doi: 10.18323/2782-4039-2025-3-73-7

Study of the temperature field formed in the process of milling with the use of ultrasonic vibrations under various processing modes

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Received 14.04.2025 *Revised 05.06.2025* *Accepted 18.06.2025*

Abstract: Study of the temperature field of the milling process with the imposition of ultrasonic vibrations (USV), under various ratios of the vibration amplitude to the depth of tooth penetration into the blank, will allow predicting the efficiency of the milling process with USV under various processing modes. The purpose of this study is to develop physical and mathematical models of the milling process with the imposition of USV, allowing identifying the influence of ultrasonic vibrations on the efficiency of the milling process under various ratios of the vibration amplitude to the depth of tooth penetration. Three sources of heat generation are considered: in the deformation (chip formation) area and in the zones of contact of the chip with the cutting plate (cutter tooth) and the plate with the blank. The authors have developed heat transfer models that take into account, in particular, the change in boundary conditions on the surfaces of the cutting plate and the blank under the USV imposition. When the plate is in contact with the blank, heat flows are directed to the blank, chips and cutter tooth, and the conditions of thermal interaction within the zones of contact of the plate with the chips and the blank are described by boundary conditions of the 2nd type. When the plate leaves the contact with the blank during the ultrasonic imposition and the chip formation process stops, then on all surfaces of the tooth (plate) and the blank that are in contact with the environment (cutting fluid or air), the convective heat transfer is described by the Newton–Richmann law (boundary conditions of the 3rd type). The results of numerical modelling are presented, confirming the assumption that the effect of using ultrasonic vibrations is higher at high values of the ratio of the ultrasonic vibration amplitude to the depth of tooth penetration into the blank.

Keywords: ultrasound; vibrations; milling; heat transfer; numerical modelling.

Acknowledgements: The study was supported by the Russian Science Foundation grant No. 24-2900206, https://rscf.ru/project/24-29-00206/.

For citation: Unyanin A.N., Chudnov A.V., Dimukhametov I.Z. Study of the temperature field formed in the process of milling with the use of ultrasonic vibrations under various processing modes. *Frontier Materials & Technologies*, 2025, no. 3, pp. 91–100. DOI: 10.18323/2782-4039-2025-3-73-7.

INTRODUCTION

High temperatures accompanying most machining processes have a significant effect on many physical processes occurring in the machining zone. The temperature of the surface layers of the blanks affects the structural and phase composition of its material [1], residual stresses formed in the surface layer of the machined part [2], and the microhardness of this layer. Defects appear on the machined surfaces of blanks made of materials with low temperatures of decomposition and melting, in particular plastics. It has been found that plastics are easily plastically deformed during machining due to heating [3]. The work [4] confirms that due to the low melting temperature, plastics are prone to undesirable plastic deformation during machining and to the formation of burrs.

The temperature of the tool surfaces in contact with the blanks and chips influences the wear rate, service life and strength of the tool, i.e. its performance [5]. Therefore, research into the patterns of formation of temperature fields of machining processes and the ability to control them are necessary to increase machining productivity and ensure the quality of the machined parts.

The efficiency of cutting processes increases with the use of vibrations, including ultrasonic vibrations (USV), since their use reduces cutting forces and temperatures in the cutting zone, which allows increasing the productivity of processing while ensuring the required quality of parts [6] or increasing the service life of the cutting tool. Analytical and experimental studies of mechanical treatment processes using USV have shown the possibility of reducing, due to their use, cutting forces (up to 2 times) and temperatures in the cutting zone during turning and boring [7], grinding [8] and gear milling [9].

A widely used processing method is milling with cylindrical and end mills. In the milling process, the thickness of the cut per one tooth of the tool changes depending on the position of the tooth on the trajectory of its contact with the blank. The variable thickness of the cut causes a change in many parameters of the process of treatment, including cutting and friction forces, powers and densities of heat sources. The process of heating the cutter tooth is non-stationary. The tooth heats up in a short period of time while in contact with the blank, then cools down. When modelling this process, the mutual influence of heat sources from successively operating teeth should also be taken into account. Experimental studies indicating an increase in the efficiency of the milling process using USV have been carried out, in particular, when machining non-rigid parts [10] and blanks made of corrosion-resistant steels [11].

The results of numerical modelling of the temperature field of the process of milling using ultrasonic vibrations, carried out on the basis of an analytical study of this process, are given in [12] with varying the pitch of the cutter teeth and in [13] with varying the thermal conductivity of the cutter material. However, these results were obtained with the ratios of the vibration amplitude A to the maximum depth of penetration of the cutter tooth (cutting plate) into the blank a_{mmax}, at which the tooth does not come out of contact with the blank, while at different moments of contact time during processing with ultrasonic vibrations, the depth of tooth penetration can be both greater and less than the depth achieved during processing without vibrations (Fig. 1 a). When the values of these parameters differ insignificantly or the amplitude A exceeds the value a_{mmax}, in certain sections of the trajectory of contact with the blank, the tooth comes out of contact (Fig. 1 b).

When using ultrasonic vibrations in the cutting process, the reduction of thermal and force intensity is ensured by changing the kinematic parameters of the cutting process, reducing the friction coefficients in the cutting zone [7] and changing the mechanical characteristics of the blank material [14]. During the period when the tooth leaves contact with the blank, the cutting and friction forces, power and density of heat sources are zero, therefore, with an increase in the ratio of the USV amplitude A to the depth of tooth penetration into the blank, the effect of changing the kinematics of the process of treatment should be higher. However, to calculate the temperature field of this process, it is necessary to develop appropriate physical and mathematical models. These models should take into account, in particular, that the boundary conditions on the surfaces of the cutting plate (cutter tooth) and the blank change with USV imposition if the plate leaves contact with the blank. When the cutting plate contacts the blank, heat flows are directed to the blank, chips and plate (milling cutter tooth), i.e. the conditions of thermal interaction within the zones of contact of the plate with the chips and the blank are described by boundary conditions of the 2[nd] type. When the milling cutter plate comes out of contact with the blank and the chip formation process stops, the heat flows disappear on all surfaces of the plate and the blank that are in contact with the environment (cutting fluid or air), and the convective heat exchange is expressed by the Newton–Richmann law (boundary conditions of the 3[rd] type).

