The influence of micro- and nanodots lubricating and cooling technological means (LCTM) on the process of blade cutting of materials

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Abstract. Improving the efficiency of cutting tools and the quality of the processed surfaces in the course of metal blade processing is largely determined by the intensity of adhesive interactions between the tribo-conjugated surfaces of the tool and processed materials. This is due to the high chemical activity of the juvenile surfaces formed in the process of chip separation in tribo-conjugated contact. As it is illustrated by theory and practice, one of the main mechanisms effecting on the amount of adhesion is the formation of separation lubricant films at the interface between the tool and the processed material by introducing external technological means into the contact zone (lubricating and cooling technological means – LCTM).

1. Introduction

According to the theory of radical chain mechanism, juvenile surfaces formed during friction and cutting of metals not only show great activity to physical adsorption and chemical reactions, but also emit a stream of energy particles (electrons, radiation quanta), the intensity of which is at its maximum at the moment of opening the layers. These particles have a significant impact on the flow of chemical processes occurring on the contact surfaces of the cutting tool and the processed material. As a result of their interaction with the molecules of the external environment, the latter are activated and decay with the formation of reaction particles – active atoms, radicals and radical groups, whose activity is due to the presence of an electron with uncompensated spin on the valence shell. Having a high chemical activity, these particles interact with juvenile surfaces, resulting in intensive formation of compositions (secondary structures), the main function of which is to separate clean metal surfaces, i.e. to reduce adhesion interactions.

The formation of chemical radicals can occur both naturally and forcibly. The general patterns of the processes of forced radical formation do not differ from the natural ones. As a result of external effects on LCTM, its components receive additional energy, which transfers them into a metastable (intermediate) state, which is characterized by a weakening or partial violation of intramolecular bonds of LCTM elements. One of the most important conclusions of this theory is that the lubricant oil films are formed only in the contact zone, where there are necessary conditions for its implementation.
Therefore, only a small amount of the external environment is sufficient to initiate the lubricating effect.

This condition has been repeatedly confirmed both directly by the authors of this work, as well as by other domestic and foreign researchers and manufacturers. The conducted research on the effect on the cutting process of sprayed lubricants and coolants has found that, to ensure the lubricating effect, it is sufficient to supply 0.5–3.0 g/hour of sprayed oil or 50–150 g/hour of sprayed water-based lubricants and coolants (1 g of sprayed liquid has the same surface as 27 kg of unsprayed). When studying the effect of water on the steel cutting process, it was found that a drop of water has the same effect on the cutting process as a stream with a flow rate of several liters.

In this work, the quality of tool materials is understood as the compliance of the controlled parameters of the physical and mechanical characteristics of tool materials with those values that determine the performance properties of a metal-cutting tool or, comparing them with each other, we can give preference to those that have advantages in performance characteristics [1]. The paper also uses approach and software environments that allow, in comparison with other specified approaches and software environments, to more accurately model the stress state of the tool material and, thereby, increase the accuracy of designing tool parameters for specific operating conditions [2].

2. Results and discussion

Our research [3], aimed at studying the lubricity of nanoscale iodine-containing structures pre-formed in the surface of tools, revealed a significant improvement in the characteristics of the cutting process and increasing the performance of high-speed tools in various machining operations (figure 1).

![Figure 1. Dynamics of changes in the total teeth wearing of P9 steel cutters from the length of the cutting path when milling grooves in U8 carbon steel without the use of LCTM: 1 – without additional hardening; 2 – hardened by chemical-heat treatment; 3 – hardened by chemical-heat treatment with additional introduction of iodine vapors in the amount of 0.05 %, V = 1.6 m/s, S = 315 mm/min.](image)

The second conclusion is based on the position that the volume of lubricating oil films formed as a result of radical chain reactions must be sufficient for the implementation of the lubricating action, i.e. it is directly dependent on the number of active atoms and radicals in the contact zone. Under otherwise identical conditions, the concentration of active particles is determined by the binding energy in the molecules of the external environment and the work of the electron output of LCTM components.
In figure 2 there are presented the results of studies on the use of LCTM microdoses as a technological tool, each of them had a shell made of an impervious material – in the form of microcapsules, the sizes of which varied from 1 to 45–50 microns [4]. To increase the efficiency of such LCTM microcapsules were given the ability to direct movement to the wedge of the tool. In the course of research, it was found that the optimal consumption of microcapsules was in the range of 5.5–8.5 g/hour. Thus, the reduction in the amount of LCTM supplied to the contact zone, compared to traditionally used tools, was more than 10,000 times, while an increase of 1.5–2.0 times was recorded in the durability of tools.

