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Influence of cutting speed on pulse changes in the temperature of the front cutter surface during turning of heat-resistant steel 0.17 C-Cr-Ni-0.6 Mo-V

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ABSTRACT

Introduction. This paper is devoted to the evaluation of the influence of periodic fluctuations of machining mode parameters on the change of the maximum temperature of the front surface of the cutter. **Subject of research.** Fluctuations of cutting mode parameters are considered as deviations of their values relative to the nominal ones, resulting in periodic changes in the cross-sectional area of the cut layer and the interaction conditions between the chip and the tool's front surface, which affect temperature changes in the cutting zone. **The purpose of this work** is to evaluate the influence of periodic fluctuations of machining mode parameters at different cutting speeds on the variation of the maximum temperature of the cutting tool's front surface during turning of heat-resistant steel *0.17 C-Cr-Ni-0.6 Mo-V* on a long-life machine without cooling. **Method and methodology.** The finishing longitudinal turning process of heat-resistant steel *0.17 C-Cr-Ni-0.6 Mo-V* on a long-life machine without cooling was investigated. During machining, tool vibrations were measured along three coordinate axes while varying the cutting speed at constant depth of cut and feed. Using digital simulation modeling based on input data obtained from in-situ experiments, the moments in the system dynamics when each cutting mode parameter reaches extreme values due to fluctuations were identified. Deviations of the maximum design temperature from the corresponding nominal value were then determined. **Results and discussion.** It is established that variations in machining speed change the factors destabilizing the thermal state: at low speeds, the main sources of temperature deviations in the investigated cutting system are moments when extreme values of cutting depth and speed are reached; at higher speeds, fluctuations of cutting depth and feed have the greatest effect. It is revealed that when machining parameters reach extreme values, instantaneous temperature generally increases, and cutting speeds at which such deviations are minimal are identified.

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Introduction

One of the main factors determining the wear resistance of cutting tools is the temperature in the machining zone. Over the past decades, a significant number of scientific studies have been devoted to the assessment and prediction of maximum temperatures on the surface of cutting tools. Experimental methods for determining this parameter by contact measurement and analysis of heat emission have been proposed [1–3], and various analytical dependencies for predicting temperature have been presented [4–7]. Another relevant area of research is the assessment of the influence of process conditions on the temperature in

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the cutting zone. Most of the works presented in this area are devoted to studying changes in the average temperature when one of the cutting mode parameters varies, but the effect of vibrations generated by the system itself at certain processing modes on the nature of heat dissipation in the contact zone has not been analyzed [8–12]. At the same time, studies show that cutting tool vibrations and the temperature in the cutting zone are highly correlated. For example, *Songyuan Li et al.* show the results of the influence of tool vibrations on temperature for different stages of tool wear [13]. *Qiu Yu et al.* also note the significant influence of cutting modes and tool vibrations on the thermal state in the processing zone, while noting that this relationship is characterized by nonlinear properties and depends on the operating parameters of the cutting system [14].