The purpose of this study is to develop physical and mathematical models of the milling process with the imposition of ultrasonic vibrations (USV), allowing identifying the influence of vibrations on the efficiency of the milling process at different ratios of the vibration amplitude to the depth of tooth penetration into the blank.

METHODS

In the thermophysical analysis of cutting processes, three sources of heat generation are usually taken into account [15]. Therefore, we assume that during milling, heat is generated in the deformation (chip formation) zone and in the zones of contact of the chip with the cutting plate (front surface of the cutter tooth) and the plate (rear surface of the tooth) with the blank, where friction forces act.

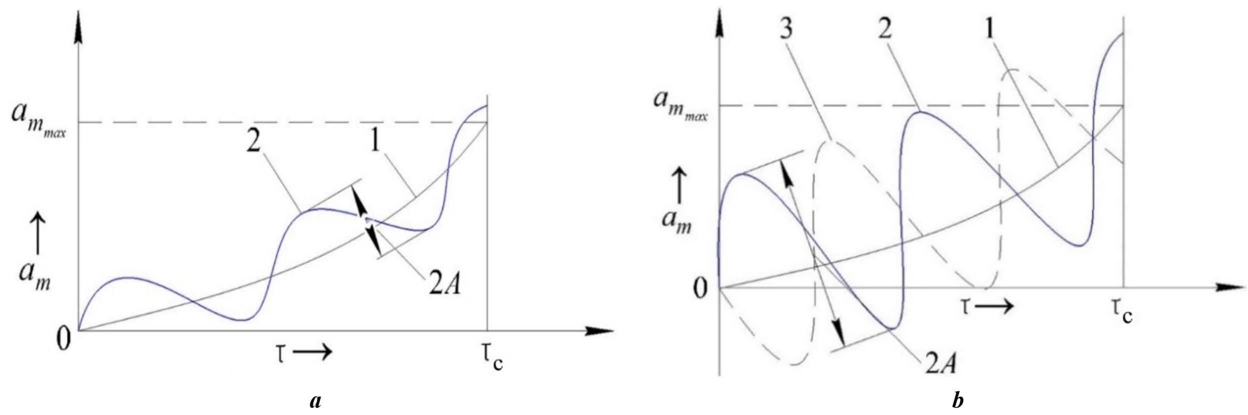

Fig. 1. *Dependence of the depth of tooth penetration into the blank a_m on the contact time τ:*
1 – without the use of ultrasonic vibrations; 2 – with the use of ultrasonic vibrations at a phase shift of φ=0°;
3 – with the use of ultrasonic vibrations at a phase shift of φ=180°. ***a*** *– $2A<a_{mmax}$;* ***b*** *– $2A=a_{mmax}$*

Рис. 1. *Зависимость глубины внедрения зуба в заготовку a_m от времени контакта τ:*
1 – без применения УЗК; 2 – с применением УЗК при сдвиге фазы φ=0°;
3 – с применением УЗК при сдвиге фазы φ=180°. ***a*** *– $2A<a_{mmax}$;* ***b*** *– $2A=a_{mmax}$*

The studies were carried out for the process of counter milling with cylindrical cutters and the periphery of end mills for the case when one tooth (plate) is located on the contacttrajectory in the plane perpendicular to the cutter axis. Thermal resistance in the zones of contact of the cutting plate with the chip and the blank is not taken into account. Therefore, it is assumed that the temperature at any point in the contact zones of these objects is the same.

The heat transfer diagram is shown in Fig. 2.

RESULTS

The powers of heat sources in the deformation (chip formation) zone W_g and in the zones of contact of the cutting plate with the chip (W_{1T}), and the blank (W_{2T}) change depending on the position of the tooth on the trajectory of the contact with the blank (contact time τ) and are calculated using the dependencies [16]:

$$W_g(\tau) = P_Z(\tau)\cdot V - \left(W_{1T}(\tau) + W_{2T}(\tau)\right);$$

$$W_{1T}(\tau) = F_1(\tau)\cdot V_1;$$

$$W_{2T}(\tau) = F_2(\tau)\cdot V,$$

where $P_z(\tau)$ is the main component of the cutting force of the cutter plate changing along the contact trajectory, N;
$F_1(\tau)$ and $F_2(\tau)$ are the friction forces in the zones of contact of the plate with the chip and the blank, respectively, N;
V is the cutting speed, m/s;
V_1 is the speed of chip movement relative to the cutting plate (front surface of the tooth), m/s;
$V_1=V/k_c$, where k_c is the chip thickening coefficient;
τ is the time, s.

To calculate the main component of the force $P_z(\tau)$ and the friction forces $F_1(\tau)$ and $F_2(\tau)$, the authors transformed the dependencies [17] obtained under the condition that the assessment of the destruction of the blank material is made on the basis of the plastic flow theory (“plastic flow method”). The angle of inclination of the chip groove of the cutter in the calculation dependencies is not taken into account, since the dependence of the force $P_z(\tau)$ and friction forces on this angle is insignificant [18].

Dependencies for calculating the forces:

$$P_z(\tau) = 1.155\cdot\sigma_{st}\cdot u\cdot a_m(\tau)\cdot b\times$$
$$\times\left(D\cdot\cos\gamma + \frac{k_c}{4u\cdot\cos\gamma} + \mu\cdot\sin\gamma + \frac{\mu_2\cdot l_2(\tau)}{u\cdot a_m(\tau)} + \frac{k_c\cdot a_m(\tau)}{4u\cdot b\cdot\cos\gamma}\right);$$

$$D = \left[1 + \mu_1(1 - \mathrm{tg}\gamma) + \frac{(0.5+\mu)\cdot u}{2k_c}\right];$$

$$F_1(\tau) = 1.155\cdot\sigma_{st}\cdot u\cdot a_m(\tau)\cdot b\cdot\left(\mu + \frac{\mu_1(1-\mathrm{tg}\gamma)}{\sin\gamma}\right);$$

