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SIMULATION AND ANALYTICAL STUDIES OF CHIP FORMATION PROCESSES IN THE CUTTING ZONE OF TITANIUM ALLOYS

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Abstract. The low machinability of titanium alloys is determined by the physical, mechanical, and chemical properties of these materials and their mechanical characteristics. It is also evident in the hardened state of the material being processed during cutting and in the initial state. This phenomenon is caused by thermodynamic parameters that determine the properties of titanium material at elevated temperatures. The peculiarities of the cutting and chip formation processes during titanium alloy machining are presented in this article. The peculiarity of the described approach is the analysis of the results of simulation modeling of cutting in Deform 2D software. It is proved that the frictional factor in the formation of the thermal characteristics of the cutting process, which arises as a result of the chip sliding along the tool, dominates the load factor (caused by force and deformation processes in the chip root). It has been established that the length of contact between the chips and the tool's rake face has a certain tendency to change: the contact length first increases and then decreases with increasing cutting speed. An analysis of the dependence of the chip compression ratio on changes in cutting speed has shown that with an increase in cutting speed, the average value of the compression ratio practically does not change, but the amplitude of its oscillation increases significantly, which is equivalent to a change in the shear angle. This parameter changes dynamically due to the adiabatic nature of chip formation

Keywords: titanium alloy, cutting, stress-strain state, adiabatic shear, chip compression ratio.

Introduction

Titanium alloys are known to be difficult to machine compared to other structural materials due to some specific mechanical, physical, and chemical properties. The main reasons for the relatively low machinability of titanium alloys are low thermal conductivity, high chemical reactivity, and low elastic modulus [1]. The machining processes of these materials are characterized by high cutting temperatures, which causes a significant reduction in the service life of the cutting tool and a significant intensity of vibration processes in the Machine-Fixture-Tool-Workpeace (MFTW) system [2].

The most effective steps to reduce the impact of factors associated with the poor machinability of titanium alloys are the development and implementation of new materials and surface coatings for cutting tools, improvement of their design and geometry, and optimization of cutting parameters [2]. However, any innovations should be based on the results of studies of power, stress-strain, and thermodynamic processes of cutting heterogeneous titanium alloys. Only in this case, the proposed technological implementations will not be random and stochastic but will implement a process of logical, scientifically based directed choice based on solving problems whose causes are clearly understood, quantitatively and qualitatively assessed, and adequate.

Literature review

The analysis of the use of modern scientific methods for optimizing the cutting parameters of hard-to-machine materials and the choice of cutting tools in high-tech engineering is still imperfect. Viktor Astakhov presents the following results of an analysis of machining operations in the US automotive industry [3]:

1) only less than 30 % of the cutting tools have the correct geometry;

2) optimal machining parameters are used for only 48 % of operations;

3) only 57 % of the tools are used until they reach their full calculated life;

4) the correct tool material is selected for less than 30 % of the tools used;

5) only 42 % of operations use rational grades of coolants and conditions of their supply to the machining zone.

Such shortcomings in the technological preparation of production are explained by the fact that the existing theories and models of metal cutting based on them do not correspond to reality even in the first approximation [3]. Therefore, the design of the structure and parameters of machining operations is still based on purely empirical data and production experience. An adequate description and modeling of the cutting process are particularly important when optimizing titanium alloy machining.

A study to determine the conditions that reduce the cost of machines [4] showed that a 20 % reduction in the number of cutting tools leads to a reduction in the cost of the product by only 0.6 %. A double increase in the service life of the cutting tool also contributes to a slight reduction in the cost of the product (by 1.5 %). However, a 20 % increase in machining productivity due to the use of more efficient cutting parameters and the correct geometry of the cutting edges leads to a 15 % reduction in the cost of the product!

Thus, it can be concluded that the technological capabilities of cutting processes in real production conditions are usually not fully utilized. Most often, this is because research into the conditions for reducing the power stress parameters of the cutting process is ineffective. This is extremely important when machining titanium alloys, as this material is expensive, the products are of very high quality, and the operational requirements are high. In this regard, further research into these processes based on modeling and systematic analysis of the mechanics of the cutting process is relevant. This will make it possible to evaluate the technological possibilities of increasing productivity and processing quality from a systemic point of view.

The advantage of titanium alloys compared to alternative aluminum and magnesium alloys are high heat resistance, which, under conditions of intensive use in difficult thermodynamic conditions, more than compensates for the difference in density (for magnesium-based alloys, this difference is 1.8 times, for aluminum – 2.7 times) [4]. Moreover, a more significant advantage of titanium alloys over aluminum and magnesium alloys is observed at operating temperatures above 300 °C, given that with increasing temperature, the strength of aluminum and magnesium alloys decreases significantly, while the specific strength of titanium alloys remains virtually unchanged. On the other hand, titanium alloys outperform most stainless and heat-resistant steels in terms of strength-to-density ratio at operating temperatures up to 400-500 °C. In addition, given that it is impossible to use the full strength potential of heat-resistant alloys due to the need to ensure structural rigidity and, for aircraft products, to ensure the aerodynamic configuration of individual surfaces (e.g., turbine blade profile, etc.), it turns out that replacing steel parts with titanium parts can result in significant weight savings without losing the strength parameters of such products.

At the same time, for most high-tech products made of titanium alloys, the following operational requirements must be met at the stage of machining and thermal hardening [5, 6]:

1. Ensuring the stability of high-strength parameters during short-term and long-term operational thermodynamic loads. Compliance with the limiting requirements for the tensile strength of titanium alloy products at a temperature of 20 °C not less than 100 Pa; during a 100-hour service life of the product at 400 °C – 75 Pa, and at 500 °C – 65 Pa.

2. Ensure the following plastic properties of titanium alloy products subject to significant dynamic loads (turbine blades, etc.) at room temperature: relative elongation – at least 10 %, transverse narrowing – up to 30 %, impact strength – 3 Pam.

3. The heat resistance of a titanium alloy is ensured by long-term (at least 100 hours of operation under high temperatures and shock, cyclic and alternating stresses) maintenance of plastic properties, i.e. the alloy should not acquire more than 5 % excessive brittleness during a 100-hour operational thermal load in the range up to 500 °C.

