Numerical simulation of turning contact temperatures with varying material yield strength and tool wear

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Abstract. The results of numerical simulation the main component of cutting forces and temperatures at the contact zones of the face of the cutter with chip and flank with the workpiece depending on the tool wear and physico-mechanical properties of the workpiece material. The values of fluctuations in the cutting force and contact temperatures are determined depending on the variation of the stress yield of the workpiece material during machining of the workpieces made of steel 45 and steel 12Kh18N10T are established. The degree of influence of tool wear on the flank on cutting forces and contact temperatures is determined.

1. Introduction
The temperature of the cutting zone has a significant impact on the tool life, the quality of the machined surfaces and the machining capacity [1, 2, 3,4, etc.].

In the analytical study of the thermal physics of the cutting process, based on the accepted route of heat flows [5], determine the corresponding flows to the tool, chip and workpiece, and then make and solve the thermal conductivity equations for each object. The disadvantage of this approach is an approximate accounting of the distribution of heat flows between objects. The thermophysical characteristics of the workpiece and tool materials, as well as the mechanical characteristics of the workpiece material (tensile strength and yield strength) significantly depend on the temperature [6], but not all known methods for calculating temperatures take this into account.

The most widely used methods for calculating temperatures are those proposed by A. N. Reznikov [7] and S. S. Silin [8]. However, these methods do not take into account changes in the physical and mechanical properties of the workpiece material from temperature. The thermomechanical method for calculating temperatures is devoid of this disadvantage [9]. The common disadvantage of the above methods is that they do not take into account the effect of wear on the cutting tool (for example, on the flank) and the coolant on the temperature.

To predict quality parameters of machined parts and the tool life necessary to create a mathematical model that allows to calculate not only the expectation parameters of the machining process, but also the dispersion of these parameters. The specifics of the developed method for calculating the temperature field during turning [10, 11] do not allow us to explicitly obtain equations linking the temperature and the input parameters of the process. Therefore, the temperature dispersion fields were obtained by numerical modeling. In these studies, the degree of influence of fluctuations in the
physical and mechanical properties of the workpiece material on the dispersion of contact temperatures is established.

2. Analytical research

The method of calculating the temperature field developed by us takes into account the heat release in the deformation zone and in the contact zones of the cutter with the chip and the workpiece, the mutual movement of these objects and the conditions for their cooling when the coolant is supplied [11,12]. The dependence of parameters that characterizes the resistance of the material of workpiece to dispersion, as well as the thermal properties of objects (including the external environment) on temperature is taken into account. The dependence arguments for calculating the main component of the cutting force and the friction force of the cutter on the workpiece are the contact length of the flank of the cutter with the workpiece. The thermal conductivity equations of the contacting objects (cutter, chip, and workpiece) were solved together with the common boundary conditions in the contact zone using the finite element method.

For calculating temperatures, a method, algorithm and calculation program using the finite element method for solving differential equations of thermal conductivity have been developed. The results of calculating the temperatures according to the program were compared with experimental results, with the difference between the calculated and experimental values not exceeding 10 % [10].

The developed software allows us to calculate the tangential component of the cutting force \( P_Z \) and the temperature at various points of objects (grid nodes) through a time interval determined based on the stability of the integration step over time [12].

The program is written in the Basic programming language. Pre-enter the following input data: dimensions of the cutter and the workpiece; physical, mechanical and thermal properties of the materials of the workpiece and the cutter; geometric parameters of the cutter (rake angle \( \gamma \), angle of cutting edge \( \phi \)); tool wear; elements of the turning mode (cutting speed \( V \), feed \( S_{rev} \), depth of cut \( t_r \)); parameters of the calculated grid.

We fixed the component of the cutting force \( P_Z \) and temperature at points located on the contact areas of the face of the cutter with the chip and its flank with the workpiece.

3. Numerical simulation of turning contact temperatures

The established tolerance for the percentage content of various chemical elements in steel, as well as alloying components corresponds to a fairly wide range of mechanical properties. In carbon, structural and low alloy steels, it reaches 20%, in high-alloy up to 30 ... 40% [6, 13]. We assume that the yield strength of the workpiece material varies within \( \sigma_S \pm 10\% \). The mechanical and thermophysical characteristics of the workpiece and cutter material (yield stress \( \sigma_S \), density, thermal conductivity and heat capacity coefficients) depending on the temperature were determined according to [6, 9].