The presented correlations clearly show that there is a certain range of microcapsule concentrations, in which the durability of tools increases with an increase in the amount of LCTM. Overcoming a certain critical value of the concentration of microcapsules leads to stabilization of resistance indicators and with a further increase in their number, the stability of the cutting tool practically does not change.

As noted above, for the active formation of separation lubricant films, it is necessary that there is a sufficient number of active particles involved in this process in the contact zone. The problem of intensifying the formation of reaction particles in the contact zone was solved by pre-transmitting energy to individual elements of the process medium by affecting LCTM by various physical and chemical methods – physical and chemical activation of LCTM [5]. As a result, LCTM molecules pass into an excited state before the contact zone and, further natural energy impact on them from the contact zone, becomes quite sufficient for their destruction with the subsequent formation of chemically active atoms and radicals. LCTM activation methods are most relevant for substances with high values of binding energy between atoms in molecules.

Recently, much attention has been paid to the use of atmospheric air activated by corona discharge as LCTM [6]. The observed effect is due to facilitation units between the tool and the material being treated lubricating effect of the oxide structures, the initiator of education which is active oxygen and hydroxyl groups, the resulting impact on air corona discharge. However, the authors of the research do not take into account that the air composition is quite complex.
The main components of air can be divided into three groups: constant, variable and random. The first are oxygen (about 21%), nitrogen (about 78%) and inert gases (about 1%). The content of these components is almost independent of the place where the sample was taken. The second group includes carbon dioxide (0.02–0.04%) and water vapor (up to 3%). The content of random components (the third group) depends on local conditions. Often there are mixed products of industry and transport, products of life of biological objects (microorganisms, plants, animals, etc.).

Our research has determined that each of these air components in one way or another affects the characteristics of the blade cutting process. Thus, it was found that the presence of moisture in the air contributes to a significant increase in the resistance of cutting tools, and the maximum increase is observed at a low concentration of water vapor (figure 3). Pre-activation of humidified air by corona discharge leads to an even greater increase in the durability of tools.

**Figure 3.** High-speed tools resistance when cutting steel 45 with humidified air blow-off at the contact zone $V = 1.2 \text{ m/s, } t = 0.5 \text{ mm, } S = 0.1 \text{ mm/rev.}$

**Figure 4.** The size and microhardness changes of the plastic deformation zone when turning titanium $VT1-0$, $V = 0.5 \text{ m/s, } t = 0.5 \text{ mm, } S = 0.1 \text{ mm/rev:}$

- ● – without LCTM,
- × – blow-off with compressed air,
- × – blow-off with compressed air enriched with water vapor.
The presence and size of plastic deformation zones is one of the main parameters that characterize the intensity of adhesive interactions between the working surfaces of the tool and the processed material. Under certain conditions, this indicator can also be used to evaluate the effectiveness of separating lubricant films. Thus, the analysis of the experimental curves presented in figure 4 shows that the use of humidified air flow as LCTM reduces the depth of distortion of the matrix structure of the processed material. This can be interpreted as a decrease in the strength of adhesion. At the same time, the experiments recorded a decrease in the microhardness of the distorted standing, which indicates a quantitative decrease in the points of contact surfaces setting.