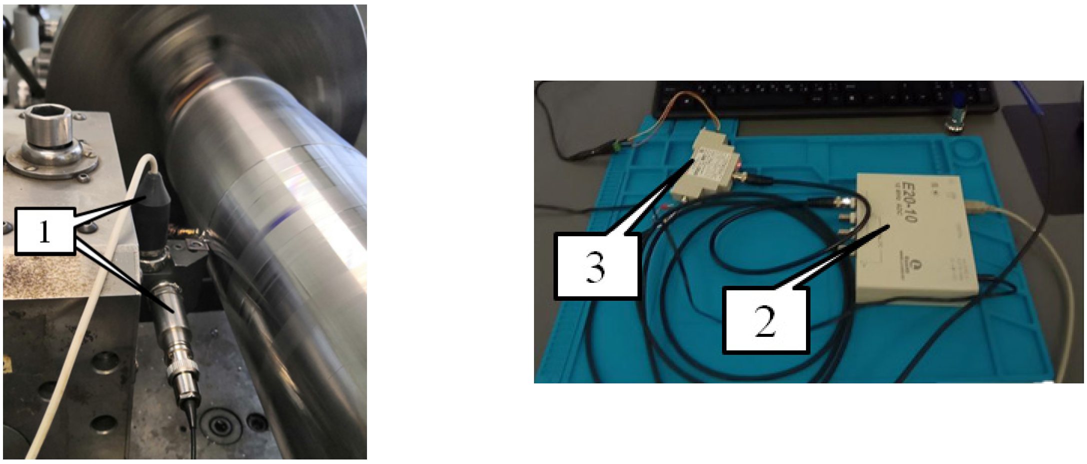
The temperature in the cutting zone reaches its maximum value at the end boundary of the secondary plastic deformation (*SPD*) zone on the tool rake face. The "tool rake face-chip" interface is a heavily loaded tribological system, in which the cutting edge of the tool heats up as a result of viscous dissipation of friction energy in the surface deformable microvolume of the chip. By applying hydrodynamic analogies to the assessment of deformation processes in the *SPD* layer, *A.V. Chichinadze* and *K.G. Shuchev* obtained an analytical dependence describing the temperature distribution along the rake face and allowing the maximum temperature at this edge to be determined [15]. The parameters of the volumetric heat source in the chip are determined by the specified cutting modes. At the same time, as a result of various vibration disturbances in the cutting system, one or more of the initially specified processing parameters (speed, feed, cutting depth) periodically deviate from their nominal values, changing the set of tribodeformation indicators that determine the maximum instantaneous contact temperature. As a result of the variable nature of the heat sources on the rake face, there will be periodically repeating impulsive changes in the instantaneous temperature associated with mechanical vibrations of the machine's actuators. The specific deviation of this indicator from the nominal value will be determined by a set of values that each of the processing mode parameters takes at the moment of fluctuations. An increase in the amplitude of the variable temperature component leads to an increase in the temperature gradient in the cutting wedge as a whole and to an increase in undesirable heat flows. Temperature fluctuations in areas adjacent to the zone of primary plastic deformation change the characteristics of the material being processed and affect the cutting forces. The unstable thermal state of the cutting zone and the variable nature of the thermal load on the cutter surfaces cause intensification of oxidative and diffusion wear of the working edges of the tool [17–19]. At the same time, thermodynamic processes on the tool face largely determine the thermal state and wear processes on its flank face [20, 21]. Negative temperature effects are particularly acute during dry cutting of heat-resistant materials with low thermal conductivity [22–24]. The use of equipment with a long service life is an additional factor that increases tool vibrations and increases the temperature in the processing area. Such equipment is prone to significant kinematic disturbances originating from the feed drives and the main drive during machining.

The purpose of this work is to evaluate the influence of periodic fluctuations in processing parameters, induced at different cutting speeds, on changes in the maximum temperature of the cutter's rake face when turning heat-resistant *0.17 C-Cr-Ni-0.6 Mo-V* steel on a machine with a long service life without coolant.

Methods

Real-life tests were carried out in production conditions (*Atommash* factory, Volgodonsk) on a *DIP-300* universal turning machine. External longitudinal turning of workpieces with a diameter of 109 mm and a length of 400 mm made of *0.17 C-Cr-Ni-0.6 Mo-V* steel was performed using cemented carbide inserts (*WC* 79 %; *TiC* 15 %, *Co* 6 %) with the following cutting edge geometry: back rake angle $\gamma = 6°$, clearance angle $\alpha = 6°$, major cutting edge angle $\varphi = 95°$, and nose radius $r = 0.5$ mm. Turning was performed at a feed rate of $s = 0.198$ mm/rev, a cutting depth of $t = 0.5$ mm, and a spindle speed of $n = 630–1{,}000$ rpm (cutting speed $V = 215.5–343.6$ m/min). The workpieces were centered and pre-turned. To increase the rigidity of the workpiece subsystem, a reinforced precision rotating tailstock *BISON 8814-5 NC PRECISION 20/30* was used.

Tool vibrations measured in the directions of its mobility were selected as the main information channels about the dynamics of the cutting process, as they have a greater impact on fluctuations in technological modes. To measure tool vibrations, a stand consisting of three *A603C01* accelerometers, an *LCard E20-10* analog-to-digital converter (*ADC*) with an input signal sampling frequency of up to 10 MHz, and a *BTK-2-010 ICP* converter for amplifying and proportionally converting vibration acceleration signals into alternating voltage with a frequency range of 0.1–50,000 Hz (Fig. 1) was used. The signal sampling frequency was 10 kHz per channel. Signals were recorded using *L-Graph II* software, and experimental data processing and identification of the parameters of the digital model of the cutting process were performed using *Matlab* and *Simulink* software.



a *b*

Fig. 1. General view of the equipment for the study:

a – vibration accelerometers (**1**); *b* – continuous vibration monitoring system of the tool: *ADC E20-10* (**2**) and *ICP* transducer *VTK-2-010* (**3**)

The dynamic cutting system model is represented as a set of three interconnected subsystems. The first subsystem controls the movement of the cutting tool relative to the workpiece, i.e., it sets the cutting parameters and the inertial-dissipative properties of the system. The second subsystem models the elastic deformations and cutting forces acting on the tool. The third subsystem implements a block for simulating uncontrolled disturbances, the source of which are kinematic disturbances from the machine's drive system and spindle runout [25].

