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Comprehensive analysis of tribological factor influence on stress-strain and thermal state of workpiece during titanium alloys machining

The article describes how different friction coefficients under certain cutting conditions and parameters affect the formation of the stress-strain and thermal states of the product when titanium alloy machining. A new research methodology is used for the study. Firstly, in the initial data for simulation, each time a different declared coefficient of friction is proposed, and every such task of the cutting process modelling is solved for various cutting parameters. The second stage analyzes how these coefficients influence the stress-strain and thermodynamic state of the workpiece and tool during cutting, as well as the tool wear dynamics. In the third stage of the study, ways for ensuring these analytically-grounded tribological cutting conditions are proposed. The analysis of different wear criteria in the simulation models of titanium alloys cutting is carried out. Experimental studies confirm simulation results.

1. Introduction

It is well known that the essential characteristics of titanium alloys are high specific strength and low density in combination with high heat resistance and corrosion resistance in various chemically active mediums [1]. These properties make it possible to use titanium-based alloys in various industries as structural materials. As a rule, titanium alloys are used mainly for manufacturing expensive parts (automobile and aircraft disks, turbine blades, etc.), which under operating conditions are exposed to significant force vibration loads at a sufficiently high temperature. It is known that the ability to withstand vibration loads is determined by the state of the surface layer and the sensitivity of these alloys to machining

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conditions. This is the reason for the efficiency of the use of function-oriented technological processes. The peculiarity of the technological processes type consists in the priority of high functional properties of the manufactured products, but not in the reduction of the production cost.

The performed research and production experience showed that types of machining and cutting parameters significantly influence the operational properties of titanium alloy parts. It is especially true for the products operating in difficult dynamic conditions. Therefore, the primary task is to increase the resistance to vibration loads, reduce the cutting-induced residual tensile stresses and increase the strength of the surface layer [2]. Complex dynamics of loads at the titanium alloy processing results from high ductility and viscosity of the processed material [3]. Thus, the effective machining of titanium alloys is possible only when two main tasks are solved: definition of rational cutting conditions and investigation of ways for achieving the required quality of the treated surface and the adjoining layer, which would preserve the initial physical and mechanical properties of the alloy or other values that guarantee the necessary strength characteristics, prolonged high-quality operation and reliability of the products.

Unfortunately, the used scientific methods for optimizing cutting parameters and making the correct choice of equipment for machining are insufficient. Viktor P. Astakhov gives the following results of the analysis of machining operations in the automotive industry [4]:

1) the correct geometry is chosen only for less than 30% of the cutting tool;
2) the optimal machining parameters are used only for 48% of operations;
3) only 57% of the tools are used before the total design durability is reached;
4) the correct tool material is selected only for less than 30% of the tools used;
5) rational brands of coolant and the conditions for its supply to the processing zone are applied only for 42% of operations.

This is because the existing theories, and the models of metal cutting based on them, do not correspond to reality even in the first approximation [5]. Therefore, the design of machining operations is still based on purely empirical data and experience. Adequate description and modelling of the cutting process is essential when optimizing the machining of titanium alloys.

A study on the determination of conditions ensuring cost price reduction of machinery [6] has shown that a reduction in cutting tools by 20% leads to a decrease in the cost of the product by only 0.6%. A twofold increase in the service life of the cutting tool also contributes to a low decrease in the cost of the product (only by 1.5%). But, an increase in processing productivity due to the use of more efficient cutting parameters and the correct geometry of the cutting edges by 20% leads to a decrease in the cost of the product by 15%!

Thus, it can concluded that the technological capabilities of cutting processes in actual production conditions, as a rule, are not fully used. It is most often due to the fact that the studies on the conditions for reducing the parameters of the power tension of the cutting process are ineffective. It is crucial for the processing of titanium alloys since this material is expensive, the products are of very high quality and the operational requirements are high. In this regard, further research on these processes based on the simulation and system analysis the mechanics of the cutting process are relevant. It will make it possible to evaluate, from a systematic perspective, the technological possibilities of increasing the productivity and quality of processing.

2. Literature review

J. Paulo Davim [7] and F. Klocke [8] conclude that the friction force related to the cut area is the decisive factor that determines the course of the entire chip formation process when machining titanium alloys. Based on numerous studies [4, 7–10], it has been established that an increase in the average coefficient of friction leads to an increase in the degree of plastic deformation of the removed layer, an increase in the cutting temperature and, as a consequence, to an increase in tool wear. However, it is essential to establish the trend of changes in these indicators and quantitatively assess each technological factor's influence on the operational parameters of machined products [7].

Stefan G. Larsson, a leading SECO expert, argues [11] that it is not that difficult to understand the basics of metal cutting: one only needs to know the geometry and the pre-state of the workpiece and the machine tool, and the cutting parameters that are determined analytically depending on the machining method. However, understanding the whole cutting process is a lot more complicated. Firstly, it is necessary to present this process as a tribological system, which can be defined as a system of surfaces coming into mechanical contact and moving relative to each other [11, 12]. Depending on the material of the workpiece, machining strategy, machine rigidity, material and coating of cutting tools, coolant, edge preparation, etc., different types of tribological systems can vary greatly, and any change in the system can completely change the wear rate of the tool.

In work [13], the primary condition for the efficiency of titanium alloy processing is a decrease in the radial component of the cutting force, which is due to the intense friction between the coming-off chips and the rake face the cutter. This can be achieved by reducing the coefficient of friction of the processed and tool materials, using the so-called oblique cutting, referred to as oblique. By oblique cutting is understood the process of removing allowance by the tool the cutting edge of which in the interaction with the workpiece has an angle Φ between the normal to this edge and the vector of longitudinal cutting speed. This is achieved by sharpening the main cutting edge at an angle or by an additional movement of the tool's cutting edge along with itself. There is the geometric oblique cutting in the first case, and in the second case, there is the kinematic oblique cutting.

The analysis of the results obtained in [14] makes it possible to estimate the upper value of the thermobaric load on the cutting tool in a wide range of cutting conditions when processing a titanium alloy. In turn, this makes it possible to establish a tool wear mechanism characteristic within a specific temperature and stress range on the tool working surfaces.

The following important issue is the analysis of possible and most effective methods for ensuring a low coefficient of friction, such as application-specific grades of tool materials, advanced coating and high-pressure metalworking fluid (MWF) supply [10].

