Modeling of Non-Stationary Processes When Cutting Hard-to-Process Materials

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Abstract. In the conditions of high-speed processing of parts of complex configuration, with a large end and longitudinal length, from hard-to-work steels and alloys, it is difficult to ensure the wear resistance of the cutting tool in the aisles of one technological passage. To ensure the appropriate quality indicators of the surface layer, it is impossible to replace a worn-out cutting tool. In connection with the above, the problem of ensuring the operability (wear resistance) of the cutting tool is acute. The results of theoretical and experimental studies of contact phenomena in blade cutting based on the thermodynamics of non – equilibrium processes and from the standpoint of self-organization of the tribosystem are presented. the developed thermodynamic model of blade processing with variable cutting modes (non-stationary) allows to minimize the wear of the cutting tool and generally increase production efficiency by accelerating the drive of the main movement of the metal-cutting machine.

1 Introduction

A feature of the use and operation of cutting tools on modern metal-cutting equipment equipped with numerical software (CNC) and adaptive control (ADSU) systems is the variability of many parameters of the blade processing process. Operations such as multi-step machining, machining complex contours on a copier, face, vibration and interrupted turning are performed with variable elements of the cutting mode and, as a consequence, with non-stationary temperature-force conditions of loading of the cutting tool. External factors - fluctuations in the stock allowance and their physical and mechanical inhomogeneity, beats and vibrations, variability of technological parameters of the turning process (speed, feed and depth of cut), and internal, associated with changes in forces and temperatures in the cutting zone due to friction and irreversible growth of wear of the cutting tool, is made as significant contribution, to the non-stationarity of blade processing and, in particular, the contact “tool-part” [1-4].

Practical recommendations used by the industry, possible non-stationarity are taken into account by correction factors for a decrease in processing modes or not taken into account at all, which leads to a decrease in productivity and in most cases is not justified [5 – 7].

A wide variety of new materials with increased strength properties, the need to reduce the time of their development and increase the overall efficiency of the cutting tool operation puts forward among the urgent tasks the development of methods for the theoretical study of non-stationary turning in order to determine functional and mathematical models of machinability characteristics suitable for solving optimization and control issues cutting process in various technological conditions based on the relationship of variable elements of the cutting mode with contact phenomena during blade processing.

In the process of cutting, due to tool wear, there is a continuous change in the spatial shape of the contact surfaces. This, even with constant values of the elements of the cutting mode, can lead to a change in the distribution of stresses and temperatures in the actual contact zone, which in turn affect the wear rate [1, 5, 6]. Thus, contact wear and the distribution of specific

loads and temperatures are interdependent processes, which must be taken into account when developing analytical dependencies for calculating the wear rate in non-stationary cutting.

Currently, the generally accepted [1, 4, 8 – 10] is a complex theory of friction and wear, which combines the molecular-kinetic and structural-energy approaches. Its main concept is the need for multiple frictional action to destroy the friction surfaces. In this case, the process of friction is considered as a loss of mechanical energy during the period of relative motion of the contacting areas of materials. Destruction (wear) occurs as a result of the accumulation of internal energy in the deformed volume, spent on the formation of defects in the crystal lattice of rubbing bodies and on increasing the temperature of their surface layers.

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2 Theoretical and experimental hypothesis

Based on the first law of thermodynamics for the processes of friction and wear, the change in internal energy (ΔW) can be represented in the form

$$\Delta W = \Delta W_{mv} + \Delta W_{ph} + \Delta W_d + \Delta W_f \qquad (1)$$

Where ΔW_{mv} - is the energy spent on separating the wear particle,

ΔW_{ph} - energy spent on structural-phase transformations;

ΔW_d - the energy spent on plastic deformation;

ΔW_f - energy spent on shaping rubbing surfaces.

Since at the present time there are no analytical dependences, according to which it is possible to estimate with sufficient accuracy all components of dependence (1), we assume in the first approximation that as a result of frictional contact interaction, the internal energy will dissipate due to:

- plastic deformation of a single microroughness as a result of a shift by the average diameter of the contact spot;
- shaping the surface layer of the wear material as a result of the formation of a wear fragment;
- the formation of new free surfaces as a result of the separation of wear particles.