When modeling the dynamics of the machining process, the values of the cutting speed $\boldsymbol{V}$, feed rate $\boldsymbol{s}$, and cutting depth $\boldsymbol{t}$ were determined as follows: for each parameter, the value was determined by the sum of the value set by the control system (V_0, s_0, t_0), deformation displacements $H = \{H_X, H_Y, H_Z\}$, mm, and deformation displacement rates $\eta = dH/d\tau = \{\eta_X, \eta_Y, \eta_Z\}$, mm/s, as well as vibration disturbances $\Delta = \{\Delta_X, \Delta_Y, \Delta_Z\}$, mm. Vibration disturbances are periodic functions of time and can be represented as:

$$\Delta_i(\tau) = \sum_{n=1}^{k} A_n \sin(\omega_n \tau),$$
$$v_i^{\Delta}(\tau) = d\Delta_i / d\tau = \sum_{n=1}^{k} A_n \omega_n \cos(\omega_n \tau), \quad (1)$$

where A_n, ω_n are the amplitudes and frequencies of the oscillators disturbing the movement of the tool in the directions of movement $i = \{X, Y, Z\}$, determined experimentally.

The final representation of the cutting modes was modeled as follows:

$$V = V_0 - \eta_Z + v_Z^{\Delta};$$
$$s = \int_{\tau-\tau_0}^{\tau} \left(V_x - \eta_X + v_X^{\Delta}\right) d\tau; \quad (2)$$
$$t = t_0 - H_Y + \Delta_Y,$$

where $\tau_0 = 1/\Omega$ is the time of one rotation of the part, s; Ω is the rotation frequency of the part, Hz; V_x is the feed speed, $V_x = s_0 \cdot \Omega$, mm/s.

The maximum contact temperature on the rake face was calculated for each combination of ***V***, ***s***, and ***t*** values that they take at the moments of fluctuations due to tool vibrations using the *Chichinadze-Shucheva* analytical dependence [15]:

$$T = \left(\frac{\omega_{01}}{k_1 + m_1} + \frac{\omega_{02}}{\frac{l_1}{V_C} k_2^3 a_2} \left(\frac{l_1}{V_C} k_2^3 a_2 + 1 - 2k_2 \sqrt{a_2 \cdot \frac{l_1}{V_C}} \cdot \frac{1}{\pi} - \exp\left(\frac{l_1}{V_C} k_2^2 a_2 \right) \cdot rfc\left(k_2 \cdot \sqrt{a_2 \cdot \frac{l_1}{V_C}} \right) \right) \right) \times$$

$$\times \left(\lambda_1 \cdot m_1 + \frac{2\lambda_2}{\pi \cdot a_2 \frac{l_1}{V_C}} \right)^{-1}, \quad (3)$$

where ω_{01} is the maximum volumetric density of the heat source from friction forces in the tool body, W/m^3; $\omega_{02} = \dfrac{q_0 k t_H}{t_m h \left(1 - \exp\left(-k \dfrac{T_H}{T_m} \right) \right)}$ is the initial density of the heat source in the material being processed, W/m^3; q_0 is the specific friction power for the front surface, W/m^2; k_1, k_2 are the heat absorption source localization coefficients for the tool and the material being processed, respectively, m^{-1}; a_2 is the thermal conductivity coefficient of the workpiece, m²/s; λ_1, λ_2 are the thermal conductivity coefficient of the solid alloy and the workpiece material, respectively, W/m·°C; V_c is the chip feed rate on the front surface, m/s; τ_k is the average tangential stresses on the front surface, Pa; T_m is the melting point of the workpiece material, °C; k is the temperature coefficient, °C; $k = 7.143 \cdot 10^{-4} \cdot T_m$; h is the average thickness of the plastically deformed layer in the chip, m; T_H is the temperature difference within the plastically deformed layer, °C; l_1 is the length of the *SPD* zone on the rake face, m; $m_1 = \sqrt{\dfrac{\alpha_1}{\lambda_1 \left(\dfrac{A_1}{P_1} \right)}}$, A_1 is the tribocontact area on the *SPD* zone, m^2; P_1 is the perimeter of tribocontact on the SPD zone, m; α_1 is the heat transfer coefficient of the tool material, m^2/°C.

