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Calculation of temperatures during finishing milling of a nickel based alloys

Dmitry Gubin [a], *Anton Kisel* [b, *]

Omsk State Technical University, 11 Prospekt Mira, Omsk, 644050, Russian Federation

[a] https://orcid.org/0000-0003-1825-1310, gubin.89@list.ru, [b] https://orcid.org/0000-0002-8014-0550, kisel1988@mail.ru

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ABSTRACT

Introduction. One of the most important tasks in cutting metals and alloys is the control of the temperature factor, since temperature is one of the limitations in determining cutting conditions. This approach makes it possible to determine rational (in some cases, optimal) milling modes. Experimental methods for determining the temperature are labor-consuming, costly and not always available. The labor-consuming nature lies in the need for constant adjustment of experimental equipment due to changing cutting conditions, electrical insulation of the tool and workpiece, the appearance of parasitic electrical micro-voltage (if we are talking about temperature measurement methods with thermocouples), constant calibration of instruments and selection of thermal radiation coefficients (if we are talking about non-contact measurement methods). In this regard, there is a need for a theoretical determination of temperatures during milling with minimal use of experimental data. **The purpose of the work:** to develop a method for theoretical calculation of temperature during milling (cutting) of nickel-based heat-resistant materials on the example of *56% Ni -Cr-W Mo-Co-Al* alloy (56% *Ni*, 0.1% *C*, 10% *Cr*, 6.5% *W*, 6% *Al*, 6.5% *Mo*, 0.6% *Si*, 13 % *Co*, 1% *Fe*). **Research methodology**. To determine theoretically the cutting temperatures, a mathematical model is formed that takes into account the mechanical and thermophysical properties of the material being processed and its change depending on the temperature variations during milling, the geometry of the cutting tool and the features of the schematization of the milling process. The experimental part of the study is carried out on a console milling machine *KFPE-250* with a *CNC* system *Mayak-610*. The *56% Ni -Cr-W Mo-Co-Al* material is processed with a *Seco JS513050D2C.0Z3-NXT* cutter with different speeds and feeds. The temperature is measured using a *Fluke Ti400* thermal imager. **Results and discussion.** A theoretical model for calculating the temperature (for the group of *77% Ni - Cr - Ti - Al - B, 66% Ni - Cr - Mo - W - Ti - Al, 73% Ni-Cr-Mo-Nb-Ti-Al* and *56% Ni -Cr-W Mo-Co-Al* alloys) during milling of heat-resistant nickel-based alloys is developed, which makes it possible to predict the temperature value at the face and flank of the tool when changing cutting conditions (speed, feed, depth, cutting tool geometry), as well as the cutting temperature. An analysis of the experimental and theoretically predicted values of the cutting temperature showed a satisfactory agreement between the corresponding values.

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Introduction

Nickel-based heat-resistant alloys are widely used in the space, aircraft and power industries to design parts with high mechanical stress and high operating temperature. The processing (milling, turning, etc.) of heat-resistant alloys is always accompanied by high cutting temperatures. This is caused by high values of mechanical characteristics (ultimate strength and actual ultimate strength), low coefficients of thermal conductivity and thermal diffusivity [1–4]. The study of temperature phenomena during cutting of materials is of interest, due to the fact that temperature can act as one of the limiting factors, so it is important to predict the temperature to optimize the cutting process and increase tool life [5, 6]. Thus, at high temperatures, increased tool wear (plastic deformation), loss of dimensional stability and rapid failure are observed [5, 7,

*** Corresponding author**
Kisel' Anton G., Ph.D. (Engineering), Associate Professor
Omsk State Technical University
11 Prospekt Mira,
644050, Omsk, Russian Federation
Tel.: +7 (999) 458-08-25, **e-mail:** kisel1988@mail.ru

8]. In this connection, temperature is associated with such a factor as wear intensity and is further used as a limiting factor in determining rational (or optimal) cutting modes [5] (Figure 1).