$$F_2 = 1.155\cdot\mu_2\cdot\sigma_{st}\cdot l_2(\tau)\cdot b,$$

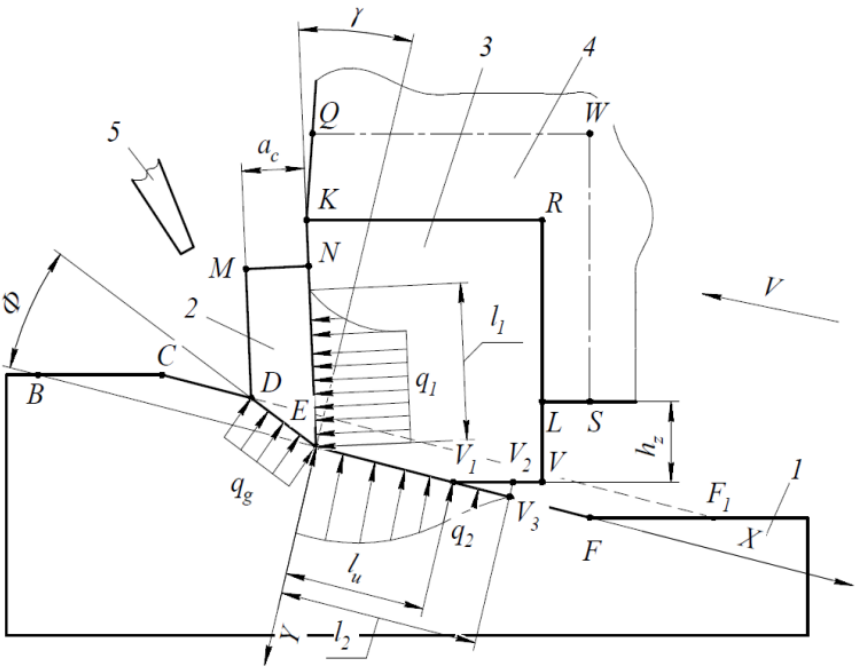

Fig. 2. *Diagram of heat transfer during cut-up milling:*
1 – blank; 2 – chips; 3 – cutting plate; 4 – cutter body; 5 – cutting fluid supply nozzle
Рис. 2. *Схема теплообмена в процессе встречного фрезерования:*
1 – заготовка; 2 – стружка; 3 – режущая пластина;
4 – корпус фрезы; 5 – сопло для подачи СОЖ

where σ_{st} is the yield stress of the blank material in the deformation region, determined depending on the temperature in this region, Pa;
μ is the friction coefficient for yield stress;
μ_1, μ_2 are the coefficient of friction of the chip on the plate (front surface of the tooth) and the plate (tooth) on the blank;
γ is the cutting plate rake angle, deg.;
l_2 is the size (length) of the plate-blank contact zone, m;
u is the coefficient;
$a_m(\tau)$ is the depth of plate penetration into the blank depending on contact time τ, m;
b is the size of the machined surface in the direction parallel to the cutter axis, m.

To calculate the $a_m(\tau)$ parameter, a dependence [16] is proposed, the arguments of which are: the amplitude of the ultrasonic vibrations in the direction perpendicular to the machined surface A_u; the vibration frequency f; the time of contact of the cutting plate (tooth) with the blank τ; the depth of plate penetration into the blank a, depending on the feed per cutter tooth S_z and the angle of contact of the plate with the blank.

The length of the contact zone l_2 can be determined by the dependence:

$$l_2 = l_u + \frac{h_u}{tg\alpha},$$

where α is the clearance angle, deg.;
l_u is the size of the wear area on the plate, m;
h_u is the height of the elastic uplift of the blank material [19]:

$$h_u = 1.155 \cdot \frac{\sigma_{sz}}{E_z} \cdot h \cdot B;$$

$$B = \sin^2\gamma + \mu_1 \cdot (1 - tg\gamma) + \frac{0.5 + \mu}{k_c} - \mu \cdot \sin 2\gamma,$$

where h is the size of the blank in the direction perpendicular to the machined surface, m;
σ_{sz} is the yield stress of the blank material in the deformation zone, Pa;
E_z is the elastic modulus of the blank material in the zone of contact of the plate (tooth) with the blank, determined depending on the temperature in this zone, Pa.

The size of the wear area l_u is related to the radial wear h_u by the dependence:

$$l_u = h_u \cdot (\text{ctg}\alpha - tg\gamma).$$

Since the parameters being the arguments of this dependence depend to a small extent on the τ time of contact of the tooth with the blank, we assume that the friction force F_2 also does not depend on τ. This assumption is confirmed by the results of subsequent numerical modelling.

The yield stress of the blank material in the deformation zone σ_{st} is calculated using the formula [17] depending on the temperature T_d in this zone and the melting temperature T_{melt} of the blank material.

The heat generation density in the chip formation zone with a uniform law of heat source power distribution [15]:

$$q_g(\tau) = \frac{W_g(\tau) \cdot \sin\Phi}{a_m \cdot b},$$

where Φ is the shear angle, deg.

We assume that the power of the heat source in the contact zone of the chip with the front surface of the cutter tooth is distributed according to a combined law, which is a combination of two laws – uniform and exponential [15], and the maximum density of the heat source with this law is:

$$q_{1\text{T}}(\tau) = \frac{1.5 \cdot W_{1\text{T}}(\tau)}{b \cdot l_1(\tau)}.$$

The size (length) of the zone of contact of the cutting plate with the chip is a variable value on the trajectory of contact of the plate with the blank and can be determined using the formula obtained by transforming the dependence [20]:

$$l_1(\tau) = a_m(\tau) \cdot k_c^{0.1} \cdot \left[k_c \cdot (1 - \text{tg}\gamma) + \sec\gamma\right].$$

Heat release density in the section located at a distance x_{u1} from the section with the maximum heat release density:

$$q_{1T}(x_{u1}, \tau) = q_{1T}(\tau) \cdot \exp\left[-k_{01} \cdot x_{u1}\right],$$

where k_{01} is the coefficient, m^{-1}.

Heat release density (maximum) in the zone of contact of the plate with the blank for an asymmetric normal law of the heat release source power distribution [15]:

$$q_{2\text{T}}(\tau) = \frac{2 \cdot W_{2\text{T}}(\tau) \cdot \sqrt{k_0}}{b \cdot \sqrt{\pi} \cdot \text{erf}\left[l_2\sqrt{k_0}\right]},$$

where k_0 is the coefficient;
erf is a function depending on the k_0 and l_2 parameters.

