Modeling of the temperature field on the rake surface of the lathe cutter taking into account the evolution of cutting forces

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Abstract. This paper is devoted to modeling the temperature field on the rake surface of the hard alloy lathe cutter when turning the work piece from structural steel 30 for a given value of the operating time of the cutting system. The assessment of the thermal state is made taking into account the change in cutting forces during machining. To do this, a model of the evolution of the radial and axial components of the cutting force was built, taking into account its growth in time and the influence of irregular kinematic vibrational perturbations. The calculation of the average temperature values for each section of the rake surface was made on the basis of the scientific approach described earlier, according to which the heating of the contact occurs due to the viscous dissipation of the friction energy in the surface plastically deformed micro layers of the chip. The calculation of the temperature values along the rake surface was carried out by the finite element method on a solid-state model of a fragment of the cutting part of the tool, as a result of which temperature values for the control planes were obtained. The results of digital modeling demonstrate a good correspondence of the calculated temperature values to the experimental data obtained by the semi artificial thermocouple method. The error of modeling the temperature field without taking into account heat exchange with the environment was 7.7-8.6%.

1 Introduction

One of the most important characteristics of the cutting system is the temperature in the machining zone. High values of this parameter contribute to the manifestation of a number of factors unfavorable for the cutting process, among which we can highlight the deterioration of the tribological characteristics of the ‘tool-chip’ friction pair, an increase in the strength of thermal currents in the circuit, an intensification of the oxidative type of wear and a rapid increase in the size of the wear pit on the rake surface, etc. [1,2]. The temperature field on the rake surface of the cutting tool blade is formed due to heat generation in three successively located areas: in the zone of primary plastic deformations (PPD), in the zone of secondary plastic deformations (SPD) and the elastic contact zone (EC). The contact temperature

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reaches its maximum value at the border of the SPD and EC zones, in the same area due to the active access of oxygen the formation of a wear pit takes place [2].

Among the various directions for determining the temperature on the rake and flank surfaces of the tool blades, it is possible to distinguish a scientific approach based and developed at the Department of Metal-Cutting Machines and Tools of the Don State Technical University, and associated with the application of hydrodynamic analogies to the assessment of the SPD processes in the processed material [3-5]. In this case, the surface micro volume in the chip is considered as a zone of quasi-viscous flow of the material, the release of heat in which occurs due to the viscous dissipation of frictional energy. As a result of the application of this approach, mathematical dependencies describing the non-stationary temperature field in the subsurface plastically deformed layer of the processed material are obtained. These dependencies also make it possible to determine the change in the temperature of the ‘chip-rake surface’ contact over time.

The parameters that determine the contact temperature on a real cutting system and are taken into account as inputs in the mathematical model under consideration are characterized by both evolutionary changes and fluctuations as a result of vibrational perturbations of various types. These include, in particular, an increase over time in the cutting forces as well as the length of contact of the chip with the rake surface, resulting in a gradual increase in temperature. Fluctuations in these parameters lead to periodic or abrupt one-time changes in temperature. The consequences of these evolutionary changes in the dynamic cutting system are errors in the manufactured surface and the suboptimal consumption of the operational life of the cutting tool. Therefore, today it is of paramount importance to integrate the existing scientific base and analytically derived patterns based on experimental data and taking into account the evolutionary dynamics of the system into the composition of digital systems for designing processing processes on a metal-cutting machines.