Figure 1 shows that the minimum wear rate of the tool for *70% Ni-Cr-W-Mo-Ti-Al* and *70% Ni-Cr-W-Mo-Ti-Al-Nb* alloys is the same and corresponds to a temperature value of about 750 °C at a cutting speed of 25 m/min.

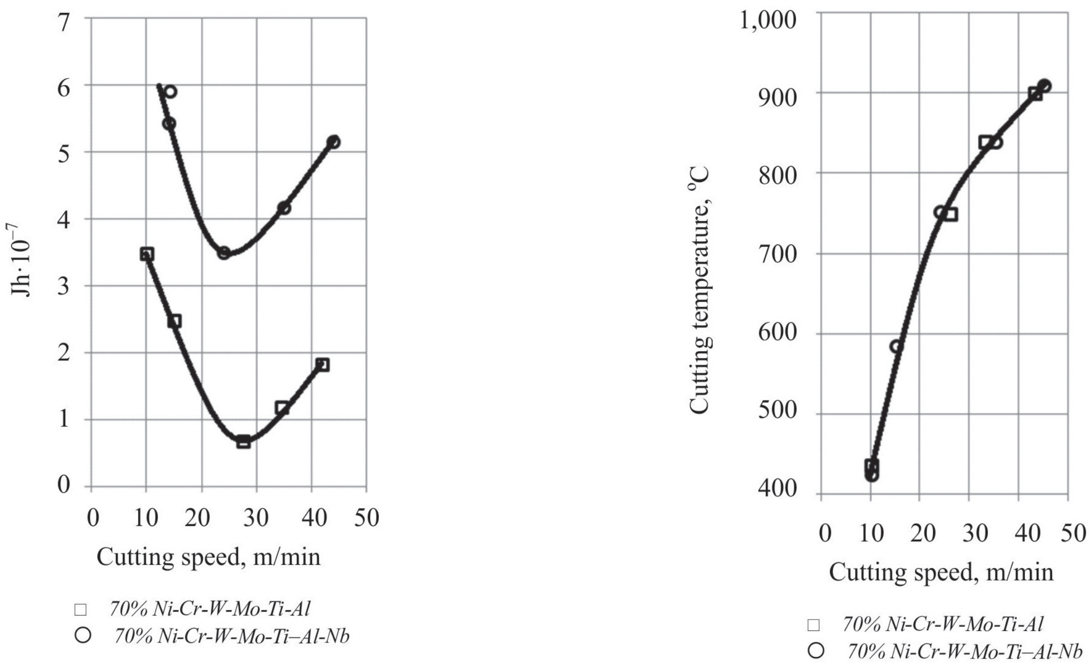

Fig. 1. Dependence of the wear rate of the cutter and the cutting temperature on the type of workpiece and cutting speed [5]

So there are recommendations [5, 9], according to which it is expedient to assign cutting modes, maintaining rational (optimal) temperature values. In the work of *A. D. Makarov* [5], it was proposed to take into account the effect of cutting temperature on cutting speed. He formulated the principle that with various combinations of cutting speed, feed and depth of cut, a constant temperature in the cutting zone (optimal temperature) can be found, corresponding to the minimum average wear rates.

In a number of works [10-12], the cutting temperature was determined either experimentally (by the method of natural – artificial thermocouple), or theoretically [6, 13]. Temperature measurement by experimental methods in production conditions is inefficient and leads to great difficulties. These difficulties are primarily associated with setting up expensive equipment for constantly changing cutting conditions (for example, the material of the workpiece has changed, the geometry of the cutting tool has changed, etc.) and calibration of the received thermal EMF signals (for thermocouples). If temperature measurements are made by non-contact methods (thermal imagers), then in this case there is a need to calibrate constantly the device when changing the processed material and to produce constant focusing when the cutting tool moves. In addition, it is impossible to measure the temperature by non-contact method when milling using coolant, or when the cutting zone is closed by the processed material, or chips. In this connection, it is advisable to use programs (methods) that allow theoretically calculating (predicting) the temperature for a certain group of processed materials, taking into account the influence of changes in mechanical characteristics during the cutting process, without resorting to a large number of experiments.

