Technological stability of processing the machine part surface by methods of surface plastic deformation with elastic action tools

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Abstract. The article presents the results of physical modelling of the processes of diamond burnishing of machine part surfaces with a complex differentiable profile and the concept of technological stability of treatment processes by methods of surface plastic deformation of surfaces with elastic action tools. The criteria for technological stability of the treatment process under the specified conditions are determined.

1. Introduction

Forming the surface quality parameters of a machine part processed by surface plastic deformation (SPD) methods with elastic action tools (Fig. 1) is greatly influenced by the dynamic characteristics of the treatment process. Elastic action tools are considered as mechanical devices with spring-loaded mass and lubrication, which are a second-order vibrating system with damping. It is believed that when the SPD is processed with an elastic action tool of a wavy surface, the waviness is copied, which does not always correspond to reality, since the dynamics of the indenter displacements, determined by the amplitude- and phase-frequency characteristics of the tool, affects the stability of forming the surface quality parameters, especially geometric ones [1, 2].

Figure 1. Elastic action tools for diamond burnishing (rolling): a – flat surfaces of machine parts; b – cylindrical surfaces of machine parts; 1 – treated surface; 2 – tool body; 3 – insert with a diamond indenter; 4 – spring; 5 – slider
Analyzing the surfaces treated by SPD methods with the waviness height $W_{max}$ and the centreline pitch $Smw$ showed that they had untreated areas or areas with different values of the roughness parameters. This is due to the fact that, depending on the design ($m$ is mass of the moving parts of the tool, kg; $c$ is spring stiffness, N/m) and technological factors ($V$ is processing speed, m/min; $W_{max}$, $Smw$, $\mu m$), fluctuations in the values of SPD processing force may occur, it is possible that the indenter does not contact the surface with subsequent impact on it.

It is known from the theory of automatic control that a signal can pass through dynamic systems without distortion, with amplification or attenuation determined by the frequency characteristics. In the case under consideration, the input quantity $Z_{in}(X)$ is waviness or another deviation law from the nominal plane of the initial surface, and the output quantity $Z_{out}(X)$ is vibration of the indenter (diamond smoother, ball) together with the moving part of the SPD tool along its axis Z. This approach makes it possible to establish influencing the waviness parameters of the processed surface and the dynamic characteristics of the SPD tool on the indenter vibrations $Z_{out}(X)$ depending on the processing speed.

2. Experimental results

Experiments were carried out to determine the contact nature of the tool indenter with the machined surface under various processing conditions.

Diamond burnishing of flat surfaces of machine parts made of steel 45 was carried out on a 6R13F3 vertical milling machine. On the sample surface, waviness was preliminarily formed with the height $W_{max} = 350 \mu m$, the step of the mean line the waviness profile $Smw = 8000 \mu m$ and 5500 $\mu m$. In this case, the roughness $Ra = 1 \mu m$ was ensured. The waviness profile differed from the sinusoidal shape as the radius of the top $p_t$ was much larger than the radius of the trough $p_b$ (Fig. 2) [1, 2].

The surfaces were processed at the speed of the burnishing tool 80, 160, 200, 250, 315, 400, 500, 630 min$^{-1}$. With the indenter rotation diameter $D = 40$ mm (Fig. 1a) the processing speed values varied in the range $10 - 79,2$ m/min, and the frequencies of the indenter forced vibrations varied within $f = 20,9 - 240$ Hz, including resonant frequency $f_0$. Burning power $Q = 30$ N, diamond indenter radius $r = 2$ mm, feed $S = 0,1$ mm/rev [3, 4].