Using the principles of nonequilibrium thermodynamics [5, 7, 8, 10-12], contact processes in unsteady cutting can be most fully described using dissipative functions (DF), which represent the rate of change (dW_i/dt) of the energy spent on a process (for example, plastic deformation of the processed material) per unit of actual contact area (A_r).

$$\overline{\Psi}_i = dW_i / d\tau \cdot 1 / A_r \qquad (2)$$

To ensure the irreversibility of the process, it is necessary to have a generalized thermodynamic flow (I_i) and a force ($\Delta\sigma_i$) [4,5], i.e. the supported gradient of the values of the state of the thermodynamic system, which prevents the reverse process and taken with the opposite sign. The DF of such a process is equal to the product of the generalized flow and force

$$\overline{\Psi}_i = I_i \cdot (-\Delta\sigma_i) \qquad (3)$$

Taking into account the above assumptions, the change in the internal energy of the frictional dynamic system (ΔW) as a result of the action of external forces can be represented as the sum of the energy spent on dispersing (wear) the instrumental and elastic-plastic deformation of the processed material. In this case, the law of conservation of energy can be represented in the form of a balance of dissipative functions

$$\overline{\Psi}_b = \overline{\Psi}_f + \overline{\Psi}_d \qquad (4)$$

where $\overline{\Psi}_b, \overline{\Psi}_f, \overline{\Psi}_d$ - respectively, DF of external forces; the process of plastic deformation of the processed material as a result of shear by the average diameter of the contact spot; dispersion and reshaping of the surface layer of the worn tool material.

Based on the analysis of contact processes during nonstationary turning, the DF of external forces is presented as

$$\overline{\Psi}_b = P_z(\tau) \cdot V(\tau) / (l_1 + h_з) \cdot b \qquad (5)$$

where $P_z(\tau), V(\tau)$ - respectively, the current values of the force and cutting speed, N, m / s;

$l_1, h_з$ - respectively, the length of the tool contact on the front and back surfaces, mm;

b - width of the cut layer, mm.

From the analysis of the shape stability of the cutting wedge, the model of the accumulation of damage in the near-contact layers of the tool with variable elements of the cutting mode and the probabilistic nature of the separation of the wear particle [1,3, 13-15],

$$\overline{\Psi}_f = I_h \cdot V(\tau) \cdot \left(\frac{HV_u}{HV_\phi}\right)^{\alpha} \cdot erfP \cdot \left[p_r + \frac{12 \cdot (1+\mu)}{E} \cdot \sigma_T^2 \right] \qquad (6)$$

where I_h is the wear rate of the cutting tool;

$\frac{HV_U}{HV_\phi}$ - the ratio of microhardness of the instrumental and processed materials;

α - an indicator that takes into account the effect of cutting temperature;

$erfP$ - probability of separation of wear particles;

p_r - normal specific load in the contact zone N / m;

$\sigma_T = \frac{1}{2\sqrt{3}} HV_u$ - the yield point of the tool material, MPa.

The DF of plastic deformation of the processed material is determined on the basis of the dislocation theory of the process, taking into account the concept of the modified temperature, by the rate of deformation and is determined by the current value of the cutting temperature (deformation $(\Theta(\tau))$, degree of plastic deformation ($\Delta\gamma$), physical and mechanical properties ofthe processed material ($\sigma_{m.\partial.}, G_\partial$)) [6, 8], a See also vibrationcharacteristics of the cutting process (f_r).

$$\overline{\Psi}_{\text{в}} = 10^4 \cdot \Theta(\tau) \cdot \Delta\gamma \cdot \left[f_r \cdot \frac{\sigma_{m.\partial.}}{G_{\partial.}} \cdot \frac{\Theta(\tau)}{\Theta_{onm.}} \cdot exp \frac{\Theta_{onm.}}{\Theta(\tau)} \right]^{\frac{1}{n}} \qquad (7)$$