Heat release density in the section located at a distance x_u from the section with the maximum heat release density [16]:

$$q_{2T}(x_u, \tau) = q_{2T}(\tau) \cdot \exp\left[-k_0 \cdot x_u^2\right].$$

When machining with a cutter equipped with a replaceable multi-faceted plate, the heat conductivity equations for the blank 1, chip 2, plate 3, and cutter body 4 (Fig. 2) are as follows:

$$\frac{\partial T_1}{\partial \tau} = \left[\frac{\partial}{\partial x}\left(\frac{\lambda_1}{c_1 \cdot \rho_1} \cdot \frac{\partial T_1}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_1}{c_1 \cdot \rho_1} \cdot \frac{\partial T_1}{\partial y}\right)\right] - V \cdot \frac{\partial T_1}{\partial x};$$

$$\frac{\partial T_2}{\partial \tau} = \left[\frac{\partial}{\partial x}\left(\frac{\lambda_1}{c_1 \cdot \rho_1} \cdot \frac{\partial T_2}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_1}{c_1 \cdot \rho_1} \cdot \frac{\partial T_2}{\partial y}\right)\right] - V_1 \cdot \cos\gamma \frac{\partial T_2}{\partial y} - V_1 \cdot \sin\gamma \frac{\partial T_2}{\partial x};$$

$$\frac{\partial T_3}{\partial \tau} = \left[\frac{\partial}{\partial x}\left(\frac{\lambda_3}{c_3 \cdot \rho_3} \cdot \frac{\partial T_3}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_3}{c_3 \cdot \rho_3} \cdot \frac{\partial T_3}{\partial y}\right)\right];$$

$$\frac{\partial T_4}{\partial \tau} = \left[\frac{\partial}{\partial x}\left(\frac{\lambda_4}{c_4 \cdot \rho_4} \cdot \frac{\partial T_4}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_4}{c_4 \cdot \rho_4} \cdot \frac{\partial T_4}{\partial y}\right)\right],$$

where λ_1, λ_3, λ_4 are the coefficients of thermal conductivity of the materials of the blanks (chips), cutting plate and cutter body, respectively, W/(m·K);
c_1, c_3, c_4; ρ_1, ρ_3, ρ_4 are the heat capacities (J/(kg·K)) and densities (kg/m^3) of the materials of these objects;
T_1, T_2, T_3, T_4 are the temperatures of the blanks, chips, plate and cutter body, respectively, K.

We assume that the thermophysical characteristics of the chips are equal to the corresponding characteristics of the blank ($c_2=c_1$, $\rho_2=\rho_1$, $\lambda_2=\lambda_1$).

When machining with a cutter without a plate, the thermophysical characteristics of the cutter body are equal to the corresponding characteristics of the cutter tooth ($c_4=c_3$, $\rho_4=\rho_3$, $\lambda_4=\lambda_3$), then the last equation will have the form:

$$\frac{\partial T_4}{\partial \tau} = \left[\frac{\partial}{\partial x}\left(\frac{\lambda_3}{c_3 \cdot \rho_3} \cdot \frac{\partial T_4}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\lambda_3}{c_3 \cdot \rho_3} \cdot \frac{\partial T_4}{\partial y}\right)\right].$$

This form of recording differential equations of thermal conductivity assumes that the physical characteristics of the materials of the blank, cutter body and plate (cutter tooth) depend on temperature.

Initial condition: the temperature of all objects at the initial moment of time $T(x, y, 0)=T_a$, where T_a is the ambient temperature (air and/or coolant).

Within the contact zone EV_3 of blank 1 and plate (tooth) 3, the thermal interaction is expressed by the boundary condition of the 2nd type [16]:

$$\frac{\partial T_1}{\partial y} = -\frac{q'_{2T}(x_u)}{\lambda_1(T_1)}; \ \frac{\partial T_3}{\partial y} = -\frac{q''_{2T}(x_u)}{\lambda_3(T_3)};$$

$$T_{1k} = T_{3k}; \ q'_{2T}(x_u) + q''_{2T}(x_u) = q_{2T}(x_u),$$

where $q'_{1T}(x_{u1})$, $q''_{1T}(x_{u1})$ are the heat flows directed to blank 1 and plate (cutter tooth) 3, respectively, at a distance x_{u1} from the section with the maximum heat release density, W/m^2;
T_{1k}, T_{3k} are the temperatures on the surfaces of blank 1 and plate (cutter tooth) 3 within their contact zone, K.

Similar boundary conditions of the 2nd type can express thermal interaction within the contact zone DE of blank 1 with chip 2 and within the contact zone EN of chip 2 with plate (tooth) 3 in the section with maximum heat generation density.

Boundary condition of the 2nd type within the zone EN in the section with variable heat generation density:

$$\frac{\partial T_2}{\partial n} = -\frac{q'_{1T}(x_{u1})}{\lambda_1(T_2)}; \ \frac{\partial T_3}{\partial n} = -\frac{q''_{1T}(x_{u1})}{\lambda_3(T_3)};$$

$$T_{2k1}(x_{u1}) = T_{3k1}(x_{u1}); \ q'_{1T}(x_{u1}) + q''_{1T}(x_{u1}) = q_{1T}(x_{u1}),$$

where $q'_{1T}(x_{u1})$, $q''_{1T}(x_{u1})$ are heat flows directed to chip 2 and plate (cutter tooth) 3, respectively, at a distance x_{u1} from the section with maximum heat generation density, W/m^2;
$T_{2k1}(x_{u1})$, $T_{3k1}(x_{u1})$ are temperatures on the surfaces of chip 2 and plate (cutter tooth) 3 within the zone of their contact at a distance of x_{u1} from the section with the maximum heat release density, K.

We assume that at the junction of plate 3 with cutter body 4, the thermal resistance is insignificant, therefore the temperatures of the contacting surfaces of the plate T_{3k2} and body T_{4k} are equal (boundary condition of the 4th type): $T_{3k2}=T_{4k}$.