The development of such digital systems, implemented in the form of a digital twin of the machining processes attracts special attention of the scientific community and the industrial sector. Their creation will help to increase productivity, reduce the financial costs of providing production with the necessary tools and reveal complex nonlinear relationships between cutting subsystems 6. There are a number of works devoted to the modeling of special cases occurring in the cutting process and affecting the quality of the manufactured surfaces and tool wear for systems of the "digital twin" type. An analysis of modern scientific material has shown that the most popular methods in the design of models of the cutting process are neural network modeling, the surface response method (RSM), numerical modeling of the ratios of cutting forces, tool geometry, technological modes and the method of finite elements and points [7-11]. It is important to note that globally the main changes in the dynamic cutting system are due mostly to the evolution of cutting forces, temperature gradients and external vibrational perturbation influences, which are interrelated with each other 12. Digital modeling of these factors and consideration of special cases of their manifestation in the dynamics of the cutting process was reflected in numerous works [13-16]. However, traditionally, when modeling the relationship, two or three parameters are used, the totality of which does not fully reflect the output characteristics of the cutting process. In the models of Elsadek, Gaafer etc. to predict and optimize the cutting temperature in the cutting zone when turning, a linear expression of the cutting temperature determination was proposed depending on the technological modes and the rigidity of the work piece [17]. As a result of the study, it was demonstrated that rigidity had a major effect on the temperature change in the cutting zone, and the modeling is consistent with the experiments conducted with an error of not more than 5%. The work of Yash R. Bhoyar provided a simulation model of the formation of the surface temperature of the tool in the contact zone based on 3D modeling by the finite element method 18. The main parameters of the model are technological modes, the main factor affecting the change in temperature is the cutting
forces, but it is worth noting that the article does not indicate information on the coordination of the results with full-scale experiments. The review article by Rodriguez, Carbonell & Jonsen provided comprehensive information on the methods and techniques for modeling the cutting process with particular emphasis on finite element modeling and its various variations as the method with the most interesting application potential. The paper also notes that the symbiosis of numerical and analytical solutions, establishing a connection between cutting subsystems and the CNC system, will create a powerful tool for designing digital dynamic cutting systems. Mathematical modeling and study of the influence of vibrations on the properties of the dynamic cutting system and the output characteristics of the quality of the machined surface were given in the work of Zakovorotny & Gvindjilija. These results in the publication reveal the relationship between external vibrations, cutting forces and the formed topology of the surface of the part.

The presented analysis of the works confirms the high importance of modeling the process of manufacturing parts on a metal-cutting machines, based both on the fundamental representation of the dynamic relationships between the cutting parameters (temperature, cutting forces, technological modes, external perturbations) and on modern numerical methods.

This work is devoted to modeling the temperature field on the rake surface of the cutter during turning on the basis of the evolution of cutting forces, taking into account the vibrational perturbations of the system, as well as subsequent comparison with experimental results. The purpose of the work is to develop and implement a method for predicting the temperature on the working surfaces of the tool. The task seems relevant, since it allows you to rationally choose both the modes and the duration of the cutting process while maintaining the specified parameters of accuracy and quality of processing.

2 Materials and methods

Temperature calculation and modeling of the temperature field on the rake surface was carried out for the process of longitudinal turning of the work piece made from structural steel with a diameter of 120 mm by a cutter with an insert made of hard alloy T15K6 without lubricant. Cutting speed \( v = 3 \) m/s, feed \( s = 0.43 \) mm/rev, cutting depth \( t = 1 \) mm, rake angle \( \gamma = 10^\circ \), clearance angle \( \alpha = 10^\circ \), main angle in plan \( \phi = 45^\circ \), generalized work piece weight \( m = 4 \times 10^{-3} \text{ kg·s}^2/\text{mm} \). The results of the simulation were compared with the results of a previous real experiment conducted with similar cutting modes.

The basic properties of the cutting system can be determined using the basic equation of tool dynamics relative to the workpiece:

\[
m \frac{d^2X}{dt^2} + h \frac{dX}{dt} + cX = F_\Sigma(X, t_p^{(0)}, S_p^{(0)}, V_p, \Delta X),
\]