The average thickness of the *SPD* zone is determined by the empirical relationship [26]:

$$h = \frac{\tau_k l_1}{\lambda_2 T_m}. \quad (4)$$

To account for the influence of cutting force variations during fluctuations on the values of parameters $\boldsymbol{\tau_k}$ and ***h***, the average shear stress on the rake face was determined as $\tau_k = F_{XY}/A_k$, Pa, where *FXY* is the resultant cutting force for the longitudinal (*X*) and radial (*Y*) directions, and $\boldsymbol{A_k}$ is the total contact area between the chip and the rake face, defined as $A_k = 2 \cdot l_1 \cdot b$. The values of the contact length l_1 and the width of the cut layer ***b*** were determined using the methods [27] and [28], respectively.

Results and Discussion

The data on oscillatory accelerations recorded by vibration sensors were analyzed and processed. The oscillation velocity and displacement of the tool relative to the workpiece were calculated. Fig. 2 shows the vibration characteristics of the cutting process in the longitudinal direction, which is responsible for variations in the area of the cut layer. Based on the spectral characteristics of the data from the measuring system, the dominant frequency components of the system and kinematic disturbances were established.

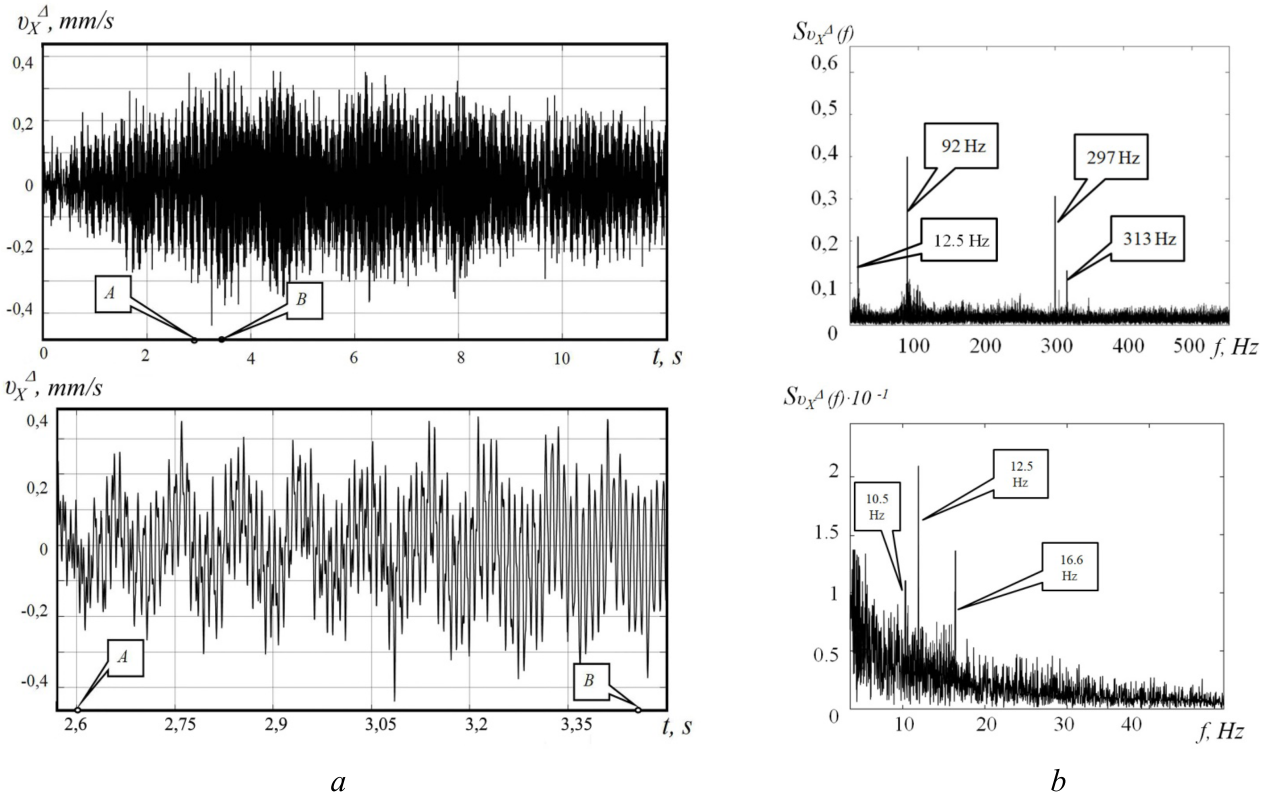


Fig. 2. Example of processed data for tool oscillatory velocity in the longitudinal direction:
a – time-domain signal; *b* – amplitude spectrum of oscillatory velocity in mid-frequency and low-frequency range

Vibration characteristics, as exemplified by the tool holder assembly, exhibit a broadband signal. Analysis of the low-frequency range shows that three main frequencies can be distinguished in the vibration spectrum of the tool holder assembly. The first of these coincides with the frequency of the spindle assembly vibrations. The others, including those in the mid-frequency range, are components of kinematic disturbances.