4. The requirements for fatigue strength at high temperatures are guaranteed by ensuring that the endurance limit of products without stress concentrators during operation without thermal load (20 °C) is at least 45 % of the ultimate strength, and at 400 °C – at least 50 % of the ultimate strength.

5. High creep resistance should be ensured for products subject to dominant tensile stresses (e.g., compressor disks) at operating temperatures up to 400 °C by guaranteeing a residual deformation of up to 0.2 % during 100 hours of operation.

The technological implementation of these requirements is complicated by the fact that titanium alloys belong to the group of difficult-to-machine materials due to the high ratio of yield strength to temporary fracture resistance [1]. For example, this ratio for titanium alloys is in the range of 0.85–0.95, while for steels it is only 0.65–0.75. At the same time, the mechanical characteristics of titanium alloys (relative elongation and reduction of the cross-sectional area of the product) are much lower (by 8–12 %) compared to heat-resistant steels. However, a decrease in the plastic properties of the machined layer of the workpiece during machining contributes to the appearance of micro- and macro-cracks in front of the cutting tool edge [6]. This phenomenon significantly complicates the process of plastic shear during the formation of the machined surface and creates the risk of cyclic residual tensile stresses [7].

Therefore, the chips formed during titanium alloy machining have distinct cyclic serrated chip defects that divide them into slightly deformed elements connected by a thin and highly deformed contact layer [8] (Fig. 1).

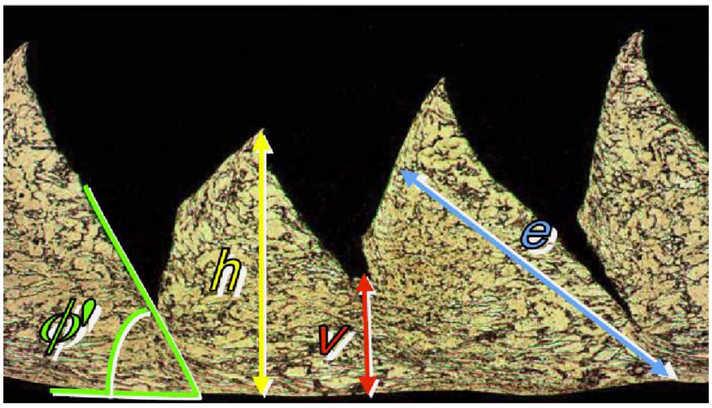


Fig. 1. The serrated shape of the chips formed during the machining of the titanium alloy Ti-6Al-4V [9]

Since the chip formation process is a generalized reflection of the complex action of power, thermodynamic, and stress-strain processes of cutting, it is important to have a more in-depth understanding of the main factors that form the chip formation mechanism. Many studies have paid attention to the tooth formation mechanism of chip formation, which can be mainly summarized as the adiabatic shear theory [4, 7, 10] and the periodic crack theory [9, 11]. The chip formation is dominated by the factors of mechanical properties of the material and force factors during the cutting process when the material undergoes a large localized strain in the primary shear zone. However, the dynamic mechanical behavior of materials under the influence of the frequency of large and high-frequency deformations and at elevated temperatures is still poorly understood, and the corresponding theoretical analysis is difficult to perform. It is more convenient and expedient to analyze the material's behavior in the chip formation process by the finite element method.

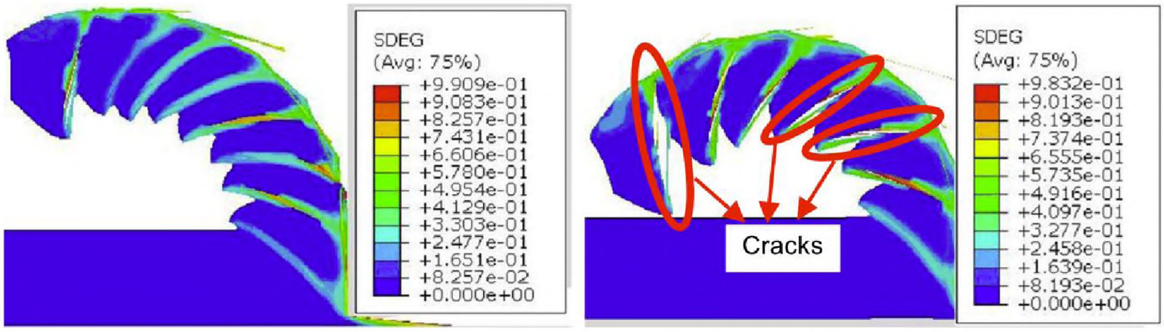


Fig. 2. Results of simulation of the chip forming process in the Abaqus/CAE system [12].

On the other hand, due to the strong adhesion and high temperatures, the titanium alloy material to be machined adheres to the cutting tool, which causes a significant increase in friction and uncertainty in the microgeometric shape of the cutting edge. The shear angle when cutting titanium alloys reaches 38 ... 44. However, when the cutting speed exceeds 60 m/min, chips are formed under conditions of a shrinkage factor greater than 1, i.e., the chips have a shorter length than the cutting path. Moreover, it is noted in [13] that the temperature in the cutting zone increases significantly with increasing cutting speed and to a lesser extent with increasing feed. This is a consequence of the combination of high tensile strength and high heat resistance of the material, which is characteristic of titanium alloy.

P. G. Davim notes [5] that the specific properties of titanium, including high strength at elevated temperatures, low elastic modulus, high chemical reactivity, and low thermal conductivity, negatively affect the machinability of titanium-based materials, the latter two being the most significant. However, there is very little or no research on quantifying these effects. For example, the relationship between the cutting parameters caused by induced vibration and the resulting dynamic cutting forces needs to be studied. There is also a lack of research on quantifying the chemical reactivity between titanium and tool material and the relationship between cutting parameters and workpiece forming. Most of the studies conducted on the machinability of titanium alloys were based on different cutting conditions, which makes it difficult to compare the results obtained by different authors.