where \( m, h, c \) are symmetrical, positively defined matrices with dimension 3x3; \( X = \{X_z, X_x, X_y\}^T \in \mathbb{R}^{3} \) - vector of elastic deformations of the tool relative to the bearing system; \( F_\Sigma(X, t_p^{(0)}, S_p^{(0)}, V_p, \Delta X) = \{F_{\Sigma,z}, F_{\Sigma,x}, F_{\Sigma,y}\}^T \in \mathbb{R}^{3} \) - vector-function of the forces acting on the instrument (dynamic connection of the process); \( t_p^{(0)} \), \( S_p^{(0)} \), \( V_3 \) - depth, feed and cutting speed; these are control parameters that depend on the controlled trajectories of the actuators, set, for example, by a CNC program. The system is further analyzed with constant values of technological modes; \( \Delta X \) - spatial harmonic oscillations introduced into the cutting zone as an external perturbation, represented as:
\[
\Delta X(t) = \Delta X_0 \sin \Omega \ t \{(\chi_1(\Delta), \chi_2(\Delta), \chi_3(\Delta))^T
\]

where \( \chi^{(\Delta)} = \{\chi_1(\Delta), \chi_2(\Delta), \chi_3(\Delta)\}^T \) - orientation coefficients satisfying the rationing \((\chi_1(\Delta))^2 + (\chi_2(\Delta))^2 + (\chi_3(\Delta))^2 \equiv 1\), \( \chi_1 = 0.351 \), \( \chi_2 = 0.401 \), \( \chi_3 = 0.847 \); \( \Delta X_0 \), \( \Omega \) - amplitude and frequency of perturbation.

The longitudinal turning of the work piece is analyzed, in which the main power of the oscillation source has a greater influence in the radial \( P_y \) and the axial \( P_x \) directions. The forces have a constant orientation, i.e. \( P_i(t) = P_{i0}(\chi_S), \ t = z, x, y; \ s = 1, 2, 3 \). Then the law of the formation of forces acting on the rake face of the instrument:

\[
\begin{bmatrix}
P_x
\end{bmatrix} = \begin{bmatrix}
T^{(0)} 
\int \left[ (\rho \chi_1(1 + \mu \exp[-(\zeta(V_y - dX_z)/dt)])[t^0 - X_z(t) + \Delta X] \left( \frac{dX_z}{dt} \right) \right] d\xi - P_{x0}(dt)
\end{bmatrix}, \ (3)
\]

where \( \rho \) - is the chip pressure on the rake face [kg/mm²]; \( T^{(0)} \) - time constant [s]; \( \zeta \) - steepness coefficient, which determines the steepness of the reduction of forces with increasing speed [mm/s].

The emulation of the stationary thermal conductivity process was carried out in the APM FEM program by the finite element method. To do this, a three-dimensional model of a fragment of the cutting insert of the lathe cutter was created at the site of the formation of the wear pit formation on the rake surface (Fig. 1).

Fig. 1. Three-dimensional model of a fragment of the cutting part of a lathe cutter.

In real experiments, for which the model was developed, the measurement of the actual temperature \( T_f \) took place by the method of semi artificial thermocouple. A constantan wire temperature sensor was welded to the surface of a groove obtained by EDM cutting in a hard alloy insert at a distance \( l \) from the main cutting edge (Fig. 1). When calculating and modeling the temperature, successive stages of heat dissipation and heating of surface micro layers of chip in the PPD, SPD and EC zones were taken into account. To do this, the rake surface at the site of contact with the chip was represented as four equal in length in the radial direction sections, for each of which an average temperature value was set, calculated as mean for its two extreme points.
The multiparameter model of the contact temperature used in this study contains a number of input parameters, the values of which can either be obtained by experimental studies or are amenable only to approximate calculation. Thus, on the basis of experimental data, a function describing the change in the length of the chip contact with the rake surface of the cutter was obtained. The second type of data includes the magnitude of the tangential stresses \( \tau_k \) and the thickness of the SPD layer in the processed material (chip) \( h \). The contact temperature increases nonlinearly with increasing \( \tau_k \) and decreases nonlinearly with increasing \( h \) [3-5].

The values of \( \tau_k \) were determined in three variants. The first two values were obtained by methods [28,29], which suggest that these values are independent of evolutionary processes and fluctuations in the cutting system, i.e. \( \tau_k = \text{const} \). In this case, the increase in temperature over time according to the mathematical model [3-5] will occur only by increasing the contact time of the chip with the rake surface.