To understand a specific cutting process, in order to make the best choice for insert geometry, grade and edge preparation, it is of utmost importance to realize all of these possible influences of the cutting process. The optimization of tribological processes in metal cutting results in the following [9]:

- Reduction of the energy spent in cutting due to energy losses during tribological interactions.
- Proper selection of application-speci?c tool material and tool coating for chosen performance criterion such as tool life, quality of the machined surface, efficiency, etc.
- Proper selection of tool geometry, which de?nes the state of stress in the deformation zone, stresses, temperatures and relative velocities at the tool–chip and tool-workpiece interfaces, the optimized tribological parameters.
- Control over machining residual stresses imposed (induced) in the machined surfaces.
- Proper selection of cooling and lubricating media as well as the method of their delivery and application technique.

Many researchers have tried to apply the methods of plasticity theory for analyzing the cutting process. The most significant number of studies were performed using sliding lines, in which only an idealized rigid-plastic model of the processed material can be used [15]. Methods of analysis of plastic flow in the area of chip formation, which are used in classical works on the cutting theory [16–18] are approximate engineering methods and do not answer a number of questions important for theory and practice, and even more so for quantitative assessment of such factors as the influence of geometric parameters of the tool on the cutting force, on the chip thickness ratio, on the intensity of residual stress and the thickness of the hardened layer of the treated surfaces, etc.

Analytical description of elastoplastic deformation when cutting metals and titanium alloys, in particular, is complicated [8, 12]. It involves mutual relations with other factors and phenomena that accompany the cutting process. Therefore, a more complete characterization of the physical cutting bases of titanium alloys can only be obtained by a comprehensive study of thermal phenomena, strains of the surface layers, cutting forces, cutting tool wear, and the machined surface quality. An effective modern tool for studying these properties is a simulation of the cutting process using the finite element method [15]. These are programs, such as DEFORM 2/3D, AdvantEdge, LS Dyna, Abaqus.

Thus, the main goal of the given work is to investigate how different friction coefficients under certain cutting conditions and parameters affect the formation of the stress-strain and thermal states of the product. A comprehensive analysis of these factors will allow for an analytical assessment of the effectiveness and feasibility of measures allowing the tribological improvement of the processing conditions of titanium alloys and, consequently, an increase in machining productivity, thus ensuring the specified quality of the treated surface layer. In addition, we must know which particular technological parameters are most important to ensure efficient machining conditions for titanium alloys.

3. Research methodology

The use of simulation allows us to offer a new approach for studying the influence of tribological factors on the stress-strain and thermodynamic state of the workpiece and tool during cutting. The classical task involves the formation of initial data (workpiece and tool materials, cutting parameters, organization of the technological environment – cooling and lubrication, availability of tool coatings, etc.) The friction state in chip-tool interface in this case is formed based on such conditions. However, in the given study, it is proposed to solve the inverse problem: in the initial data for simulation, the declared coefficient of friction is assumed and the task of modeling the cutting process is solved. The second stage analyzes how these coefficients affect the stress-strain (including residual) and thermodynamic state of the workpiece and tool during cutting, as well as the dynamics of tool wear, etc. The third stage of the study proposes ways of providing these analytically-based tribological cutting conditions. The results of the analysis make it possible to choose such design, technological or organizational decisions that implement the optimal machining conditions in the most efficient way. Usually, the most effective method for reducing the friction coefficient when cutting titanium alloys is the use of special wear-resistant and antifriction coatings, as well as the use of special lubricant-cooling liquids. The effectiveness of this methodology consists in a solution more focused on the problem of organizing a functionally oriented technological environment.

The modern software DEFORM-2D (Scientific Forming Technologies Corp.) was used for predictive research of the machining process [19]. This system is a multi-purpose FEM analysis program, which is designed to solve two- and three-dimensional dynamic nonlinear problems of the mechanics of a solid body deformation, as well as problems related to this process. Explicit and implicit finite element method with the possibility of constructing a Lagrangian, Euler and hybrid meshes, multicomponent hydrodynamics, a smoothed lattice method based on Galerkin's method are implemented in them. Procedures for automatic adjustment and smoothing of ordinary-element meshing in the degeneration of elements, highly efficient algorithms for solving contact problems, a wide range of problem-oriented specifications of materials, user programming capabilities were used in this software.

The source conditions for the DEFORM pre-processor during simulation of the machining (cutting) operation are: 2D model of machining part (surface); cutting parameters; geometry of the cutting edge, tool material and a covering; mechanical and thermophysical characteristics of the processed material (Ti6Al4V); model of tool's wear (Archard and Usui); total remeshing criteria (calculated as a sum of the reduced errors of modeling on a power vector, vector of speed and admissible geometrical error); type of the strain simulation (Lagrange Incremental); iteration method (Direct Iteration), type of the deformation and temperature solver (Skyline method).

An important step in the method of studying the stress-strain state of a titanium alloy workpiece during cutting is the correct choice of the most effective format of the FEA analysis solver (including the matrices of irregular structure), which is Sparse or Skyline. Author's experience with similar problems suggests that the Skyline Conjugate Gradient runs faster and requires less memory than the Sparse matrix solver. However, in combination with an iterative solver, it shows difficulty in converging solutions due to a problem with insufficient points of contact. It was found that, for example, when simulatiing the cutting process with the small depth, as soon as a small number of nodes are found in the contact, then, if the Skyline solver is used, there arise problems with the convergence of the results of the study. Therefore, it is advisable to use the Sparse solver for this class of tasks. However, for problems with a large number of tetra-elements (four-node Lagrangian meshes), the Sparse matrix solver requires more memory than a computer can allocate, and therefore the calculation can be stopped without warning. It is experimentally found that the maximum limit for the Sparse solver is 140 thousand elements. Therefore, the use of the Skyline solver is more efficient for modelling cutting processes with a cutting thickness greater than 0.5 mm.

The continual approach to the description of fracture processes implies the construction of theoretical models of the continuous medium describing fracture as a process based on the constitutive equations written in a single form for the fractured and unfractured states of the machined material

The component of the dissipation rate, which characterizes the plastic deformations of the workpiece, is a homogeneous function of the first order of this plastic strain rate, which corresponds to the case of an elastic-plastic state, independent of the time scale of the cutting process. It is evident that plastic deformation increases under dynamic load. The resistance of the workpiece matherial, which is characterized by the modulus of elasticity (for cutting – the shear modulus G and yield strength σ_{YS}), in addition to temperature, also depends on an additional parameter of the state, characterized by the fracture criterion D.

