Simulation of the thermal state of the blank surface layer at thermal-friction turn-milling

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Abstract. As a result of research, it was revealed that there is a problem of turning accurate large-sized, long parts, which is associated with an increase in productivity and quality of processing, as well as with a decrease in the cost of turning operations. To solve this problem, the authors developed a method of thermo-friction turn-milling and tool design. However, the lack of knowledge of the thermal phenomena occurring in the contact layer "blank-tool" during processing inhibits the widespread use of the proposed method. In this regard, this article simulated the thermal state of the surface layer during cutting. The results of modeling the thermal state of the surface layer when processing parts from difficult materials with thermo-friction turn-milling are presented. The influence of cutting conditions and geometric parameters of the tool on the distribution of the temperature field of the surface layer of the workpiece during thermo-friction turn-milling is considered.

1. Introduction and research relevance

The most important conditions for increasing the competitiveness of products are to increase productivity, reduce costs and improve quality in their production.

As a result of the research conducted in the conditions of machine-building enterprises of the Republic of Kazakhstan, in particular, JSC "Almaty Heavy Plant Engineering", LLP "Maker", KLMZ and LLP "Kurylysmet", Production No.2 etc., it was revealed that there is a problem of lathe by turning large, long parts, associated with an increase in productivity and quality of processing, as well as with a decrease in the cost of turning operations.

Figure 1. Photographs of the large, long parts such as shanks of rotation.
Figure 1 shows photographs of the large-sized long parts such as shanks of rotation.

When turning large-sized long parts of shanks of rotation, one of the main reasons affecting the quality and productivity of cutting is the occurrence of an impact load on the cutter and the formation of discharge chips of various shapes and sizes.

With the creation of multifunctional lathes equipped with a tool head with its own drive, it became possible to carry out milling operations, which eliminates the noted difficulties [1,2,3]. However, when using standard face mills equipped with carbide teeth, another problem arises related to the cost of the milling operation [4,5]. The use of a high-performance method of milling in the conditions of machine-building enterprises of the Republic of Kazakhstan is also hindered by the lack of multifunctional CNC lathes.

In the conditions of machine-building enterprises, where universal machine tool equipment is mainly used, this problem is still compounded. To solve the above problems, the authors within the framework of the grant topic: 2162 / GF4 “Development of the design of a special machine that allows the supply of pulsed cooling and replacing the cutting tool from hard alloy with a tool made of structural steel during thermo-friction cutting of metal billets” developed a method of thermo-friction turn milling using a special cutting tool - friction cutter [6,7,8,9,10].

To implement the thermo-friction turn milling method, a special device based on a lathe was developed and manufactured [11]. The main advantage of the proposed method is the use of a special friction cutter from non-tool material instead of standard end mills.

Figure 2 shows photographs of a special device and a friction mill for milling.

**Figure 2.** Photo of a special device for turn milling. a - device for turn milling: 1 - blank; 2 - friction mill; 3 - device mounted on a support of the machine; 4 - handle for vertical delivering; b - friction mill.

One of the main differences of the developed method is the use of a special friction cutter made of non-tool material instead of standard end mills. The results of the study may lead to the improvement of the structural elements of the cutting tool, and also will explain and correctly use in practice the power and resistance dependencies.

Processing by traditional cutting of high-strength steels is characterized by extremely low plastic deformation during cutting [12]. Mechanical work is spent mainly on elastic deformation and friction of the workpiece on the back surface of the tool. The growth during processing by cutting these materials, as a rule, is absent. For these reasons, tool wear is very intense and occurs primarily on the rear surface. When processing these materials, due to the high values of the mechanical characteristics, large values of the cutting force arise, which lead to a decrease in tool life. In thermo-friction milling, the cutting mechanism is implemented differently, due to the appearance of a current layer [7, 13] under certain temperature conditions, which is in a fairly plastic state close to the recrystallization temperature. The appearance of the current layer reduces friction on the surface of the tool-blank, therefore, to reduce wear and improve the quality of the processed surface.
It is known that carbon steel retains its strength characteristics at temperatures up to 400 °C [14]. These values are for high-speed steels 600°C, for hard alloys 800°C ÷ 900°C. The degree of softening of the material of the cut layer continuously goes up with increasing temperature. Considering the interaction in the process of cutting the tool and workpiece materials, the cutting conditions and, above all, the speed are selected based on the maximum allowable red resistance of the tool material. The higher the cutting speed and material strength, the higher the temperature in the cutting zone. In this case, the degree of temperature equalization over the section of the slice, i.e. the nature of the temperature fields and their intensity in the cutting zone.