Based on the above and the obtained dependences for the components of the balance of dissipative functions (4 -7), we can write:

$$\frac{p_z(\tau) \cdot V \cdot f}{(l_1 + c) \cdot b} = 0{,}186\theta(\tau) J_\partial J_\theta +$$
$$+ J_h \cdot V \cdot \left(\frac{HV_u}{HV_\phi} \right) \cdot erfP(\tau) \cdot \left[P_r + \frac{12 \cdot (1+\mu)}{E} \cdot \sigma_m^2 \right], \qquad (8)$$

Solving this equation with respect to the tool wear rate J_h, we obtain an expression for calculating the tool wear

$$J_h = \frac{p_z(\tau)\cdot V\cdot f/(l_1+c)\cdot b - 0{,}186\theta(\tau)J_\partial J_\theta}{V\cdot\left(\frac{HV_u}{HV_\phi}\right)^{\alpha}\cdot erfP(\tau)\cdot\left[P_r+\frac{12(1+\mu)}{E}\sigma_\tau^2\right]} \qquad (9)$$

From equation (9) it follows that the main ways to reduce the wear rate of blade cutting tools are:

– reduction of the coefficient of friction f on frictional contact with the processed material (due to the formation of secondary structures and phases on the working surfaces - products of self-organization of the tribosystem, as well as the use of lubricating and cooling technological means and unsteadiness of cutting, contributing to this phenomenon) [16,17];

– increasing the value of the ratio of the hardness of the contacting surfaces of the tool $HV_и$ and the workpiece $HV_ф$ (by reducing the dependence of the physical and mechanical properties of the contacting surfaces on the temperature in the working zone - taking into account the phenomena of self-organization during friction) [18-20];

– optimal change in temperature and power conditions of cutting, using the change in cutting speed over time (acceleration) by the main motion drive (PGD).

3 Results and discussion

To confirm the mathematical model of the wear rate of the cutting tool, a series of experimental studies of the temperature-power parameters with the variability of the elements of the cutting mode were carried out. A comparative analysis of the dependences of the components of the cutting force on the cutting speed, both in stationary and non-stationary turning, showed that they have different levels, i.e. the value of the components of the cutting force when machining with positive accelerations is much lower (Fig. 1).

Based on the results of experimental studies of the cutting force of the "Evrika" programs, mathematical models for the tangential component of the cutting force were obtained. The Evrika application package allows the least squares method to approximate functions, statistical data and is widely used for engineering calculations.

With non-stationary turning (with variable cutting speeds) for one of the investigated pairs of tool and machined materials (XN73MBTU – H10), the dependence of the tangential component of the cutting force on the cutting speed and its acceleration has the form:

$$P_z(\tau) = 219{,}37 + 32{,}632\tau\cdot V_0^{-1{,}4(1\pm a_V)} \qquad (10)$$

at S = 0.1 mm / rev; t = 0.5 mm.

With a continuous change in feed in the area of practically applied cut configurations for finishing and semi-finishing turning (S=0,05÷0,15 mm / rev), the components of the cutting forces Px, Py, Pz change proportionally 2: 1, 5: 1 (Fig. 2).

Experiments have shown that the cutting force during non-stationary turning changes non-linearly with a change in feed according to a linear law. When turning with positive rates of change in feed (aS >0), the cutting forces increase monotonically, but decrease monotonically at negative rates of change (aS <0).

The approximate dependence of the tangential component of the cutting force on the feed and the rate of its change (a_s) in time (τ) is as follows:

$$P_z(\tau) = 260{,}66 + 514{,}2\tau\cdot S^{1.3(1+a_s)} \qquad (11)$$

at S = 0.5 m / s; t = 0.5 mm.

