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Evaluation of the Influence of Lubricating and Cooling Agents on the Course of Dissipative Processes and Cutting of Materials

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Abstract—The results of studies of the influence of lubricating and cooling agents on the friction and wear characteristics of hard alloys for tools in the conditions of cutting hard-to-process materials are presented. To assess the effectiveness of the use of lubricants in the cutting of metals, an integrated approach was applied in which the consideration of the chemical processes of thermal destruction of polymer-containing lubricating and cooling agents is closely linked to the processes of heat and mass transfer. To obtain additional information about the processes occurring on the contact pads of the tool, a set of energy-entropy statistical characteristics of random realizations of fluctuations in the parameters of the tribosystems is used, which makes it possible to assess the orderliness of the system at the macro level during the transition to the formation of a dissipative structure in the field of optimal processing modes in terms of wear resistance. A methodology for assessing the dissipative capabilities of a tribosystem has been developed. A correlation between the wear intensity of hard alloys and the energy-entropy criterion depending on the friction-cutting mode was established, a thermodynamic justification for changing this criterion from the cutting path was given, and the possibility of its application for selecting the optimal cutting modes the optimal composition of lubricating, and cooling agents and friction pair materials was shown.

Keywords: thermodynamic processes, energy dissipation, entropy, lubricating and cooling agents, dissipative structures, tool materials, cutting materials

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INTRODUCTION

The main directions for improving tool materials and increasing the efficiency of the cutting process are currently associated with the development of their new compositions, with changing the properties of thin surface layers of existing hard alloys and high-speed steels, the use of wear-resistant coatings and other types of hardening (electrospark alloying; ion implantation; laser hardening, etc.); using new compositions of lubricant cooling liquids (LCLs) and methods of their supply to the cutting zone, with further study of the patterns of the wear process of tool materials, primarily hard alloys, in order to control the wear process based on modern concepts of thermodynamics of irreversible processes [1–4].

Quite a lot of research is devoted to the application and scientific substantiation of the effectiveness of new compositions of LCLs. It has been established by the practice of metalworking that the durability of the cutting tool increases when using any LCL, both oil-based and water-based, which reduce the cutting temperature, but the effectiveness of their use is different. From the point of view of the physicochemical mechanism of the effect of LCLs on contact processes and wear of tool materials during cutting, the overwhelming majority are reduced to models [5–7] based on the lubricating-cooling, dispersing, and detergent properties of LCLs, as well as on the ability of its components to enter into chemical and physical interaction with the activated surfaces of the contacting bodies and form hydrodynamic, adsorption, and chemical lubricating films that can withstand significant loads and significantly reduce the wear rate of cutting tools. The need to solve these problems requires considerable attention to be paid to the expansion of existing ideas about the nature and regularities of the physical and chemical processes occurring in the "tool–workpiece" tribosystem, taking into account the influence of the "third body," the active environment. A feature of the study is the attraction to the analysis of the phenomena that occur during the cutting of metals, the fundamental representation of the thermodynamics of irreversible processes in open systems exchanging energy and entropy with the environment, as well as the complexity of the approach to the problem of contact interaction, which consists in the fact that consideration of the chemical processes of destruction of polymer-containing coolants is closely linked with the consideration of the process of heat and mass transfer. To obtain additional information about the processes occurring on the contact pads of the tool, a set of energy-entropic statistical characteristics of random realizations of tribosystem parameter fluctuations was used, which allows us to assess the ordering of the system at the microlevel during the transition to the formation of a dissipative structure in the region of optimal wear resistance modes.

Objective—To evaluate the effectiveness of the use of LCLs, predict the cutting properties of the tool, and search for optimal cutting conditions.

FORMULATION OF THE PROBLEM

The tool—workpiece friction pair during cutting is an open thermodynamic system that actively exchanges matter and energy with the environment. The energy-entropy state of the cutting system ultimately determines the kinetics of structure formation at the contact and the mechanisms of surface destruction, that is, the wear of rubbing materials. The action of the external environment on the friction zone changes the contact processes and wear of tool materials, is inevitably associated with the occurrence of instability (bifurcations), phase transitions on the contact surface, and is reflected in the system of fluctuations of various parameters of the friction process.

Of fundamental importance in determining the degree of order in a friction (cutting) system is the behavior of entropy, in particular configurational entropy, which reflects the accumulation of defects in the surface layer before its destruction and correlates with the wear of tool materials. However, the definition of configurational (structural entropy) causes significant difficulties. In open systems that receive "negative" entropy (negentropy) from the external environment, stationary nonequilibrium states with a high degree of order can arise. Such an evolution begins, as a rule, as a result of the localization of the zone of maximum temperature, stress, and their fluctuations in a thin surface layer of the contact. It is precisely such conditions, which are necessary for the possible occurrence of ordered processes in the contact zone, that occur during friction under cutting conditions.