In the third variant, the value of the tangential stresses was defined as:

\[
\tau_k = \frac{P_{xy}}{S}, \tag{4}
\]

where \( P_{xy} \) - the resultant of radial \( P_y \) and axial \( P_x \) components of the cutting force; \( S \) - the area of the contact zone on the rake surface.

Such an approach, on the one hand, makes it possible to take into account evolutionary changes in cutting forces when calculating temperature, on the other hand, it requires data on the evolution of the contact area. The values of this parameter obtained by formula (5) are consistent with the calculated data according to the method 29.

To determine the thickness of the SPD layer \( h \), the relationship [30] was used in all cases:

\[
h = \frac{\tau_{k1}}{C_V T_m}, \tag{5}
\]

where \( l_1 \) - the length of the chip contact with the rake surface of the cutter in the SPD zone; \( C_V \) - specific volumetric heat capacity of the workpiece material \([J/m^3\cdot^\circ C]\); \( T_m \) - the melting point of the workpiece material \[^\circ C\].

To analyze the influence of the cutting forces evolution on the properties of the machining process through a change in the temperature field of the front surface of the lathe, a dynamic relationship between two transformational processes was adopted through the trajectory of tool wear \( w(h) \) [27]. Modeling of the above relationship taking into account two hypotheses. The first is that the contact temperature depends on the change in the thickness of the SPD chip zone (5). The second hypothesis is that the change in parameter \( h \) occurs as tool wear develops:

\[
h_i = h_0 + \Delta h_i \left( w^{(h)} \right), \tag{6}
\]

where \( h_0 \) - initial value of the parameter; \( \Delta h_i \) - increment of the parameter with increasing tool wear \( w^{(h)} \). The influence of wear leads both to a change in the resulting force \( P_{xy} \) (an increase of 1.5-2 times is possible), and the thickness \( h \), which according to expressions (3)-(6) can be represented as follows:

\[
h_i = \left( \frac{\left( P_{xyX_{L0}}(X_{t0} p^{(0)}, s^{(0)} P_{xy}, \Delta X) \right)}{b_0} + \frac{P_{xyX_{L0}}(X_{t0} p^{(h)}, s^{(0)} P_{xy}, \Delta X, w^{(h)})}{\Delta b_i} \right) \left( \frac{1}{C_V T_m} \right), \tag{7}
\]

where \( b_0 \) and \( \Delta b_i \) - initial value and increment of the cut layer’ width.

The increase of wear during the operation of the tool is modeled by a characteristic wear curve with areas of various wear increases: the run-in area, normal working wear and catastrophic wear. Modeling of the temperature field on the front surface of the lathe, taking into account the evolution of cutting forces, including tool wear, can become a tool for designing processes with increased accuracy of transfer to a real object. When modeling the
curve, it is important to take into account competing processes – adaptation and degradation of the surface properties of the contacting bodies, then the curve is approximated by two exponential functions:

\[
w_t^{(b)}(\Delta T_i) = \beta_1 [1 - \exp(-\frac{\Delta T_i}{T_1})] + \beta_2 [1 - \exp(-\frac{\Delta T_i}{T_2})],
\]

where \(\Delta T\) - the average time of the tool wear measurement period [s], \(T_1, T_2, \beta_1, \beta_2\) - parameters dependent on tool wear and determined by experimental dynamics methods; \(T_1, T_2\) [mm], \(\beta_1, \beta_2\) - dimensionless parameters [31]. In our case, \(T_1, T_2\) are determined on the basis of experimental data 24. The simulation was carried out in the Matlab software, the Simulink application. To build a dynamic model of cutting forces, experimental data on wear on the rake surface and vibration characteristics in the cutting system (vibration velocity along three axes) were used; the remaining input parameters were calculated using the [2,24,29,32]. To verify the results of calculations and modeling, the thickness of the SPD zone \(h\) was used, established by examining the micro section of the chip root by microscopy 24. The flank surface on the model (Fig. 1.) in all calculation options was presented simplified in the form of one face, to which the average value of the temperature load was applied.

