Theoretical determination of effective drilling modes with epilamited tool

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Abstract. The article is devoted to one of the promising methods of increasing the penetrating ability of COTS into the zone of contact interaction between a tool and a workpiece and accordingly increasing operational characteristics of tool life by applying to the working surface fluorine-containing surface-active (FLUOR-SAS) from epilame solutions. Tribological tests were carried out using a special installation, where the test conditions are close to the conditions characteristic of the drilling process. Based on the results of the experiment, it was found that the effectiveness of epilamiting directly depends on the cutting speed, which determines the temperature in the contact zone.

1. Introduction
In modern engineering, high requirements are imposed on the machining of holes, since the accuracy of their size, shape, surface quality directly affects the nature of the mating parts. The quality of the machining of holes is greatly influenced by the condition of the cutting tool, the degree of wear, therefore, it is very important for modern engineering to increase the resistance of the axial tool and the technological procuring its rational use.

To increase the efficiency of machining with high-speed steel drills, methods are applied that are related to improving the properties of the tool material, changing the composition and properties of the surface layer of the tool, applying thin film coatings, reducing the roughness of working surfaces and improving the operating conditions of the tool using COTS.

An analysis of the literature data shows that one of the most promising methods for increasing the tool life (6 ... 8 times) is the deposition of fluorine-containing surface-active substances (fluorinesurfactant) from epilame solutions on its working surface – epilamination.

Despite the high test results of epilamited drills, during production testing of the method, there is often a slight increase in tool life or lack of introduction effect. This is due to insufficient knowledge of the mechanism of action of coatings in the machining process, the lack of recommendations on the operation and maintenance of tools with epilam coating [3].

2. Theory
When testing drills made of high-speed coated steel, it is noted that the effectiveness of the method is mainly determined by the machining parameters that determine the temperature in the contact zone of the tool - part and the durability of epilame films on the working surfaces of the tool [1]. Also, in theoretical and experimental studies of determining the optimal operating conditions of epilamited parts of friction units, it was found that the optimal operating parameters of epilame coatings are in a...
rather limited range of temperature values. The optimal area of operation of the tribosystem is limited on the one hand by the temperature of the heat resistance of the coating, and on the other hand, by the temperature that provides the required level of surface mass transfer of epilame molecules for dynamic restoration of the coating. The temperature criteria for the optimal functioning of the coating were determined [1], [2]:

- a criterion for the process of mass transfer of epilame molecules to the surface of the counterbody and areas free from adsorbed molecules

\[ T \geq \frac{Q}{R} \left[ \ln \left( \frac{\sqrt{N \cdot v_c \cdot l}}{4D_0} \right) \right]^{1/4}, \]  

where \( T \) - temperature of the friction surface; \( Q \) - activation energy of surface diffusion; \( R \) - universal gas constant; \( l \) - size of the surface area free from coating; \( N \) - average density of contact spots; \( D_0 \) - preexponential factor; \( v_c \) - sliding speed;

criterion for effective operation of the coating

\[ T \leq T_T, \]  

where \( T_T \) - temperature of thermal destruction; \( T \) - temperature of the friction surface.

With an increase in the sliding velocity, the interval of optimal temperatures decreases, and for \( v_c > v_{c,O} \) (\( v_c \) - sliding velocity, \( v_{c,O} \) - optimal sliding velocity), the coating is effective only at the initial stages of contact interaction. Experimental data indicate that with an increase in sliding speed, the coefficient of friction increases.

When considering these criteria regarding applicability to the cutting process, it should be noted that metal cutting by its physical nature is a complex process. When removing a metal layer on the contact surfaces of the tool with the processed material, high pressures arise (up to 2000 MPa and more), high deformation rates occur, temperature increases, favorable conditions for the development of adhesion, mutual diffusion, oxidation, hydrogenation of surfaces, change in their structural-phase composition, the generation of electromotive force (EMF) [4], [5]. At the same time, one of the main sources of heat and deformation factors of the surface layers of the cutting wedge during cutting is friction. When the metal layer is removed, external friction occurs between the constantly re-emerging “renewed” surfaces and proceeds on relatively small contact surfaces at high temperatures and high pressures.