EVALUATION OF PROCESSES OCCURRING ON THE CONTACT SURFACE AND IN THE CUTTING ZONE

The study of friction and wear processes suggests the need to consider the friction surface (the boundary of two rubbing bodies) as an important element of the tribosystem structure, which defines the energy of a material system as a measure of various forms of matter motion. Therefore, it can be argued that the contact surface connects energy and entropy. In this case, the well-known thermodynamic parameters "energy E—entropy ΔS" are parameters of the type of structure or order [8]. In the simplest case, we have the well-known relation of thermodynamics:

$$E = T\Delta S, \tag{1}$$

where T is the absolute temperature.

For assessment of processes occurring on the contact surface and in the cutting zone, two fluctuation quantities are accepted: the amplitude of the fluctuation of the signal of the variable component of the thermoEMF and the vibration velocity of the linear displacements of the cutter. These two physical quantities are considered as parameters of the tribosystem, characterizing its properties and reflecting its response to changes in the processes in the contact zone. An analysis of the studied fluctuation characteristics during cutting shows [9] that the main energy spectrum lies in the sound region, and the observed processes are generally random, so to assess the dissipative capabilities of the system, the concept of static entropy was used, which is calculated when studying fluctuation processes in the cutting zone. In this case, the entropy values in all states should be normalized to the same value of the average energy, that is, the S-theorem should be applied. However, after a period of running-in, under conditions of normal wear of the tool material, the studied fluctuations can be qualified as stationary random processes, and their probabilistic characteristics are invariant with respect to the choice of the origin of time. In this case, the mathematical expectation and one-dimensional probability density of this process will not depend on time.

With this approach, the entropy of fluctuation processes in the cutting zone was determined through the distribution function for nonequilibrium states according to the dependence:

$$\tilde{S}(\tau) = -\int \ln f(x,\tau) f(x,\tau) dx. \tag{2}$$

One-dimensional stationary distribution function $f(x)$ is calculated as the limit of the relative residence time of values in the interval at: $X_i \le X \le X_i + \Delta X$ at $\tau \to \infty$.

$$f(x_i)\Delta x = \lim_{\tau\to\infty} \frac{\Delta\tau_i}{\tau}, \tag{3}$$

where $\Delta\tau$ is the time integration step.

Function $f(x)$ is normalized per unit value of the average energy, that is, apply the S-theorem, and the entropy was calculated from the spectrograms of the vibration velocities of the linear displacements of the cutter and the thermoEMF variables according to discrete relation:

$$\tilde{S} = -\sum_{i=1}^{n} f(x_i) \ln f(x_i). \tag{4}$$

The intensity of fluctuations as a quantity proportional to the energy of fluctuation processes was calculated by formula:

$$\tilde{E} = \sum_{i=1}^{n} x_i^2 f(x_i), \quad (5)$$

where $f(x_i)$ is the distribution function of random variable x_i.

Considering that the processes of friction and chip formation during metal cutting are kinetic and proceed under conditions of active interaction with the environment, then fluctuations in vibration velocity and thermoEMF can be considered sources of negative entropy (negentropy) relative to the friction (contact) zone in which entropy accumulates, degradation of energy and wear of rubbing materials.

Thus, to evaluate the process of dissipation of friction energy and wear of tool materials, one can use the analysis of the statistical entropy of fluctuation processes (vibration velocity and alternating thermopower signal) and the intensity of these fluctuations as a measure of the energy of fluctuation processes. In this case, the value of entropy in all states should be normalized to the same value of the average energy, that is, the S-theorem proposed in [9, 10] should be applied.

METHODOLOGY AND RESULTS OF THE STUDY OF THE DISSIPATIVE CAPABILITIES OF THE CUTTING SYSTEM

With progressive development, that is, under certain conditions, material systems reach a limit characteristic of each set of external and internal conditions, which can be expressed by the maximum value of the corresponding type of negentropy.

The entropy coefficient of fluctuation energy utilization was used to evaluate the friction process (wear intensity of the tool material). This value can be reduced to the ratio of the achieved increase in negentropy to the expended energy, i.e., negentropy coefficient energy use in form

$$K_S = -\frac{\tilde{S}}{\tilde{E}}. \quad (6)$$

If the values of the negentropy coefficient reaches its maximum value, then the system with friction acquires maximum orderliness, is characterized by increased dissipation of energy from the friction (cutting) zone without its accumulation and destruction of the contact surfaces. The minus sign in expressions (4), (6) indicates that there is an outflow of entropy from the contact zone.