Based on the high plastic properties of titanium alloys, we can conclude that, according to the existing models of cutting using deformation, the force and energy fracture criteria (McClintock, Oyada, Ayada, Osakada and other methods [21]) in general adequately describe the rheological pattern of the chip-formation process. However, the most adequate are models that use energy criteria of destruction, such as the Cockcroft-Latham (D1) or Rice-Tracy (D2) normalized criterion [22]. These fracture criteria are based on the calculation of the potential energy of plastic deformation, i.e., the area of the figure, which is bounded by the stress-strain curve:

$$D_1 = \int^{\overline{\varepsilon}} \frac{\sigma_{\max}}{\overline{\sigma}} \, d\overline{\varepsilon}, \tag{1}$$

$$D_2 = \int^{\overline{\varepsilon}} e^{\frac{\alpha \sigma_m}{\overline{\sigma}}} \, d\overline{\varepsilon}, \tag{2}$$

where $\overline{\varepsilon}$ is the accumulated equivalent strain; $\sigma_{\max}$ is the maximum principal stress; $\overline{\sigma}$ – effective Mises stress; α is the coefficient that depends on the properties of the material; σ_m is the hydrostatic pressure.

Thus, the given study is devoted to solving the following problems. Firstly, it is necessary to investigate the influence of tribological cutting parameters on loading, stress and thermodynamic parameters of titanium alloy cutting for different cutting parameters. Then, it should be analyzed how these coefficients influence the stress-strain and thermodynamic state of the workpiece and tool during cutting, as well as the dynamics of tool wear. Then, already in the third stage of the study, ways for providing these analytically grounded tribological cutting conditions will be proposed. This approach to solving the best provision of cutting hard-to-machine materials seems the most effective and scientifically grounded.

4. Results of investigation

The analysis of the loading, stress-strain and thermodynamic state of the workpiece during cutting of the most commonly used titanium alloy Ti6Al4V at cutting speeds from 50 m/min to 200 m/min and various friction coefficients

(0.3–0.6) was carried out. In addition, studies on the cutting edge wear rate for these conditions were carried out in Deform 2D. The purpose of such studies was to determine the optimal cutting conditions and the use of the specific technological environment (cooling, lubrication, tool coatings) that provides the specified friction conditions.

The studies carried out have shown that the coefficient of friction significantly affects the loading parameters during the titanium alloy machining. The dynamics of the cyclic change in the cutting force is a consequence of the adiabatic shear in the chip formation zone and is confirmed by the sawtooth shape of the chip [3]. The mechanism of sawtooth chip formation in machining titanium alloys is due to thermo-plastic instability within the primary shear zone. The cyclicity of the dynamic process of loading the cutting tool during machining of titanium alloy Ti6Al4V depends on the speed and depth of cut. Its period is 1–1.2 milliseconds at a speed of 50 m/min (Fig. 1a) and 0.6–0.8 milliseconds at a speed 100 m/min (Fig. 1b).

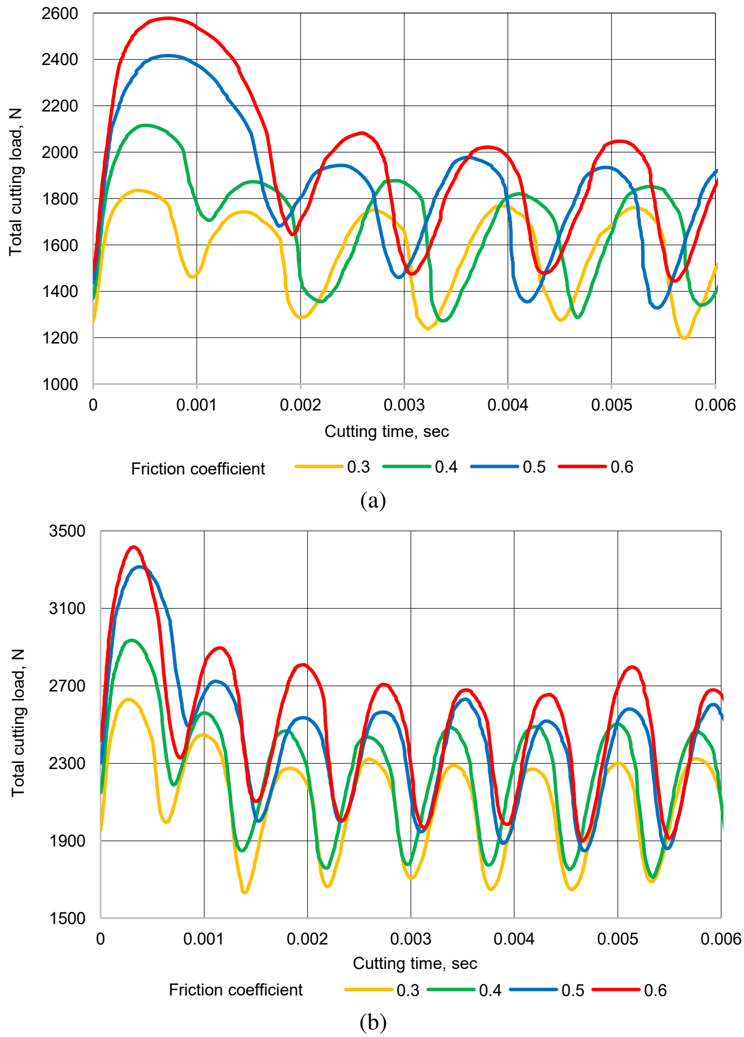


Fig. 1. Dependence of the cutting force when machining titanium alloy at speed of 50 m/min (a) and 100 m/min (b) on provided tribological cutting conditions

The analysis of the influence of tribological cutting conditions shows a significant effect of the avowed friction ratio on the cutting force. For example, at a speed of 50 m/min, the average value of the cutting force increases by 5.8% with an increase in the friction coefficient from 0.3 to 0.4; by 13.0% with an increase in the friction coefficient from 0.3 to 0.5 and by 17.6% with an increase in the friction coefficient from 0.3 to 0.6. At a cutting speed of 100 m/min, these ratios are approximately the same and amount to 6.6%, 14.9% and 16.6%, respectively (Fig. 2).