Based on the foregoing, it can be assumed that the wear rate of the films on the friction surfaces of machine parts will be significantly lower than the rate of wear of the films on the contact surfaces of the cutting wedge of the tool.

When a metal layer is removed without the use of COTS, the presence of abrasive wear and the occurrence of adhesive bonds in areas free of coating, as well as the flux transfer of fluorine-surfactant molecules under certain thermodynamic loads on the machined surfaces mated to the cutting wedge (Fig. 1), will contribute to the gradual destruction and removal of the film epilame from the contact surfaces of the instrument. Moreover, it is likely that when the cutting part leaves the cutting zone due to the high surface mobility of the epilame molecules, adsorption “overgrowing” of free areas and partial or complete restoration of the coating will occur.

However, the main factor affecting the state of the coating during machining is likely to be the temperature factor, since the cutting process, as a rule, is accompanied by intense heat in the cutting zone and significant heating of the tool. Heating the epilamited tool above the temperature of thermal destruction of the coating will lead to the destruction of this coating and, accordingly, to inefficient use of the tool. The second criterion for the optimal operation of epilame films during machining will be:

\[ Q_{av} \leq T_T, \]  

where \( T_T \) - temperature of thermal destruction; \( Q_{av} \) – average cutting temperature.
Figure 1. Scheme of tribo-transfer of fluorine-surfactant molecules from the working surfaces of the tool to the surface of the part and chips.

Since the performance of epilame coatings directly depends on the temperature in the chip formation zone, the main task in designing machining operations using an epilamited tool is to determine the optimal cutting temperature and technological factors ensuring the fulfillment of condition (3).

Thermal phenomena were studied on the basis of a comprehensive theoretical tool (CTI), and the admissibility of using the theory of fast-moving sources to model the action of the teeth of an instrument was based on the Pecle Re criterion.

As a result of research, calculation and analysis of temperature fields and taking into account the heating of the cutting zone with the front teeth, the influence of the transverse edge on the chip formation process (it was found that up to 94% of the transverse edge length is involved in the cutting process) A.V. Baranov obtained a simplified expression for determining the cutting temperature during drilling

\[
Q_{cp} = 2.56 \pi r P e^{0.45} E^{0.09} \Pi^{0.035} F^{0.25} (1 + \delta_t / \rho_1)^{0.06} \text{erf} (0.64 Pe^{0.02} B)^{0.5} * \\
* \exp \left[ \frac{0.25 + (Pe B)^{0.5} (1 - \cos \varphi + \alpha_1 / \tau)}{c p B^{0.4} F^{0.14} D^{0.05} (1 - \sin \gamma)^{0.23} \sin^{0.03} \alpha} \right],
\]

(4)

where \( Pe = v \alpha / \rho \); \( E = p_f / p \); \( \Pi = 2 \alpha_1 / (\pi \alpha) \); \( T = d_0 / \rho \); \( D = a_1 / b_1 \); \( F = \lambda_0 \beta / \lambda \); \( B = a_0 / \alpha \); - dimensionless complexes - similarity criteria; allowing to take into account when calculating the cutting temperature a whole complex of both operational parameters and the mechanical and thermophysical characteristics of the processed and tool materials, as well as the specific features of the drills and the condition of their cutting edges; \( B \) - tangent of the angle of inclination of the conditional shear plane, determined analytically; \( \tau_p \) — resistance of the processed material to plastic shear, Pa; \( c p \) - specific volumetric heat capacity of the processed material, J / m^3 * K; \( F \) - thermal diffusivity of the processed material, m^2 / s; \( \lambda \) - coefficient of thermal conductivity of the processed material, W / m * K; \( \lambda_0 \) - coefficient of thermal conductivity of the tool material, W / m * K; \( \alpha_0 \) - heat transfer coefficient, W / m^2 °C; \( P_f \) - radius of the rounding of the cutting blade, m; \( z \) - number of teeth; \( d \) - drill diameter, m; \( d_0 \) - diameter of the core of the tool, m; \( a_1 \) - thickness of the cut, m; \( b_1 \) - width of the cut, m; \( \beta, \varepsilon \) - respectively, the peripheral angle of sharpening and the angle at the top of the tooth in the plan, glad; \( \gamma \) - average integral value of the front angle of the tooth of the tool, rad; \( \alpha \) - average integral value of the rear angle, rad; \( \delta_t \) - tool tooth wear on the rear surface.

