Deposition process of an epilam film during surface plastic deformation

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Abstract. The article deals with the conditions of contact between the tool and the nominal surface during surface - plastic processing with balls due to centrifugal force. The dependences reflecting the impact of the oblique impact of the ball on the surface are given. It has been established that the deformation process can be significantly influenced by the epilamic coating of the working elements of the tool, which significantly changes the energies of the interaction of the contacting surfaces.

1. Introduction
In the course of testing various tools with an epilam coating, it was found that epilam coating increases the durability of the cutting tool by a factor of 1.5 or more.

Despite the positive test results, the method does not find proper application in production due to the lack of a clear understanding of the nature of epilams and their mechanism of action during cutting, as well as recommendations for the operation and maintenance of the epilamated tool.

Epilam coating is the process of deposition of surfactants on a solid surface. The nature of adsorption and the orientation of the deposited molecules are determined by the interaction of the adsorption centers of the surface with the active centers of the molecules. The spatial arrangement of adsorbed molecules depends on their polarity and deposition conditions and can be both vertical and horizontal, or can form any angle with a solid surface.

Epilam coating involves the formation of multimolecular layers with regularly oriented molecules on the surface of a solid. The degree of orientation and the thickness of the oriented layer depend on the nature of the solid and surfactant molecules. Thus, within the homologous series of fatty acids, the degree of orientation increases with an increase in the chain length of the molecule.

From the experience of using Epilam Efren, we know that if a relatively “thick” layer of surfactant is applied to the surface of a solid (for example, from a solution of 10 times higher concentration), then during subsequent exposure at a temperature of 150 °C, the applied film is better resistant to mechanical and chemical influences.

2. Theory
The knurling head (hardener) acts as a tool, and balls act as a tool medium. When the hardener rotates, the balls hit the part under the action of centrifugal force. Such processing is accompanied by the formation of such technological defects as microcracks, individual scratches, risks, dents, etc., both on the part and on the tool, which leads to tool wear.

The phenomenon of the impact of an absolutely rigid body on a surface with a significantly greater mass has been devoted to many works [1,2,3,4].
At (PPD), there is an oblique impact on a fixed surface under the assumption that the body (ball) performs a plane motion and has a point contact. In this case, it is assumed that the impact forces of interaction are much greater than the rest of the forces, which implies the effect of the latter to be neglected. The classical model of Newton's impact is based on the hypothesis that the impact time is infinitely small and the movement of a body in space can be neglected. It was also assumed that during impact, the coefficient of recovery (the ratio of the moduli of the body's velocities before and after the impact) is determined by the interval between collisions of bodies and does not depend on the speed of the colliding bodies. The collision process was divided into two phases. In the deformation phase, the deformation rate of the ball decreases to zero and the energy of elastic deformations accumulates. In the recovery phase, the accumulated potential energy is released and the ball accelerates and moves in the other direction (with an oblique impact). Later, other definitions were introduced \( k \) \[4\] - the coefficient of recovery is the ratio of the impulses of the impact force of interaction in the phases of recovery of deformation.

This value characterizes the physical properties of the colliding bodies.

The ratio of the velocity modulus of the ball at the end of the impact to the modulus of its velocity at the beginning of the impact is the coefficient of recovery upon impact:

\[
k = \frac{|u|}{|v|},
\]

where: \( u \) - is the speed of the ball at the end of the impact;
\( v \) - is the speed of the ball at the end of the impact.

Real materials always have different energy losses and the coefficient of recovery, even for sufficiently elastic materials, only approaches to one degree or another one. In addition, the recovery factor depends on the speed at which the impact occurs (\( k = k(v) \)).

The recovery factor also determines the ratio between the impulses of impact force in two phases: basic impact equation for the first phase

\[
0 - mv = \int_{r_1} N_1 \, dt = S_1,
\]

for the second

\[
mu - 0 = \int_{r_2} N_2 \, dt = S_2
\]

Hence, the impulse of the second phase and the total impulse of the impact force in two phases depends on the recovery factor:

\[
k = \frac{|u|}{|v|} = \frac{S_2}{S_1}, \text{ and } S_2 = kS_1, \text{ hence }
\]

\[
S = S_1 + S_2 = S_1 + kS_1 = (1 + k)S_1 = (1 + k)mv.
\]