Furthermore, the simulation results obtained show that, when the cutting speed of titanium alloy Ti6Al4V increases from 50 m/min to 100 m/min, the cutting force increases significantly (by about 35%) and then when the speed increases to

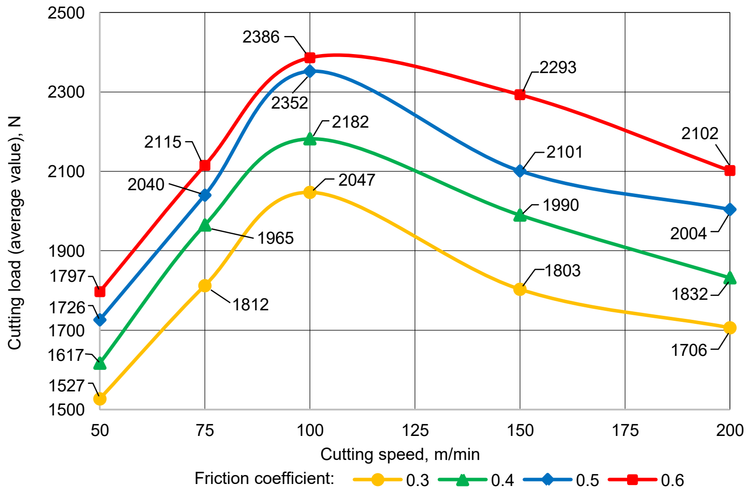


Fig. 2. Dependence of the cutting load when machining titanium alloy at a speed of 100 m/min on provided tribological cutting conditions

200 m/min, it decreases slightly (by about 10%). These results can be explained by specific thermophysical and physical-mechanical features of titanium alloys [23]. Such a state is characteristic for all provided tribological conditions of cutting. These simulation results are well correlated with the experimental and theoretical results described in [24].

The correlation dependences of the cutting force are presented in the form of polynomial equations for cutting speeds from 50 to 200 m/min and for the provided friction coefficients of 0.3–0.6 obtained as a result of mathematical analysis of the graphs in Fig. 1:

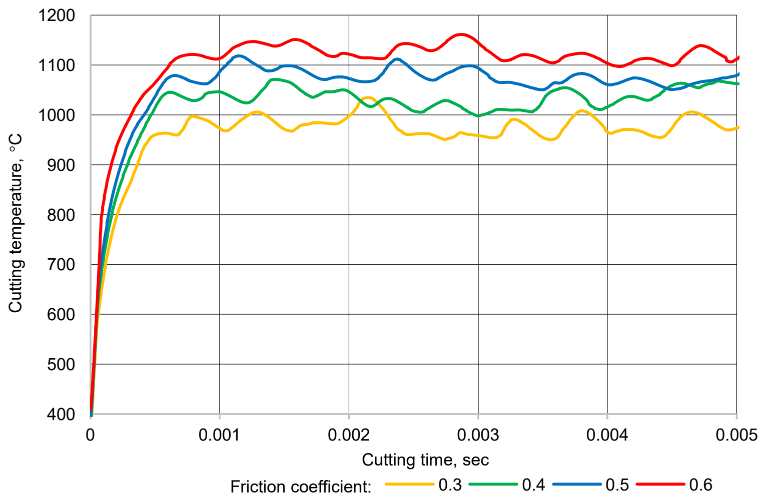
$$\begin{aligned} P_{0.6} &= 0.0006V^3 - 0.27V^2 + 44.34V - 210, \\ P_{0.5} &= 0.0009V^3 - 0.44V^2 + 60.22V - 334, \\ P_{0.4} &= 0.0009V^3 - 0.40V^2 + 55.56V - 281, \\ P_{0.3} &= 0.0009V^3 - 0.41V^2 + 54.64V - 319, \end{aligned} \tag{3}$$

where P_i is the average cutting load when machining a titanium alloy Ti6Al4V at different speeds on the assumed friction coefficient i ($i = 0.3, \ldots, 0.6$).

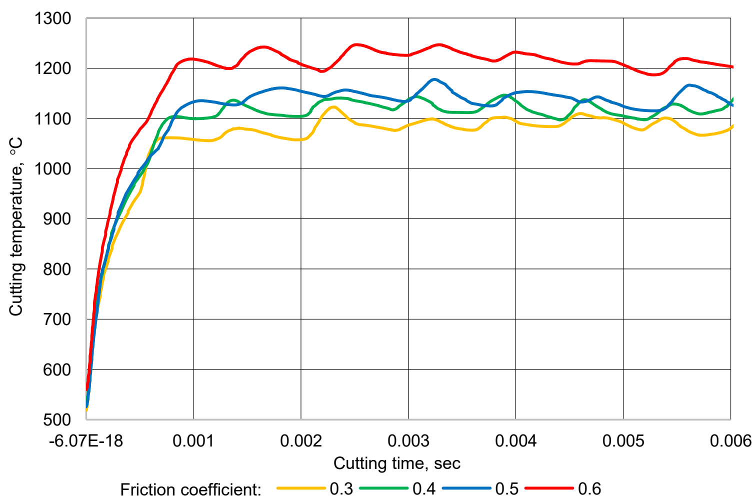
An important stage of the research is studying the influence of tribological factors on the thermodynamic state of the cutting process of titanium alloys. It is crucial due to the presence of specific thermophysical properties of titanium alloys and their influence on the power indicators of the cutting process and the stress-strain state of the cutting zone. All these factors ultimately have a significant impact not only on the loading state of the tool but also on the intensity of tool wear and the formation of the functional properties of the machined workpiece surface (roughness, residual stresses and strains, etc.) [25].

The conducted research confirmed the conclusions of the known studies [26] that the cutting parameters significantly affect the thermodynamic state of the workpiece and tool. For example, increasing the cutting speed from 50 m/min to 100 m/min increases the cutting temperature of titanium alloy by about 10% for different tribological cutting conditions (Fig. 3).

It should be noted that the established friction coefficient has a significant influence on the thermodynamic state of the cutting process. For example, at 50 m/min, the average cutting temperature increases by 5.5% when the friction coefficient increases from 0.3 to 0.4; by 10.1% when the friction coefficient is



(a)



(b)

Fig. 3. Dependence of the cutting temperature when machining titanium alloy at the cutting speed of 50 m/min (a) and 100 m/min (b) on provided tribological cutting conditions

increased from 0.3 to 0.5 and by 14.5% when the friction coefficient is increased from 0.3 to 0.6. These ratios are slightly lower at 100 m/min cutting speed and are 3.1%, 4.8%, and 12.3%, respectively (Fig. 4).