The results of experimental studies performed by the author using the method of natural thermocouple and the method of cut thermocouple confirmed the high accuracy of theoretical equations for determining the cutting temperature and temperature fields on the back surface of the teeth of the tool (the deviation of the calculated values from experimental did not exceed 10%).
In the course of research, it was found that there is an optimum cutting temperature $Q_{о}^{*}$, which ensures the minimum relative wear of the tool $h_{опт}$, and its maximum dimensional resistance $T_{опт}$. Given the presence of an optimal cutting temperature, a single analytical expression was obtained for the optimal cutting speed 

$$v_{о} = \frac{a}{a_{1}} k_{1} k_{2} k_{COTC} k_{H.M},$$

where $a$ - thermal diffusivity of the processed material, m$^2$/s; $a_{1}$ - thickness of the slice, m; $k_{1}, k_{2}, k_{3}$ - coefficients analytically determined for various types of processing, taking into account, respectively: mechanical and thermophysical properties of the processed and tool materials; tool geometrical parameters; tool wear over the period of its durability and the depth of the machined hole; $k_{COTC}$ and $k_{H.M.}$ - coefficients that take into account the influence of, respectively, SOTS and wear-resistant tool coating.

Ya. V. Moscovskim based on the work of A.V. Baranov and independent theoretical and experimental studies of cutting mechanics during drilling, temperature fields, heat energy balance also derived theoretical equations for determining the average cutting temperature $Q_{ср}$, optimal tool wear resistance $v_{о}$ (cutting without cooling) and the drill radial resistance when machining with optimal cutting speed 

$$Q_{ср} = 3.25 \frac{\tau_{о}}{cp} \exp \left[ 0.12 \left( \frac{\alpha_{о}}{\tau_{о}} \right)^{7} \left( 1 - \sin \gamma \right)^{0.2} \left( 0.5 Pe \right)^{0.09} E^{-0.09} H^{0.04} T^{0.24} \left( 1 + \frac{\delta}{\rho} \right)^{-0.06} \right],$$

$$v_{о} = 0.985 \left( \frac{\lambda}{\delta_{о}} \right)^{1.17} \left( \frac{cpT_{о}}{\tau_{о}} \right)^{1.82} \left( \frac{b_{о}}{h_{о}} \right)^{0.15} \left( \frac{b_{о}}{h_{о}} \right)^{0.04} \left( \frac{b_{о}}{h_{о}} \right)^{0.06} \left( \frac{\beta_{о}}{\tau_{о}} \right) \left( \frac{\delta}{\rho} \right)^{0.17} \left( \frac{\sin^{0.12} \alpha}{\tau_{о}} \right),$$

at $3l \leq d \leq 12l$

$$T_{р} = \frac{h_{р}}{v h_{о} \left( v / v_{о} \right)^{0.794}},$$

where $n_{1}=0.53+0.035 F^{0.12} ; n_{2}=0.95 F^{-1.42} \cdot$ dimensionless complexes; $\gamma$ - value of the rake angle on the periphery of the drill; $\alpha_{о}$ - yield strength of the processed material; $Q_{о}$ - optimum cutting temperature, °C; $b_{о}$ - cut width for the transverse edge, m; $b$ - the perimeter of the working sections of the tooth drill, m; $D_{о}$ - diameter at which the ends of the transverse edge lie, m; $L$ - hole drilling depth, m; $h_{р}$ - accepted permissible radial wear of the tool, mm; $v$ - cutting speed during drilling; $k$ - indicator taking the following values $k=2.19 \left( Q_{о} / Q_{о}^{*} \right)^{0.23} B^{1.2}$ for $v>v_{о}$; $Q_{о}=700^\circ$C - constant for high-speed steel tools (Fig. 2).

