Increasing the efficiency of vibration treatment of complex surfaces

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Abstract. The article is devoted to improving the quality and reliability of high-loaded parts that ensure the service life of responsible products. It is recommended to apply vibro-impact hardening treatment in combination with nano-coatings of working tool elements. It is revealed that calculations based on classical ideas about the elastic properties of coatings of materials lead to overestimated values of allowable tangential stresses on the treated surface. According to the results of an experimental study of the process, the interrelation of the parameters of the vibro-impact and possible instrument defects that have a direct impact on the surface quality of the workpiece was established. The analysis of the effect of various nanocoatings of working elements on the surface quality of a complex configuration is given. It has been established that when using epilams the number of defects in the instrument decreases sharply.

1. Introduction
Improving the quality, reliability and durability of aviation equipment, shipbuilding, power plants for many decades and now is an important economic problem. This problem has become particularly relevant in connection with the creation of new generations of helicopters, airplanes, ships, engines and heightened competition in the global market. The designs of these types of products include groups of high-loaded parts, the reliability and durability of which greatly determine the service life and reliability of the entire product. A significant amount of this kind of parts has a complex shape, large size, limited stiffness and high demands on the quality parameters of the surface and surface layer.

These parts, depending on the type of product and its purpose, have different structural shapes and sizes, are made, as a rule, from structural alloy steels or aluminum alloys.

High requirements are imposed on the surface quality due to harsh operating conditions - high level of alternating loads, high speed and contact loads, fluctuations in the temperature gradient, corrosion and erosion processes. In this regard, the surface roughness is limited - \( Ra = 0.5 \div 1.25 \mu m \), the structure and direction of the micrelief is specified; the surface layer is subjected to hardening treatment by surface plastic deformation (PPD). The noted features require an unconventional approach to solving technological problems of hardening processing: the development and improvement of vibro-impact methods, new technological schemes for vibro-impact processing of parts, the use of nano-coatings of working parts of tool surfaces [1, 2].
2. Theory

Epilation implies the formation of multimolecular layers with regularly oriented molecules on the surface of a solid. The degree of orientation and thickness of the oriented layer depend on the nature of the solid and the surfactant molecules. Within the homologous series of the deposition of molecules on the surface, the degree of orientation increases with increasing length of the epilam molecules.

The surface of the metal base of the product has an orienting effect due to the presence of a near-surface electric field with intensity $E \sim 10^9 \text{ V/m}$ — for each specific material this value can be estimated by physical methods. When the coating material is connected with the base its atoms or molecules continue the atomic lattice of the base. This is equivalent to the fact that the same atoms are rotated by the orienting field of the base material distributed along the contact surface at a certain angle $\omega$, while doing work against the internal forces of the coating material. Because of this, in this material, even in the absence of external influences in the surface layer, a stress state is developed, a certain energy $\Delta$ of elastic deformations is concentrated. For these reasons, the expression is \[1\]:

\[
\frac{h \tau^2_{\text{max}}}{2 \mu} + \Delta = F_a
\]

$\tau_{\text{max}}$ - allowable shear stress
$h$ - is the coating thickness;
$\mu$ - Lame parameter;
$F_a$ - adhesion energy.

Then, when estimating the allowable tangential stress $\tau_{\text{max}}$, the inequality is true:

\[
\tau_{\text{max}}^* = \sqrt{\frac{2 \mu (F_a - \Delta)}{h}} < \tau_{\text{max}} = \sqrt{\frac{2 \mu F_a}{h}}
\]

This inequality suggests that a calculation based on the classical concepts of the elastic properties of coatings of materials leads to overestimated values of permissible tangential stresses.

To estimate the values $\mu$ and $\Delta$ it is proposed to use the micropolar theory of elasticity. It is based on the idea that a particle of a continuous elastic medium has not three, as in the classical case, but six degrees of freedom. Accordingly, to describe its movement, the displacement vector $\vec{u} = \vec{u}(\vec{r})$ and the vector of small rotation angle $\vec{\omega} = \vec{\omega}(\vec{r})$ are used ($\vec{r}$ - radius is the center of mass of the particle’s vector).