The indenter contact length $L$ with the surface profile, which in the first approximation has an ideal sinusoidal wave in the interval $(a, b)$, is determined by the relation:

$$L = \int_{a}^{b} \sqrt{1 + \cos^2 x} \, dx = \sqrt{2} \int_{a}^{b} \sqrt{1 - k^2 \sin^2 x} \, dx, \text{where } k = 1 / \sqrt{2},$$

(1)

Determining the profile length of a sinusoidal wave due to the presence of an incomplete elliptic integral of the 2-nd kind causes certain difficulties, therefore it is proposed to determine the indenter contact coefficient $K$ with the treated surface as the ratio of the projection sum $PrXLa$ of the indenter contact areas with the surface to the base measurement length $L_b$ (Fig. 2):

$$K = \sum_{i=1}^{a} PrXLa / L_b,$$

(2)

Some experimental results are shown in Fig. 2. Continuous lines above the profile records correspond to the projections of the surface areas contacting with the diamond indenter while processing. Processing without “detaching” the indenter from the surface was observed up to the burnishing rate $V \approx 20,1$ m/min.

For the chosen simulation conditions, the average value of the contact coefficient $K$ with increasing the frequency of the indenter forced vibrations caused by the presence of surface waviness decreases monotonically from $K = 1$ at $f = 20$ Hz till $K = 0,2$ at $f = 130$ Hz and higher.

Diamond burnishing of cylindrical surfaces with deviations from roundness was carried out on the samples of steel 45. The diameter of the samples was $D = 50$ mm (Fig. 1b). Macrodeviations on the surface were created by applying longitudinal flats (profile 1 in Fig. 3). Burnishing was fulfilled with the force $Q = 100$ N. The diamond indenter radius was $r = 3.5$ mm. The longitudinal feed was
$S = 0.1 \text{ mm/rev} \ [3, 4]$. Fig. 3 shows typical microtopographies of sample surfaces after diamond burnishing at different processing speeds $V_{DB} = 15.5 - 100 \text{ m/min}$.

![Figure 2](image1.png)

**Figure 2.** Simulation results of diamond burnishing of machine parts flat surfaces: 

- **a** – fragments of profile records and micrographs of areas of burnished surfaces with waviness $Smw = 5000 \mu\text{m}$; 
- **b** – dependence of the contact coefficient values of the indenter with the surface on the indenter oscillation frequency; 
  - $K_v$, $K_p$ – average values of the contact coefficient with the surfaces of troughs and projections of waves, respectively; 
  - $K$ – average value of the contact coefficient over the entire surface profile

![Figure 3](image2.png)

**Figure 3.** Profile 1 of the surface with macrodeviations and its circular diagram 2 and typical photographs of the surface areas processed at different burnishing speeds $V_{DB}$ (DB – diamond burnishing)

The pre-treated surface is visible as a uniform light strip. At the processing speed of up to 25 m/min, a uniform topographic structure is also observed. When processing at a speed of more than 30 m/min, untreated areas are observed on surfaces, which make it possible to determine the flight phase for the diamond indenter (there is no contact with the surface) and the contact phase, during which there is a technological effect on the treated surface.
The analysis of the research results indicates the need to introduce the concept of technological stability of the process in terms of quality parameters for the processes of SPD processing with elastic action tools [5].

If we accept the condition $R(t) = \text{const}$, where $R(t)$ – are surface quality parameters of the workpiece (geometric, physical and mechanical, etc.), then in practice it is very difficult to ensure the constancy of $R(t)$ values, since a significant number of unaccounted factors, including random ones, act while processing. It is proposed to introduce a certain dead zone $\Delta \delta$, (as in the theory of automatic control), and then the condition of technological stability will take the form:

$$R(t) = R(t_{0\alpha}) \left(1 \pm \delta\right),$$  \hspace{1cm} (3)

where $R(t_{0\alpha})$ – are set values of surface quality parameters with a permissible regulated deviation $\delta$.

Then, for the processes of SPD processing with elastic action tools, technological stability is the ability to provide the required quality parameter values of the surface layer with regulated deviations $\pm \delta R$ and with a given continuous reliability $P(R_i \in (R_i \pm \delta R))$ over the entire workpiece surface.

3. Criteria for technological sustainability

To ensure technological stability of the treatment process, it is necessary to determine the condition for supporting constant contact of the indenter with the surface to be processed and to identify the range of processing speeds within which the burnishing force $Q$ will be maintained in the permissible regulated range ($Q_{\min}$, $Q_{\max}$), which must be kept in order to form quality parameters in given intervals.