The translational motion of a ball of mass \( m \) at a speed \( v \), making up a certain angle (angle of incidence) to the normal of a stationary massive surface (obstacle) - with centrifugal ball processing is shown in the diagram (Figure 1):

![Figure 1](image-url)
Basic Impact Equation:

\[ m(\ddot{\mathbf{u}} - \ddot{\mathbf{v}}) = \dddot{\mathbf{S}}. \]  

(5)

The projection of the vector equality onto the normal and tangent to the surface:

\[ m(u_n - v_n) = m(u \cos \beta + v \cos \alpha) = S \]
\[ m(u_t - v_t) = m(u \sin \beta - v \sin \alpha) = 0. \]  

(6)

Then

\[ u = \frac{u \sin \alpha}{\sin \beta} \]  

(7)

And the recovery factor:

\[ k = \frac{|u_n|}{|v_n|} = \frac{u \sin \alpha}{v \sin \beta} = \frac{v \sin \alpha \cos \beta}{\tan \alpha \tan \beta} \]  

(8)

Since the recovery factor is \( k < 1 \), the reflection angle is greater than the incidence angle. The angle of reflection is equal to the angle of incidence only in the case of elastic impact (\( k = 1 \)).

Velocity module after impact:

\[ u = \sqrt{u_t^2 + u_n^2} = \sqrt{v_t^2 + k^2 v_n^2} = \sqrt{(v \sin \alpha)^2 + k^2 (v \cos \alpha)^2} = v \sqrt{\sin^2 \alpha + k^2 \cos^2 \alpha} \]  

(9)

At very large angles \( \alpha \) of incidence, close to the right angle, the velocity after impact approaches the velocity before impact (\( u \to v \)).

Impact Impulse:

\[ S = mu \cos \beta + mv \cos \alpha = mv(\sqrt{\sin^2 \alpha + k^2 \cos^2 \alpha} \cos \beta + \cos \alpha). \]  

(10)

Having the values of the momentum when the ball hits the surface of the part and using the provisions of the similarity theory [5], it is possible to predict the depth of its penetration into the surface of the part and the diameter of the resulting impression.

In this work, this approach made it possible, on the basis of the assumption that a high-speed impact is similar to an explosion, to determine the diameter and depth of penetration of meteorites into the Earth's surface.

The volume of a dimple on the surface of a part is determined based on the assumption that their formation is determined by a combination of momentum and ball energy.

\[ V = E^a \times S^b, \]  

(11)

where: 
\( E \) – kinetic energy; 
\( S \) – ball impulse; 
\( a, b \) – define similarity ranges.

Taking into account the results of the experimental data, it is possible to obtain the values «h» - the depth of penetration of the ball into the surface of the part and «d» - the diameter of the indentation on the treated surface.

The values of \( h \) determine the frequency and density of impacts. 
The values of \( d \) indirectly characterize the depth of the layer with increased hardness and residual stresses in the surface of the part.

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

The connection of the epilam molecular film with the working surface of the instrument can be realized through the mechanism of physical or chemical adsorption. With the physical mechanism of adsorption, van der Waals interactions arise between the solid surface and the polar part of the group of epilam molecules.

They are determined by intermolecular interaction within the contacting phases, a measure of the balance of forces at the interface during the interaction of molecules (ions) of different phases.

The interaction between ions (including molecular ones) is realized by means of Coulomb forces. According to Coulomb's law, the force \( f \) arising from the interaction of two point charges \( q_1 \) and \( q_2 \) at a distance \( r \) is determined by the expression
\[ f = q_1 q_2 / r^2, \]

from which it follows that the potential energy of the Coulomb interaction \( U_{\text{Coul}}(r) \approx 1/r. \)

The interaction of uncharged molecules (van der Waals interaction) is of an electrical nature and consists of attractive forces (orientational, induction, and dispersive) and repulsive forces.

The quantitative characteristic of intermolecular interaction is the potential energy \( U \), which is the sum of the potential energies of attraction and repulsion. As a rule, intermolecular attraction is realized by a complex of forces and strongly depends on the chemical nature of the interacting phases; therefore, the division by the value of \( U \) for various types of interaction is rather arbitrary. It is more important to have an idea of the distances at which the action of intermolecular forces is manifested.