In accordance with a single analytical expression for the optimal cutting speed, equation (7) contains analytically determined coefficients that take into account the influence of the mechanical and thermophysical properties of the processed and tool materials $k_{1}=\left( \frac{\lambda}{\tau_{о}} \right)^{0.17} \left( \frac{cpQ_{о}}{\tau_{о}} \right)^{1.82}$, the geometric parameters of the cutting part of the tool and the cut section $k_{2}=(b_{о} / h_{о})^{0.12} \left( a_{о} / h_{о} \right)^{0.44} (b / h)^{0.06} (\beta_{о})^{0.17} \sin^{0.12} \alpha$, allowable wear of the teeth during the life and depth $L$ 

$$(D / D_{о})^{0.22} \left( p_{о} / a_{о} \right)^{0.27} \left( a_{о} / \pi D \right)^{0.08} \left( 1 - \sin \gamma \right)^{0.76},$$
of the hole to be machined for $3d < L \leq 12d$ (the effect of secondary heat transfer is taken into account)

$$k_3 = \frac{0.65 (1 + D / L)^{3.1}}{(1 + \delta_{p} / p_{0})^{0.13}}$$ [6].

When calculating the cutting speed during processing with epilated drills, the $Q_o$ value will be determined not only by the wear resistance of the tool, but how much by the operational properties of the epilame coating to ensure its operability during cutting. When replacing the cutting temperature $Q_o$ with the thermal destruction temperature of $T_T$ coatings of various epilame grades in expression (7), it is possible to set the maximum allowable cutting speed $v_{\text{max,cool}}$, coating when drilling with these coatings without using COTS

$$v_{\text{max,cool}} = 0.985 \frac{a}{a_1} \left( \frac{\lambda}{\lambda_T} \right)^{0.17} \left( \frac{cpT_T}{\tau_T} \right)^{1.92} \left( \frac{b_{on} / b_1}{b / b_1} \right)^{0.12} (a / b_1)^{0.44} (b / b_1)^{0.06} (\beta_{c})^{0.17} \sin^{0.12} \alpha \times \left( \frac{1 + D / L}{1 + \delta_{p} / p_{0}} \right)^{5.1} (p / a_1)^{0.27} (a, z / \pi D)^{0.06} (1 - \sin \gamma)^{0.26}$$ (9)

at $3d < L \leq 12d$

In turn, the presence of epilame coating on the working surfaces of the tool, which reduces the friction work by improving the formation of the lubricant layer when using SOTS and acting as a lubricating boundary film without the use of SOTS, should help reduce the temperature in the cutting zone and should be taken into account when calculating the cutting speed of the epilamited tool and its dimensional stability. The ability of cutting fluids to reduce the overall thermal stress of the cutting process and to remove heat from heated sections of the processed material and the cutting tool should also be taken into account when determining $v_{\text{max,cool}}$. The effect of COTS on the value of $v_{\text{max,cool}}$, coating will be determined by the state of the thin-film coating, the properties of the processed material and the lubricating-cooling technological environment, and the methods of its supply.

Figure 2. Drill elements and cutting elements that are taken into account when determining the cutting temperature $Q_{cp}$ and optimal cutting speed $v_o$ for tool wear
The combined effect of the epilame coating and COTS when calculating the cutting speed should be taken into account in the form of the correction coefficient $k_{ИПСОТС}$ and expression (8) will have the form

$$ v_{max, покр} = 0.985 k_{ИПСОТС} \frac{a}{a_1} \left( \frac{\lambda}{\lambda_1} \right)^{0.17} \left( \frac{c p T_f}{\tau_p} \right)^{0.92} \left[ \frac{(b_s / b_1)^{0.12} (b / b_1)^{0.06} (b_c / b_1)^{0.17}}{(D_0 / D_1)^{0.25} (p_1 / a_1)^{0.25} (z / zD_1)^{0.08} (1 - \sin \gamma)^{0.75} } \right] ; \quad (10) $$

To calculate the cutting speed with epilamition drills, it is necessary to know the $k_{ИПСОТС}$ values. The value of the $k_{ИПСОТС}$ coefficient $k$ can be determined on the basis of the measurement results of such quantities as cutting forces $P_o$, $H$, torque $M_k$, $M_H$, thermoEMF $E$, $B$, reflecting physical phenomena during drilling. Since, when processing with an epilated tool, the main factor affecting the performance of epilame coatings is the temperature factor and when drilling with a cutting speed $v_{max}$, the coating must satisfy the condition $Q_{II} \leq T_T$, the most complete picture of the influence of technological factors and drilling conditions on the coating condition will show the results of experimental studies of cutting temperature. In this case, the value of the coefficient of the joint influence of the epilam coating and SOTS $k_{ИПСОТС}$ on thermal processes during drilling can be determined as

$$ k_{ИПСОТС} = \frac{Q_{II}}{Q_{II}} , \quad (11) $$

where $Q$ - average value of the cutting temperature obtained during processing with an uncoated tool and without SOTS at a cutting speed of $v_{max, покр}$; $Q_{II} = $ cutting temperature when machining with an epilam-coated tool using COTS and at a cutting speed $v_{max, покр}$.