The paper by J. I. Armarego and R. Brown discusses the specifics of chip formation during the cutting of titanium-containing alloys that are difficult to machine. Based on the special conditions of cutting such materials, it was concluded that the main cause of wear of cutting tools is the specificity of plastic shear. A model of the metal deformation zone is presented in [14], which has two types – a model with a single shear plane and a model with a developed plane. Since the machinability of titanium alloys is 3–4 times less than that of carbon steels and 5–7 times less than that of aluminum alloys [1, 5], the question arises of choosing such parameters of machining modes, cutting-edge geometry, and technological environment at which the power and thermodynamic load will be the lowest. For example, the coefficient of machinability of titanium alloys Ti-6Al-4V relative to AISI 1045 steel is 0.22–0.26 [2]. Therefore, most researchers [4–6, 9] recommend using low cutting speeds (up to 50 m/min) at low feeds (up to 0.2 mm/rev) with an intensive supply of lubricating and cooling fluids during the machining of titanium alloys [16]. This recommendation is further justified by the fact that at high (more than 50 m/min) cutting speeds, a chemical reaction occurs between the chip and the cutting tool material, which can lead to sudden chipping and the destruction of the cutting insert. For this reason, tool materials should be selected with high thermodynamic strength (i.e., tungsten-cobalt alloys are preferred over titanium-cobalt alloys), low cobalt content, and inertness in terms of chemical interaction with titanium. Under these conditions, the cutting tool should be made of more wear-resistant tool materials for machining titanium alloys than for carbon steels, with preference given to WC carbide grades [17].

Sandvik [18] recommends using GC1105 tool-grade inserts for titanium products. This PVD-coated carbide ensures high reliability of the cutting edges and high stability when machining materials that are prone to sticking or building up on the inserts. The specifically pointed geometry of the cutting edge guarantees high tool life combined with uniform wear of the blade. However, even if these conditions are met, it is recommended [18] to reduce the cutting speed by 3–4 times compared to the same parameter when machining medium-carbon steels to ensure sufficient tool life, especially for CNC machines [19].

When cutting titanium alloys, it is necessary to take into account the occurrence of several negative factors that will significantly affect the machinability of such material [1, 2, 15]:

– High temperature in the cutting zone leads to softening of the tool's hard alloys. This reduces tool wear resistance and cutting speed, which in turn negatively affects overall machining performance;

– high hardness and strength of titanium alloys, which create high contact stresses in the cutting zone, increase the likelihood of brittle fracture of the cutting tool;

– low thermal conductivity and high strength of materials lead to an increase in the intensity of heat flow in the direction of the tool. This leads to a reduction in tool life as a result of plastic fracture of the cutting edge;

– the high chemical activity of titanium-containing materials with difficult machinability, especially at high cutting temperatures, leads to the activation of physical and chemical processes on the tool blades, and this is the main reason for increased adhesive fatigue and diffusion wear of the tool;

– the tendency of titanium alloys to intense abrasive tool wear during machining.

Comparing the mechanical characteristics of hard-to-machine alloys and conventional carbon steels shows that the values of the real tensile strength and hardness of the HC at normal temperature and in the absence of deformation (hardening) are approximately equal. Therefore, the worse machinability of titanium alloys is determined by other physical, mechanical, and chemical properties and, above all, by the structure, mechanical characteristics that determine their properties not only in the initial but also in the hardened state and when heated, and are due to thermodynamic parameters that determine the properties of the material at elevated temperatures [20]. Most scientists note the following features of cutting difficult-to-machine alloys (including titanium):

1. The most significant reason for the difficulty of machining the above materials is the significant hardening of the material as a result of the process of plastic deformation of the metal during cutting [5]. The increased tack is explained by the specific features of the crystal lattice structure of these materials. The characteristic that determines the plasticity or ability of a material to harden is the value of the conditional yield strength, which corresponds to a 0.2 percent residual strain to the tensile strength - $\sigma_{0.2}/\sigma_V$. The smaller this ratio is, the more ductile the material is and the more work and cutting forces it requires for cutting. The value of this ratio for titanium alloys is 0.4–0.45, while for conventional structural steels, this value is 0.6...0.65 or more. Due to the increased ability to harden under plastic deformation of such alloys, the value of c can increase by a factor of 2 (from 600 to 1200 MPa), while the relative elongation decreases from 40–65 to 5–10 %.

2. Another important reason for the low machinability of titanium alloys is the relatively low thermal conductivity, which leads to an increased temperature in the contact zone, and thus to the activation of diffusion phenomena, intense adhesion of contact surfaces, and destruction of the cutting part of the tool [34].

3. Scientific sources [6, 22] emphasize that an important reason for the low machinability of most titanium alloys is the ability to maintain their original strength and hardness at elevated temperatures. This property leads to a high specific load on the contact surfaces of the tool during the cutting process. The low

thermal conductivity of these materials increases the effect of this factor. Therefore, the high temperature on the contact surfaces does not allow for an increase in plasticity and reduces the hardness of the cut layer.

4. Reduced vibration resistance of the MFTW system is due to the high hardening factor of titanium-containing materials with uneven plastic deformation [1]. The occurrence of vibrations leads to high-frequency fluctuations in the power and thermal parameters of cutting and the vibration load on the tool. This contributes to micro and macro cracking of the cutting edge. The phenomenon of chip adhesion to the tool's rake face is intensified in the presence of vibrations, which, in turn, has a particularly unfavorable effect on tool life.

There are many solutions to improve the machinability of titanium-containing materials in modern engineering. The priority is to ensure the most effective conditions for frictional interaction in the tool/workpiece subsystem. The most common ways to implement this idea are methods aimed at increasing the stability of cutting tools [23]. This is effective, first of all, if the tool material grade and the geometry of the cutting part of the tool are selected correctly. Special cutting fluids are another effective method of improving the machinability of hard-to-machine materials [24]. The application of special wear-resistant coatings that significantly reduce the friction coefficient in the contact group "Tool-Chip-Workpeace" has great potential in improving the efficiency of machining titanium alloys. To increase the efficiency of the machining process of difficult-to-machine alloys, including titanium alloys, the tool material must be carefully selected, and the cutting edge's geometry must be optimized considering the conditions and conditions and machining parameters [2].