Based on the data obtained, the dynamics of the cutting process were simulated, taking into account the influence of vibration disturbances (1) [29]. Examples of cutting force dynamics for different cutting speeds are shown in Fig. 3. The range includes both speeds used in full-scale experiments on the machine: $\boldsymbol{V}$ = 216 m/min, $\boldsymbol{V}$ = 270 m/min, $\boldsymbol{V}$ = 343 m/min, and intermediate values obtained by simulation digital modeling.

Regarding the cutting process power indicator dynamics, the upper limit of the optimal workpiece spindle speed range will be values below the first frequency component of kinematic disturbances (12.5 Hz (Fig. 2)), i.e., $\boldsymbol{n} < 700$ rpm or $\boldsymbol{V} < 252$ m/min. Spindle speeds $\boldsymbol{n}$ = 800 rpm ($\boldsymbol{V}$ = 270 m/min) and $\boldsymbol{n}$ = 930 rpm ($\boldsymbol{V}$ = 318 m/min) can be used as processing parameters, provided that the part rotation frequency remains constant, since variations in the rotation frequency of the workpiece by 1 Hz can lead to a significant deterioration in the dynamics of the cutting process (Fig. 3). In this case, small variations in the cutting parameters in the quasi-stable parameter zone ($\boldsymbol{V}$ = 343 m/min) correspond to significant variations in cutting forces, exceeding the variations of similar parameters at $\boldsymbol{V}$ = 216 m/min and $\boldsymbol{V}$ = 270 m/min by 1.6 to 2 times.

The results of modeling variations in three cutting parameters using the example of processing speed within the optimal range (216.5 m/min) and beyond it (343.6 m/min) in terms of minimizing variations in the cut-off layer are shown in Fig. 4, *a*, *b*. It is worth noting the effect of suppression of high-frequency components of disturbances from the spindle assembly and the establishment of natural vibrations of the cutting system at $\boldsymbol{V}$ = 343.6 m/min, while kinematic disturbances from the tool holder assembly continue to disturb the trajectory of the tool in the longitudinal direction, which leads to variations in the area of the cut-off layer.