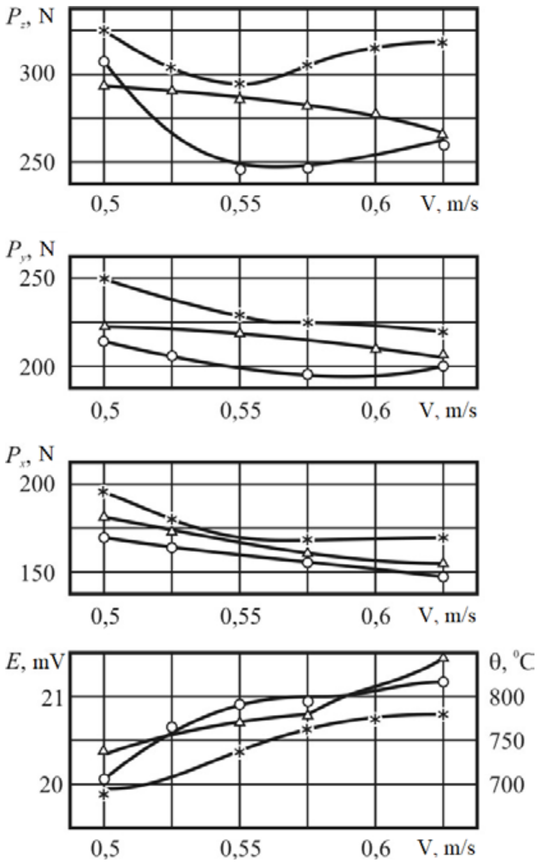


Fig. 1. Dependence of the components of the cutting force, thermo-EMF and temperature on the cutting speed when turning XN73MBTU – H10
(- av> 0; - av <0; - av = 0; s = 0.1 mm / rev; t = 0.5 mm)

Thus, we can say that in non-stationary turning with a change in cutting speed and feed according to a linear law, the cutting force differs significantly in magnitude than in stationary turning (a_v=$a_{s=0}$) and is a function of the magnitude and sign of the rate of their change (a_v, a_s).

The dependences of the cutting temperature on the speed and feed for non-stationary and stationary turning for various combinations of tool and work materials are shown in Fig. 1 and 2.

When analyzing the data obtained, it was found that for the investigated combinations of "cutter - part" the dependences θ(V) have a non-monotonic character from the point of inflection (inversion) when working at optimal cutting speeds, but with a point shift towards high speeds when turning with positive accelerations ($a_V>0$) in comparison with work with $a_V = 0$ and towards lower speeds when working with negative accelerations ($a_V > 0$).

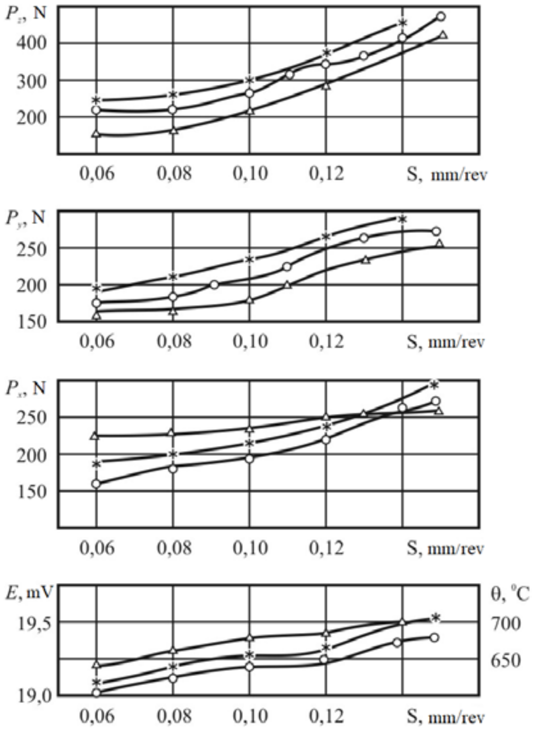


Fig. 2. Dependence of the components of the cutting force, thermo-EMF and temperature on the cutting speed when turning EI698-VK8
(- aS> 0; - aS <0; - aS <0; V = 0.66 m / s; t = 0.5 mm)

Analysis of the dependences of temperature on speed and feed in non-stationary turning confirms that the main influence on the cutting temperature is exerted by the cutting speed and the workpiece material, all other things being equal. During non-stationary turning, as well as during stationary turning of machined materials, tool materials have an ambiguous effect on the cutting temperature, which is associated with the complex nature of their influence, first of all, on the processes of frictional interaction, which largely determine the temperature in the cutting zone.