Thus, *Ezel et al.* [14] proposed a theoretical model for calculating the temperature for high-speed end milling of die steels based on the finite element method. Based on the experimental data, the coefficients of the model were obtained, which were included in the *DEFORM-2D* software. Thus, the numerical method was limited to a specific material and specific machining conditions, and accuracy was compromised by assuming that the yield strength of the material is independent of strain, strain rate, and temperature during the milling process.

This paper is devoted to the development of a theoretical method for calculating the temperature during milling for a group of nickel-based alloys. To achieve this purpose, it is necessary to develop a mathematical model that takes into account the effect of strain, strain rate and temperature on the change in the yield strength during milling and to confirm the results of theoretical prediction of cutting temperature experimentally (by non-contact method of temperature measurement). As an example, theoretical and experimental studies will be carried out for the *56% Ni-Cr-W-Mo-Co-Al* heat-resistant alloy obtained by vacuum remelting.

Research technique

The first thing to consider when calculating the cutting temperature is the mechanical and physical properties of the material.

Secondly, it is necessary to take into account the geometry of the cutting tool (back rake angle γ°, front clearance angle α°, side cutting edge angle φ°, rake angle λ°), as well as the schematization of the milling process, namely the infeed depth *e*, take into account the number of simultaneously working teeth, ratio of milling width to cutter diameter. The geometry of the cutting tool was taken into account through the *Peclet* criterion, which determines the heat exchange between the material being processed, the environment, and the tool, and through the *Peclet* coefficient, which takes into account the rate of heat removal [15]:

$$Pe = \frac{v}{60} \cdot \frac{a}{1000} \cdot \frac{1}{\omega}, \tag{1}$$

$$K_{Pe} = \left[1 + \frac{1 - \exp(Pe \cdot \mathrm{tg}\varphi_y)}{Pe \cdot \mathrm{tg}\varphi_y}\right]^{-1}, \tag{2}$$

$$a = S_z \cdot \sin\varphi \cdot \cos\lambda, \tag{3}$$

$$\varphi_y = \mathrm{arctg}\frac{\cos\gamma}{\zeta - \sin\gamma}, \tag{4}$$

where a is the thickness of the cut layer in mm, ν is the cutting speed in m/s, ω is the thermal diffusivity m^2/s (reference value), S_z is the feed per tooth in mm/tooth, φ is the actual cutting edge angle in degrees, λ is the rake angle of the cutting edge in degrees, γ is the back rake angle in degrees, φ_y is the angle of inclination of the conditional shear plane in degrees, ζ is chip shrinkage.

Thirdly, it is necessary to take into account the influence of temperature itself on the change in the mechanical properties of the material. High temperatures during the cutting process can lead to a significant change in the mechanical properties of metals and alloys. It is known [16–18] that in the process of cutting under the influence of high strain rates, the material being processed can be significantly hardened, and under the influence of temperature, it can be softened.

For the study, a group of heat-resistant alloys was selected, which obeys the same softening law (Figure 2), and therefore, the change in the yield strength of the above alloys can be described by one generalizing equation, and it is permissible to choose any of it for research.