In the case of a plane shift, which is interested when considering the problem raised in this paper, the displacement and micro-rotation vectors take the form:

\[
\vec{u} = (u_x(x^2), 0, 0) \quad \text{and} \quad \vec{\omega} = (0, 0, \omega_3(x^2))
\]

(3)

In this case, the axis $Ox_1$ is directed along the plane of the contact of the coating and the base in the direction of the tangential stress parallel to it $\tau \equiv \tau_1$. The axis $Ox_2$ is directed perpendicular to the plane of contact. Shift occurs in the plane $x_1 Ox_2$. As a result, only the following values are considered:

\[
\gamma_{12} = u_{1,2} + \omega_3 \quad \kappa_{12} = \omega_{3,2} \quad \gamma_{(12)} = \frac{1}{2} u_{1,2} \quad \kappa_{(12)} = \frac{1}{2} \omega_{3,2} 
\]

(4)

The equilibrium equations in stresses are in the general case of the form:

\[
\sigma_{ij} = 0; \quad \mu \epsilon_{ij} + \epsilon_{ijk} \sigma_{jk} = 0
\]

(5)
In this flat case of pure shear on the basis of (5), writing the second equation in displacements, we can get:
\[
\sigma_{21,2} = 0; \quad (\gamma + \varepsilon) \omega_{3,22} + 2\alpha u_{1,2} - 4\alpha \omega_3 = 0. \quad (6)
\]
The boundary conditions for them are the relations:
\[
\sigma_{21}(h) = \tau; \quad \mu_{23}(h) = 0; \quad u_1(0) = 0; \quad \omega_3(0) = \omega^0 \quad (7)
\]
Taking into account the first of the boundary conditions (7), the first equation of system (6) suggests that, as with the classical model of a linear elasticity, in the framework of the considered model, the tangential stress shifting the coating is uniformly distributed over its thickness \( h \) effective shear stress on the surface.
\[
\sigma_{21} = \tau \quad (8)
\]
Based on (3) and taking into account (4), this conclusion leads to the statement that the energy of the elastic deformation \( W \), concentrated under the unit of the surface area of the coating, can be written in the form:
\[
W = \frac{h \tau^2}{2\mu} + \frac{1}{2} \int_0^h \left( -u_{1,2} \left( x_2 \right) + \omega_3 \left( x_2 \right) \right)^2 dx_2 + \frac{\gamma + \varepsilon}{2} \int_0^h \left( \omega_{3,2} \left( x_2 \right) \right)^2 dx_2 \quad (9)
\]
Comparing it with the left side of equality (3), we can verify that
\[
\Delta = \frac{\alpha}{2} \int_0^h \left( -u_{1,2} \left( x_2 \right) + \omega_3 \left( x_2 \right) \right)^2 dx_2 + \frac{\gamma + \varepsilon}{2} \int_0^h \left( \omega_{3,2} \left( x_2 \right) \right)^2 dx_2 \quad (10)
\]
It can be seen that the classical estimate of the adhesion energy is less compared to the one that can be made by equating (9) to the value \( F'_{\alpha} \). Obviously, for sufficiently large values of \( \alpha \) and \( \gamma + \varepsilon \), classical estimates \( \tau_{\text{max}} \) can not be used.

In the overall assessment machining it is a complex set of mechanical, physical and chemical phenomena that have a significant effect on the state, first of all, of the surface and the surface layer of the workpiece and also technological system. The physical essence of the process is characterized by a complex effect on the workpieces and their surface by a number of factors caused by vibration and by the presence of the working environment of a corresponding characteristic.

The main effect of applying a thin film of epilam on the working surface of the tool is to hold the oil in the contact zone, reduce the friction coefficient, and maintain its long-term performance. An additional advantage of working with an epilaminated tool is the adsorption decrease in the strength of processed material, an increase in the plasticizing effect of the cutting fluid, and a decrease in the deformation forces due to the Rebinder effect.