To determine the degree of influence of the cutting mode on the characteristics of the process of contact interaction and to assess the wear of tool materials, a study was made of the probabilistic characteristics of oscillatory (fluctuation) processes. During statistical processing of continuous random processes, the main object is a sample function of time, called the implementation $X(t)$. For implementation $x(t)$ of random processes, given on the time interval of temperatures (O,T), the main statistical characteristics are: the average value over the entire temperature range (O,T), dispersion, root mean square value, distribution estimate, energy of the oscillatory process, and its entropy.

When cutting various materials in the corresponding cutting modes, the amplitude-frequency dependence of the change in the signal of the variable component of the thermoEMF and the vibration velocity of the linear displacements of the cutter was visually analyzed. Dependence analysis showed that the amplitudes decay starting from 5 kHz and above. Taking into account that the maximum intensity of a thermal fluctuation source appears at frequencies of 5–12 kHz, realizations at the maximum informative frequency of 8 kHz were studied.

The results of experimental studies to determine the influence of the cutting mode on the main probabilistic characteristics of the change in vibration velocity and thermoEMF showed that the nature of changes in the average values of thermoEMF and vibration velocity are different. If with increasing cutting speed the average values of thermoEMF, dispersion and standard deviation increase, then similar vibration velocity parameters may change nonmonotonically or show a tendency to decrease. Therefore, it is difficult to predict the course of the process of contact interaction and wear of tool materials by statistical characteristics, since, in essence, these characteristics are not closely correlated with the wear rate.

In this regard, the calculation of the energy and entropy of fluctuations was carried out through the distribution function of random signals for non-equilibrium states according to expressions (4) and (5). The results of these calculations are presented in Figs. 1 and 2 for the pair "T14K8–12X18H10T" and analyzed from the energy-entropy standpoint.

As can be seen from Fig. 1, with increasing cutting speed, the negentropy of thermoEMF fluctuations monotonically increases, and the negentropy of vibration velocity (Fig. 2, curve *2*) has an extreme section in the range of 1.2–2.0 m/s. In both cases, the negentropy energy utilization factor or negentropy per unit of energy has a maximum value in the cutting speed range from 1 to 2 m/s. Comparison of these results with data on wear of tool materials shows that it is in this range of speeds that the minimum wear rate of the cutting tool is observed (Fig. 1, curve *3*). The results showed that in this speed range there is an increased dissipation of energy from the friction zone, that is, the optimal cutting speed corresponds to the maximum of criterion K_S.

Obviously, if the value of $\tilde{S}$ or parameter K_S reach the maximum value, then the friction system is char-

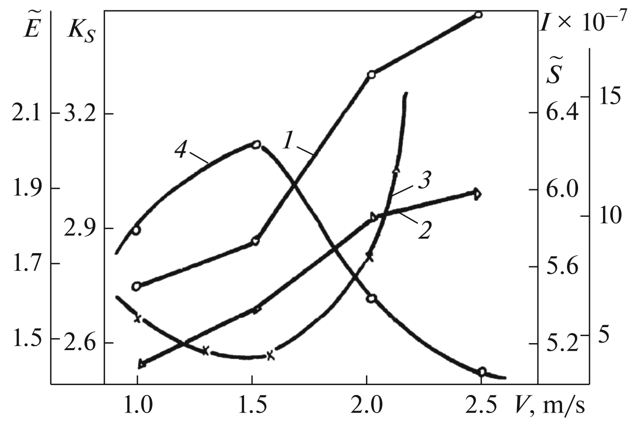

Fig. 1. Influence of the cutting speed on energy $\tilde{E}$ (*1*), entropy $\tilde{S}$ (*2*) of fluctuations of TEDF, the intensity of amortizations I (*3*) and on criterion K_S (*4*) for the pair of 12X18H10T—T14K8 (S = 0.39 mm/rev, t = 0.5 mm, f = 8 kHz).

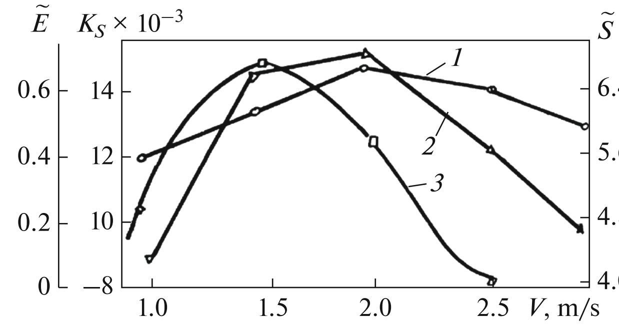

Fig. 2. Influence of the cutting speed on energy $\tilde{E}$ (*1*), entropy $\tilde{S}$ (*2*), criterion K_S (*3*) based on estimations of fluctuational vibrospeed during cutting of 12X18H10T steel by means of T14K8 alloy (S = 0.39 mm/rev, t = 0.5 mm, f = 8 kHz).

acterized by increased dissipative capabilities of the contact zone, due to which the accumulation of entropy and wear intensity decrease.