The nature of the London-Van der Waals dispersion forces is due to the fact that even neutral atoms are systems of oscillating charges, as a result of which the instantaneous value of the dipole moment of an uncharged molecule. A dipole arising from fluctuations creates an electric field that polarizes neighboring molecules. The energy of interaction between non-polar molecules is the average result of the interaction of all kinds of instantaneous dipoles with the dipole moments that they induce in neighboring molecules due to induction. Potential energy of dispersive interaction of molecules. Dispersion forces act between all atoms and molecules, since the mechanism of their appearance does not depend on the magnitude of the dipole moment of the molecule. An essential feature of dispersion interactions is their additivity: for two volumes of condensed phases located at a distance \( h \), there is a summation of the attraction of individual molecules.

Induction forces arise from the interaction of polar and non-polar molecules. A polar molecule creates an electric field that polarizes a non-polar molecule. As a result, there is a displacement of electric charges uniformly distributed over the volume of the molecule prior to interaction. As a result, a dipole moment is induced in the non-polar molecule.

Repulsive forces arise when two molecules (atoms) come close together due to the reluctance of their electron clouds to overlap. In comparison with the energy of the forces of attraction, the potential energy of repulsion decreases very strongly with an increase in the distance \( r \) between the ions.

The resulting interaction between uncharged molecules is approximately described by the Lenard-Jones potential:

\[ U = \sum \approx -\alpha / r^6 + b / r^{12}, \]

Where \( a \) and \( b \) are coefficients, from which it follows that at distances exceeding the diameters of interacting molecules, the most significant role is played by attractive forces.

In the first approximation, the specific free surface energy can be represented as the sum of the dispersion \( \gamma^d \) and polar \( \gamma^p \) components \( \gamma = \gamma^d + \gamma^p \). Such a separation is advisable, since dispersive ones exist in the volume of any phase.

The dependence of the surface tension of liquids on the chemical nature is illustrated by the data in the table 1.

| liquid           | \( \gamma_{LV} \) (mJ / m²) | \( \gamma^d_{LV} \) | \( \gamma^p_{LV} \) |
|------------------|-----------------------------|------------------|------------------|
| nitrogen (T = 80K) | 8.3                         | -                | -                |
| octane           | 21.8                        | 21.8             | 0                |
| ethylene glycol  | 48.3                        | 29.3             | 19.0             |
| water            | 72.6                        | 21.8             | 50.8             |
| hydrargyrum      | 471.6                       | 200.0            | 271.6            |
For films, the tension \( \gamma_{dLV} \) and \( \gamma_{pLV} \) depends not only on the structure of the chains, but also on the morphology of surfaces, which is significantly influenced by the prehistory of manufacture (the method of film formation, the nature and rate of solvent evaporation, annealing, etc.).

To predict adhesion, it is necessary to take into account what forces of intermolecular interaction act inside the phases of the adhesive and the substance and which of them can be balanced when molecules of different phases interact at the interface.

There are a number of thermodynamic theories describing adsorption at various interfaces. For the analysis of adhesion, the Gibbs adsorption equation is of interest, which relates the specific free surface energy of interphase boundaries with the value of adsorption:

\[
\Delta \Gamma = - \sum_i \Gamma_i \mu_i ,
\]

where \( \mu_i \) – is the chemical potential of the i-component. For a two-phase three-component system (for example, a solution at the boundary with saturated vapor), which is close to ideal in volume at a constant temperature \( T \), the Gibbs equation takes the form:

\[
G = -\left(\frac{c}{RT}\right) \Delta \gamma / dc ,
\]

where \( c \) – is the concentration of the solute, \( R \) - is the universal gas constant, \( T \) - is the temperature.

Since the value of \( G \) in the equation is an excessive value, \( G < 0 \) corresponds to the lack of substance in the surface layer compared to the volume of the phase, and \( G > 0 \) corresponds to the concentration of the substance in the surface layer. Substances for which \( G > 0 \) are called surfactants (surfactants). Surfactants have a diphilic chemical structure (Figure 2).

**Figure 2.** Schematic representation of the simplest surfactant molecule

The non-polar or hydrophobic part of the molecule is a hydrocarbon moiety. The polar or hydrophilic part can be neutral (nonionic surfactants), positively charged (cationic surfactants) or negatively (anionic surfactants). There are surfactants with a more complex chemical structure than schematically shown in the figure [6, 7].