A similar improvement in the characteristics of the cutting zone and tool stability is observed in the case of introduction of organic matter into the air stream – industrial oil I-20A in concentrations of 0.1–1.0 g / hour. There was an increase in the resistance of the incisors, a decrease in chip thickening and roughness of the treated surface. Under other identical conditions of the experiments, it can be stated that the introduction of microdose of organic substances with a high lubricating capacity into the air improves the tribological state of the contact zone. For figure 5 presents a tribogram of the friction process according to the disk-disk scheme of 45 steel by 45 steel, hardened to a hardness of 57 units by HRC. As follows from the figure, the introduction of 0.5 g/hour of I-20A oil into the air flow effectively reduces the friction moment (zone “b”) compared to dry friction (zone “a”) to a value comparable to that of 100% I-20A oil. Pre-ionization of the air-oil flow (zone “c”) leads to a further reduction of the friction moment and at the same time improves the dynamics of the contact interaction processes by stabilizing it.

![Figure 5](image)

**Figure 5.** Tribogram of the friction moment of 45 steel on 45 steel hardened under loads: a) 2.6 MPa, b), c) 3.6 MPa, $V = 0.5$ m/s.

The study of the effect of the main components of air (oxygen and nitrogen), as well as their quantity, on the parameters of the cutting process during shaping was carried out on the author's installation, located under the vacuum cap of the vacuum post VUP-4 (figure 6). Rotation from the electric motor 1 through the reduction gear 2 is transmitted to the drive shaft 11, which is a screw with a nut. Upon rotation of the shaft results in translational movement of a nut fixed thereto a horizontal guide 8. On this guide, a plate with a vertical guide 5 is fixed, on which a cutter 7 is installed using clips 6, the vertical movement of which is regulated by a micrometer screw 4. The Test sample 10 is fixed motionless on the base plate 3 with clips 9.

In the course of research, the influence of air, as well as nitrogen and oxygen separately on the formation of separation films at different pressures (from normal to $10^{-5}$ mm Hg) was studied by the amount of cutting forces, chip roots, development and change of microhardness of plastic deformation zones.
The materials used were 45 steel, 12H18N10T austenitic stainless steel, and VT1-0 titanium alloy. The samples were 0.8 mm thick plates. Cutting was carried out with cutters made of high-speed steel R6M5 at a cutting speed of \( V = 2 \text{ mm/s} \) and a cutting depth of \( t = 0.05 \text{ mm} \).

Figure 6. Physicaal appearance (a) and installation diagram (b) for controlled atmosphere cutting.

In the course of research, it was found that changes in the type of gaseous LCTM and its amount have a noticeable effect on facing separation processes and cutting characteristics.

Figure 7 shows images of the facing roots obtained by the falling cutter method when turning the VT1-0 titanium alloy. It follows from the photos that a decrease in the pressure in the vacuum chamber, and, consequently, the amount of potential lubricant (in these cases, air), significantly leads to an increase in the facing thickening coefficient \( \xi \) and a decrease in the conditional shear angle \( \beta \).

Figure 7. Pictures of facing roots obtained during free turning in a vacuum chamber of VT1-0 alloy with a R6M5 steel cutter when using air as LCTM: a) at normal pressure; b) at a pressure of \( 10^{-5} \text{ mm Hg} \). \( V = 2 \text{ mm/s}, t = 0.1 \text{ mm} \times 300 \).

The theory of radical chain reactions describing the formation of separation lubricant films on tribo-conjugated surfaces when using air as LCTM is based on physical and chemical phenomena involving oxygen and its oligomers. More recent studies conducted by the authors of this work have found that in this case, when describing the physical and chemical processes in the contact zone, it is necessary to take into account the fact that the amount of nitrogen is more than 3 times higher than the concentration of oxygen [7]. When studying the behavior of nitrogen in the composition of air used as
an external technological medium, it was determined that the amount of energy released in the contact zone during the destruction of metal during cutting is quite sufficient to transfer the nitrogen molecule to an excited state and its subsequent decay. Therefore, the combined effect of air on the kinetics of contact interaction is a more complex process, in which not only oxygen, but also nitrogen takes part. These studies have shown that the use (separately) of both oxygen and nitrogen as LCTM has a noticeable effect on chip separation processes (figure 8).

Figure 8. The results of cutting forces studies (a) and facing thickening (b) during free turning in a vacuum chamber of steel 45 when using air (I), oxygen (II), nitrogen (III), helium (IV) as LCTM at a pressure of: 1 – normal, 2 – 10⁻¹ mm Hg, 3 – 10⁻² mm Hg, 4 – 10⁻³ mm Hg V = 2 mm/s, t = 0.1 mm.