Heat transfer from the surfaces of the objects participating in heat exchange – the cutting plate, cutter body, chip and blank contacting with the environment (cutting fluid or air) is expressed by the Newton–Richmann law (boundary conditions of the 3rd type) [16]. One of the arguments of the dependence describing this law is the coefficient of heat transfer from the surface. The heat transfer coefficients to the environment (cutting fluid and air) depend on the temperatures of these surfaces, which are not known in advance. Therefore, if a preliminary calculation of the coefficients is performed without taking into account the actual surface temperatures, unreliable results can be obtained.

When solving analogues of differential heat conduction equations using the numerical finite element method, the calculation of heat transfer coefficients is performed in parallel with the calculation of heat conduction equations. When calculations are performed using this method, the time, during which the heat exchange process is considered, is divided into finite small intervals $\Delta\tau$. The temperatures of objects determined at the previous moment in time are used to calculate heat transfer coefficients at the current moment, and the obtained values of the coefficients are used to calculate the temperature field at the next moment.

If the surface temperature of the object exchanging heat with the cutting fluid (NK, V_2V and VL of the plate (tooth), MD and MN of the chip, CD, V_3F, BC and FF_1 of the blank, KQ and LS of the cutter body (Fig. 2)) is lower than its boiling point, then the heat transfer coefficient in the cutting fluid is

$$\alpha_g = \frac{Nu_f \cdot \lambda_{gf}}{\ell_x},$$

where Nu_f is the Nusselt criterion;
λ_{gf} is the thermal conductivity coefficient of the cutting fluid, W/(m·K);
ℓ_x is the characteristic surface size, m.

As a characteristic size, we can take: for chips – their thickness a_c, for a blank – the size of the contact trajectory FB of the plate (cutter tooth) with the blank, and for the plate (cutter tooth) – the size h (Fig. 2).

The Nu_f criterion is calculated using the equation:

$$Nu_f = C \cdot Re_f^m \cdot Pr_f^n \cdot \left(Pr_f / Pr_w\right)^k,$$

where C, m, n, k are coefficients whose values are determined by the surface shape and the coolant flow mode (laminar, transitional, turbulent);
the Prandtl number Pr and Reynolds number Re:

$$Pr_f = \frac{\mu_{gf} \cdot c_{gf}}{\lambda_{gf}};$$

$$Re_f = \frac{V_g \cdot \ell_x}{\nu_{gf}},$$

where μ_g is the dynamic viscosity of the cutting fluid, Pa·s;
c_g is the specific heat capacity of the cutting fluid, J/(kg·K);
ν_g is kinematic viscosity of the cutting fluid, m^2/s;
V_g is the speed of the cutting fluid movement, which can be calculated in cut-up milling as

$$V_g = V_{g1} + V,$$

where V_{g1} is the speed of the cutting fluid flow from the nozzle used to supply it, m/s.

Parameters with f index in their designations are determined based on the temperature of the cutting fluid at the nozzle outlet; if w index is used in the parameter designation, it is determined depending on the average temperature of the corresponding surface.

In most cases, a mixture of cutting fluid and air is present in the cutting zone; therefore, the calculations use the reduced heat transfer coefficients, which depend on the percentage of air in the air-liquid mixture.

If the surface temperature of the object participating in the heat exchange exceeds the boiling point of the liquid, the calculations use the reduced heat transfer coefficient, the value of which depends on the heat transfer coefficient during coolant boiling α_k.

To calculate the α_k coefficient, you can use the equation

$$Nu_k = C_k \cdot Re_k^m \cdot Pr_k^{0.33},$$

where C_k and m are coefficients;
$Nu_k = \alpha_k \cdot l_{x1} / \lambda_{g1}$;
$\mathrm{Re}_k = w_k \cdot l_{x1} / \nu_{g1}$;
$\mathrm{Pr}_k = \nu_{g1} / a_{g1}$,
where λ_{g1}, ν_{g1} are physical parameters of the cutting fluid at the saturation temperature;
w_k is conventional boiling speed of cutting fluid vapor, m/s;
a_{g1} is thermal diffusivity coefficient of the cutting fluid at the saturation temperature, m^2/s;
ℓ_{x1} is characteristic size of the surface whose temperature exceeds the cutting fluid saturation temperature, m.

Coefficient of heat transfer to air is

$$\alpha_b = \frac{Nu_{bf} \cdot \lambda_{bf}}{\ell_x},$$

where λ_{bf} is thermal conductivity coefficient of air, W/(m·K);
Nu_{bf} is Nusselt criterion calculated using dependencies similar to those for calculating Nu_f.

When applying ultrasonic vibrations, the depth of the plate (tooth) penetration into the blank changes. If the vibration amplitude A_y exceeds the depth of the plate (tooth) penetration into the blank, the plate may come out of contact with the blank. During the absence of contact between the tooth surface and the blank, which were subject to the above boundary conditions of the 2nd type during cutting, heat will be exchanged with the environment (cutting fluid or air), and the boundary conditions will change.

For the surfaces of the blank and the cutter tooth, the boundary conditions of the 3rd type will take the form:

$$-\lambda_1(T_1) \cdot \frac{\partial T_1}{\partial n} = \alpha_1 \cdot \left(T_{1f} - T_w\right);$$

$$-\lambda_3(T_3) \cdot \frac{\partial T_3}{\partial n} = \alpha_3 \cdot \left(T_{3f} - T_w\right),$$

where α_1 and α_3 are the coefficients of heat transfer to the environment from the surfaces of the blank and the plate (cutter tooth), respectively, $W/(m^2 \cdot K)$;
T_w is the temperature of the environment (cutting fluid or air), K;
T_{1f}, T_{3f} is the temperature of the flow surface of the blank and the plate (tooth), respectively, K.

To solve the equations of thermal conductivity of the objects participating in the heat exchange, the numerical finite element method is used.

Discrete analogues of differential equations of heat conductivity are obtained based on the fact that the sum of all heat flows entering and leaving the element under consideration over a time interval $\Delta\tau$ is equal to the change in the enthalpy of this element (finite volume). To ensure the stability of the numerical solution of discrete analogues of differential equations of heat conductivity, expressions are obtained for calculating the limitations per a step of the difference grid.

The temperature of the deformable layer is used in the programme when calculating the yield stress of the blank material in the chip formation area.

The adequacy of the above method for calculating the temperature field was assessed by comparing the calculated value of the average temperature in the surface layer of the blank with the results of its measurement by a semi-artificial thermocouple. The difference between the calculated and experimental values does not exceed 12 %, which indicates the possibility of using the proposed method.