Burnishing force when processing flat surfaces is determined by equation [3]:

$$Q = m\ddot{Z} + F\dot{Z} + c(Z - Z_0) + mg.$$

where $Z$ – is indenter displacement; $m$ – is mass of the tool moving part; $F$ – viscous friction coefficient; $c$ – stiffness coefficient of the tool elastic element.

With the idealized representation of the treated surface waviness in the form of a sinusoid, the solution of equation (4), when the left side is equal to zero, has the form:

$$Z = 0.5W_{\text{max}} e^{-\omega t} \sin(2\pi X / Smw) - 0.5W_{\text{max}} - mg / c.$$

(5)

Differentiating equation (5) with $n = 0$ (non-damping process) [6] and substituting the result into (4), we obtain the condition under which the indenter does not detach from the processed wavy surface:

$$\left(\frac{c}{m} - \left(\frac{2\pi V}{Smw}\right)^2\right) \sin\left(\frac{2\pi}{Smw} X\right) + \lambda c \geq 0 \quad \text{or} \quad \left(\omega_0^2 - \omega^2\right) \sin \omega t + \lambda \omega_0^2 \geq 0.$$  \hspace{1cm} (6)

Here, $\lambda = Z_0 / W_{\text{max}}$ – is the coefficient taking into account how many times the value of spring pretension 4 of the tool (Fig. 1) is greater than the wave height of the processed surface.

To ensure the indenter contact with the surface, it is necessary that $\lambda \geq 1$. Then:

$$\omega^2 \leq 2\lambda \omega_0^2.$$  \hspace{1cm} (7)

Based on inequality (7), it is possible to determine the critical frequency at which the indenter will detach from the treated surface:

$$\omega_{cr} \leq \sqrt{\frac{2\lambda c}{m}} = \sqrt{\frac{2Z_0 Q g}{W_{\text{max}} Z_0 G}} = \sqrt{\frac{2Q}{m W_{\text{max}}}},$$  \hspace{1cm} (8)

As $\omega_{cr} = 2\pi V / Smw$, then with the known parameters of the treated surface waviness and a given burnishing force $Q$ for a specific SPD tool, the processing speed $V$, admissible from the condition of the constant contact of the indenter with the surface, must satisfy the inequality, which determines the criterion of technological stability of the process of treating waved flat surfaces by SPD methods with elastic action tools:

$$V \leq \frac{Smw}{2\pi} \sqrt{\frac{2Q}{m W_{\text{max}}}}.$$  \hspace{1cm} (9)

The change in the processing force can be found by solving the equation:

$$\ddot{Z} + 2n\dot{Z} + \omega_0^2(Z + Z_0) + g = Q / m.$$  \hspace{1cm} (10)
At \( n = 0 \) extreme values of the machining force are:

\[
Q_{ext} = Q_0 \pm \frac{W_{max}}{2} m \left( \frac{2\pi V}{Smw} \right)^2.
\]

(11)

Raising the damping coefficient \( n \) contributes to increasing dynamic forces while processing, which leads to an uneven distribution of the quality parameters values over the surface to be processed.

The model of the longitudinal profile of a cylindrical surface having longitudinal waviness with a pitch that is a multiple of the circumference of nominal machining \( \pi D_0 \) can be represented as a sweep (Fig. 4). This profile corresponds to the equation

\[
Y = a \sin(\omega t + \varphi_0) = 0.5 W_{max} \sin(2\pi V t / Smw + \gamma_0),
\]

Here \( \varphi_0 \) is initial phase angle; \( \omega = 2\pi / T \) is circular frequency; \( \gamma_0 \) is phase angle.

![Figure 4. Sweep of a circle of diameter \( D_0 \) with superimposed original longitudinal waviness](image)

The total machining force acts on the treated surface from the indenter side \( Q_\Sigma \), which is determined by the relation:

\[
Q_\Sigma = c(Y_0 + Y) + m\ddot{Y},
\]

(13)

where \( Y_0 \) is value of the spring preload of the SPD tool; \( Y \) is current ordinate of the machined surface; \( m\ddot{Y} \) is force of inertia.