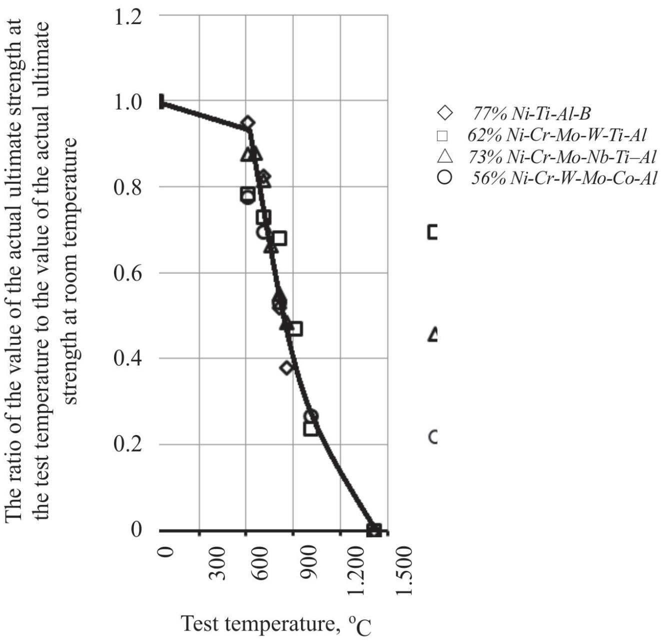

Fig. 2. Change in the mechanical properties of nickel based alloys during static tensile tests [15, 16]

The *56% Ni-Cr-W-Mo-Co-Al* heat-resistant alloy was chosen for the study. The physical and mechanical properties of this material are presented in Table 1 [17, 18]

Table 1

Mechanical characteristics and physical properties of heat-resistant alloys required for temperature calculation

Material grade	Ultimate strength σ_u, MPa	Percentage elongation %EL, %	Thermal-conductivity coefficient λ, W/m·K	Volumetric heat capacity C_V, kJ/m^3·K	Thermal diffusivity coefficient ω, m^2/s	Density ρ, kg/m^3
56% Ni-Cr-W-Mo-Co-Al	1,050	17	10.53	4.39	$2.858 \cdot 10^{-6}$	8,400

The calculations are based on the dependences of the change in the actual ultimate strength on temperature during high-temperature tensile tests of heat-resistant alloys (Figure 2), as well as information on the effect of strain and strain rate on the change in the yield strength of the selected alloys [19]. Based on these data, a constitutive equation was built to determine the yield strength, which is suitable for any alloy shown in Figure 2:

$$\frac{\tau_p}{S_{b_0}} = A\varepsilon_p^m K_\varepsilon \exp(-B_q \Delta T'), \tag{5}$$

$$A = \left\{\sqrt{3}\left[\sqrt{3}\ln(1+\varepsilon_z)\right]^m\right\}^{-1}, \tag{6}$$

where $\frac{\tau_p}{S_{b_0}}$ is the ratio of the value of the actual ultimate strength at the test temperature to the value of the ultimate strength at room temperature, $A \cdot \varepsilon_p^m$ is the equation of the material to be hardened (simple loading), m is the strain hardening coefficient, K_ε is an empirical constant characterizing the effect of strain rate on the yield strength, B_q is an empirical constant characterizing the effect of temperature softening of the material, $\Delta T'$ is the increment of the homological temperature.

In the literature there are similar models of the change in the yield strength depending on the strain, strain rate and temperature, for example, the *Johnson-Cook* model [20]

$$\sigma = (A + B \cdot \varepsilon^{p^n})(1 + C \cdot \ln \dot{\varepsilon})(1 - T^m). \tag{7}$$

But both the defining equation (5) and the *Johnson-Cook* model (7) have drawbacks. For example, in both equations, temperature acts as an independent factor, i.e. one can change the temperature by simply heating the material. In order to take into account the dependence of the combined effect of temperature, strain and strain rate during milling, it is necessary to replace in the constitutive equation (5) the ratio of the actual ultimate strength at the test temperature to the value of the actual ultimate strength at room temperature on the ultimate resilience [15]:

$$\frac{\tau_p}{S_{b_0}} = \frac{dA_w}{d\varepsilon_p}, \tag{8}$$

$$A_w = \int_0^{\varepsilon_u} \frac{\tau_p}{S_{b_0}} d\varepsilon. \tag{9}$$

Due to the fact that during milling the conditions are quasi-adiabatic (there is an exchange with the environment and the material being processed), the temperature can be determined as follows:

$$\Delta T' = K_{Pe} \cdot A_w \cdot A_1, \tag{10}$$

$$A_1 = \frac{S_b}{C_V T_{melt}}. \tag{11}$$

Now the defining equation will take the following form:

$$A_w = A\varepsilon_p^m K_\varepsilon \exp(-B_q A_1 A_w K_{Pe}) d\varepsilon. \tag{12}$$

