Application of finite element method (FEM) to study stress-strain state and distribution of temperatures in cutting zone in turning of various structural materials by carbide tools with coatings of various composition and architecture

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Abstract. The paper considers simulation of cutting process conditions and state of a metal-cutting tool using the finite element method (FEM). The study considered the distribution of normal equivalent and tangential stresses in workpiece material during turning of aluminum-deformable alloy G-AlMg5 (DIN 1725) and copper C11000. Based on the calculated stress values, the values of plastic strains of the workpiece material were determined throughout the whole process of turning with the necessary time sampling of the process. The distribution of temperatures in cutting zone during turning of steel 5135 by carbide tools with coatings of different composition and thickness was studied. The obtained results were compared with the data obtained during the corresponding cutting tests. The paper considered the influence of such coating parameters as thickness, element composition and architecture on distribution of temperatures in a workpiece, cutting tool and chips during the cutting process.

1. Introduction
Simulation of the process of material-cutting using the finite element method (FEM) has a quite long history. Gunasekera et al [1] note that the finite element method (FEM) is actively used to simulate the metal-cutting processes. Simulation of the stress-strain state of a coated substrate, in general, for orthogonal cutting conditions [2-5, 11, 13]. Modeling of the friction and wear conditions and thermomechanical state for cutting tools with monolayer [6, 12, 14, 15] and multilayer [7-10, 13] coatings were conducted in a large number of studies.

Together with the development of new models for cutting with coated tools, modifying coatings of a new type multilayer, composite, gradient, and nano-structured are being created and studied. In particular, the study of the properties of multilayer wear-resistant coatings of various composition and architecture is considered in [16-22]. Meanwhile, real cutting tests are still an unchallenged and quite irreplaceable method to study the properties of a coated tool, and in some cases, it is reasonable to combine such studies with mathematical modeling of the process. Such a combination of methods makes it possible not only to obtain confirmation of the experimental data, but also to study much deeper the processes occurring in the cutting zone. The most important factors affecting tool life and reliability of a cutting tool are stress-strain state and temperature distribution in the cutting zone.

The temperature arising in the cutting system is generated as a result of the processes occurring in the zones of action of three main heat sources strain and two frictional ones from friction along rake and flank faces of a tool [23]. Given the weak possibilities of the influence of coatings on strain heat sources, it is of great interest to consider the possibilities of its influence on frictional heat sources along rake and flank faces of a tool. In the process of cutting, almost all mechanical energy is converted into thermal
energy. Meanwhile, wear resistance of a tool is largely determined by temperature conditions of a cutting system. For a tool-workpiece system, regardless of the cutting modes, there is an optimum cutting temperature to minimize tool wear. That means that if during machining the cutting temperature is less than optimum, then it should be increased, and if the cutting temperature exceeds optimal, then it is necessary to create conditions for its reduction. Control over the cutting temperature and its maintenance at a pre-set level excludes the factor of negative effect of temperature on tool wear. Such control can be achieved due to the regulation of heat flows in a tool-workpiece-chips-environment system.

The conceptual role of a coating is in a dual function [16, 18], since it can not only sufficiently change the surface characteristics of tool material (frictional properties, thermal conductivity, propensity of tool material to physicochemical interaction with the material being machined, etc.), but it also can affect contact processes. Thus, the multifunctional performance of the intermediate technological medium like coating makes it possible to predict the possibility of directional control over cutting temperature [16-22].

In fact, on the one hand, a coating can significantly reduce the friction coefficient in the tool-workpiece system and reduce the power of frictional heat sources. On the other hand, the coating, characterized by screening function, can significantly reduce the intensity of heat flows into cutting wedge of a tool and thus increase the temperature threshold of the beginning of the adhesion interaction in the workpiece-tool system and reduce the intensity of interdiffusion between them [20-22].

2. Materials and experiments

Let us consider the challenge of kinematics for the process of turning of a workpiece [23].

The turning process was simulated based on the calculation of the stress-strain state of a workpiece, using a number of the following assumptions:

1. The coefficient of friction along rake face of a cutter is assumed as constant along its entire length and independent from tangential stresses.
2. The coefficient of friction along flank face is assumed as constant and equal to the coefficient of friction on rake face.

ANSYS Workbench software was selected as a simulation tool, with spatial mode as 3D and calculation type as dynamic. The calculation purpose is in the stress-strain analysis of a workpiece at the current moments of the cutting process. Finite element mesh is based on the SOLID186 element. In a tool-workpiece interface, the heat from the cutting zone is distributed between a workpiece, tool, environment and chips, that is, some heat is transferred into the workpiece, some into the tool, and some into the chips [16, 23].