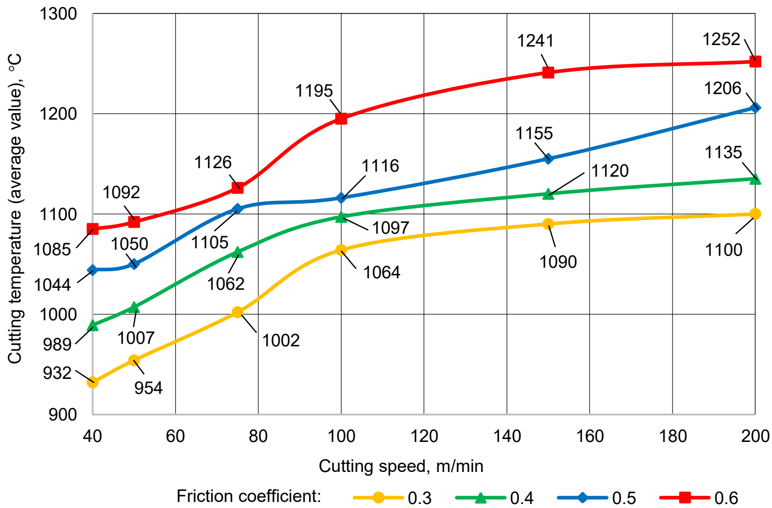


Fig. 4. Dependence of the cutting temperature when machining titanium alloy at a speed of 100 m/min on the assumed tribological cutting conditions

Moreover, the dynamics of temperature change with increasing cutting speed is always positive, in contrast to the load. There is no explicit temperature extremum in the cutting speed range from 40 m/min to 200 m/min. However, it should be noted that this positive trend after 100 m/min is negligible. That is, with a significant increase in cutting speed, the temperature changes very slowly and non-equivalently. Studies of high-speed machining (HSM) (not described in this paper) conducted by the authors, as well as works [27, 28] confirm that at cutting speeds of 800 m/min and above, the temperature is significantly redistributed: the chip temperature increases and the temperature of the machined ball of the workpiece decreases significantly. Different types of hard tool materials, including ceramic, diamond, and cubic boron nitride (CBN), are highly reactive with titanium alloys at high temperature. However, binder-less CBN (BCBN) tools, which do not have any binder, sintering agent or catalyst, have a remarkably longer tool life than the conventional CBN inserts even at high cutting speeds. To get a deeper understanding of high-speed machining of titanium alloys, the generation of mathematical models is essential. The models are also needed to predict the machining parameters for HSM [27]. Strangely enough, the coefficient of friction has virtually no effect on the shear angle during cutting and thus also on the chip thickness (compression) ratio. Fig. 5 shows the simulation results for these parameters. It can be concluded that the change in the chip compression with a friction coefficient of 0.3 and a friction coefficient of 0.6 changes by only 4.3%.

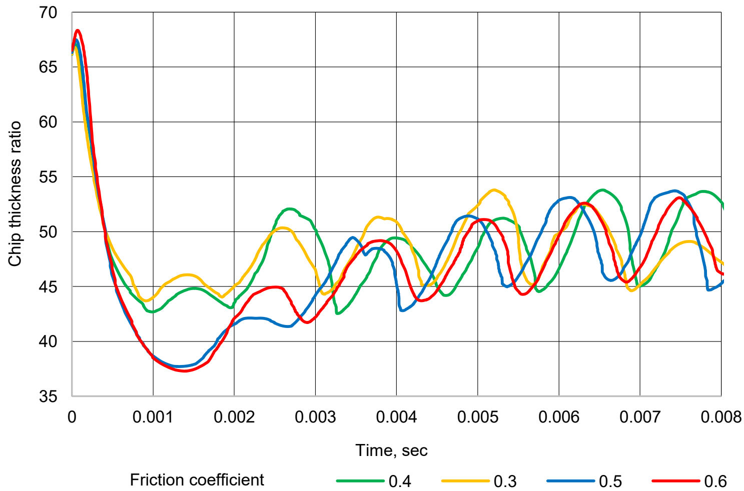


Fig. 5. Dependence of the chip thickness ratio when machining titanium alloy at speed of 50 m/min on provided tribological cutting conditions

As studies have shown, the influence of the assumed friction coefficient has a rather significant impact on the stress-strain state of the cutting zone when machining titanium alloy Ti6Al4V. For example, at 100 m/min, the average cutting stress increases by 6.5% when the friction coefficient increases from 0.3 to 0.4; by 8.9% when the friction coefficient increases from 0.3 to 0.5 and by 10.0% when the friction coefficient increases from 0.3 to 0.6 (Fig. 6).

The tool wear simulation research method is significant. Firstly, it is necessary to find out distinct zones of the tool with the maximum wear rate. There are two

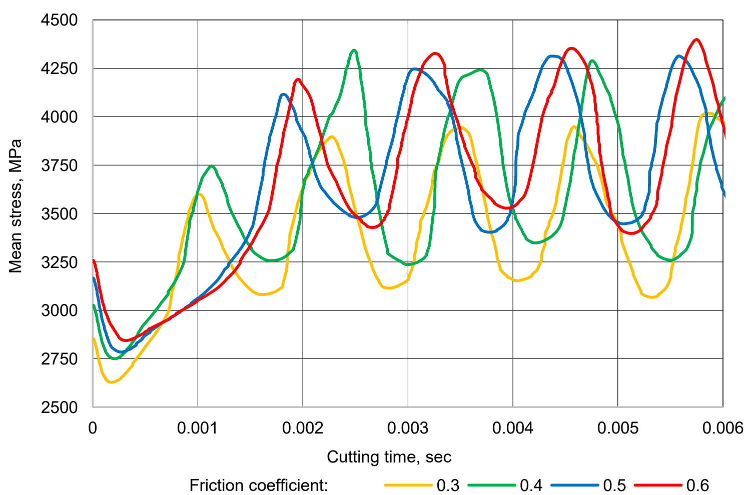


Fig. 6. Dependence of the cutting mean stress when machining titanium alloy at speed of 50 m/min on provided tribological cutting conditions

zones of a greatest wear when machining titanium alloy (Fig. 7a). Thus, wear at 2 points must be simulated: A – on the rake tool face and B – on the flank (relief) face). Therefore, we tracked these points and conducted a comparative analysis of the dominant wear (Fig. 7b). The results of the influence of the coefficient of friction on these parameters will be presented below.