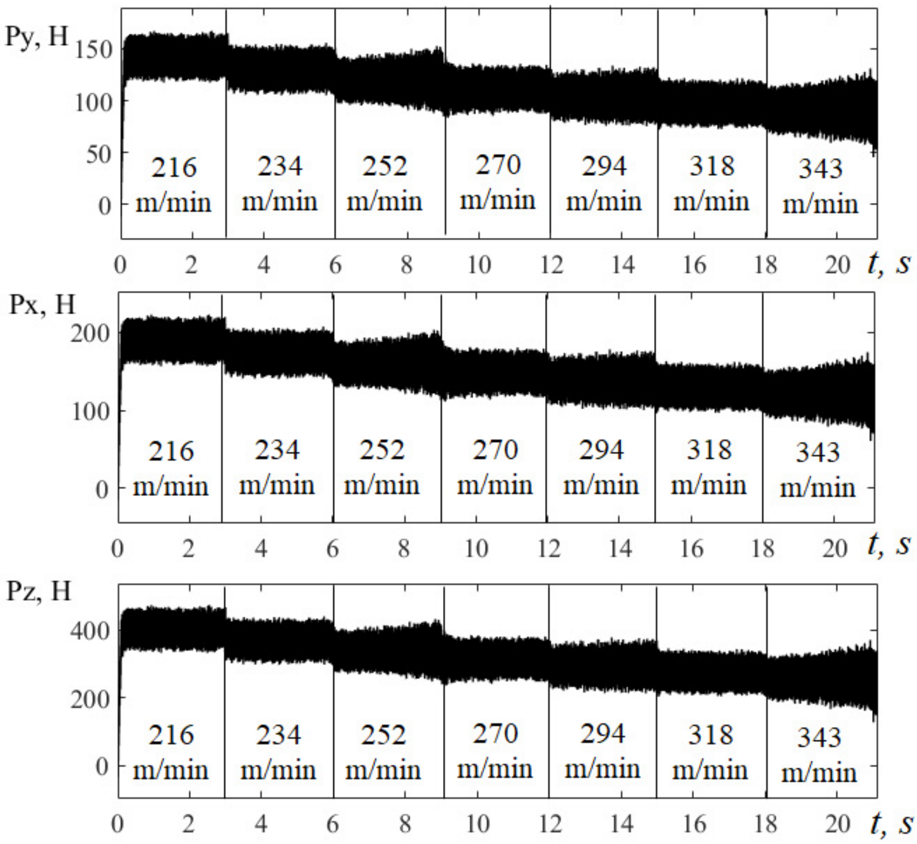


Fig. 3. Modeling of cutting forces along *X*, *Y*, *Z* directions for s = 0.198 rpm, t = 0.5 mm over the spindle speed range V = 216–343 m/min

Periodic changes in the area of the cut-off layer due to fluctuations in cutting conditions (V, s, t) relative to their nominal values cause periodic variations in cutting forces, which lead to periodic changes in chip pressure on the tool rake face. In fact, there is a periodic restructuring of the functioning of the "chip-rake face" tribosystem, the characteristics of which directly affect the temperature change in the cutting zone. In this case, a complex relationship is formed between mechanical and thermodynamic processes, which is determined not only by the characteristics of the interacting subsystems of the mechanical part but also by tribophysical phenomena that affect the properties of the environment in the cutting zone. Although the formation of these relationships is caused by external disturbances originating from the mechanical systems of the machine tool, the thermodynamic state of the contact zone is more strongly influenced by the physical and mechanical properties of the tool and workpiece materials, which determine the characteristics of elastic-plastic deformation.

Deformation processes at the points of contact between the chip and the front face of the tool are both a consequence of the dynamics of the cutting process and a source of new nonlinear transformations in the machining zone, including those affecting tool wear and the quality of the machined surface. This necessitates an analysis of the mutual influence of the mechanical and thermodynamic characteristics of the cutting process dynamics based on parameters that can be measured in the system.

To evaluate the temperature change at the tool rake face due to variations in cutting modes and forces characteristic of each spindle speed, we will identify quasi-static instances in the system dynamics when the speed, feed, and cutting depth reach their extreme values as a result of fluctuations. For each of these time points, we will determine the values of the other two parameters of the machining modes and the values of the resultant cutting forces F_{XY} at that moment (Table 1, 2, column 2–5).

Based on the data obtained, the main tribological indicators (3) are calculated using Eq. 3, which determine the maximum temperature of the front edge T_{max}, at the moments of extreme values of the parameters V, s, and t (Tables 1, 2, column 6–10). The deviations of the maximum surface temperature