Numerical simulation of the temperature field was performed with the following initial data: material of workpiece – steel 45 and 12Kh18N10T; material of the cutting part of the tool – hard alloy T15K6; the tool angles \( \gamma = -4^\circ, \phi = 45^\circ \); the cutting speed \( V \) and feed \( S_{rev} \) varied; depth of cut \( t_r \), 0.5 mm; friction coefficients of the chip on the face of the cutter and the flank of the cutter on the workpiece \( \mu_1 = \mu_2 = 0.3 \). Simulation of temperatures during processing of workpieces of steel 45 was performed at the nominal value of the yield strength \( \sigma_S = 355 \) MPa, as well as at the maximum and minimum values equal to \( \sigma_S + 0.1 \cdot \sigma_S = 391 \) MPa and \( \sigma_S - 0.1 \cdot \sigma_S = 319 \) MPa.

The calculation results are presented in table 1.
Table 1. Results of calculating the cutting force and cutting contact temperatures when the parameter is varied $\sigma_S$: material of workpiece – steel 45.

| Yield strength $\sigma_S$, MPa | Cutting speed $V$, m/min | Feed $S_{rev}$, mm/rev | Depth of cut $t$, mm | The temperature on the face $T_1$, °C | The temperature on the flank $T_2$, °C | Tangential component of the cutting force $P_Z$, N |
|-------------------------------|--------------------------|------------------------|---------------------|--------------------------------------|--------------------------------------|-----------------------------------|
| 391                           | 60                       | 0.15                   | 0.5                 | 357                                  | 331                                  | 70                                |
|                               | 240                      | 0.15                   | 0.5                 | 749                                  | 520                                  | 68                                |
|                               | 60                       | 0.3                    | 0.5                 | 392                                  | 430                                  | 111                               |
|                               | 240                      | 0.3                    | 0.5                 | 1156                                 | 809                                  | 106                               |
| 355                           | 60                       | 0.15                   | 0.5                 | 326                                  | 304                                  | 63                                |
|                               | 240                      | 0.15                   | 0.5                 | 680                                  | 476                                  | 62                                |
|                               | 60                       | 0.3                    | 0.5                 | 358                                  | 393                                  | 101                               |
|                               | 240                      | 0.3                    | 0.5                 | 1059                                 | 740                                  | 97                                |
| 319                           | 60                       | 0.15                   | 0.5                 | 298                                  | 278                                  | 57                                |
|                               | 240                      | 0.15                   | 0.5                 | 611                                  | 431                                  | 56                                |
|                               | 60                       | 0.3                    | 0.5                 | 324                                  | 355                                  | 91                                |
|                               | 240                      | 0.3                    | 0.5                 | 961                                  | 670                                  | 88                                |

The calculation results show that when the parameter $\sigma_S$ of steel 45 changes within $\pm$10%, the temperature fluctuations on the face are 20% ($T_1$ ± 10%), on the flank – 18% ($T_2$ ± 9%). Fluctuations in the tangential component of cutting force $\Delta P_Z = 20\%$ ($P_Z$ ± 10%). The temperature on the face of the tool $T_1$ changes by 9-10% at the cutting speed $V=60$ m/min and 54-57% at the cutting speed $V=240$ m/min when the $S_{rev}$ feed varies from 0.1 to 0.3 mm/rev. As the feed increases in the above range, the temperature on the flank of the tool changes by 29% at the cutting speed $V=60$ m/min and 55% at the cutting speed $V=240$ m/min. Varying the cutting speed from 60 to 240 m/min increases the temperature $T_1$ - 2.1-3.0 times, $T_2$-1.6-1.9 times.

A similar study was conducted for a contact couple 12KH18N10T – T15K6. The results are presented in table 2.

Table 2. Results of calculating the cutting force and cutting contact temperatures when the parameter is varied $\sigma_S$: material of workpiece – steel 12KH18N10T.