Another critical aspect of the accuracy of the cutter edge wear simulation is the selection of an adequate analytical wear model. The wear mechanism of cutting tool materials in the machining of titanium alloys is fundamentally different from that in the machining of steel and nickel-based alloys. The administrative panel of

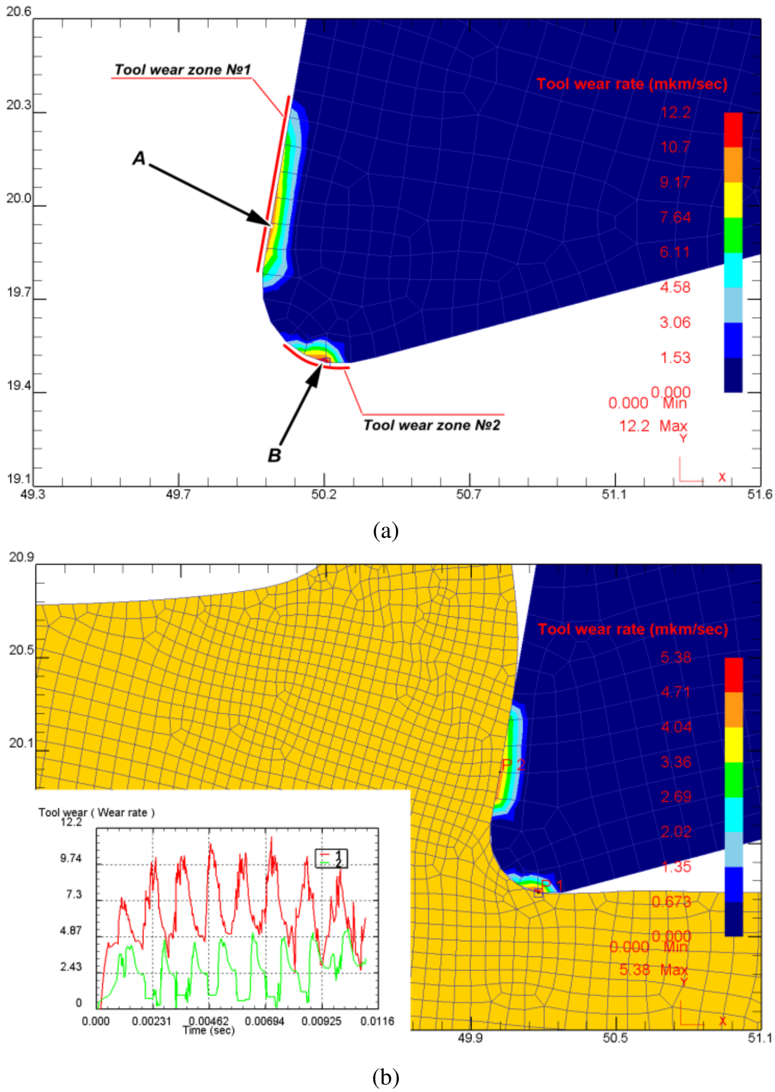


Fig. 7. Schematic (a) and simulation (b) of tool wear during titanium alloy machining

the DEFORM 2/3D system offers 2 main wear criteria - the Usui criterion and the Archard criterion [29].

The Usui criterion is described by the equation [30]:

$$w = \int a\,P\,V\,e^{-b/T}\,\mathrm{d}t, \tag{4}$$

where w is the wear rate of the tool, which is the amount of wear in µm per second (µm/m); p is the interface pressure; V is the sliding velocity of the chip; T is the interface temperature in the cutting zone; dt is the time increment; a, b are the experimentally calibrated coefficients.

According to the Archard law [31] of adhesive wear, the wear volume is proportional to the normal force (P), the chip's sliding velocity (V), and inversely proportional to the hardness (H) of the tool material:

$$w = \int K\frac{P^a V^b}{H^c}\,\mathrm{d}t, \tag{5}$$

where a, b, c, K are the experimentally calibrated coefficients (a, b are commonly taken as 1, and $c = 2$ for tool steels).

The above law mainly describes the adhesive wear process [32]. However, the friction coefficient is not explicitly included in Archard's equation. Let us introduce into the equation the friction force F_n [33] instead of the normal load. This value can be defined in Deform 2D as a result of a simulation of the cutting process. Believing that the friction factor plays a significant role in the assessment of tool wear, wewill modify the Archard formula by replacing the normal load with the friction force and, accordingly, introducing a new coefficient of wear K_n:

$$w = \int K_n\frac{(F_n f)^a\,V^b}{H^c}\,\mathrm{d}t, \tag{6}$$

where f is the coefficient of friction.

In the same way, the formula for the tool wear rate according to Usui's law is transformed as:

$$w = \int a\,F_n\,f\,V\,e^{-b/T}\,\mathrm{d}t. \tag{7}$$

The analysis of equation (7) allows us to conclude that the provided friction coefficient significantly influences tool wear both on the rake and the flank faces when cutting titanium alloy. Moreover, fluctuations in the tool load will lead to synchronous changes in the wear rate. For example, at 50 m/min, the average tool wear increases by 13.5% when the friction coefficient increases from 0.3 to 0.4; by 28.6% when the coefficient of friction is increased from 0.3 to 0.5 and by 38.2% when the coefficient of friction is increased from 0.3 to 0.6. At a 100 m/min cutting speed, these ratios are 10.8%, 25.9%, and 40.3%, respectively.

In addition, it should be noted that the maximum wear rate of the rake face (point A – Fig. 7) is more intense than the highest rate of wear of the flank surface (point B – Fig. 7), regardless of the cutting speed and the provided tribological cutting conditions. So, at a cutting speed of 100 m/min, the average wear rate of the tool edge on the rake face (point A) exceeds the corresponding value on the flank face (point B) approximately 1.8 times (15.5 µm/sec and 8.5 µm/sec with the assumed friction coefficient of 0.3; 22.1 µm/sec and 12.0 µm/sec with the coefficient of friction 0.6) (Fig. 8).