Using the developed software, the process of milling polycarbonate blanks was simulated at a cutting speed of

V=8 m/s using ultrasonic vibrations with a frequency of 18,600 Hz and an amplitude of A=10 μm. The imposition of vibrations in the direction perpendicular to the blank surface being machined was simulated.

The maximum depth of tooth penetration into the blank depends on the elements of the milling mode – the cutting depth t and the feed per tooth S_Z. Consequently, with a fixed ultrasonic vibration amplitude, different ratios A/a_{mmax} can be achieved by varying these elements of the mode.

When machining without ultrasonic vibrations with a cutting depth of t=0.5 mm and a feed per tooth of S_z=0.12 mm/tooth, the maximum depth of tooth penetration into the blank is a_{mmax}=36 μm, and when applying ultrasonic vibrations, the ratio A/a_{mmax} is 0.27. In this case, the tooth comes out of contact only during the initial period of its contact with the blank. With further movement of the tooth along the contact trajectory, the application of vibrations leads to a change in the depth of tooth penetration, both decreasing and increasing. Therefore, changing the kinematics of the milling process due to the use of vibrations at small values of the ratio A/a_{mmax} does not have a noticeable effect on the efficiency of the process.

In the mode of t=0.1 mm and S_z=0.05 mm/tooth, when machining without ultrasonic vibrations, the value of a_{mmax} is 7.6 μm, i.e. less than the vibration amplitude, the ratio A/a_{mmax} is 1.3. In this case, when vibrations are applied, the contact of the tooth with the blank is interrupted throughout the entire trajectory of the tooth movement relative to the surface being machined. When machining with ultrasonic vibrations in a mode with the ratio A/a_{mmax}=1.3, compared to machining without vibrations, the force P_z decreased by 45 %, and the temperatures in the contact zones of the tooth with the chips and the blank decreased by 15 %. At lower ratios A/a_{mmax}, these parameters decreased to a lesser extent.

DISCUSSION

The developed set of mathematical models and dependencies for calculating the main component of cutting force and temperatures during milling has the following differences from the dependencies given in works [6; 15].

1. The change in the depth of tooth (cutting plate) penetration into the blank is taken into account when using ultrasonic vibrations.

2. The change in the boundary conditions on the surfaces of the tooth and the blank is taken into account if, when using ultrasonic vibrations, the plate comes out of contact with the blank. In work [6], heat transfer from the surfaces of objects participating in heat exchange is not taken into account.

3. The models allow taking into account the dependence of the thermophysical properties of objects (milling cutter, blank and chips) on temperature and the effect of the temperature of the deformed layer of the blank material on the deformation stresses and cutting forces of individual milling cutter teeth.

The proposed method for numerically solving analogues of differential equations of heat conductivity with general boundary conditions in the contact zone of objects allows determining the distribution densities of heat flows between the contacting objects (milling cutter, chips and blank).

The developed method and software make it possible to take into account the influence of a larger number of factors on the temperature field than, for example, in [6]: the dimensions of the blank and the milling cutter, including the tooth angles (cutting plate); wear of the milling cutter; thermophysical characteristics of the materials of the blank and the milling cutter (cutting plate); yield strength of the blank material; friction coefficients; elements of the milling mode (cutting depth, cutting speed and feed); thermophysical characteristics of the external environment (cutting fluid and air); the rate of cutting fluid flow through the nozzle for its supply; the number of successively working teeth of the milling cutter, etc., and also to determine both the temperature in the surface layers of the blank and the temperatures in the contact zones of the tooth with the chips and the blank and the temperature of the chips.

The assumption that the effect of using ultrasonic vibrations during milling is higher at higher values of the A/a_{mmax} ratio was confirmed. Previously conducted studies have found a decrease in cutting forces during turning [7] and grinding [8] with an increase in the vibration amplitude. In [9], it is noted that the efficiency of using ultrasonic vibrations during gear milling increases with an increase in the amplitude. Consequently, the results of numerical modelling indicating a decrease in the thermal and force stress of the milling process correlate with studies conducted using other processing methods.

One of the reasons for the decrease in forces and temperatures is a change in the kinematic parameters of the milling process with an increase in the ultrasonic vibration amplitude, as it has been found in other studies [7; 9].

In the present study, it was found that the use of ultrasonic vibrations during milling leads to a decrease in the milling force to a greater extent (by 45 %) than in temperatures (by 15 %). The obtained result coincides with the study [9], which also recorded that temperatures decrease to a lesser extent than cutting forces.

CONCLUSIONS

1. Analytical studies of the temperature field were performed and software was developed that allows establishing the influence of ultrasonic vibrations on the parameters of the milling process at different ratios of the vibration amplitude to the depth of tooth penetration into the blank.

2. It was found that changing the kinematics of the milling process using ultrasonic vibrations has a more significant effect on the process parameters at a cutting mode that provides a greater ratio of the vibration amplitude to the depth of penetration.

3. The results of the studies will allow predicting the efficiency of the milling process with ultrasonic vibrations at different processing modes.

REFERENCES

1. Khramov A.V., Gorshkov M.G., Nguen Kh.T., Kiselev E.S. Improving the efficiency of turning heat-resistant alloys by introducing the energy of an ultrasonic field into the cutting zone. *Voronezh Scientific and technical Jour-*

