A = 10$ µm)

Figure 12. Trajectory of the processing trace position depending on the change in the amplitude $A$:

- $A = 10$ µm; 
- $A = 20$ µm; 
- $A = 30$ µm ($V = 10$ m/min, $S = 0.05$ mm/rev, $f = 20$ kHz, $\beta = \pi / 2$)

Figure 13. Trajectory of the processing trace position depending on the change in the angle of vibration input $\beta$:

- $\beta = \pi/2$, 
- $\beta = \pi/4$, 
- $\beta = 0$ ($S = 0.05$ mm/rev, $V = 10$ m/min, $f = 20$ kHz, $A = 10$ µm)

It is seen in the figures that the width of the trajectory corridor varies from 0 to 2A. Under our conditions of processing the maximum value of the angle $\phi = 0.714^o$ ($V = 200$ m/sec, $f = 66$ kHz; $S = 0.05$ mm/rev), and the minimum value $\phi = 0.019^o$ ($V = 10$ m/sec; $f = 20$ kHz, $S = 0.15$ mm/rev).
Studying the kinematic parameters of the ultrasonic surface deforming with introducing the vibrations tangentially to the processed surface allows us to reveal the principles of the tool displacement on the part surface and the possible variants of the traces and their relative position. The knowledge obtained gives the possibility to control the character of the tool displacement and form the different micro-geometry of the surface.

4. Conclusion
1. The kinematic principles of the ultrasonic finishing processing with implementing the vibrations tangentially are obtained, which allow us to control the forming of the surface layer micro-geometry.
2. The trajectory of the tool displacement in the chosen range of the technological parameters of processing is similar to sinusoidal. The corridor width of the trace is determined by the angle of the vibration input $\beta$. In this case, at $\beta = 0$, the trace trajectory is of a character similar to a straight line.
3. Different values of the ratio between the period of one revolution and the frequency of the tool vibrations can cause the appearance of the phase shift of the adjacent trajectories of the processing traces, which leads to the changing distance between the adjacent traces.
4. The length of the trace trajectory for one vibration period is determined by the ratio between the part speed and the vibration frequency, which allows us to increase the efficiency of the method by changing these parameters.

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