Determining the cutting speed taking into account the temperature of thermal destruction of the epilam coating allows you to set the radial (dimensional) resistance of the epilamited drill

$$ T_p = \frac{h_p}{v h_{max, покр} \left( \frac{v}{v_{max, покр}} \right)^{0.794}} = \frac{h_p}{v h_{max, покр} k^{0.794} Q_{II}} T_T^{1.524} \quad (12) $$

where $v$ - arbitrary cutting speed, m / s; $Q_{II}$ - cutting temperature at an arbitrary cutting speed, °C; $h_p$ - accepted permissible radial wear of the tool, mm; $h_{max, покр}$ - relative linear wear at a cutting speed $v_{max, покр}$, mm; $k$ - indicator taking the following values $k = 2.19 (Q / T_T)^{0.25} B^{1.7}$ for $v > v_0$; $Q_{II} = 700°C$ - constant for high-speed steel tools.

In Figures 3, 4, 5 show the dependences of the thermoelectromotive force (thermoEMF) on the cutting speed $v$, m / s, the depth of the hole to be machined when drilling steel 45 with Ø 6.7 mm twist drills from R6M5 high-speed steel with coatings from 6SFK-180-05 and Efren -2. The processing was performed at a feed of $s = 0.14$ mm / rev, cutting speed $v = 0.09$ m / s with a hole depth of $L = 50$ mm and $v = 0.125$ and $v = 0.175$ m / s at $L = 10$ mm without and with the use of oil-based SOTS: MP-7 and MP-7 with the addition of surfactants based on chlorine paraffin. The cutting speed $v$, m / s was determined analytically (expression 9) for these cutting conditions.
Figure 3. Change in thermoEMF according to the time of processing the hole \( t \) with a tool without SOTS (\( v = 0.09 \text{ m} / \text{s}, l = 50 \text{ mm} \)): 1 - without coating; 2-6SFK-180-05; 3 - Efren-2

Figure 4. Change in thermoEMF according to the time of hole machining with a tool with 6SFK-180-05 coating under various cutting conditions (\( v = 0.125 \text{ m} / \text{s}, l = 10 \text{ m} \)): 1 - without coverage and COTS; 2 - MP-7; 3 - MP-7 + surfactant; 4 - 6SFK-180-05; 5 - 6SFK-180-05 + MP-7; 6 - 6SFK-180-05 + MR-7 + surfactant

Figure 5. Change in thermoEMF by the time of hole machining with an Efren-2 coated tool under various cutting conditions (\( v = 0.125 \text{ m} / \text{s}, l = 10 \text{ m} \)): 1– without coverage and COTS; 2 – MP-7; 3 - MP-7 + surfactant; 4 - Efren-2; 5 - Efren-2 + MP-7; 6 - Efren-2 + MP-7 + surfactant
Figure 6. Change in thermoEMF with respect to the time of processing a hole \( t \) with an uncoated tool and with a coating 6СФК-180-05 using various SOTS \( (v = 0.09 \text{ m / s}, l = 50\text{m}) \):
1 - MP-7; 2 - MP-7 + surfactant; 3 - 6SFK-180-05; 4 - 6SFK-180-05 + MR-7 + surfactant

Figure 7. Change in thermoEMF with respect to the time of hole machining with an uncoated tool and with Efren-2 coating using various SOTS \( (v = 0.09 \text{ m / s}, l = 50\text{m}) \):
1 - MP-7; 2 - MP-7 + surfactant; 3 - Efren-2 + MP-7; 4 - Efren-2 + MP-7 + surfactant