After integrating equation (12), and then differentiating, the points were found at which the highest values of cutting strength on the face surface are achieved:

$$\frac{\tilde{\tau}_p}{S_{b_0}} = \frac{m\exp\left(\frac{-m}{m+1}\right)}{B_{q1}\left(1-\frac{S_{b\theta_0}}{S_{b_0}}\right)A_1 K_{Pe}\tilde{\varepsilon}_{\tau n}}, \tag{13}$$

$$\tilde{\varepsilon}_{\tau n} = \left[\frac{m}{AK_{\varepsilon n}B_{q1}A_1 K_{Pe}\left(1-\frac{S_{b\theta_0}}{S_{b_0}}\right)}\right]^{\frac{1}{m+1}}. \tag{14}$$

To calculate the temperatures on the major flank of the tool, the same formulas were used, but with different values of the coefficients:

$$\frac{\tilde{\tau}_p}{S_{b_0}} = \frac{m\exp\left(\frac{-m}{m+1}\right)}{B_{q2}\left(1-\frac{S_{b\theta_0}}{S_{b_0}}\right)A_1 K_{Pe}\tilde{\varepsilon}_{\tau з}}, \tag{15}$$

$$\tilde{\varepsilon}_{\tau n} = \left[\frac{m}{AK_{\varepsilon з}B_{q2}A_1 K_{Pe}\left(1-\frac{S_{b\theta_0}}{S_{b_0}}\right)}\right]^{\frac{1}{m+1}}. \tag{16}$$

Due to equations (10–12), dependences (13 and 15) are heat sources on the face and flank surfaces, respectively. Then, using the iteration method in the *Excel* software environment, the temperatures on the face and flank surfaces were calculated and graphs were plotted. Below are graphs of the theoretical calculation of temperatures on the face surface of the cutting blade (Figure 3) and on the flank surface of the cutting blade (Figure 4) on the example of milling *56% Ni-Cr-W-Mo-Co-Al* alloy with a *Seco JS513050D2C.0Z3-NXT* carbide cutter (diameter 5 mm, number of teeth 3, helix angle 46°, end cutting edge angle $\varphi = 90°$, rake angle $\lambda = 0°$, actual back rake angle $\lambda = 8°$) with the following milling modes: $V = 15.7$ m/min; $S_{min} =$ $= 52$ mm/min; $S_z = 0.0175$ mm/tooth; $n = 1{,}000$ rpm; $t = 0.1$ mm.

These graphs help to analyze and control the temperature process during milling because temperature change is directly related to changes in milling (cutting) modes.

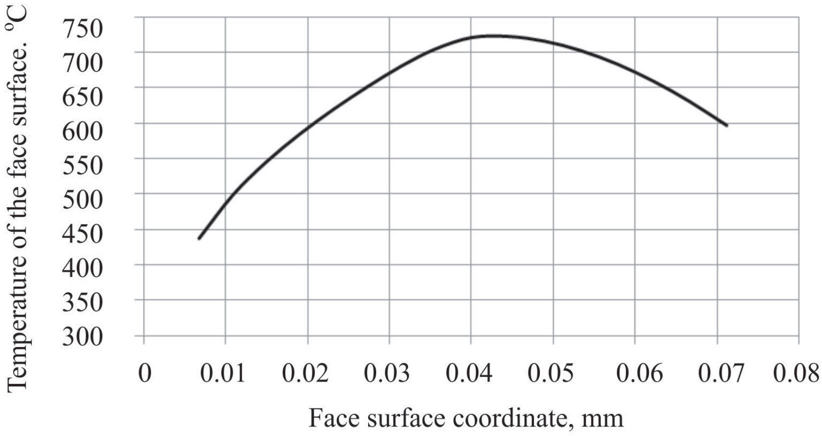

Fig. 3. Temperature distribution over the face surface during milling of nickel based alloy *56% Ni-Cr-W-Mo-Co-Al* – theoretical method