Research methods

Research in the field of cutting dynamics is mostly based on one of two methods. This is either an analytical cutting analysis based on the study of chip formation and related processes as a special case of plastic deformation of the workpiece material or simulation modeling of the stress-strain and thermodynamic state of the workpiece based on the analysis of the results of finite element software products. Moreover, the simulation type of research is carried out not only to establish the adequacy of the theoretical foundations of the formation of surfaces to be machined but mainly to effectively study the dynamic stress-strain state of the workpiece in different chip formation zones using variational modeling data (tool geometry, materials, cutting parameters, etc.) for subsequent use in optimization models. These structural and parametric models can also effectively implement a functionally oriented technological process.

The input data for cutting simulation in the DEFORM system are:

- 2D or 3D model of the part;
- cutting parameters and modes;
- 2D or 3D tool model, cutting blade geometry, material, and coating;
- strength, physical, mechanical, thermal, and physical characteristics of the material being machined;
- model of tool edge wear;
- standard error of conformity of the modeling results in terms of the force vector, velocity vector, and permissible geometric error;
- type of deformation (Lagrangian Incremental or Steady-State Machining);
- type of iterative calculation method (direct iterative or Newton-Raphsen);
- selection of the calculation kernel (sparse matrix or Skyline method).

An important factor for understanding and qualitative analytical description of the shape formation pattern during titanium alloy cutting is the formalization of the process of chip tooth formation, its parameters, and measuring the actual length of contact between the chips and the cutting tool's rake face.

To study these parameters, finite element simulation was performed using DEFORM-2D software. The material of the part is the titanium alloy Ti6Al4V. This study considers the thermo-elastic-viscoplastic type of finite element modeling. This methodology involves modeling the cutting process of an elastic-viscoplastic workpiece with a mesh containing 10.000 elements in the form of a tetrahedron with element size from 10 to 50 μm in the primary study area (i.e., the area of intense changes in the stress-strain state of the workpiece). The tool was modeled as a rigid, undeformed body with a mesh containing 2500 elements.

A high-density mesh in the zone of primary deformation was used, as shown in Fig. 3. The tool geometry uses a radius of curvature of the cutter tip r = 0.1 mm; the material of the cutting part of the tool is an uncoated WC/Co alloy. In this case, the following cutting parameters were taken for simulation: cutting speed V = 100 m/min, feed rate F = 0.25 mm/rev, variable depth of cut t = 0.5...1.5 mm.

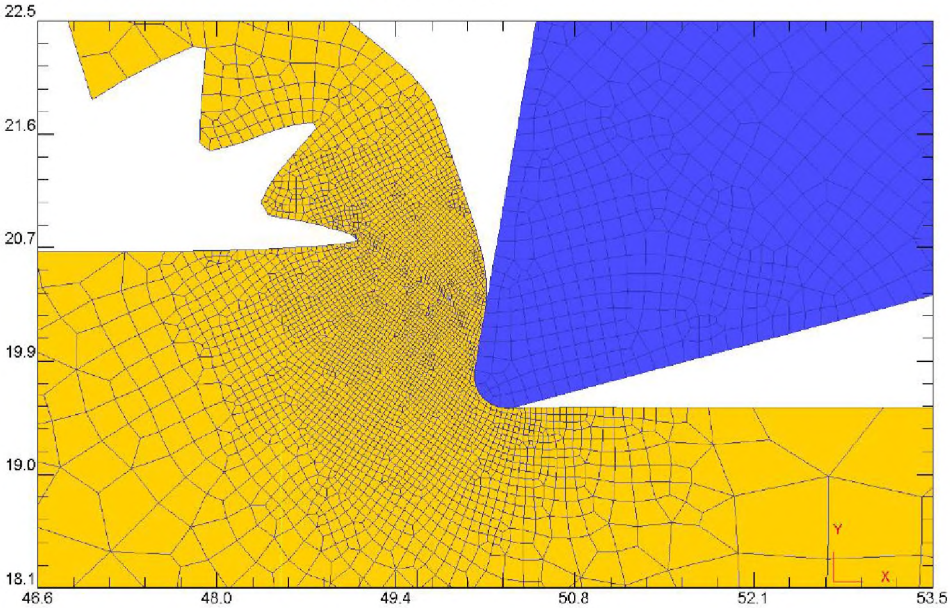


Fig. 3. Mesh generation in the DEFORM 2D simulation task

Research results

One of the most influential factors in forming the secondary deformation zone is the chip velocity along the tool's rake face. This parameter will have the greatest impact on tool wear and the thermodynamic pattern of cutting. The simulation modeling results allow us to clearly distinguish 3-speed zones of chip movement (Fig. 4).

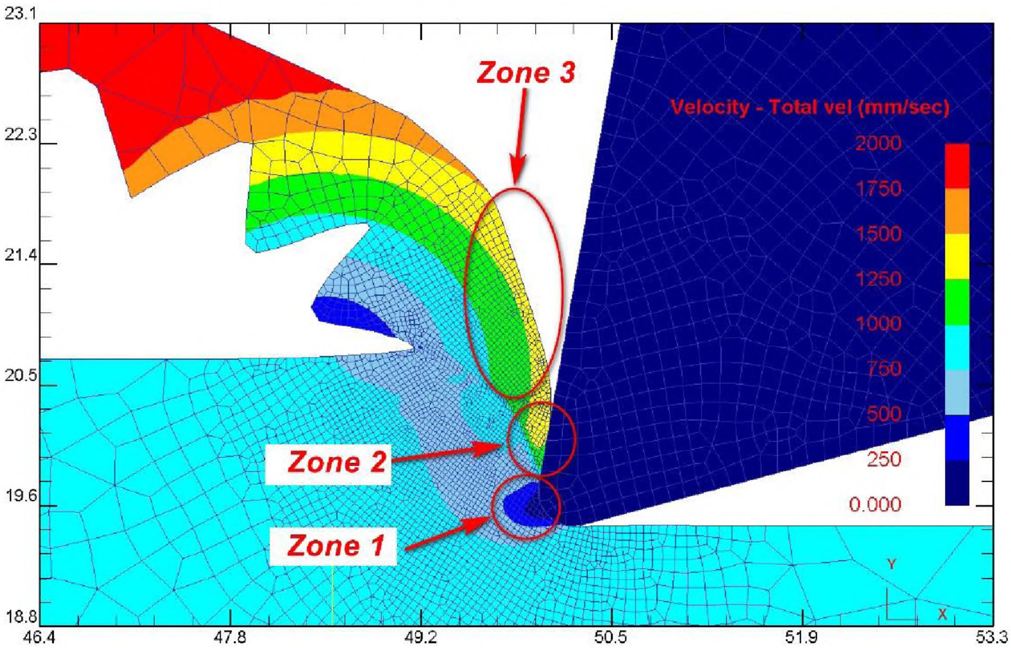


Fig. 4. The result of simulating the chip movement along the rake face of the tool