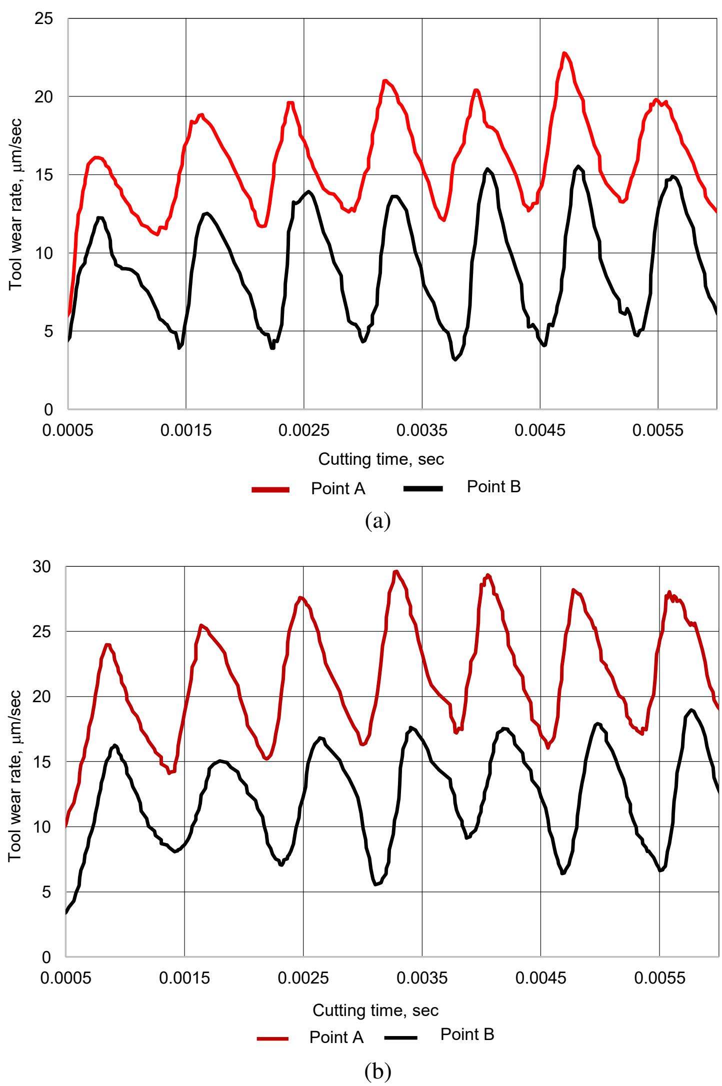


Fig. 8. Average wear rate of the tool on the rake face (point A) and on the flank face (point B) with provided for simulation friction coefficients: 0.3 (a) and 0.6 (b)

Different wear models (Usui or Archard) give different results of wear dynamics depending on the cutting speed. Thus, when using the Usui model for the speed range of 50–200 m/min, the average tool wear increases by 8.4% when the friction coefficient is increased from 0.3 to 0.4; by 22.5% if the friction coefficient increases from 0.3 to 0.5 and by 37.2% if the friction coefficient increases from 0.3 to 0.6 (Fig. 9). Using the Archard model, these ratios are 6.1%, 15.1%, and 25.6%, respectively (Fig. 10). Different priorities can explain this difference in the description of the physical model of the tool wear process [34].

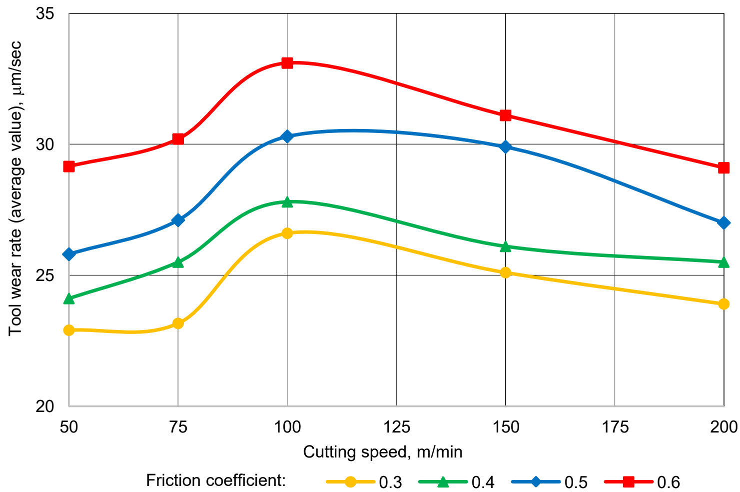


Fig. 9. The relationship of the average tool wear rate (Usui model) when machining titanium alloy at different speeds on provided tribological cutting conditions

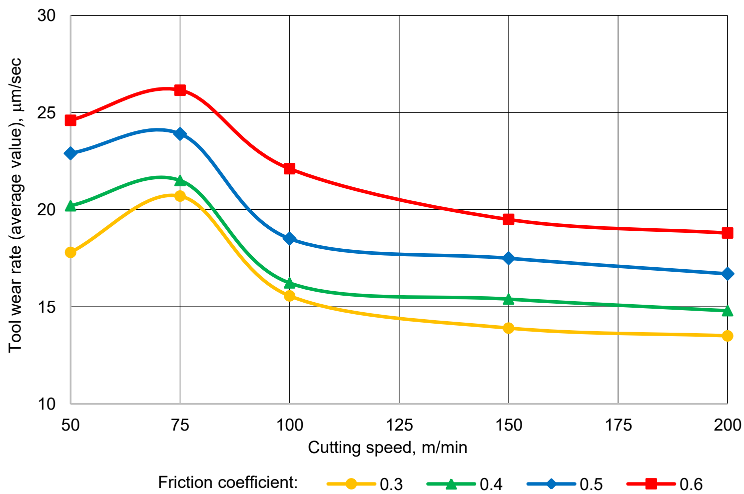


Fig. 10. The relationship of the average tool wear rate (Archard model) when machining titanium alloy at different speeds on provided tribological cutting conditions

Experimental studies were conducted to validate the theoretical and simulation researches. Different lubricating media were proposed to provide the different friction coefficients during experimental studies [35]. An unbiased experiment can be achieved in this way without using a different tool material or a new coating. The use of a cutter with tungsten carbide (WC8) brazed insert without coolant provides a friction coefficient of approximately 0.6. A friction coefficient of 0.5 is achieved by using machining fluid Blasocut 2000 (5% concentration). A 10% concentration of this lubricant reduces this coefficient to 0.4. A 10% solution of Blasocut 4000 CF coolant provides the lowest friction coefficient of 0.3 [36].

The cutting edge wear rate (Fig. 11) was analyzed after machining way of 100 m of titanium alloy workpiece (cutting depth was 1 mm, feed was 0.25 mm per revolution) at cutting speeds of 30 m/min, 50 m/min, 100 m/min and 150 m/min. The results of the experimental studies are shown in Fig. 12.

Fig. 11. Device for measuring the dimensional wear of the tip of a cutting tool edge

The most effective method for reducing the friction coefficient when cutting titanium alloys is the use of special wear-resistant and antifriction coatings [37], as well as the use of lubricant-cooling liquids [38]. Several technologies, such as cryogenic cooling, solid coolants/lubricants, minimum quantity lubrication (MQL)/near-dry machining (NDM), high-pressure coolants (HPC), internal tool cooling and compressed air/gases have been developed in recent years to reduce temperature in the cutting zone and increase the overall effectiveness of the cooling and lubrication process [39].