Figure 8. Effect of cutting speed \( v \), m / s on thermoEMF under various drilling conditions with an epilamited tool: 1 – without coating and COTS; 2 - MP-7; 3 - MP-7 + surfactant; 4 - Efren-2; 5-6SFK-180-05; 6 - Efren-2 + MP-7; 7-6SFK-180-05 + MP-7; 8 - Efren-2 + MP-7 + surfactant; 9 - 6SFK-180-05 + MR-7 + surfactant
3. Findings

Analysis of the measurement results showed:

When machining with an epilame-coated tool without using SOTS, the observed decrease in thermoEMF at a low cutting speed \( v = 0.125 \text{ m/s} \), \( L = 10 \text{ mm} \) (dependence 4 of Fig. 4, 5) and \( v = 0.09 \text{ m/s} \), \( L = 50 \text{ mm} \) (Fig. 3), indicates that at low temperatures in the contact zone of the tool-part, the thin film coating acts as a lubricating composition, i.e. helps to reduce the temperature in the zone of chip formation by reducing the work of friction forces and plastic deformation, protects the contact surfaces of the tool and the workpiece from adhesive interaction.

Minimum values of thermoEMF and their insignificant fluctuations during drilling with the use of oil-based SOTS: MP-7 and MP-7 with the addition of surfactants - chlorine-paraffin (dependences 5, 6 Fig. 4, 5, dependencies 3, 4 Fig. 6, 7) at a cutting speed of \( v = 0.125 \text{ m/s} \), the assumption is confirmed that the coating promotes the penetration and retention of lubricant in the contact zone of the tool and workpiece surfaces. This helps to reduce thermal stress in the cutting zone.

An increase in the cutting speed over the maximum thermal destruction temperature of the epilame coating (dependences 2, 3 of Fig. 8) negatively affects their state due to changes in the adsorption layer, leading to a deterioration in the performance of the coatings. These results indicate the need for selection of cutting conditions taking into account the properties of coatings.

At a cutting speed of \( v = 0.175 \text{ m/s} \), a slight decrease in thermoEMF when using MP-7 oil with surfactants based on chlorine-paraffin is most likely due to the ability of chlorine additives to form chlorides (FeCl2) at temperatures above 150 °C, which act as solid lubricating films. These films withstand high pressures and temperatures, reduce the coefficient of friction and, accordingly, the temperature in the contact zone, which positively affects the state of the epilam coating. These results also confirm that the effectiveness of using an epilame-coated tool directly depends on the properties of the lubricating-cooling process media.

Thus, it was found that in order to ensure the operability of epilame coatings during machining, the temperature in the cutting zone should be lower than the temperature of thermal destruction of coatings, i.e. the condition \( Q_{cp} \leq T_T \) must be satisfied. This condition allows at the design stage of the technological process to determine the maximum allowable cutting speed when drilling with an epilamited tool \( v_{max,tool} \) and its radial (dimensional) resistance \( T_p \). The ability of epilame coatings to reduce thermal stress during machining using lubricating-cooling technological media when calculating the allowable speed must be taken into account in the form of a correction factor \( k_{HFICOTC} \), determined on the basis of the results of measuring the cutting temperature during drilling.

References

[1] A. p. 1543177 USSR, MKI F16N15 / 00 Method for preparing the friction surface.
[2] Garbar I.I., Kisel A.S., Ryabinin N.A., Sapgir E.N. The nature and mechanisms of action of epilams during friction. I. The effect of epilation on the structure and surface energy of a metal. Friction and wear 1990. Volume 11. No. 5. C. 792-800.
[3] Garbar I.I., Kisel A.S., Ryabinin N.A., Sapgir E.N. The nature and mechanisms of action of epilams during friction. 11. Tribological characteristics of epilaminated materials. Friction and wear 1990. Volume 11. No. 6. S.987-995
[4] Kharchenko M.I. Increase in the after-repair life of automotive engine parts (for example, 3M3 - 53) by epilation and FABO - epilation. Abstract of the thesis Ph.D. M. 2002 S. 180.
[5] Kirichek A.V., Zvyagina E.A. Epilams and their use in machining with an axial tool, Bulletin of the Orel State Technical University. Series Engineering. Instrument making, 2006. No. 3. S.26-30.
[6] A. V. Kirichek, E. A. Zvyagina, Epilation - nanotechnology to increase the efficiency of mechanical processing, Reference. Engineering Journal, 2007, No. 2, p.15-18.