Zone 1 is characterized by inhibited chip movement. The speed of its movement along the rake face of the cutter for the specified cutting parameters ranges from 100 to 300 mm/sec. In this area, the zone of the highest specific pressure in the chip-tool subsystem is formed (Fig. 5), which causes significant equivalent stress (Fig. 6, *a*). However, the temperature in this zone is relatively low (Fig. 6, *b*), which indicates that it is the frictional factor in the formation of the thermal characteristic of the cutting process (arising from the sliding of chips along the tool) that dominates the load factor (caused by force and deformation processes in the chip root).

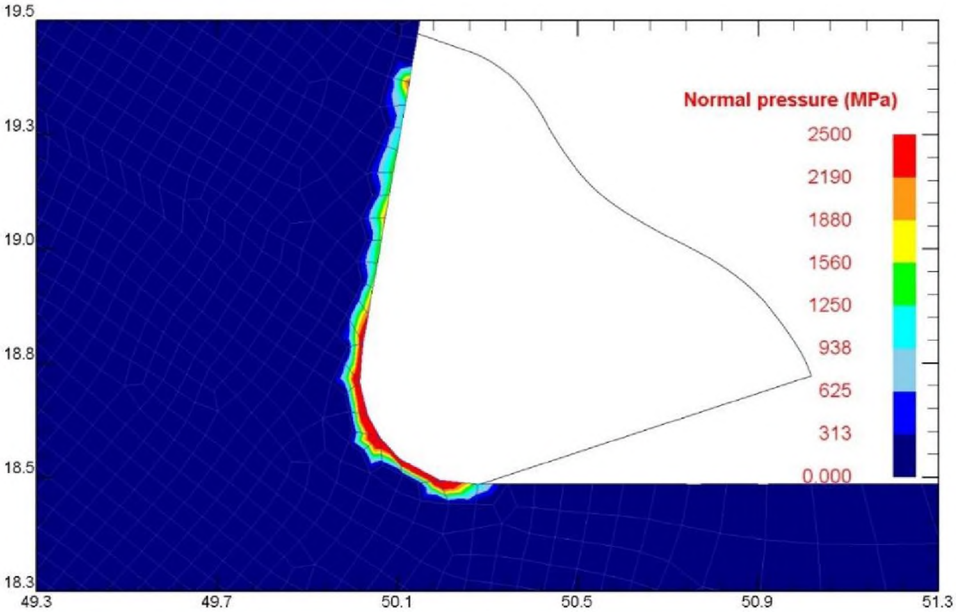
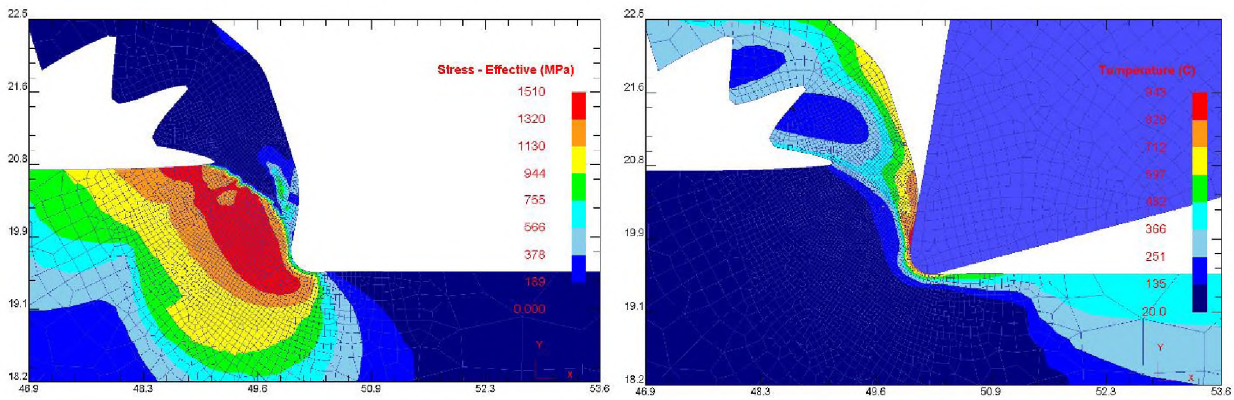


Fig. 5. Specific pressure force in the chip formation zone



a *b*

Fig. 6. Simulation pattern of stress formation (a) and temperature (b)
in the chip formation zone during titanium alloy machining

Zone 2 is characterized by accelerated chip runout along the tool's rake face (700–1200 mm/sec) with lower specific pressure. However, due to the influence of frictional interaction in the tool-chip system, the cutting temperature in this zone is significantly higher than in zone 1 (940 °C vs. 720 °C). Zone 3 is characterized by the highest chip runout rate (about 2000 mm/s) because the chips are free from the frictional influence of the tool's front surface. The temperature decays to 300 °C. There is no force interaction.

The presented picture of chip flow qualitatively explains the causes of stress-strain and thermodynamic processes in the cutting zone and correlates with the classical conclusions on the analysis of the influence of various factors on the formation of the force field and zones of primary and secondary deformation.

The formation of a serrated chip shape is a consequence of the high-frequency oscillation of the longitudinal and transverse cutting forces arising from the adiabatic nature of chip formation [7] in the secondary deformation zone. Moreover, the dynamic picture of the cutting force components clearly shows their dissonance on the time scale (Fig. 7). That is, the maximum value of the longitudinal component of the cutting force in a certain period corresponds to the minimum value of the transverse cutting force, and vice versa.