Their molecules can contain two hydrophilic fragments and one hydrophobic (gemini-surfactant), two hydrophilic fragments and one hydrophobic (bola-form surfactants); with different charge signs of the polar groups of bolaform surfactants, they are called zwitterionic. Many substances exhibit surface activity. Due to the diphilic structure, surfactant molecules are able to concentrate at the interface, orienting themselves, in accordance with the Rebinder polarity equalization rule, in such a way as to maximally compensate for the polarity difference of these phases (Figure 3).

**Figure 3.** Orientation of surfactant molecules at the interface "Aqueous solution-air" at low (upper) and high (lower) concentrations in solution.
The greater the difference in the polarities of the contacting phases, the less balanced the forces of interaction of molecules of different phases at the interface, and, consequently, the greater the interphase energy $\gamma$. Thus, the difference in the polarities of the contacting phases is a stimulus for the adsorption of surfactants [8, 9, 10].

Surfactant characteristic is surface activity

$$G = -\lim_{c \to 0} (dy/dc)$$

showing the ability of a surfactant to reduce surface energy at a moving interface ($LV$ or $LL$). In accordance with Traube’s rule, within the homologous series, G increases by 3 - 3.5 times with an increase in the length of the hydrocarbon fragment of the surfactant molecule by one methylene (-CH$_2$-) group.

Another important characteristic of surfactants is the hydrophilic-lipophilic balance (GLB), a number that expresses the degree of hydrophilicity or hydrophobicity of a surfactant. There are a number of techniques for calculating GLB. The most commonly used is the Davis formula, which relates GLB to the surfactant distribution coefficient between the hydrocarbon and water phases:

$$HLB = 7 + 0.36 \ln \left( \frac{S_v}{S_m} \right),$$

where $S_v$ and $S_m$ are the surfactant concentrations in the water and hydrocarbon (oil) phases, respectively. With an increase in HLB, the hydrophilicity of the surfactant increases. When GLB = 7 PAV, the surfactant has the same affinity for both water and hydrocarbon.

The equation describes the adsorption PAV of surfactants not only at mobile interfaces, but also at the “solid - liquid” interface. In general, the adsorption PAV of surfactants leads to a decrease in the specific free surface energy of the interface.

The main component of epilams are polyesters of carboxylic acids, which are high molecular weight compounds. Such polyesters are insoluble in water and contain up to 10,000 mono-residues in the chain. In terms of chemical structure, polyesters are a fluorocarbon radical with polar end groups attached to it.

Epilams include a fluorinated surfactant (fluoride surfactant) and a solvent. As a fluorine-

$$(-CF - CF_O -)_{n}$$

- surfaceant C$_n$F$_{2n+1}$CONH(CH$_2$)$_2$N[C$_2$H$_5$]$_2$, the composition contains a substance of

CF$_3$

the general formula or an amidoamine of a fluorinated acid of the general formula, and as a solvent - a polar one, selected from the group methyl, ethyl, propyl, isopropyl alcohol, water, and / or non-polar, selected from the class of hydrocarbons with the number of atoms hydrogen, and / or a halogenated solvent selected from the group trichlorethylene, tetrachlorethylene, freon 12.

As solvents used fluorocarbon, fluorochlorohydrocarbon solvent or mixtures thereof with ethyl, methyl and other alcohols, acetone. Although the solvent plays the role of a surfactant carrier, its effect on the formation of the epilam nanofilm is as great as the effect of the main component, the surfactant. Solvents are chosen, on the one hand, in terms of volatility, in order to provide the required film thickness, and, on the other hand, in terms of the surfactant solubility in them in order to ensure a stable surfactant deposition process. The properties of the solvent affect the adsorption rate, epilation time, the structure of the deposited surfactant layer, as well as the interaction of the composition with the substrate material.

The solvent, in the presence of which the polar surfactant molecule is adsorbed, itself forms a quasicrystalline lattice at the surface of the solid. Due to the fact that the length of the solvent molecule is much shorter than that of the surfactant, this lattice is formed faster than the adsorption of polar molecules, which is the initiation of a more organized orientation of the latter. After evaporation of the solvent, a layer of molecules with a more rigid structure remains on the surface of the solid, and adsorption on a non-polar solvent (isooctane) is easier than on a polar one.