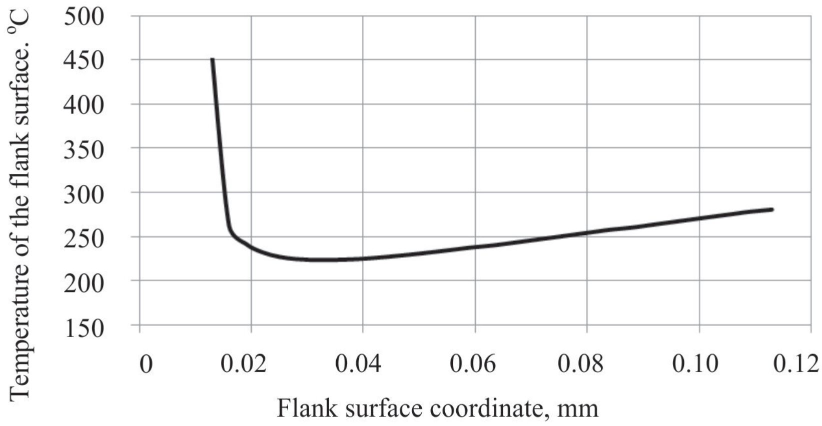

Fig. 4. Temperature distribution over the flank surface during milling of nickel based alloy *56% Ni-Cr-W-Mo-Co-Al* – theoretical method

Results and discussion

Theoretical calculations of the cutting temperature have been confirmed by a number of experimental studies. The study of the cutting temperature was carried out on a console milling machine *KFPE-250* with a *CNC* system *Mayak-610* during symmetrical milling of the *56% Ni-Cr-W-Mo-Co-Al* alloy with a *Seco JS513050D2C.0Z3-NXT* carbide cutter. The milling depth for all experiments was 0.1 mm. To measure the cutting temperature, a *Fluke Ti400* thermal imager was used with an error in measuring the non-stationary temperature field of 5 %. Milling was carried out with different feeds and cutting speeds (table 2).

The cutting temperature (Figure 5) was calculated based on the average temperatures on the face and flank surfaces according to the formula:

$$T_{cut} = \frac{T_{face_{average}} \cdot c + T_{flank_{average}} \cdot h}{(c+h)}, \tag{17}$$

where $T_{face_{average}}$ and $T_{flank_{average}}$ are the average temperatures on the face and flank surfaces of the cutting blade, c and h are the coordinates of the face and flank surfaces of the cutting blade along which the temperature is distributed.

Table 2

Temperature measurement results and corresponding theoretical calculations for milling

Experiment No.	1	2	3	4	5	6	7
T_{exp}, °C	327	280	294	374	206	273	237
T_{calc}, °C	342	276	316	349	216	264	231
V, m/min	15.7	15.7	15.7	22	7.9	22	15.7
S_z, mm/tooth	0.0175	0.0095	0.0135	0.0095	0.0055	0.0055	0.0015