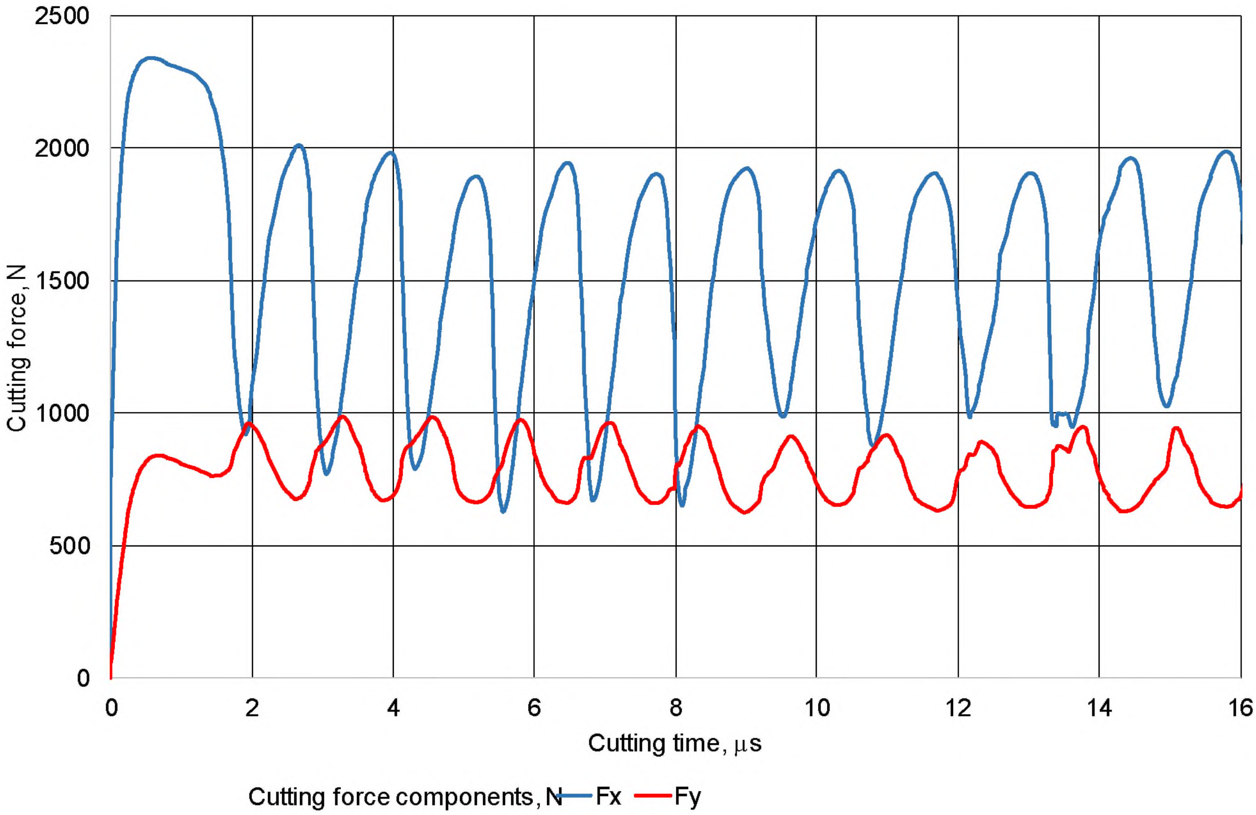


Fig. 7. Dynamics of formation of transverse and longitudinal cutting force of titanium alloy TI6AL4V

The values of cutting forces are formed depending on the machining parameters. Therefore, the range of fluctuations can be different, and therefore the geometric parameters of the chips will be different. Some scientists [8–10] recommend concluding the cutting forces' dynamics based on the chip shape's geometric analysis.

Fig. 8 shows the results of the simulation in DEFORM 2D of the chip geometry during the machining of the titanium alloy TI6AL4V depending on the depth of cut (V = 100 m/min, S = 0.25 mm/rev). As can be seen from these graphical results, the difference in thickness of the chip elements *a* increases in proportion to the cutting depth t. At a depth of cut of 0.5 mm, this value is only 0.39 mm, at t=1 mm the thickness difference is a = 0.5 mm, and at t = 1.5 mm a = 0.7 mm. The upper part of the figures shows an enlarged and 10 times larger fragment of the chip formed.