According to the results of experimental studies, approximation dependences for the cutting temperature were obtained with a continuous change in the cutting speed (V) with acceleration (a_V) in time (τ)

$$\theta(\tau) = 295{,}6 + v_0^{0{,}8(1 \pm a_v)} \cdot \tau \text{, К} \quad (12)$$

and with a continuous change in feed:

$$\theta(\tau) = 512{,}4 + 33{,}2 S_0^{0{,}8(1 \pm a_s)} \cdot \tau \text{, К} \quad (13)$$

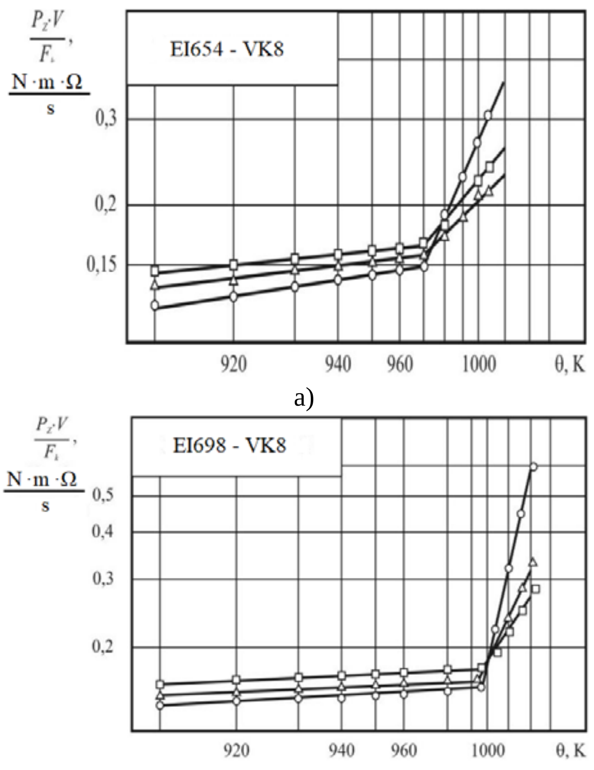
To concretize the dependence of the components of the balance of dissipative functions (ψ_t, ψ_d, ψ_f) and to ensure the conditions for minimizing the intensity of tool wear (J_h) during non-stationary turning, the dependences of the main output parameters (tangential component of the cutting force P_z, relative linear tool wear $h_{ол}$, cutting speed V, in the form of specific energy $\left(\frac{P_z \cdot V}{F_k}\right)$ - spent on the processes of friction and wear of the cutting tool - from the cutting temperature during non-stationary turning (Fig. 1).

Specific energy expended on the processes of friction and wear, according to [8,9], is expressed as

$$\Delta W = \frac{P_z \cdot V}{F_k}, \frac{H \cdot м}{c \cdot м^2} \quad (14)$$

where F_k is the area of contact surfaces of the tool with the processed material and chips.

Analysis of experimental data (Fig. 3) - dependences of cutting temperature (θ) and specific energy spent on friction and wear processes for all studied pairs during non-stationary turning showed that:
– the graph of dependence has a characteristic break at temperatures corresponding to the optimum temperature of stationary turning;
– at temperatures $\theta > \theta_{опт}$, the dependence has a different angle of inclination for different accelerations of PGD;
The specific energy for different accelerations of PGD, both in sign and in magnitude, has a different value (different level) and a minimum during acceleration ($a_v>0$), as already noted, corresponding to a lower temperature-force tension of the cutting zone.



a)

b)

Fig. 3. Dependence of power and electrophysical parameters, speed versus cutting temperature for non-stationary and

discrete turning (S = 0.1 mm / rev; t = 0.5 mm; - av> 0; - av <0; - av = 0)

Experiments carried out with a continuously varying cutting speed with different accelerations of the main motion drive (MD) both in sign and in value ($a_v \neq 0$) showed that for all the pairs under study, wear prevails along the rear main and auxiliary surfaces of the tool. For finishing and semi-finishing (S = 0.05 - 1.5 mm / rev; t = 0.25 - 0.5 mm), the hole on the front surface is located closer to the main cutting edge. As the tool wears out, the holes can join with the wear chamfers, which predetermines the onset of catastrophic wear.