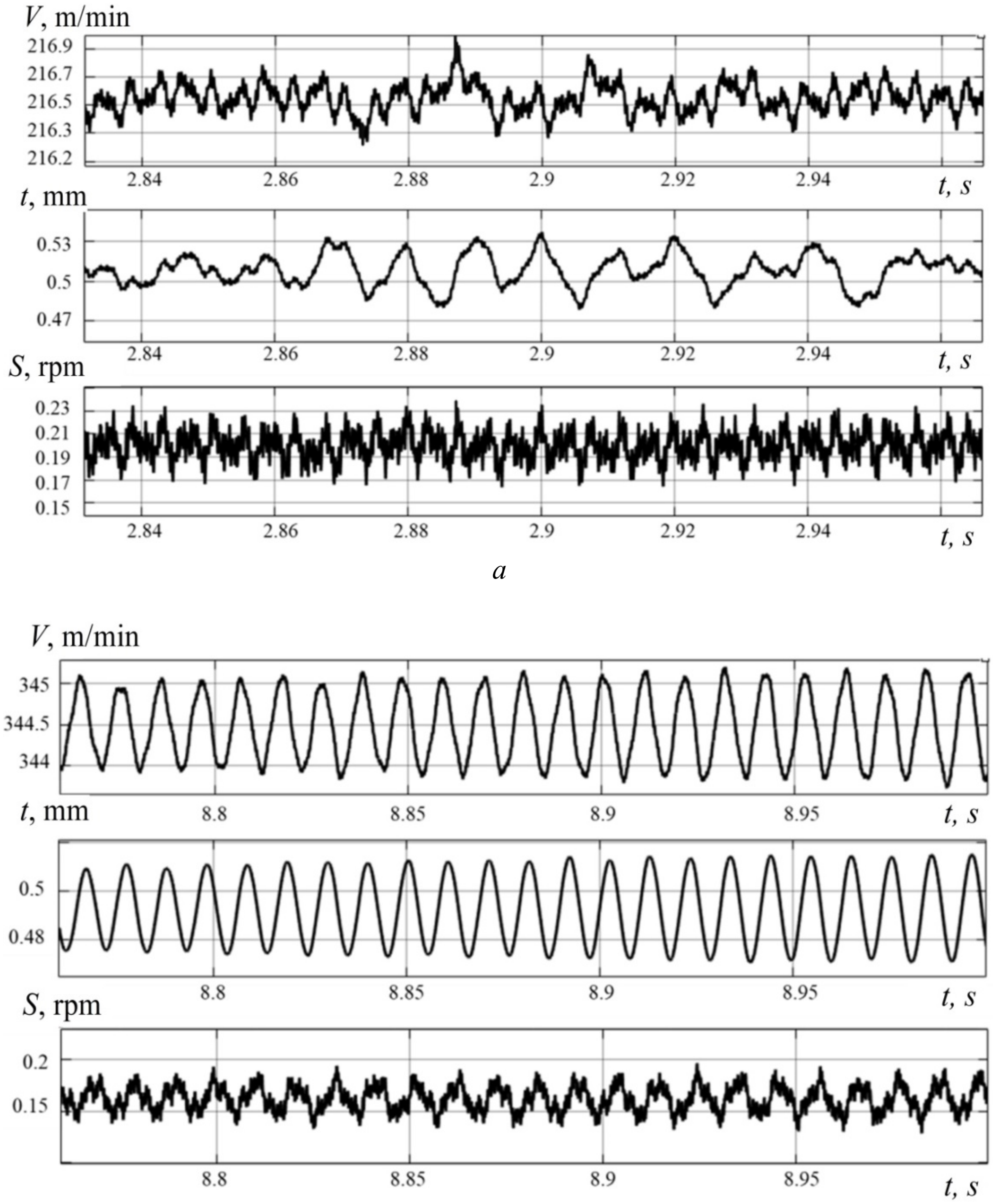


Fig.4. Fluctuations of technological modes:
a – ***V*** = 216.5 m/min; *b* – ***V*** = 343.6 m/min

Table 1

Variations of technological modes, cutting forces and main tribological parameters for *V* = 216.5 m/min

Parameter state at the moment of fluctuation	V, m/min	s, mm/rev	t, mm	F_{XY}, N	l_l, mm	h, µm	$\tau_к$, MPa	K_a	T_{max}, °C	ΔT, °C	A_T, °C
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
nominal	216.5	0.198	0.5	228	0.24	23	508	2.005	1139.2	0	–
V→max	**217**	0.234	0.51	257	0.28	25	471	1.998	1134.5	−4.7	26.8
V→min	**216.2**	0.173	0.48	230	0.21	24	619	2.013	1161.2	+22.1	
s→max	216.8	**0.242**	0.49	271	0.29	27	498	1.998	1149.7	+10.6	10.6
s→min	216.3	**0.157**	0.47	218	0.19	21	576	2.703	1142.6	+3.4	
t→max	216.8	0.225	**0.53**	247	0.28	24	460	1.998	1133.1	−6.1	35.9
t→min	216.3	0.176	**0.46**	235	0.20	25	651	2.014	1168.9	+29.8	

Table 2

Variations of technological modes, cutting forces and main tribological parameters for V = 343.6 m/min

Parameter state at the moment of fluctuation	V, m/min	s, mm/rev	t, mm	F_{XY}, N	l_l, mm	h, µm	$\tau_к$, MPa	K_a	T_{max}, °C	ΔT, °C	A_T, °C
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
nominal	343.6	0.198	0.5	142	0.24	14	319	1.962	1092.2	0	–
V→max	**345.4**	0.17	0.507	149	0.21	15	386	1.967	1117.9	+25.8	32.8
V→min	**343.5**	0.158	0.47	139	0.19	15	423	1.974	1124.9	+32.8	
s→max	344.2	**0.207**	0.509	205	0.25	20	430	1.959	1152.8	+60.7	60.7
s→min	344.5	**0.151**	0.47	119	0.17	13	382	1.975	1101.3	+9.1	
t→max	344.7	0.168	**0.519**	194	0.21	19	496	1.966	1162.5	+70.3	70.3
t→min	343.8	0.157	**0.45**	139	0.18	15	447	1.976	1132.6	+40.4	

from the nominal value ΔT and the amplitude of its change at the moments of A_T fluctuations are also presented (Table 1, 2, column 11–12). According to the simulation results, at ***n*** = 630 rpm, the greatest increase in instantaneous temperature occurs when the cutting depth reaches its minimum value. At the same time, at the moments of fluctuations, there are combinations of parameters ***V***, ***s***, and ***t***, at which their complex values practically level out the change in instantaneous temperatures (at ***V*** → max; ***s*** → min). It should also be noted that, as a result of vibrations under these processing conditions, the maximum instantaneous temperature may decrease relative to the nominal value (at ***V*** → max; ***t*** → max). When the cutting speed is increased, negative temperature deviations at moments of fluctuation are less pronounced or cease altogether. Thus, when turning at a speed of ***V*** = 343.6 m/min, for any combination of cutting mode parameters, the instantaneous temperature changes only increase (Table 2, column 11).