At the second stage of epilating, surfactant molecules are adsorbed on the working surface of the tool, and the polar part of the surfactant molecule is adsorbed by the solid, and the hydrophobic part is directed outward (Figure 4).
Figure 4. The process of deposition of the epilam coating on the surface of the instrument

In this case, the location of the polar part of the surfactant molecule is homeotropic, i.e., perpendicular to the working surface of the tool. When a layer of fluorine-surfactant molecules is formed on the instrument, a balance is observed between the polar group and the non-polar hydrocarbon radical, i.e., anisotropy is observed [19, 20]. With an increase in the asymmetry of the polar and non-polar groups of large molecules, the surface activity increases. Anisotropy also increases with distance from the solid surface of the instrument (Figure 5).

Figure 5. Scheme of the formation of epilam molecules on the surface of the instrument

The concentration of fluorine-surfactant in the solvent, temperature and holding time in the technological process of epilating the tool are selected from the condition of the formation of a continuous nanofilm on the working surface, which completely shields the surface energy of the tool. The formation of a too thick surfactant layer is also undesirable, since in this case the orientation of the molecules in the upper part of the layer is disturbed.

The connection of the epilam molecular film with the working surface of the instrument can be realized through the mechanism of physical or chemical adsorption. With the physical mechanism of adsorption, van der Waals interactions arise between the solid surface and the polar part of the group of...
epilam molecules. During chemisorption, fluorine-surfactant molecules enter into a chemical bond with solid surface molecules, which is possible only during low-temperature heat treatment. When heated, the chemical reaction of the addition of the surfactant molecule to the solid surface occurs with the elimination of hydrogen from the polar part of the molecule and the reaction of hydrogen with hydroxyl-containing groups on the surface of the solid [17].

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Usually, only one of the mechanical aspects of the phenomenon is considered—the development of material damage due to the arising inhomogeneity of the structure. To describe it, we used the non-classical theory of a deformable solid, based on taking into account the nonlocal many-particle interaction of its infinitesimal elements.

An increase in microhardness, the formation of compressive residual stresses, is a consequence of a change in the internal microstructure, which, with a certain degree of justice, allows us to consider a part of the material in which these characteristics differ from the base material as different in relation to the base material.

It is assumed that the material of the bodies is linearly elastic and is described based on the theory of elasticity of second-order materials. The proposed method is based on taking into account the energy changes accompanying the adhesion phenomenon that occur in the layers of the material that form these structures [15, 16].

It is assumed that each elementary section $S_0$ of the surface of the apparent contact of bodies $B_{(1)}$ and $B_{(2)}$ is the union of two sections

$$dS_0 = dS_{\alpha} + dS_{1-\alpha}.$$  \hspace{1cm} (16)

On the first of them $dS_{\alpha} = \alpha dS_0$, adhesion exists, on the second $dS_{1-\alpha} = (1-\alpha)dS_0$ it is not.

During formation $B = B_{(1)} \cup B_{(2)}$, energy changes occur in this system. Among all possible states for the system $B = B_{(1)} \cup B_{(2)}$, the one that corresponds to their minimum occurs. Therefore, in the equilibrium state of the system in the absence of external mechanical influences, the equality

$$\frac{\partial F}{\partial \alpha} = \frac{\partial W_{(1,2)}}{\partial \alpha} = 0.$$  \hspace{1cm} (17)

The displacement $B_{(i)}$ of body particles at the boundary of its contact $S_u$ with another body of the system is the sum of displacements arising both in the presence of adhesion and in its absence $B = B_{(i)} \cup B_{(2)}$, taken with coefficients equal to the relative fractions of the boundary sections at which it is observed [5].

The above reasoning makes it possible to solve the problem [5], having previously considered, independently of each other, two problems. The first is about adhesion $B_{(1)}$ and $B_{(2)}$ on the assumption of its absolute continuity along $S_0$. The second is the problem of their stress-strain state in the absence of their mutual influences.