nal, 2023, vol. 2, no. 2, pp. 4–10. DOI: 10.34220/2311-8873-2023-4-10.
2. Evdokimov D.V., Skuratov D.L., Bukatyy A.S. Technological residual deformations prediction of GTE blades by numerical method after end milling. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences*, 2022, vol. 24, no. 1, pp. 11–19. DOI: 10.37313/1990-5378-2022-24-1-11-19.
3. Alauddin M., Choudhury I.A., El Baradie M.A., Hashmi M.S.J. Plastics and their machining: A review. *Journal of Materials Processing Technology*, 1995, vol. 54, no. 1-4, pp. 40–46. DOI: 10.1016/0924-0136(95)01917-0.
4. Jahan M.P., Ma Jianfeng, Hanson C., Chen Xingbang, Arbuckle G.K. Experimental and numerical investigation of cutting forces in micro-milling of polycarbonate glass. *Machining Science and Technology*, 2019, vol. 24, no. 3, pp. 366–397. DOI: 10.1080/10910344.2019.1698608.
5. Duan Zhenjing, Li Changhe, Ding Wenfeng et al. Milling Force Model for Aviation Aluminum Alloy: Academic Insight and Perspective Analysis. *Chinese Journal of Mechanical Engineering*, 2021, vol. 34, article number 18. DOI: 10.1186/s10033-021-00536-9.
6. Bezyazychnyy V.F. The development of the research of thermal processes in mechanical engineering technology. *Spravochnik. Inzhenernyi zhurnal*, 2024, no. 8, pp. 38–48. DOI: 10.14489/hb.2024.08.pp.038-048.
7. Kumabe D. *Vibratsionnoe rezanie* [Vibrating cutting]. Moscow, Mashinostroenie Publ., 1985. 424 p.
8. Unyanin A.N., Khazov A.V. Analytical study of grinding forces with the imposition of ultrasonic vibrations with high amplitude. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences,* 2022, vol. 24, no. 1, pp. 37–43. DOI: 10.37313/1990-5378-2022-24-1-37-43.
9. Agapov S.I., Prokhvatilov A.S., Bezrukov E.K., Potapov A.A. Peculiarities of the process of ultrasonic vibration machining. *Izvestiya Volgogradskogo gosudarstvennogo tekhnicheskogo universiteta*, 2019, no. 8, pp. 7–10. EDN: CZJTYY.
10. Kiselev E.S., Nazarov M.V. *Osobennosti tekhnologii izgotovleniya nezhestkikh korpusnykh detaley* [Special aspects of the technology of manufacturing non-rigid body parts]. Moscow, RUSAYNS Publ., 2022. 218 p. EDN: JUSXTL.
11. Ivanova T.N. Modern technological techniques improving the efficiency of mechanical processing corrosion-resistant steels, working in aggressive environments. *University proceedings. Volga region. Technical sciences*, 2024, no. 4, pp. 143–156. DOI: 10.21685/2072-3059-2024-4-12.
12. Unyanin A.N., Dimukhametov I.Z. Investigation of the Effect of Milling Cutter Tooth Spacing and Milling Mode Features on the Process of Machining Polycarbonate Workpieces Using Ultrasonic Vibrations. *Russian Engineering Research*, 2024, vol. 44, no. 9, pp. 1317–1322. DOI: 10.3103/S1068798X24702010.
13. Unyanin A.N., Dimukhametov I.Z. Influence of Tool's Thermal Conductivityon Milling with Ultrasound. *Russian Engineering Research*, 2024, vol. 44, no. 11, pp. 1598–1601. DOI: 10.3103/S1068798X24702617.
14. Vologin M.F., Kalashnikov V.V., Nerubay M.S., Shtrikov B.L. *Primenenie ultrazvuka i vzryva pri obrabotke i sborke* [Application of ultrasonic vibrations and explosion when processing and assembling]. Moscow, Mashinostroenie Publ., 2002. 264 p.
15. Reznikov A.N., Reznikov L.A. *Teplovye protsessy v tekhnologicheskikh sistemakh* [Thermal Processes in Technological Systems]. Moscow, Mashinostroenie Publ., 1990. 288 p. EDN: SCUAQX.
16. Unyanin A.N., Dimukhametov I.Z. Study of the influence of cutter wear and mode on the parameters of the process of milling blanks of polycarbonate parts using ultrasonic vibrations. *Izvestia of Samara Scientific Center of the Russian Academy of Sciences*, 2024, vol. 26, no. 3, pp. 54–62. EDN: CRNSBF.
17. Vorontsov A.L., Sultan-Zade N.M., Albagachiev A.Yu. Development of a new theory of cutting. 9. Practical calculations of cutting parameters in turning. *Russian Engineering Research*, 2008, vol. 28, no. 9, pp. 878–888. DOI: 10.3103/S1068798X08090116.
18. Bobrov V.F. *Osnovy teorii rezaniya metallov* [Fundamentals of metal cutting theory]. Moscow, Mashinostroenie Publ., 1975. 344 p.
19. Vorontsov A.L., Sultan-Zade N.M., Albagachiev A.Yu. Development of a new theory of cutting 7. Mathematical description of the formation of different chips, pulsation of the cutting force, and contact parameters of the machined billet surface and the rear cutter surface. *Russian Engineering Research*, 2008, vol. 28, no. 7, pp. 674–680. DOI: 10.3103/S1068798X08070101.
20. Vorontsov A.L., Sultan-Zade N.M., Albagachiev A.Yu. Development of a new theory of cutting: 6. Determining the basic parameters of cutting. *Russian Engineering Research*, 2008, vol. 28, no. 6, pp. 571–578. DOI: 10.3103/S1068798X08060129.

СПИСОК ЛИТЕРАТУРЫ

1. Храмов А.В., Горшков М.Г., Нгуен Х.Т., Киселев Е.С. Повышение эффективности токарной обработки жаропрочных сплавов введением в зону резания энергии ультразвукового поля // Воронежский научно-технический вестник. 2023. Т. 2. № 2. С. 4–10. DOI: 10.34220/2311-8873-2023-4-10.
2. Евдокимов Д.В., Скуратов Д.Л., Букатый А.С. Расчетное прогнозирование технологических остаточных деформаций лопаток ГТД на этапе концевого фрезерования // Известия Самарского научного центра РАН. 2022. Т. 24. № 1. С. 11–19. DOI: 10.37313/1990-5378-2022-24-1-11-19.
3. Alauddin M., Choudhury I.A., El Baradie M.A., Hashmi M.S.J. Plastics and their machining: A review // Journal of Materials Processing Technology. 1995. Vol. 54. № 1-4. P. 40–46. DOI: 10.1016/0924-0136(95)01917-0.
4. Jahan M.P., Ma Jianfeng, Hanson C., Chen Xingbang, Arbuckle G.K. Experimental and numerical investigation of cutting forces in micro-milling of polycarbonate glass // Machining Science and Technology. 2019. Vol. 24. № 3. P. 366–397. DOI: 10.1080/10910344.2019.1698608.
5. Duan Zhenjing, Li Changhe, Ding Wenfeng et al. Milling Force Model for Aviation Aluminum Alloy: Academic Insight and Perspective Analysis // Chinese Journal of Mechanical Engineering. 2021. Vol. 34. Article number 18. DOI: 10.1186/s10033-021-00536-9.