Comparative study of the effect of LCLs on the change in the spectrogram of the variable component of the thermoEMF signal and vibration velocity in the range of 5–16 kHz is presented in Tables 1 and 2.

An analysis of the experimental data (Tables 1, 2) made it possible to establish that the cooling of the cutting zone leads to a decrease in the average values and dispersions of random values of the thermoEMF signal and vibration velocity, to a decrease in the energy of oscillatory processes and to an increase in the negentropy coefficient compared to dry machining. Estimating the dissipative capabilities of the tribosystem by the negentropy coefficient, it can be argued that cooling by DVSL emulsion is an active process that contributes to an increase in the energy dissipa-

Table 1. Influence of Lubricant Cooling Liquid (LCL) on energoentropy characteristics of process realization of TEDF during cutting of steel 12X18H10T by means of the alloy T14K8 (S = 0.39 mm/rev, t = 0.5 mm)

Cutting speed V, m/s	Frequency of the process f, kHz	Mean value $\bar{x}$, mV	Variance D, mV	Energy $\tilde{E}$	Negoentropy $\tilde{S}$	$K_S = -\frac{\tilde{S}}{\tilde{E}}$
	Machining without LCL					
1.2	5	0.36	0.06	6.46	5.59	0.86
	8	0.19	0.016	1.77	5.57	3.15
	15	0.16	0.0066	0.58	6.26	10.9
1.8	8	0.25	0.022	2.20	5.95	2.7
	10	0.174	0.019	0.64	5.25	8.2
	Cooling by the emulsion DVSL					
1.2	5	0.32	0.046	5.22	5.65	1.08
	8	0.18	0.0092	1.17	5.62	4.8
	10	0.12	0.0027	0.33	5.95	18.0
1.8	8	0.183	0.013	1.39	5.73	4.12
	10	0.082	0.0024	0.48	4.46	9.29

Table 2. Influence of Lubricant Cooling Liquid (LCL) on energoentropy characteristics of process realization of TEDF during cutting of steel 38XC by means of the alloy T15K8 ($S = 0.39$ mm/rev, $t = 0.5$ mm)

Cutting speed V, m/s	Frequency of the process f, kHz	Mean value $\bar{x}$, mV	Variance D, mV	Energy $\tilde{E}$	Negoentropy $\tilde{S}$	$K_S = -\frac{\tilde{S}}{\tilde{E}}$
	Machining without LCL					
2.0	8	2.51	0.0029	0.28	4.9	17.5
	10	1.12	0.00035	0.039	5.66	145.1
2.6	8	3.87	0.0032	0.504	5.38	10.7
	10	1.6	0.00049	0.061	5.79	94.9
	Cooling by the emulsion DVSL					
2.0	8	1.44	0.00085	0.127	4.77	37.5
	10	0.76	0.00015	0.020	5.41	270.5
2.6	8	2.4	0.00065	0.128	5.15	40.2
	10	1.31	0.00034	0.049	5.71	116.5

tion of fluctuation processes in the friction zone according to the convective mechanism.

CONCLUSIONS

(1) The dissipative capabilities of the system increase with an increase in the frequency of fluctuation processes in the friction zone, the amplitude of temperature fluctuations, and the depth of their penetration into the body of the wear material decrease. At a distance of 100 μm from the friction surface and at a frequency of 20 kHz, the temperature fluctuations are completely attenuated. The total surface cutting temperature is reduced. As a result, tool wear is lower, and tool life is 1.5–2 times higher.

(2) Statistical processing of temporary realizations of the main energy and negentropy characteristics of the processes under study makes it possible to qualitatively assess the level of efficiency of the use of active liquid coolants, wear of tool materials, and to select the optimal cutting conditions.

(3) The maximum value of negentropy coefficient K_S indicates the intensification of the process of energy dissipation from the cutting zone and corresponds to the minimum wear intensity of hard alloys. A thermodynamic criterion for choosing the optimal cutting speed has been developed and is relatively easy to implement in practice.

NOTATION

E	energy
ΔS	entropy
T	absolute temperature
$\tilde{E}$	energy of fluctuation processes
$\tilde{S}$	entropy of fluctuation processes in the cutting zone
$f(x_i)$	random variable distribution function x_i
K_S	negentropium energy utilization factor
V	cutting speed, m/s
f	frequency of the process, kHz
$\bar{x}$	mean value, mV
D	variance, mV
S	supply, mm/rev
t	cutting depth, mm
I	intensity of incisor wear

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