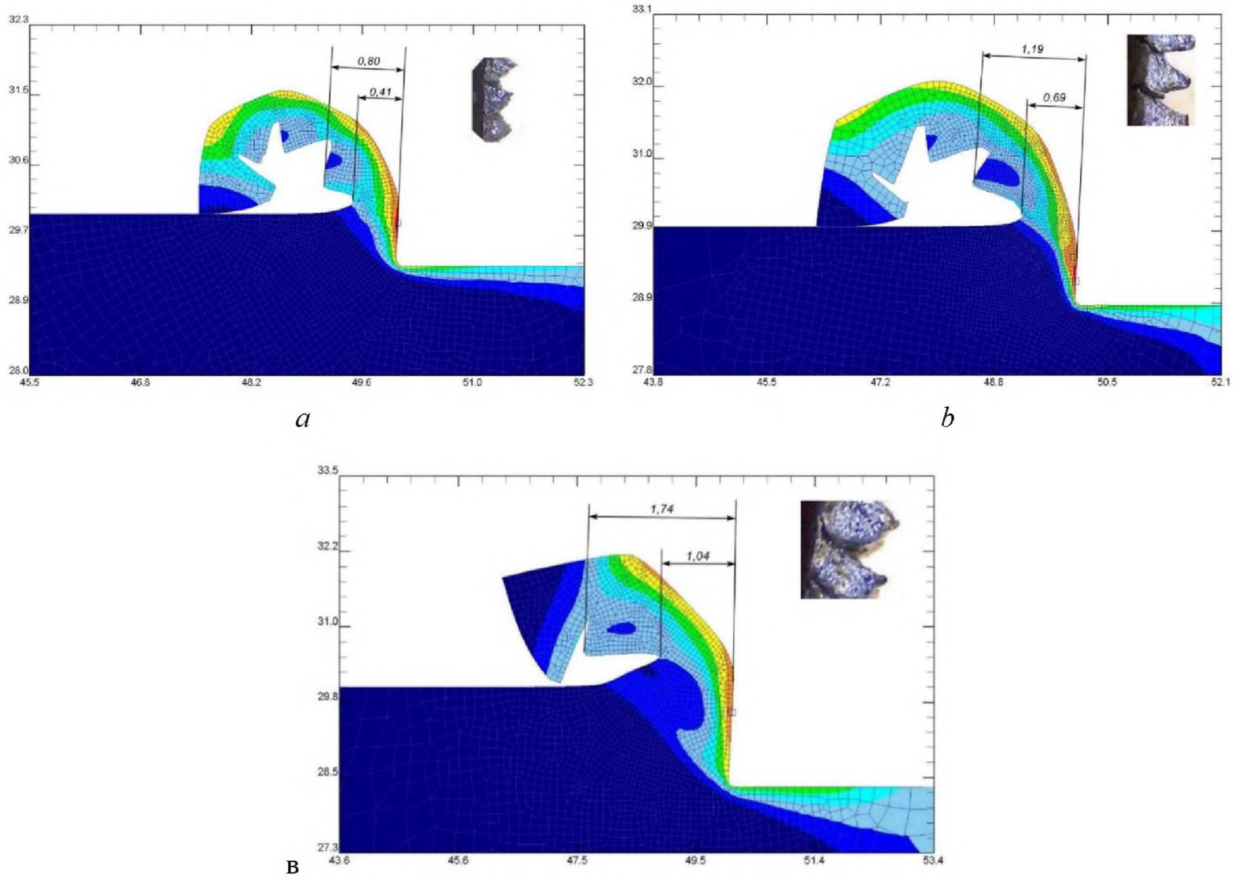


Fig. 8. Results of simulation in DEFORM 2D of chip shape during machining of TI6AL4V titanium alloy depending on the depth of cut: a – t = 0.5 mm; b – t = 1.0 mm; c – t = 1.5 mm

The following calculation scheme is used to determine the frequency and amplitude of chip formation during titanium alloy machining (Fig. 9).

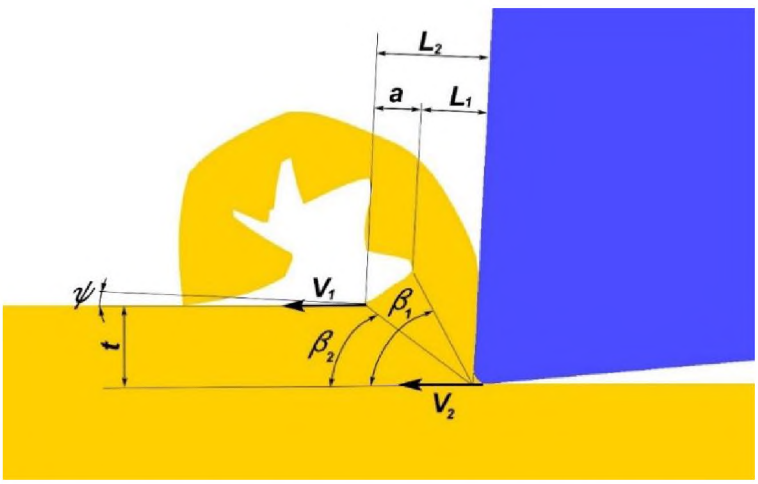


Fig. 9. Calculated scheme of chip element formation during titanium alloy machining

The cutting speed V_1, which is characteristic of the movement of the workpiece's local mesh element before the chip root's formation, is a given value V_1 = 100 m/min = 1667 mm/s. In zone 1 (Fig. 4), the speed of moving such an element slows down to V_2=1310 mm/s (in the case of a modeled cutting depth of 0.5 mm). The shear angle will be variable along the length of the chip formation zone of the convex chip segment and is β_1=75° and β_2=42°, respectively. The period of the complete chip formation cycle can be taken as τ. From Fig. 9, we obtain the frequency of the formation of serrated strips:

$$\tau = \frac{V_1 - V_2}{t} \cdot \frac{1}{\mathrm{ctg}\beta_2 - \mathrm{ctg}\beta_1} \tag{1}$$

The amplitude of oscillations of the chip thickness a is determined from geometric constructions (Fig. 9) by the equation:

$$a = t \cdot \cos\psi \cdot (\mathrm{ctg}\beta_2 - \mathrm{ctg}\beta_1) \tag{2}$$

For the given conditions of simulation studies:

$$\tau = \frac{1667 - 1310}{0,5} \cdot \frac{1}{\mathrm{ctg}(42°) - \mathrm{ctg}(75°)} = 857\ \mathrm{s}^{-1};$$

$$a = 0,5 \cdot \cos\varphi \cdot (\mathrm{ctg}(42°) - \mathrm{ctg}(75°)) = 0,42\ \mathrm{mm}.$$

The results of the simulation studies, analytical calculations, and experimental data are shown in the graph in Fig. 10. Comparing the data, we can conclude that the deviations of these results do not exceed 10–12 %. The qualitative picture of the changes is quite the same. That is, we can say that the modeling results are adequate. This is primarily important from the point of view of assessing the adequacy of conclusions about the impact of cutting parameters on the dynamics of force values in the longitudinal and transverse directions, which, in turn, affects the vibration pattern of titanium alloy cutting.