The expression for the excess of the surface energy $W_{(1,2)}$ of the united body is $B = B_{(1)} \cup B_{(2)}$:

$$W_{(1,2)} = \alpha^2 W_{a\alpha} + \alpha (1-\alpha) W_{a(1-\alpha)} + (1-\alpha)^2 W_{(1-\alpha)(1-\alpha)} = W_{(1,2)\alpha}. \hspace{1cm} (18)$$
In this record $W_{\alpha}$, it is numerically equal to the work of the generalized internal forces caused by the adhesive contact on the generalized displacements also caused by the adhesive contact. $W_{(1-\alpha)}$ - the work of the $B_{(j)}$ generalized internal forces, arising in the absence of adhesion, on displacements that appear under the influence of these forces. In view of this, both quantities $W_{\alpha}$ and $W_{(1-\alpha)}$ are positive. This means that dependence has a minimum. The corresponding value $\alpha = \alpha_0$ is determined by the condition

$$\alpha = \left(1 + \frac{2W_{\alpha} - W_{(1-\alpha)}}{2W_{(1-\alpha)} - W_{\alpha}}\right)^{-1}. \quad (19)$$

It is energetically "advantageous" for materials with different properties to have discontinuous contact between its elements. The contact absence area has a probabilistic order. An attempt to tear one body away from another - tensile stress acts on the system. In this case, the fields of deformations and stresses corresponding to cases of lack of adhesion and its presence will change. In this case, only the values, change, $W_{\alpha}$ and $W_{(1-\alpha)}$ and the value $W_{(1-\alpha)}$ does not change. This is because there is no adhesion along the area where there is no adhesion. Stretching leads to the movement of parts of the contacting bodies over these areas as absolutely rigid bodies. In this case, the denominator of the fraction of the formula for the coefficient $\alpha$ will increase due to growth, and the value $W_{\alpha}$ will decrease. If the system of bodies is compressed, then this will lead $W_{\alpha}$ to an increase in all values, $W_{\alpha}$ and $W_{(1-\alpha)}$.

Epilated tool coatings can have a significant effect on the interaction of bodies. It changes the nature of the adhesive effect, and when applying coolant technological media (COTS) can exclude adhesive interaction.

The surface of the metal base of the product has an orienting effect due to the presence of a near-surface electric field with an intensity $E \sim 10^9 \text{ V/m}$ - for each specific material, this value can be estimated by physical methods. When connecting the coating material to the base, its atoms or molecules continue the atomic lattice, the base structure. In this case, they acquire an orientation that is not characteristic of their orientation in the structure of the material, far from the surface of the adhesive contact. This is equivalent to the fact that the same atoms turn out to be rotated by the orienting field of the base material and distributed along the contact surface by moments at a certain angle $\phi$, performing work against the internal forces and moments of the coating material. Because of this, in this material, even in the absence of external influences in the surface layer, a stressed state develops, a certain energy $\Delta$ of elastic deformations $C$ is concentrated. Taking into account these reasons, the expression has the form:

$$\frac{h\tau^2_{\text{max}}}{2\mu} + \Delta = F_a, \quad (20)$$

where $\tau_{\text{max}}$ - is the permissible shear stress,

$h$ – is the thickness of the coating;

$\mu$ – Lame parameter;

$F_a$ - the energy of adhesion.

Then, when assessing the permissible shear stress, the following inequality turns $\tau_{\text{max}}$ out to be true:
This inequality indicates that the calculation based on the classical concepts of the elastic properties of the surface layer of the material leads to overestimated values of the permissible shear stresses.

To estimate the quantities $\mu$ 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 motion, the displacement vector $\bar{u} = \bar{u}(\bar{r})$ and the vector of a small angle of rotation $\bar{\omega}(\bar{r})$ (\bar{r} - the radius vector of the center of mass of the particle) are used.

The expression for calculating the bulk density of the energy of elastic deformations $w$ according to this model can be represented as:

$$w = \frac{\mu + \alpha}{2} \gamma_{ij} \gamma_{ij} + \frac{\mu - \alpha}{2} \gamma_{ij} \gamma_{ji} + \lambda \frac{\gamma_{kk} \gamma_{nn}}{2} \gamma_{ij} \kappa_{ij} + \frac{\gamma + \varepsilon}{2} \kappa_{ij} \kappa_{ji} + \frac{\gamma - \varepsilon}{2} \kappa_{ij} \kappa_{ji} + \frac{\beta}{2} \kappa_{kk} \kappa_{nn}$$  \hspace{1cm} (22)

Here $\lambda$, $\mu$, are classical constants, Lamé coefficients; $\alpha$, $\beta$, $\gamma$, $\varepsilon$ - additional constants requiring experimental or theoretical (based on physical considerations) definition; $\gamma_{ij} = u_{i,j} - \varepsilon_{ij} \omega_k$; $\kappa_{ij} = \omega_{i,j}$; tensors of material deformations ($\varepsilon_{ij}$ - three-index Levi-Civita symbol; the subscript after the decimal point means differentiation along the coordinate with the corresponding number; $u_i$, $\omega_i$ - components of vectors $\bar{u}$, $\bar{\omega}$ in the orthonormal basis $\hat{e}_i$ of the Cartesian coordinate system $x_i$).