When machining titanium alloys, the cutting parameters should be plannned taking into account, in addition to productivity, also the quality of the processed layer, i.e., a complex of factors (such as hardening, cutting-induced residual stress

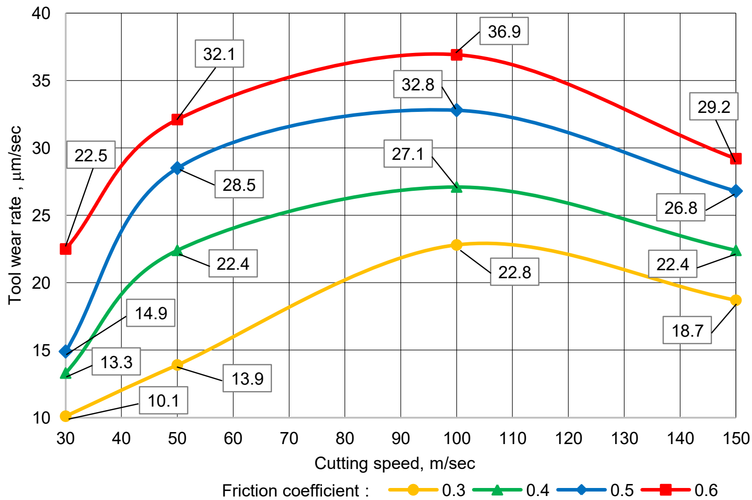


Fig. 12. Results of experimental studies

and strain, processing accuracy, surface roughness, tool wear resistance, etc.), but in each case depending on the technological and operational requirements for the product. This idea is the basis for function-oriented technological planning [40].

5. Conclusions

1. Complex dynamics of loads at the processing of titanium alloys result from high ductility and viscosity of the processed material. Therefore, the effective machining of titanium alloys is possible only when two main problems are solved: definition of rational cutting conditions and investigation of ways of achieving the required quality of the treated surface and cutting-induced operational properties of the machined layer. The related friction force is the decisive factor determining the entire chip formation process when machining titanium alloys. Thus, the main goal of the given study is to investigate to what extent different friction coefficients under certain cutting conditions and parameters affect the formation of the stress-strain and thermal states of the product. A comprehensive analysis of these factors will allow an analytical assessment of the effectiveness and feasibility of measures for tribological improvement of the processing conditions of titanium alloys and, consequently, an increase in machining productivity, thus ensuring the specified quality of the treated surface layer. In addition, it is crucial to know exactly which cutting parameters are most important to ensure efficient machining conditions for titanium alloys.
2. The proposed methodology of the described study differs from the traditional approach and consists of the following stages. Firstly, each time, a different declared coefficient of friction is proposed in the initial data for simulation. Every such task of the cutting process modelling is solved for various cutting

parameters. The second stage analyzes how these coefficients affect the stress-strain (including residual) and thermodynamic state of the workpiece and tool during cutting, as well as the dynamics of tool wear, etc. At the third stage of the study, ways for ensuring these analytically reasoned tribological cutting conditions are proposed. The analysis results make it possible to make such design, technological or organizational decisions that implement the optimal machining conditions in the most efficient way. Usually, the most effective method for reducing the friction coefficient when cutting titanium alloys is the use of special wear-resistant and antifriction coatings, as well as the use of special lubricant-cooling liquids. This methodology's effectiveness consists in a more focused solution to organizing a functionally oriented technological environment.

3. The studies carried out have shown that the coefficient of friction significantly affects the titanium alloy machining loading parameters. The dynamics of the cyclic change in the cutting force results from the adiabatic shear in the chip formation zone and is confirmed by the sawtooth shape of the chip. The mechanism of sawtooth chip formation in machining titanium alloys is associated with thermo-plastic instability within the primary shear zone. The cyclicity of the dynamic process of loading the cutting tool during machining of titanium alloy Ti6Al4V depends on the speed and depth of cut and its period is 1–1.2 µsec at a speed of 50 m/min and 0.6–0.8 milliseconds at speed 100 m/min. The significant influence of the tribological cutting conditions on the cutting force is proved by analyzing the simulation results in Deform 2D. For example, at a speed of 50 m/min, the average value of the cutting force increases by 5.8% with an increase in the friction coefficient from 0.3 to 0.4; by 13.0% with an increase in the friction coefficient from 0.3 to 0.5 and by 17.6% with an increase in the friction coefficient from 0.3 to 0.6. At a cutting speed of 100 m/min, these ratios are approximately the same and amount to 6.6%, 14.9% and 16.6%, respectively.
4. The established friction coefficient also has a significant influence on the thermodynamic state of the cutting process. For example, at 50 m/min, the average cutting temperature grows by 5.5% when the friction coefficient increases from 0.3 to 0.4; by 10.1% when the friction coefficient is increased from 0.3 to 0.5 and by 14.5% when the friction coefficient is increased from 0.3 to 0.6. At the cutting speed of 100 m/min, these ratios are slightly lower and are 3.1%, 4.8% and 12.3%, respectively. As studies have shown, the influence of the provided friction coefficient has a relatively significant impact on the stress-strain state of the cutting zone when machining titanium alloy Ti6Al4V. For example, at 100 m/min, the average cutting stress increases by 6.5% when the friction coefficient increases from 0.3 to 0.4; by 8.9% when the friction coefficient increases from 0.3 to 0.5 and by 10.0% when the friction coefficient increases from 0.3 to 0.6.

5. Tool wear both on the rake and flank faces undoubtedly depends on the tribological conditions when cutting titanium alloy. Moreover, fluctuations in the tool load will lead to synchronous changes in the wear rate. For example, at 50 m/min, the average tool wear grows by 13.5% when the friction coefficient increases from 0.3 to 0.4; by 28.6% when the coefficient of friction is increased from 0.3 to 0.5 and by 38.2% when the coefficient of friction is increased from 0.3 to 0.6. At a cutting speed of 100 m/min, these ratios are 10.8%, 25.9%, and 40.3%, respectively. Using different analytical models makes it possible to determine various extreme values of tool wear. Maximum wear results are in the range of cutting speeds of approximately 60–70 m/min according to Usui's criterion and 100–120 m/min according to Archard's criterion. Different priorities can explain this difference in the description of the physical model of the tool wear process.
6. The analysis of the experimental results allows us to draw the following conclusions:
   - in general, the simulation results adequately reflect the pattern of tool wear during titanium alloy machining. However, differences in theoretical and experimental results exist. This can be explained by the fact that only physical material properties were taken into account in the simulation. At the same time, in the actual wear process, there are complex processes that cannot be described analytically. In addition, the assumed friction coefficients in the experimental studies (when using different coolant) are approximate and contain some error;
   - the error of deviation of simulated wear values from experimental values is approximately 19% when using the Archard model and 9% when using the Usui model. In addition, the wear extremum in the experimental studies is about 90–100 m/min, which approximately corresponds to the data obtained from simulations with the Usui criterion and differs significantly from the results of simulations with the Archard's criterion. Based on the comparison with the experimental data, it can be concluded that the Usui model is more adequate for describing the process of tool wear when machining a titanium alloy.

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