The amplitudes of temperature spikes generally increase with an increase in spindle speed, and the factors contributing to the generation of positive temperature spikes also change. If at ***V*** = 216.5 m/min the main sources of temperature spikes with maximum amplitude are the moments of reaching extreme values of the parameters ***t*** and ***V***, then at higher speeds, fluctuations in cutting depth and feed rate have a significant effect. Thus, when turning at ***V*** = 343.6 m/min, fluctuations with heating of the tool surface by an additional 61–70 °C occur more frequently, which is due to significant variations in the area of the cut layer due to vibrations characteristic of this machining mode.

Table 3 shows the amplitudes of periodic temperature changes for different spindle speeds ***n***. The highest values of the A_T parameter at each machining speed are underlined, thus highlighting the cutting mode parameters whose fluctuations contribute most to the instability of the thermal state of the cutting zone at each value of ***n***.

The investigated speed range has a pronounced local minimum corresponding to a speed of 270 m/min, for which the lowest values of the A_T parameter are achieved at all extreme values of the turning modes. Increasing the spindle speed above this value leads to a change in the nature of temperature spikes (sources ***V***, ***t*** are replaced by ***s***, ***t***) and an increase in A_T amplitudes.

Table 3

Calculated amplitudes of periodic temperature variations ΔT at moments when parameters V, s, and t reach extreme values

Cutting parameters	Amplitude A_T, °C					
	216.5 m/min	252 m/min	270 m/min	294 m/min	318 m/min	343.6 m/min
V	26.8	31.1	17.8	21.2	24.8	32.8
s	14.1	18.1	12.5	36.1	42.5	60.8
t	35.9	43.2	26.4	41.6	51.4	70.3

Conclusion

Based on the results of digital simulation modeling using data from real-life experiments, deviations of the contact temperature from the nominal value were determined for instances when one of the cutting parameters takes on an extreme value as a result of fluctuations. It was established that the combination of processing parameters at such moments generally leads to an instantaneous increase in the maximum temperature on the tool rake face, characterized by the concept of a thermal flash, but at the same time, for some combinations, a slight decrease in this indicator is possible. Within the range of parameters studied, the optimal cutting speed was identified, at which the output of all three processing parameters to extreme values leads to a minimal change in temperature on the rake face.

It has also been established that this cutting speed is the boundary that divides the studied speed range into two intervals, differing in factors that destabilize the thermal state of the contact zone. When turning a workpiece at a speed below this limit, the greatest temperature deviations occur when the cutting depth and cutting speed reach extreme values. When the processing speed exceeds the optimal value, the main sources of contact temperature changes become the cutting depth and feed rate. Therefore, the factor limiting the productivity of the machining process in terms of minimizing temperature fluctuations is the variation in the area of the cut-off layer due to kinematic disturbances characteristic of the investigated cutting system at higher turning speeds.

The research results presented in this paper can be used to select rational processing parameters, taking into account the kinematic disturbances of the machine tool support group and the thermodynamic state of the contact zone, which depends on their manifestations. The methodology allows evaluating and selecting technological parameters in which force fluctuations minimize possible impulse changes in the temperature of the tool rake face during dry turning. However, it is applicable only for operations that do not use coolant; in the case of the presented work, this was the operation of finishing turning a part of the "Connecting leg" type.

The influence of coolant on pulsed heat release changes will be assessed in further studies. First and foremost, the presented methodology will be effective for machine tool fleets with medium and high degrees of wear, accelerating time-consuming tests to determine optimal operating modes when new tools are delivered. The use of temperature fluctuations caused by kinematic errors as an additional parameter for evaluating the optimality of cutting parameters in vibration monitoring and compensation systems can improve process stability and reduce the overall temperature in the cutting zone. Taking into account temperature changes calculated from the vibration activity signal of the tool is particularly relevant for metal-cutting machines with a long service life, which are characterized by significant periodic disturbances in the cutting system from the feed drives and the main drive.

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Conflicts of Interest

The authors declare no conflict of interest.