Assuming that \( Y \ll Y_0 \), then:

\[
Q_\Sigma = cY_0 + m\ddot{Y} = Q_0 + m\ddot{Y}.
\]

(14)

When the indenter contacts the surface to be processed, the condition is met \( P_T = Q_\Sigma \), where \( P_T \) is the force of SPD processing along the \( Y \) axis or the reaction to the indenter from the side of the processed surface. The condition for continuous processing is \( P_T \geq 0 \) or \( Q_\Sigma \geq 0 \). Taking into account assumption (14) for the case when \( \sin(\omega t + \gamma_0) = 1 \) the result will be \( Q_0 - m\ddot{Y} \geq 0 \). Then:

\[
\frac{c}{m} Y_0 \geq \frac{W_{max}}{2} \left( \frac{2\pi V}{Smw} \right)^2.
\]

(15)

From (15) we obtain the limitation of the maximum processing speed by diamond burnishing providing the constant contact of the indenter with the surface:

\[
V_{max} \leq \frac{1}{\pi\sqrt{2}} \frac{c(Y_0) Smw^2}{m W_{max}}.
\]

(16)

Condition (16) provides continuous machining, but the burnishing force varies within wide limits. It should be set in a certain reasonably chosen interval \( Q_\Sigma \in (Q_{\Sigma_{min}}, Q_{\Sigma_{max}}) \), symmetric with respect to \( Q_0 \) or asymmetric. For a symmetric interval, we have \( Q_\Sigma \in (Q_0 \pm \delta Q_0) \), where \( 1 \geq \delta \geq 0 \). Then:

\[
Q_0 - m\ddot{Y} \geq (1 - \delta)Q_0.
\]

(17)

After transformations, we obtain a maximum speed limit that simultaneously provides the upper and lower boundaries of the interval \( Q_0 \pm \delta Q_0 \):

\[
V_{max} \leq \frac{1}{\pi\sqrt{2}} \sqrt{\frac{\delta (cY_0) Smw^2}{m W_{max}}}.
\]

(18)

At asymmetric regulating of the indenter the action force on the treated surface: a) for the lower boundary \( \delta Q_0 \) the speed limit coincides with dependence (16); b) for the upper border \( \beta Q_0 \) the constraint takes the form: \( Q_0 + m\ddot{Y} \leq \beta Q_0 \). Here \( \beta > 1 \) is the coefficient of permissible excess of the nominal processing force, which is chosen from the conditions for limiting the possible overburden of the surface layer, etc. After a series of transformations, we obtain the condition:
It is convenient to interpret the areas of permissible processing speeds that ensure the uninterrupted process of SPD with elastic action tools using the diagrams theoretically obtained on the basis of condition (18), an example of which is shown in Fig. 5. The critical value of the processing speed $V$ on the diagrams is a point lying on the corresponding curve. The admissible values are below the curve, and the values leading to the indenter detachment from the surface are higher [3, 4, 5, 7].

![Figure 5. Diagrams for determining the permissible processing speed of cylindrical surfaces of parts by the SPD method with elastic action tools](image)

In practice, the real surface profile contains waves of different heights and pitches, but the main feature is its continuity, that is, differentiability. To apply the proposed criteria of technological stability while processing the machine part surfaces with waviness and deviations from roundness, taking into account the conditions of their differentiability, one should use the expansion of the real profile in a Fourier series, highlighting the main sinusoidal components and apply the superposition principle. In this case, the input value of the proposed dynamic models will be a periodic signal, which is the sum of sinusoidal components obtained by expanding the real surface profile in a Fourier series.

4. Conclusion
The concept of technological stability of SPD processing with elastic action tools is proposed, the condition of which is continuous providing of regulated values of the quality parameters of the surface layer in the permissible variation intervals over the entire treated surface. Criteria for assessing technological stability of the SPD process are theoretically determined from the conditions of the indenter constant contact with the processed surface. The obtained analytical dependences and diagrams make it possible to determine the values of the speeds and forces of SPD processing, which ensure the formation of surface quality parameters in the given variability intervals.

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