Increasing the hardness of the processed material increases the amount of heat released during the cutting process and, therefore, reduces the permissible cutting speed. The main factors determining the possibility of rational machining of high-strength materials by cutting are to ensure the maximum possible softening of the material of the sheared layer while maintaining a sufficiently high strength and wear resistance of the cutting tool at elevated temperatures, creating high rigidity and vibration resistance of the technological system, as well as controlling heat fluxes in the contact zone "tool-preparation".

In this regard, the study of the nature and degree of influence of the geometric parameters of the tool and processing modes on the temperature field of the surface layer of the processed surface of the workpiece during thermofriction milling is an urgent task.

2. Modeling technique.

Among the initial data for computer modeling, one of the most important is data on the mechanical properties of the processed material, i.e. about the relationship between deformations and stresses in it. These properties are described by the governing equation and the equation of state.

The well-known Johnson-Cook model is widely used as the determining equation in the works devoted to the study of the processes of plastic deformation of various materials using the FEM.

The coefficients of the Johnson-Cook equation are determined by conducting a series of special experiments in accordance with the methodology [15]. For this, special samples are made from the materials under study in accordance with the requirements of State Standard 1497-84 (ISO 6892-84), which are subjected to tensile tests at various temperatures (25 °C, 200 °C, 400 °C). The coefficients of the equations A, B, n, m, are determined by solving systems of equations taking into account the mechanical properties of the studied material of the conditional tensile strength (σ0.2), relative narrowing (ψk) and relative deformation (ε) obtained during the tests [15].

\[
\begin{align*}
\sigma_{0.2} (1 + 0.002) &= A + B(0.002)^n \\
Bn(\varepsilon^p)^{n-1}(1 + \varepsilon^p) &= A + B(\varepsilon^p)^n \\
Bn(\varepsilon^p)^{n-1} &= \sigma_B \\
A + B\left(\frac{\psi_k}{1-\psi_k}\right)^n &= \sigma(1 + 1.35\psi_k), \ \psi_B \leq 15\% \\
&= \sigma(0.85 + 2.06\psi_k), \ \psi_B > 15\%
\end{align*}
\]

To solve this system of equations and determine the coefficients, special software was used. The coefficients of the equation are removed from the finished table data (table I).

Table 1. The coefficients of the determining equation [12].

| billets   | A, Mpa | B, MPa | C  | n    | m    |
|-----------|--------|--------|----|------|------|
| 30CMCN    | 1680   | 500    | 0.5| 0.015| 1.0  |
| St. 45    | 410    | 280    | 0.47| 0.0037| 1.1  |
The methodology implements geometric and physical fracture criteria. As a geometric criterion separating the material in front of the cutting edge, the rebuilding of the finite elements (FE) of the tool mesh after passing the specified cutting path is used. The use of this criterion makes it possible to prevent FE distortion in the region of large plastic strains and thereby increase the calculation speed and stability. In the simulation, two-dimensional r-adaptive rearrangement of the finite element mesh used in problems with a flat deformation scheme was used. The algorithm implemented in Explicit-Dynamic (Ansys) creates a new mesh based on the outer border of the old mesh. As a physical criterion for the destruction of plastically deformable material, the criterion of accumulated plastic deformations in the Johnson-Cook form [16] is adopted:

$$\omega = \sum \frac{\Delta \varepsilon}{\Delta \varepsilon_f},$$

(1)

Where \( \varepsilon_f = [D_1 + D_2 \cdot \exp(D_3 \cdot \sigma^*)] \cdot [1 + D_4 \cdot \ln \varepsilon^*] \cdot [1 + D_5 \cdot T^*] \), \( D_1,..,D_5 \) - empirical coefficients (table 2).

**Table 2.** Parameters of plastic deformation of the destruction of the workpieces [16].

| Billets       | \( D_1 \) | \( D_2 \) | \( D_3 \) | \( D_4 \) | \( D_5 \) |
|--------------|----------|----------|----------|----------|----------|
| 30CMCN       | 0.54     | 4.89     | -3.03    | 0.014    | 1.12     |
| St. 45       | 0        | 1.3      | -0.17    | 0.063    | 2.8      |

In solving the thermomechanical problem, the boundary conditions consisted of a fixed cylindrical fixing of the workpiece support surface and movement, as well as forced rotation of an absolutely rigid tool along the Z axis of the workpiece with a constant speed \( v \) and cutting depth \( t \). During the calculation, the 3D problem was solved taking into account the thermal conductivity. Material properties are presented in table 3.