A directional change in the chemical heat, chemical and structural properties of the coating makes it possible to influence the distribution of heat flows in order to increase the volume of heat released into the chips (under the conditions of high-speed machining) or, on the contrary, its conservation (reclamation) in the cutting zone at low cutting speeds. By varying the thermophysical parameters and the tribological properties of the contact zone, it is possible to model the characteristics of wear-resistant coatings at the tool-workpiece interface. One of these parameters is the thermal conductivity of materials. In thermophysical analysis, the use of DEFORM and ANSYS software allows modeling and visualizing contact processes in the cutting zone at various thermal, physical, technological parameters. DEFORM 3D software was used to simulate the cutting conditions for a coated tool. Meanwhile, in DEFORM 3D, motion is applied to a rigid body modeling a cutting tool, and nothing but forces is applied to a workpiece. Therefore, the tool moves relative to the workpiece. The standard process of cutting was used, and the main cutting conditions were set up, including machining modes, configurations of a tool and a workpiece, tool coating parameters, etc. The following cutting modes were used in the calculations: n=1600 rpm, f=0.11 mm/rev, a_p=0.7 mm.

In computer simulation, it is possible to vary the thermophysical parameters and tribological properties of the contact zone by modeling the characteristics of wear-resistant coatings at the tool-workpiece interface. Such parameter is represented not only by thermal conductivity of the coating itself, but also by the initial conditions of the contact zone (for example, the coefficient of friction), which in turn influence the formation of heat sources and their intensity.

To assess the degree of influence of the above factors on the efficiency of the cutting process, the following experimental studies were performed:
• evaluation of tribological characteristics at different temperatures, carried out at adhesiometer using spherical indenters of carbide with TiAlN, Ti-TiN-TiAlCrN coatings; a friction pair was represented by special samples from aluminum deformable alloy G-AlMg5 (DIN 1725), copper C11000 and steel 5135 with hardness of 20 HRC;
• studies in longitudinal turning of steel 5135, alloy G-AlMg5 and copper C11000.

The coatings under study were obtained using the developed process of filtered cathodic vacuum arc deposition (FCVAD) at the VIT-2 station [16-22].

The studies of cutting properties of a tool made of carbide with developed coatings were conducted on a lathe CU 500 MRD in longitudinal turning.

3. Results and discussions

The temperature changes in the tool-workpiece system could be in situ measured by means of a high-speed infrared (IR) camera of type FLIR SC7600 (frame rate: 328 fps at 320 × 256 pixels, measuring range: -20 to +3000°C, accuracy:±1°C).

As a result of simulation of the turning process, it is possible to reveal the distribution of normal equivalent and tangential stresses in the workpiece material. From the known stress values, it is possible to determine the values of the plastic strains of workpiece material throughout the entire turning process. In these numerical simulations with a computer model of the turning process, the studies consider the features of the stress-strain state of workpiece material made of copper C11000. Based on the results of calculations, it is possible to view the formation of chips and their shapes at different moments of time (Fig. 2) and also determine the values of stresses and strains arising in the material against the entire process of machining of a workpiece.

Fig. 3 shows the results of calculations in ANSYS at various coefficients of thermal conductivity of material of a workpiece, tool and coating. Meanwhile, coating material, which coefficient of thermal conductivity varies depending on the type of coating, is in direct contact with a workpiece. So, in Fig. 3a, coefficient of thermal conductivity of coating is \( \lambda = 0.25 \), and in Fig. 3b \( \lambda = 0.15 \). It can be seen that the temperature in the chips increases as the coefficient of thermal conductivity of coating changes at the same contact temperature, that is, most of heat from the cutting zone is transferred to the chips.
Figure 3. Calculation of temperature fields in ANSYS.

With the use of this model, it is possible to trace the change in temperature fields in the cutting zone. In general, by changing the thermophysical properties of the friction surfaces, thickness and structural composition of the coatings for a cutting tool, it is possible to predict the thermal conditions and thereby provide the most favourable conditions to ensure higher wear resistance in blade cutting.

The most interesting results of information content were obtained during simulation in DEFORM environment (Fig. 4). In addition to thermal parameters, this software may additionally take into account cutting speed, presence of coating or CF, as well as wear of a cutting tool and their influence on the distribution of heat flows.

Figure 4. Distribution of heat flows in the contact zone of a cutting tool with Ti-TiN-TiAlCrN coating (a), uncoated tool(b) and TiAlN coating (c) at cutting speed V = 450 m/min (after 5 min and at VB = 0.10 mm).

4. Conclusions

The application of the finite element method (FEM) makes it possible to effectively simulate both the stressed-strained state of a cutting tool and the temperature distribution in the cutting zone. The application of the above method can significantly increase the efficiency of the process of designing a metal-cutting tool with coatings of new generation, while reducing its cost price.

The analysis of the obtained data makes it possible to note the following:
1. It has been found out that the highest temperature is generated during the machining of various materials with an uncoated tool.
2. The maximum decrease in the intensity of heat flows in the tool-workpiece system is provided by Ti-TiN-TiAlCrN coating with multilayer composite architecture.
3. The maximum improvement in the thermal state of a carbide tool cutting wedge is provided by three-layer Ti-TiN-TiAlCrN coating, and that is explained by favourable combination of layers in the multilayer coating architecture. In particular, for such a coating, upper layer of TiAlCrN coating provides maximum reduction of adhesion activity of carbide with regard to material being machined, intermediate layer TiN ensures strong adhesion between wear-resistant and adhesion layers, and lower
adhesion layer Ti efficiently shields heat flow action from frictional heat sources on rake and flank faces of a tool.

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