3 Results and discussion

Let's calculate the temperature for the cutting path \(L = 1000\) m, the total length of the chip contact with the rake surface is \(l_c = 0.9\) mm, the length of the SPD zone in this case was \(l_1 = 0.5\times l_c = 0.45\) mm. The plane in which the thermal sensor was installed in the real experiment was located at a distance of \(l =1.0\) mm from the edge of the blade (see Fig. 1). The mean actual temperature recorded at this point was \(\Theta_f = 1015\) °C. When using the average value of tangential stresses [28], widely used in solving thermo physical problems, and the thickness of the SPD layer according to [30], \(\tau_k = 165\) MPa and \(h = 17.2\) μm), the calculated temperature value in the reference plane is \(\Theta_1 = 821\) °C (Fig. 2, a).

Applying the techniques [28-30] to determine the parameters mentioned above, we obtain \(\tau_k = 460\) MPa and \(h = 45.7\) μm. In this case, the calculated temperature in the reference plane is \(\Theta_2 = 927\) °C (Fig. 2, b). To determine the temperature taking into account the evolution of the cutting force, a digital simulation of the change in the resultant cutting force \(P_{xy}\) was carried out, taking into account the influence of irregular kinematic vibration disturbances with a frequency of 10 Hz, the results of which are presented in Fig. 3.
The average value of the resultant force for the moment corresponding to the cutting length $L = 1000$ m will be $P_{xy} = 662.23$ N. Then according to the expressions (4) and (7) $\tau_k = 490.5$ MPa and $h = 49.36$ μm, the calculated temperature in the plane of the location of the thermal sensor will be $\Theta_3 = 935$ °C (Fig. 4, a).

When substituting the value of the tangential stresses (4) and the actual thickness of the SPD zone $h = 40$ μm, the temperature of the model in the reference plane is $\Theta_4 = 1102$ °C (Fig. 4, b). In all the cases considered, except for the last one, the calculated temperature value was less than the actual one. The greatest deviation of the calculated temperature
relative to the measured temperature ($\varepsilon_1 = -19.1\%$) was characteristic to the first case (Fig. 2, a). In this case, a strong underestimation of the $\tau_k$ parameter leads to a decrease in the calculated value of $\Theta_1$. This effect is partially compensated by the underestimation of the thickness $h$ as well, which implies a shift in the maximum temperature inside the layer closer to the surface, and, consequently, an increase in the contact temperature [3-5].

For the following cases (Fig. 2, b and Fig. 4, a), similar temperature values were obtained with satisfactory calculation errors of $\varepsilon_2 = -8.7\%$ and $\varepsilon_3 = -7.7\%$, respectively. Exceeding calculated temperature was obtained in the fourth case of the calculation when substituting the experimental value $h$, the calculation error was $\varepsilon_4 = +8.6\%$. This option can be considered the most reliable, since the simulation of the temperature field in this study was carried out for a fragment of the cutting part without taking into account the cooling due to the heat sink in the cutter holder and the environment. Taking into account the cooling factor in the first three cases will lead to a decrease in the calculated temperatures, and deviations relative to the real value will increase, whereas for the case in Fig. 4, b reducing the temperature in the reference plane of the model will help reduce the calculation error.

Thus, to calculate the temperature and obtain the most reliable model of the temperature field, it is required to use the most accurate value of the thickness of the SPD layer in the processed material (chip). The use of approximate values of this parameter leads to significantly distorted relative to real temperature values.

5 Conclusion

The temperature calculation and modeling of the thermal field on the rake surface of the hard alloy insert of the lathe cutter under conditions of the longitudinal turning of the work piece made of structural steel were carried out, taking into account evolutionary changes in cutting forces. The results of the digital simulation agree well with the temperature values obtained as a result of the full-scale experiment during the considered cutting modes. The error of the calculated temperatures obtained by the modeling of thermal processes without taking into account heat exchange with the environment was 7.7-8.6%.

References

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