**Table 3.** Thermophysical properties of materials.

| Options                        | Units | 30CMCN | St. 45 |
|-------------------------------|-------|--------|--------|
| Density, \( p \)              | kg / m³ | 7850   | 7850   |
| Young's modulus, \( E \)      | GPa   | 215    | 215    |
| Poisson's ratio, \( \nu \)    | -     | 0.3    | 0.3    |
| Specific thermal conductivity, average | J / (kgC) | 466   | 469    |
| Thermal conductivity, \( \lambda \) | W / (ms) | 39    | 79     |
| Initial temperature, \( T_t \) | °C   | 22     | 22     |
| Meltingpoint, \( T_f \)       | °C   | 1030   | 1500   |

The simulation process diagram is shown in figure 3. Table IV shows the processing conditions established during numerical experiments using the developed technique.

**Figure 3.** Diagram of the simulation process.
The friction at the pads between the tool and the part during modeling is most often described by the equation shown M.C.

### Table 4. Conditions for numerical experiments.

| Variable factors          | Stabilized factors                  |
|---------------------------|-------------------------------------|
| V = 20, 60, 120, 180 m / min | Dinst = 148mm, Dbil = 100mm,         |
| nshp= 100, 400, 800, 1000 rev / min | t = 1.0mm, βu = 15°                  |

3. **Simulation results and discussion.**

Figure 4 shows the temperature distribution in the volume of the cutting zone during thermofriction milling of workpieces from difficult to process materials.

![Image of temperature distribution](image1.png)

**Figure 4.** Temperature distribution in the shank of the workpieces.

It is noticeable that when processing steel 45, the temperature distribution is higher. And in both cases, the maximum temperature under the contact layer does not exceed the recrystallization temperature.

The temperature distribution in the volume of the cutting tool is shown below (Figure 3)

![Image of temperature distribution](image2.png)

**Figure 5.** The temperature distribution in the blade shank.
Above the picture showed the temperature distribution more clearly, but does not fully change the character. In this connection, also graphs of temperature variation and the cutting tool when processing thermo-frictional turn-milling were obtained in the shank of the preforms (figures 6 and 7).

![Graphs of temperature changes in the shank of the workpieces](image1)

**Figure 6.** Graphs of temperature changes in the shank of the workpieces during thermo-friction milling.

When the tool is inserted into the processed material, the temperature quickly increases to values of 200°C and 250°C (figure 6, a and b). Further, in a certain period of time, becoming constant, it goes to a sharp linear increase. Then the meaning retains. It should be noted that the final temperature is constant and does not exceed the temperature of recrystallization, which indicates high quality performance of the treated surface in laboratory conditions at KSTU.

![Graphs of temperature changes in the shank of the cutting tool](image2)

**Figure 7.** Graphs of temperature changes in the shank of the cutting tool during thermo-friction turn-milling.

From figure 7 it is obvious that the nature of the change and the temperature in the shank of the cutting tool are practically the same and it is ≈ 120°C.

The constant value of the temperature distributed in the cutting zone and on the contact surface of the cutting edge of the tool determines the high accuracy and quality of the machined surface and does not change the mechanical properties of the material.

It should also be noted that the main conditions for satisfactory thermo-friction machining are ensuring the maximum possible rigidity and vibration resistance of the technological system, careful sharpening of the cutting tool and the cleanliness of its working surfaces. When choosing the optimal
processing conditions, this method of milling provides the same accuracy and roughness of processing as with rough grinding, and at the same time gives the best surface quality, and therefore, greater durability and reliability of operation of manufactured parts.

This is explained by the absence of such defects characteristic for grinding as burning, structural transformations, and abrasive particles sharpening the surface layer.

4. Conclusions
In a comparative analysis, the temperature distribution during thermo-friction turn-milling of blanks from St.45 and 30CMCN materials, the following conclusions were obtained:

- it was found that the final temperature is constant and does not exceed the recrystallization temperature, which indicates high quality performance of the treated surface;
- it was revealed that the nature of the change and the temperature in the shank of the cutting tool is practically the same and it is \( \approx 120^\circ C \);
- it was found that a constant value of the temperature distributed in the cutting zone and on the contact surface of the cutting edge of the tool determines the high accuracy and quality of the machined surface and does not change the mechanical properties of the material.

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