In expression (21), the summation is performed over the repeated index.

Taking into account that internal stresses $\sigma_{ij}$ and moments $\mu_{ij}$ at constant temperature are expressed through strain tensors using the relations

$$\sigma_{ij} = \frac{\partial w}{\partial \gamma_{ij}} = 2 \mu \gamma_{(ij)} + 2 \alpha \gamma_{(ij)} + \lambda \gamma_{kk} \delta_{ij},$$  \hspace{1cm} (23)

$$\mu_{ij} = \frac{\partial w}{\partial \kappa_{ij}} = 2 \gamma \kappa_{(ij)} + 2 \varepsilon \kappa_{(ij)} + \beta \kappa_{kk} \delta_{ij},$$  \hspace{1cm} (24)

for the bulk density of the energy of elastic deformations $w$, one can obtain the expression:

$$w = \mu^* \sigma_{(ij)} \sigma_{(ij)} + \alpha^* \sigma_{(ij)} \sigma_{(ij)} + \lambda^* \sigma_{kk} \sigma_{nn} + \gamma^* \mu_{(ij)} \mu_{(ij)} + \varepsilon^* \mu_{(ij)} \mu_{(ij)} + \frac{\beta^*}{2} \mu_{kk} \mu_{nn}.$$  \hspace{1cm} (25)

In expressions (22) - (23), the parentheses denote the symmetric part, and the angular ones denote the antisymmetric part of the corresponding tensor; $\delta_{ij}$ - Kronecker symbol;

$$\mu^* = \frac{1}{4 \mu}; \quad \alpha^* = \frac{1}{4 \alpha}; \quad \lambda^* = \frac{1}{4 \lambda}; \quad \varepsilon^* = \frac{1}{4 \varepsilon};$$

$$K = \lambda + \frac{2}{3} \mu; \quad \Omega = \beta + \frac{2}{3} \gamma.$$  \hspace{1cm} (27)

In expression (24), the first term fully corresponds to the classical concepts of the volumetric energy density of elastic deformations. Further, when assessing the role of the sum of the remaining terms, we assume that the stresses coincide $\sigma_{(ij)}$ with their classical values.
In the case of a plane shear, which is of interest when considering the problem touched upon in this work, the vectors of displacements and microrotations take the form:

\[ \mathbf{\bar{u}} = (u_1(x_2), 0, 0); \quad \mathbf{\bar{\omega}} = (0, 0, \omega_3(x_2)). \]  

(28)

The equilibrium equations in stresses within the framework of the considered model of the medium have, in the general case, the form:

\[ \sigma_{g,i} = 0; \quad \mu_{g,k} + \varepsilon_{g,k} \sigma_{ak} = 0. \]  

(29)

In the considered plane case of pure shear, based on (29), having written down the second equation in displacements, one can obtain:

\[ \sigma_{21,2} = 0; \quad (\gamma + \varepsilon)\omega_{3,22} + 2\alpha u_{1,2} - 4\alpha \omega_3 = 0. \]  

(30)

The boundary conditions for them are the following:

\[ \sigma_{21}(h) = \tau; \quad \mu_{23}(h) = 0; \quad u_1(0) = 0; \quad \omega_3(0) = \omega_0. \]  

(31)

The first equation of system (30), taking into account the first of the boundary conditions (31), gives reason to believe that, as in the case of using the classical model of a linear elastic medium, within the framework of the considered model, the shear stress that shears the coating is uniformly distributed over its thickness \( h \) and is equal to the acting shear stress on the surface.

\[ \sigma_{21} = \tau. \]  

(32)