A detailed analysis of the presented results showed that in the case under consideration, pure oxygen had worse cutting forces than nitrogen and air at normal pressure. In our opinion, this is due to the lack of oxide films formed, as a result of which the adhesive interactions between the working surfaces of the tool and the processed material remain high. This confirms the previously obtained data on the study of the lubricity of ozone-containing microcapsules. Research has found that to effectively improve the characteristics of the cutting process (conditional shear angle, relative shear value, chip shrinkage, friction coefficient) and the stability of cutting tools, additional introduction of an oxygen – ozone oligomer in the composition of ozone-containing microcapsules is necessary. At the same time, it is determined that the number of additional microcapsules introduced depends on the brand of the processed material. Thus, when turning 40X and 12H18N10T steels, the effective concentration of ozone-containing microcapsules in the LCTM (distilled water) used was 4%, for VT5-1 – 2%, VT6 – 1%.

When using nitrogen as LCTM (figure 8), the minimum values of cutting forces and chip thickening coefficient are marked. This can be explained by changing the matrix structure of the surface of the processed material as a result of the introduction of nitrogen atoms into it with the formation of new compounds. During chip separation, freshly uncovered metal surfaces emit electrons, the concentration of which is quite high in the absence of passivating oxide films. The energy of these electrons is sufficient to transfer nitrogen molecules to an excited state and convert some of them into atoms and radicals. An important role in this process is played by the chemical activity of the resulting juvenile metal surfaces. The result of such physical and chemical transformations is the formation of nitride compounds of the \( \text{Fe}_n\text{N}_m \) type (\( \xi \) – and \( \varepsilon \)-phases) with orthogonal and hexagonal lattices in the contact zone. This was established by electron microscopy using replicas extracted from the incised side of the facing. Experiments have not revealed the presence of a cubic \( \gamma' \) – phase (\( \text{Fe}_4\text{N} \)). Apparently, this is due to a rather narrow area of homogeneity of this phase in the \( \text{Fe}-\text{N} \) system, or its number is very small. At the same time, electronograms recorded new phases on the front surface of the incisor, the decoding of which showed
the presence of individual inclusions of nitride compounds of the \( \text{Fe}_n\text{N}_m \) type, most of which also have a hexagonal structural lattice.

For a pair of metals of the same name with a simple cubic lattice, the friction resistance increases and decreases when metals with different crystal lattice structures or metals with a hexagonal crystal friction. Therefore, the newly formed nitride phases should contribute to improving the tribological situation of the contact zone, which is recorded in the conducted studies. On the other hand, the formation of nitride phases will inevitably lead to an increase in surface hardness, and this, in turn, will change the chip separation process, shifting it towards cutting more brittle materials, which are characterized by a decrease in the amount of longitudinal chip shrinkage, its broadening and thickening, as shown in figure 8,\( b \).

The use of ionized air increases the effect of its components, both by contributing to the intensification of the formation of lubricant films between tribo-conjugated surfaces, and by modifying the phase composition of the metal surfaces of the contact zone.

In our opinion, the relatively low cutting forces (approximately at the air level) recorded in the case of using helium are due to the following. The small size of helium (1.37 Å), for example, compared to the nitrogen molecule (4.45 Å), allows it to penetrate the surface of the processed material quite freely. Distortions of the matrix lattice and the appearance of stress concentrators caused by the introduction of helium lead to changes in the physical and mechanical characteristics of the surface layer of the processed material and, first of all, its hardness. This facilitates the chip separation process similar to the use of nitrogen as LCTM.

3. Conclusion

Thus, the research has established that for effective impact on the tribological environment of the contact zone when cutting metals, the required amount of external technological tools can be significantly reduced. When using air as LCTM, including air activated by the action of electrical discharges, the cumulative effect is an integral indicator of the effectiveness of its components, which are included in both the first and second and third groups of elements and substances that make up the air. At the same time, the effectiveness of such LCTM when cutting various materials can be regulated by varying the number of these components.

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