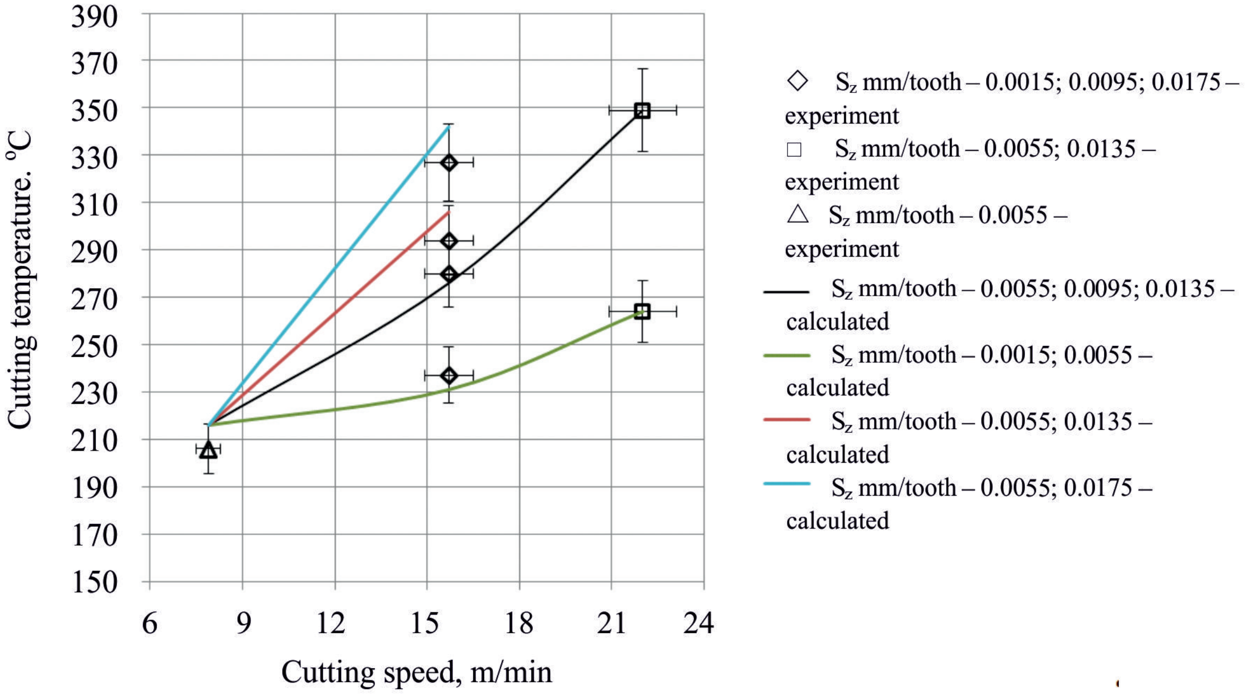

Fig. 5. Dependence of the cutting temperature on the cutting speed and feed during milling of nickel based alloy *56% Ni-Cr-W-Mo-Co-Al*

Conclusion

As a result of the research, it was found that the maximum temperature value during milling of *56% Ni-Cr-W-Mo-Co-Al* alloy with cutting speed V = 15.7 m/min, milling depth = 0.1 mm and feed S_z = 0.0175 mm/tooth was achieved on the face surface and amounted to 730 ^{o}C, while on the flank surface of the tool the temperature reached 450 ^{o}C. The cutting temperature was 327 °C. Comparison of experimental studies of milling heat-resistant alloy *56% Ni-Cr-W-Mo-Co-Al*, with a change in cutting conditions (changed feed per tooth and cutting speed) with theoretical data, gave a satisfactory result with a confidential interval of 5%. On the basis of experimental data, it can be concluded that this method makes it possible to calculate (predict) theoretically the temperatures on the face and flank surfaces of the cutting blade, as well as the cutting temperature, without labor-consuming and costly experimental studies. The same method can be extended to other grades of heat-resistant alloys (*77% Ni-Cr-Ti-Al-B, 66% Ni-Cr-Mo-W-Ti-Al, 73% Ni-Cr-Mo-Nb-Ti-Al*), since there is only one defining equation for it. When calculating, it is only necessary to change the values of its physical and mechanical characteristics. In the future, this method of theoretical calculation of temperature can be used to determine the minimum (reasonable) wear rate of the cutting tool.

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Conflicts of Interest

The authors declare no conflict of interest.