In general, it was found that the dependence of wear on cutting speed is extreme. Moreover, when operating with a positive speed acceleration ($a_v > 0$) , this dependence is flatter compared to $a_v < 0$ or $a_v = 0$ (Fig. 4).

With a change in temperature, as shown by numerous studies [1-5], the wear rate changes non-monotonically. Usually, in the course of a resistance experiment, the temperature in the cutting zone changes continuously as a result of an increase in the wear chamfer along the flank of the cutter. Changing the wear chamfer leads to a redistribution of heat fluxes on the cutting edges of the tool, which in turn changes the intensity of wear. The dependence of the logarithm of the intensity of tool wear on temperature during stationary and non-stationary turning is extreme, with a minimum at a temperature corresponding to the optimum for stationary turning (Fig. 4).

Moreover, this dependence for non-stationary turning has three sections: section I - up to the optimum temperature ($\theta_{опт}$), section II - from the optimal to critical temperatures ($\theta_{кр}$), section III - above the critical temperature. According to studies [2, 3], the appearance of a critical temperature is associated with a change in the dynamic safety factors of the contact or surface strength of the tool and processed materials.

According to the results of wear resistance studies of stationary and non-stationary turning it follows that:

– the dependence of the intensity of tool wear on the cutting speed, both in stationary and non-stationary turning, is extreme. Moreover, with non-stationary turning, the minimum intensity of tool wear is observed at higher cutting speeds;

– the intensity of tool wear during non-stationary turning (a, as) is much less than during stationary turning, which, apparently, as already noted, is associated with a decrease in the temperature-force tension of the cutting zone;

– the minimum of the dependence of the wear rate on the cutting temperature in non-stationary turning is observed at a temperature that is optimal for stationary turning. This confirms the position about the optimal temperature of A.D. Makarov [3] in relation to non-stationary turning;

– the presence of a platform on the dependence of the intensity of tool wear on the cutting temperature, i.e. temperature range $\theta_{кр}$ - opt, determines the area of rational use of any brand of hard alloy when cutting a given workpiece material with a minimum of tool wear intensity and can serve as one of the criteria for the machinability of this material and for determining the boundary conditions for cutting conditions during non-stationary turning.

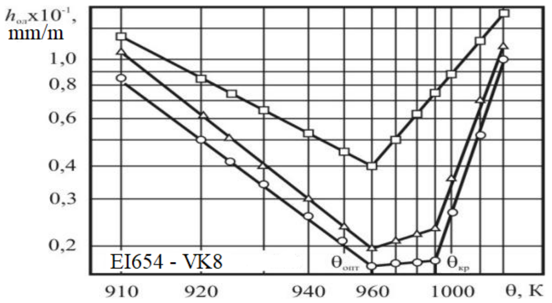


Fig. 4. Relative linear wear versus temperature when turning with different accelerations (S = 0.1 mm / rev; t = 0.5 mm)
Δ - av <0; - av = 0; - av> 0

4 Conclusion

The results of theoretical and experimental studies of contact phenomena in blade cutting based on the thermodynamics of non – equilibrium processes and from the standpoint of self-organization of the tribosystem are presented. Developed thermodynamic model of blade processing with variable cutting modes allows to minimize the wear of the cutting tool by half during high-speed processing of parts of complex configuration with large dimensions from difficult-to-machine steels and alloys while ensuring and maintaining high quality indicators of the surface layer of the processed surface.

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