6. Безъязычный В.Ф. Тепловые процессы в технологии машиностроения // Справочник. Инженерный журнал. 2024. № 8. С. 38–48. DOI: 10.14489/hb.2024.08.pp.038-048.
7. Кумабэ Д. Вибрационное резание. М.: Машиностроение, 1985. 424 с.
8. Унянин А.Н., Хазов А.В. Аналитическое исследование сил шлифования при наложении ультразвуковых колебаний с высокой амплитудой // Известия Самарского научного центра Российской академии наук. 2022. Т. 24. № 1. С. 37–43. DOI: 10.37313/1990-5378-2022-24-1-37-43.
9. Агапов С.И., Прохватилов А.С., Безруков Е.К., Потапов А.А. Особенности процесса ультразвуковой обработки // Известия Волгоградского государственного технического университета. 2019. № 8. С. 7–10. EDN: CZJTYY.
10. Киселев Е.С., Назаров М.В. Особенности технологии изготовления нежестких корпусных деталей. М.: РУСАЙНС, 2022. 218 с. EDN: JUSXTL.
11. Иванова Т.Н. Современные технологические приемы повышения эффективности механической обработки коррозионностойких сталей, работающих в агрессивных средах // Известия высших учебных заведений. Поволжский регион. Технические науки. 2024. № 4. С. 143–156. DOI: 10.21685/2072-3059-2024-4-12.
12. Unyanin A.N., Dimukhametov I.Z. Investigation of the Effect of Milling Cutter Tooth Spacing and Milling Mode Features on the Process of Machining Polycarbonate Workpieces Using Ultrasonic Vibrations // Russian Engineering Research. 2024. Vol. 44. № 9. P. 1317–1322. DOI: 10.3103/S1068798X24702010.
13. Unyanin A.N., Dimukhametov I.Z. Influence of Tool's Thermal Conductivityon Milling with Ultrasound // Russian Engineering Research. 2024. Vol. 44. № 11. P. 1598–1601. DOI: 10.3103/S1068798X24702617.
14. Вологин М.Ф., Калашников В.В., Нерубай М.С., Штриков Б.Л. Применение ультразвука и взрыва при обработке и сборке. М.: Машиностроение, 2002. 264 с.
15. Резников А.Н., Резников Л.А. Тепловые процессы в технологических системах. М.: Машиностроение, 1990. 288 с. EDN: SCUAQX.
16. Унянин А.Н., Димухаметов И.З. Исследование влияния износа фрезы и режима на параметры процесса фрезерования заготовок деталей из поликарбоната с применением ультразвуковых колебаний // Известия Самарского научного центра Российской академии наук. 2024. Т. 26. № 3. С. 54–62. EDN: CRNSBF.
17. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю. Разработка новой теории резания. 9. Практические расчеты параметров резания при точении // Вестник машиностроения. 2008. № 9. С. 67–76. EDN: JVNSAD.
18. Бобров В.Ф. Основы теории резания металлов. М.: Машиностроение, 1975. 344 с.
19. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю. Разработка новой теории резания. 7. Математическое описание образования стружки разных видов, пульсации сил резания и параметров контакта обработанной поверхности заготовки с задней поверхностью резца // Вестник машиностроения. 2008. № 7. С. 56–60. EDN: JVNRFJ.
20. Воронцов А.Л., Султан-заде Н.М., Албагачиев А.Ю. Разработка новой теории резания. 6. Определение основных параметров процесса резания // Вестник машиностроения. 2008. № 6. С. 64–70. EDN: JTDHZL.

УДК 621.91
doi: 10.18323/2782-4039-2025-3-73-7

Исследование температурного поля, формирующегося в процессе фрезерования с применением ультразвуковых колебаний, при различных режимах обработки

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Поступила в редакцию 14.04.2025 *Пересмотрена 05.06.2025* *Принята к публикации 18.06.2025*

Аннотация: Исследования температурного поля процесса фрезерования с наложением ультразвуковых колебаний (УЗК) при различных отношениях амплитуды колебаний к глубине внедрения зуба в заготовку позволят прогнозировать эффективность процесса фрезерования с УЗК при различных режимах обработки. Цель исследования – разработка физических и математических моделей процесса фрезерования с наложением УЗК, позволяющих установить влияние УЗК на эффективность процесса фрезерования при различных отношениях амплитуды колебаний к глубине внедрения зуба. Приняты во внимание три источника тепловыделения: в области деформирования (стружкообразования) и в зонах контакта стружки с режущей пластиной (зубом фрезы) и пластины с заготовкой. Разработаны модели теплообмена, учитывающие, в частности, изменение граничных условий на поверхностях режущей пластины и заготовки при наложении УЗК. Когда пластина находится в контакте с заготовкой, в заготовку, стружку и зуб фрезы направлены тепловые потоки, а условия теплового взаимодействия в пределах зон контакта пластины со стружкой и заготовкой описываются граничными условиями 2-го рода. Когда пластина при наложении УЗК выходит из контакта с заготовкой и процесс стружкообразования прекращается, то на всех поверхностях зуба (пластины) и заготовки, контактирующих с окружающей средой (смазочно-охлаждающей жидкостью или воздухом), конвективный теплообмен описывается законом Ньютона – Рихмана (граничные условия 3-го рода). Приведены результаты численного моделирования, подтвердившие предположение, что эффект от применения УЗК выше при больших значениях отношения амплитуды УЗК к глубине внедрения зуба в заготовку.

Ключевые слова: ультразвук; колебания; фрезерование; теплообмен; численное моделирование.

Благодарности: Исследование выполнено за счет гранта Российского научного фонда № 24-2900206, https://rscf.ru/project/24-29-00206/.

Для цитирования: Унянин А.Н., Чуднов А.В., Димухаметов И.З. Исследование температурного поля, формирующегося в процессе фрезерования с применением ультразвуковых колебаний, при различных режимах обработки // Frontier Materials & Technologies. 2025. № 3. С. 91–100. DOI: 10.18323/2782-4039-2025-3-73-7.