To assess the effect of epilams on tool life and conduct experimental studies under equal conditions, the 5-row separator was conventionally divided into five zones. The number (balls) of the instrumental environment in each track was 38 pieces:
- 1 zone – ball and separator surface treated with epilam EFREN-2;
- 2 zone - balls treated with epilam EFREN-2;
- 3 zone - without treatment with epilating compositions;
- 4 zone - balls treated with epilam 6SFC-180-05;
- 5 zone - balls and surface of the separator treated with epilam 6SFC-180-05;

Ball material: ball bearing steel Ø 7mm.
Processing conditions were chosen in accordance with the basic technological process:
The number of revolutions of the tool: \( n = 2500 \text{ rpm} \);
The number of revolutions of the workpiece \( n_1 = (5 - 6) \text{ rpm} \);
Longitudinal feed of tool \( S = (50 - 55) \text{ mm / min} \);
The force of separation the tool from the workpiece \( 8.5 \pm 0.25 \text{ kg} \);
Therefore, the total number of experimental hours of work of the tool was 60 hours.
Industrial oil was used as a cutting fluid. The force of separation was measured using a dynamometer.

The reverse movement of the tool was carried out using a special control unit mounted on the power panel of the machine. For tracking the process of machining, a stroboscope was used.

For a comparative assessment of the wear of the tool, measurements of the holes in the tool on the amount of departure of the tool ball relative to the surface of the separator before and after the experimental studies were carried out. Measurements were made five times for each hole with a special device according to divided epilamination zones. An analysis of the experimental data showed that the greatest wear of the tool was observed in the zone without treatment with epilating compositions. A positive effect on the amount of wear of the tool cage was observed if the balls were treated with epilams. The greatest effect on resistance was achieved when balls and the tool were treated. The ordinate axis is the size of the ball imprint on the holder (d, mm), the abscissa is the position of the ball in the tool. The tests were carried out for 60 hours.

The epilam coating in this case plays the role of boundary cutting fluid and it contributes to the retention of oil in the area of shock loads. At the same time, the technological efficiency of the oil in the area of shock loads is realized through its functional actions [4].

Because of wear, the sizes of the balls and the tool change, the gaps between the rubbing surfaces increase, and all these are cause beating and knocking.

The film on the working surfaces contributes to the penetration and retention of oil in the contact zone. As a result of the violation of the integrity of the epilam coating, the formation of energetic barrier sites which prevents the removal of oil from the friction zone, it helps to reduce friction and adhesion forces in the contact zone [5, 6].

From the analysis of experimental data can distinguish several types of wear:
- fatigue failure and chipping of the surface;
- minor scratches;

The presence of the film on the working surfaces of the balls and the tool contributes to the penetration and retention of oil in the contact zone. As a result of violation of the integrity of the epilam coating, energy barrier sections are formed that prevent oil from being removed from the friction zone, which helps to reduce friction and adhesion forces in the contact zone, while paragraph 3 of the technological efficiency of the oil in the shock load zone is realized through its functional actions.

The smallest wear of the tool’s surface was observed when epilating the balls and the separator surface with epilame and EFREN - 2.

It should be noted a general decrease in the diametral size of the scatter of the holes of the separator by 1.2 times, which associated with a decrease in the roughness of the friction surfaces.

3. Conclusions
1. It was established that the introduction of additional parameters in the methods of surface plastic deformation is accompanied by the expansion of their capabilities - increased productivity and improved properties of the surface layer of the workpiece. It is shown that the combination of cutting fluids and surface-active substances provides favorable conditions for the operation of the tool. It is shown that the operation of the tool treated by epilama without any cutting fluids is undesirable, in this case, there is a rapid abrasion of epilame nano films.

2. It was established that the calculations of tangential stresses arising in the “tool – epilam” boundary zones, made on the basis of classical concepts, lead to overestimated values. It is proposed to apply the provisions of the micromolecular theory of elasticity, which allow predicting the resistance of surface - active coatings the most reliably. A mathematical model of impact at large angles of effect with a deformable body is given.
3. It is shown that the analysis of experimental data confirms the theoretical position that using epilating coatings sharply decreases the number of ball defects. So, when epilating the balls and the separator surface with epilams and EFREN - 2, no fatigue failure and chipping were observed, and when analyzing the balls, these defects were 5.2%. When processing epilam EFREN-2 coatings, rubbing on the surface of the balls was 2.6%, which is 2 times lower than the untreated.

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