This result, as well as relations (22) and (23) connecting internal stresses and strains, and the last of relations (24), allow us to conclude that the distributions of displacements \( u_1(x_2) \) and rotations \( \omega_3(x_2) \), as well as their derivatives over the coating thickness, are nonzero. Based on (26) and (27), taking into account (28), this conclusion leads to the assertion that the elastic deformation energy \( W \), concentrated under the unit surface area of the coating, can be written in the form:

\[ W = \frac{h \tau^2}{2 \mu} + \frac{\alpha}{2} \int_0^h \left[ \frac{1}{2} u_{1,2}(x_2) + \omega_3(x_2) \right]^2 dx_2 + \frac{\gamma + \varepsilon}{2} \int_0^h (\omega_{3,2}(x_2))^2 dx_2. \]  

(33)

Comparing it with the left-hand side of equality (3), one can see that

\[ \Delta = \frac{\alpha}{2} \int_0^h \left[ \frac{1}{2} u_{1,2}(x_2) + \omega_3(x_2) \right]^2 dx_2 + \frac{\gamma + \varepsilon}{2} \int_0^h (\omega_{3,2}(x_2))^2 dx_2. \]  

(34)

It can be seen that the classical estimate of the adhesion energy is lower than that which can be done by equating (33) to the value \( F_a \). Obviously, for sufficiently large values of \( \gamma + \varepsilon \), classical estimates cannot be used \( \tau_{\max} \).

In the work, the following estimates \( E \sim 10^9 \text{B/m} \) are made for the tension values:

\[ \alpha \approx 10^8 \text{N/m}^2; \quad \gamma + \varepsilon \approx 10^6 \text{Dg/m}. \]  

For a coating with a thickness \( h \approx 10^{-3} \text{m}, u_1 \approx 10^{-6} \text{m}, \) \( \omega \approx 10^{-3} \text{rad} \) the value of \( \Delta \) may turn out to be commensurate with a value of the order of. (When estimating the value of \( F_a \), it was taken into account that the integrand has the order of its mean value \( 1 \text{Dj/m}^2 \), equal to the half-sum of its extreme values \( \Delta \), and the derivative is the ratio of the mean value to the coating thickness). Therefore, a calculation based on classical concepts can lead to \( \tau_{\max} \) significant errors. This confirms the need to take into account the views stated above when calculating cutting conditions for tools with coatings.
3. Findings
Epilated tool coatings can have a significant effect on the interaction of bodies. It changes the nature of the adhesive effect, and when applying coolant technological media (COTS) can exclude adhesive interaction.

Modern epilams are highly effective means of regulating wetting, and if in the friction unit part of the contacting surfaces is epilated, and part is unepilated, then the oil will tend to collect in the unepilated area. In the contact zone of the rubbing bodies, the epilam is erased and the oil tends to collect on this surface area. In the adjacent areas, epilam is preserved and serves as a barrier preventing oil spreading.

The specific free energy (or the numerical equal to it surface tension of solids) is not amenable to direct measurement, however, on the basis of theoretical studies, confirmed by indirect measurements, for bodies of high hardness, it was determined that $\sigma >> 500$ erg / cm The higher the hardness and melting point, the greater the free energy of a solid: its value can reach $5000$ erg / cm. Mals and their oxides - steel, ruby, etc. belong to high-energy bodies.

The surface tension of oils is in the range of $20 - 40$ erg / cm The spreading mechanism of some lubricating fluids is complex: first, a thin boundary layer spreads, which, orienting itself under the action of the force field of a solid, creates a low energy surface. The rest of the mass does not spread on this surface. However, oils with low surface energy have now been created, which do not have the ability to form boundary layers. Therefore, to prevent spreading of such oils, it is necessary to lower the surface energy of hard surfaces. This is achieved by the fact that layers of oriented molecules are created on the surface of solids, radically changing the energy properties of the surface. In this case, the wetting conditions change sharply and the wetting angle of a liquid drop on such a surface increases.

When operating the tool with the use of cutting fluids, a multilayer coating is formed, which is an epilam nanofilm that holds the cutting fluid film.

The main effect of applying a thin film of epilam to the working surface of the tool is to keep the oil in the contact zone, reduce the coefficient of friction, and maintain performance for a long time. An additional advantage of working with an epilamated tool is an adsorptive decrease in the strength of the material being processed, an increase in the plasticizing effect of cutting fluids, and a decrease in deformation forces due to the manifestation of the Rebinder effect.

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