| Yield strength $\sigma_S$, MPa | Cutting speed $V$, m/min | Feed $S_{rev}$, mm/rev | Depth of cut $t$, mm | The temperature on the face $T_1$, °C | The temperature on the flank $T_2$, °C | Tangential component of the cutting force $P_Z$, N |
|-------------------------------|--------------------------|------------------------|---------------------|--------------------------------------|--------------------------------------|-----------------------------------|
| 216                           | 60                       | 0.1                   | 0.5                 | 292                                  | 250                                  | 39                                |
|                               | 240                      | 0.1                   | 0.5                 | 925                                  | 598                                  | 37                                |
|                               | 60                       | 0.3                   | 0.5                 | 434                                  | 346                                  | 61                                |
|                               | 240                      | 0.3                   | 0.5                 | 1370                                 | 981                                  | 60                                |
| 196                           | 60                       | 0.1                   | 0.5                 | 269                                  | 230                                  | 36                                |
|                               | 240                      | 0.1                   | 0.5                 | 855                                  | 553                                  | 34                                |
|                               | 60                       | 0.3                   | 0.5                 | 398                                  | 318                                  | 56                                |
|                               | 240                      | 0.3                   | 0.5                 | 1267                                 | 907                                  | 55                                |
| 176                           | 60                       | 0.1                   | 0.5                 | 245                                  | 209                                  | 31                                |
|                               | 240                      | 0.1                   | 0.5                 | 783                                  | 506                                  | 31                                |
|                               | 60                       | 0.3                   | 0.5                 | 362                                  | 289                                  | 50                                |
|                               | 240                      | 0.3                   | 0.5                 | 1161                                 | 830                                  | 49                                |
When changing the parameter $\sigma_S$ of steel 12KH18N10T within ±10%, temperature fluctuations on the face and flank are 18% ($T_1 \pm 9\%$), fluctuations in the tangential leaving cutting force $\Delta P_Z = 20\%$ ($P_Z \pm 10\%$). An increase in the feed $S_{rev}$ from 0.1 to 0.3 mm/rev leads to a 48% increase in contact temperatures $T_1$. The temperature on the flank of the tool $T_2$ varies by 38% depending on the feed $S_{rev}$ at the cutting speed $V=60$ m/min and 64% at the cutting speed $V=240$ m/min. Varying the cutting speed $V$ from 60 to 240 m/min increases the temperature $T_1$ by 3.2 times, $T_2$ by 2.4-2.9 times.

The developed software allows you to calculate contact temperatures when the wear varies along the flank $h_w$, functionally related to the contact length of the flank of the cutter with the workpiece $l_2$.

In the course of numerical simulation, the wear value of $h_w$ varied within $h_w = 0.1 \ldots 0.5$ mm. Wear equal to 0.3-0.5 mm corresponds to the maximum tool wear during finishing [14]. The calculation results are presented in table 3.

### Table 3. The results of calculation of cutting forces and contact temperatures by varying the tool wear $h_w$: $V = 240$ m/min; $S_{rev} = 0.3$ mm/rev; $t_r = 0.5$ mm

| Material of workpiece | Tool flanks wear $h_w$, $\mu$m | The temperature on the face $T_1$, $^\circ$C | The temperature on the flank $T_2$, $^\circ$C | Tangential component of the cutting force $P_Z$, N |
|-----------------------|-------------------------------|-----------------------------------|-----------------------------------|-----------------------------------------------|
| Steel 45              | 0.1                           | 982                               | 683                               | 85                                           |
|                       | 0.2                           | 1059                              | 740                               | 97                                           |
|                       | 0.3                           | 1121                              | 802                               | 109                                          |
|                       | 0.4                           | 1371                              | 853                               | 120                                          |
|                       | 0.5                           | 1394                              | 847                               | 133                                          |
| Steel 12KH18N10T      | 0.1                           | 1292                              | 881                               | 48                                           |
|                       | 0.2                           | 1267                              | 907                               | 55                                           |
|                       | 0.3                           | 1229                              | 932                               | 62                                           |
|                       | 0.4                           | 1366                              | 955                               | 69                                           |
|                       | 0.5                           | 1391                              | 964                               | 77                                           |

When machining workpieces made of steel 45, an increase in wear on the flank of cutter $h_w$ by 0.1 mm in the range $h_w = 0 \ldots 0.3$ mm leads to an increase in the tangential component of cutting force $P_Z$ by an average of 12%, and the contact temperatures increase by 6 ... 8%. When reaching the value $h_w = 0.4$ mm, the contact temperatures increase to a greater extent. An increase in cutter wear on the flank from 0.1 to 0.3 mm leads to an increase in cutting force by 22%, and contact temperatures $T_1$ and $T_2$ by 12 and 15 %. When wear $h_w$ increases from 0.1 to 0.5 mm, cutting forces increase by 56%, and temperatures $T_1$ and $T_2$ by 42 and 24%.

When processing workpieces made of steel 12KH18N10T with an increase in wear on the flank of the cutter of $h_w$ by 0.1 mm in the range $h_w = 0 \ldots 0.3$ mm, the tangential component of cutting force $P_Z$ increases by an average of 14%, the contact temperature $T_1$ does not change, and $T_2$ increases by 3%. When the value $h_w = 0.4$ mm is reached, the temperature $T_1$ increases significantly.

### 4. Conclusions

1. It is established that when the yield strength of the workpiece material fluctuates within 20%, the range of dispersion of the cutting force and contact temperatures is 18 ... 20%.
2. The degree of influence of tool wear on the flank on cutting forces and contact temperatures is determined.
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