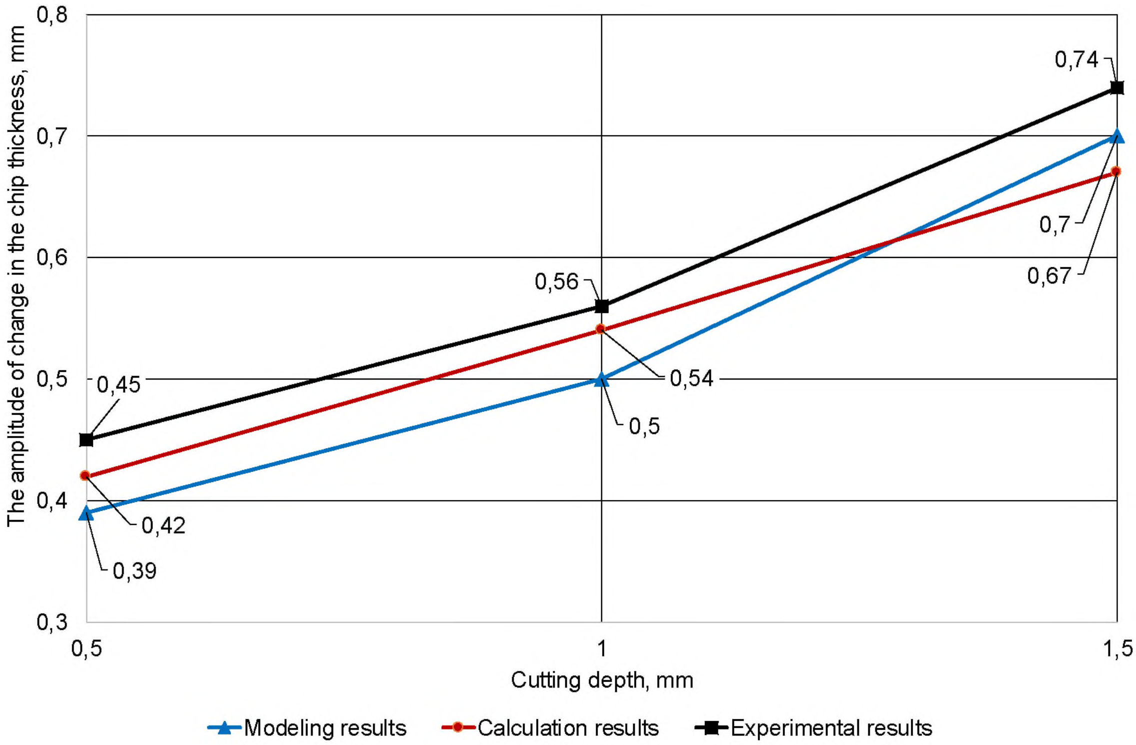


Fig. 10. Comparative values of the amplitude of change in the thickness of the serrated chip

Another important indicator of the thermodynamic state of the cutting zone is the length of contact between the chip and the tool. It is considered to be an important parameter in machining since the temperature distribution over the contact surface forms the conditions for tool wear on the rake face. Given their specific physical and mechanical properties, this is particularly important when machining titanium alloys [5].

According to Abuladze's formula [25], the length of plastic contact C_c between the rake face of the tool and the chip is defined as:

$$C_c = 2L\left[\xi\left(1-\tan\gamma\right)+\sec\gamma\right], \tag{3}$$

where L is the thickness of the undeformed chip, mm; ξ is the chip compression ratio; γ is the rake angle of the tool

The chip compression ratio significantly impacts the stress-strain characteristics of the cutting zone.

The analysis of the dependence of the chip compression ratio ξ on the change in cutting speed V showed that with an increase in cutting speed, the average value of the compression ratio practically does not change, but the amplitude of its oscillation increases significantly, which is equivalent to a change in the shear angle, which changes dynamically due to the adiabatic nature of chip formation (Fig. 11, *a*). Thus, at $V = 50$ m/min, the average value of the chip compression ratio is $\xi_{av} = 2.28$, and the amplitude of $\Delta\xi = 0.08$. At $V = 100$ m/min, the average value of the chip compression ratio is $\xi_{av} = 2.29$, and the amplitude increases to $\Delta\xi = 0.22$, and at $V = 150$ m/min, the average value of the chip compression ratio is $\xi_{av} = 2.32$, and the amplitude is already $\Delta\xi = 0.45$. At a cutting speed of V = 200 m/min, the average value of the chip compression ratio is $\xi_{av} = 2.35$, and the amplitude is the largest and amounts to $\Delta\xi = 0.61$ under steady-state cutting conditions.

The effect of the cutting depth on the chip compression ratio is almost similar (Fig. 11, *b*). Namely, with an increase in the depth of cut, the average shrinkage value does not change significantly, but the amplitude of oscillations of this parameter increases significantly. That is, at $t = 0.5$ mm, the compression coefficient is $\xi_{av} = 1.85$, while the amplitude is only $\Delta\xi = 0.06$. Already with an increase in the depth of cut to t=1.0 mm, the compression ratio acquires the value $\xi_{av} = 1.87$, but the amplitude already increases to $\Delta\xi = 0.09$. A similar increase is observed with a further increase in the depth of cut: at $t = 1.5$ mm, the compression coefficient is $\xi_{av} = 1.91$, and the amplitude is $\Delta\xi = 0.14$; at $t = 2.5$ mm, the compression coefficient is $\xi_{av} = 1.93$, and the amplitude is $\Delta\xi = 0.22$; at t = 3.5 mm, the shrinkage coefficient is $\xi_{av} = 1.99$, and the amplitude is $\Delta\xi = 0.45$.

A completely different pattern is observed when the tool geometry is changed (Fig. 11, *c*). An increase in the rake angle of the cutting blade leads to a significant increase in the chip compression ratio. Thus, at γ=-5°, the value of the compression coefficient is $\xi_{av} = 2.3$, and the amplitude is $\Delta\xi = 0.42$. At γ=0°, the compression coefficient is $\xi_{av} = 2.1$, and the amplitude is $\Delta\xi = 0.31$; at γ=5°, the compression ratio is $\xi_{av} = 1.86$, and the amplitude is $\Delta\xi = 0.23$; at γ=0°, the compression ratio is $\xi_{av} = 1.74$, and the amplitude is $\Delta\xi = 0.16$.

Fig. 12 shows the relationship between contact length and cutting speed. The paper [doi 10.1007/s00170-008-1582-6] shows that for AISI 1045 steel, the contact length tends to decrease with increasing cutting speed. The same decreasing trend is observed for all values of the thickness of undeformed chips. However, based on the results of simulation modeling of the machining process of the titanium alloy Ti6Al4V based on formula (3), it was proved that the contact length has a different tendency to change (as shown in Fig. 6). Here, the contact length first increases and then decreases with increasing cutting speed. Analyzing the results of the studies shown in Fig. 12, the following conclusions can be drawn: a cutting speed of approximately 150 m/min, at which the contact length is maximum, lies within the transitional range between the normal and high-speed machining of titanium alloys. This initial increase and then decrease in the contact length for Ti6Al4V at higher feed rates can be explained by the effect of chip geometry changes due to the adiabatic shear phenomenon.

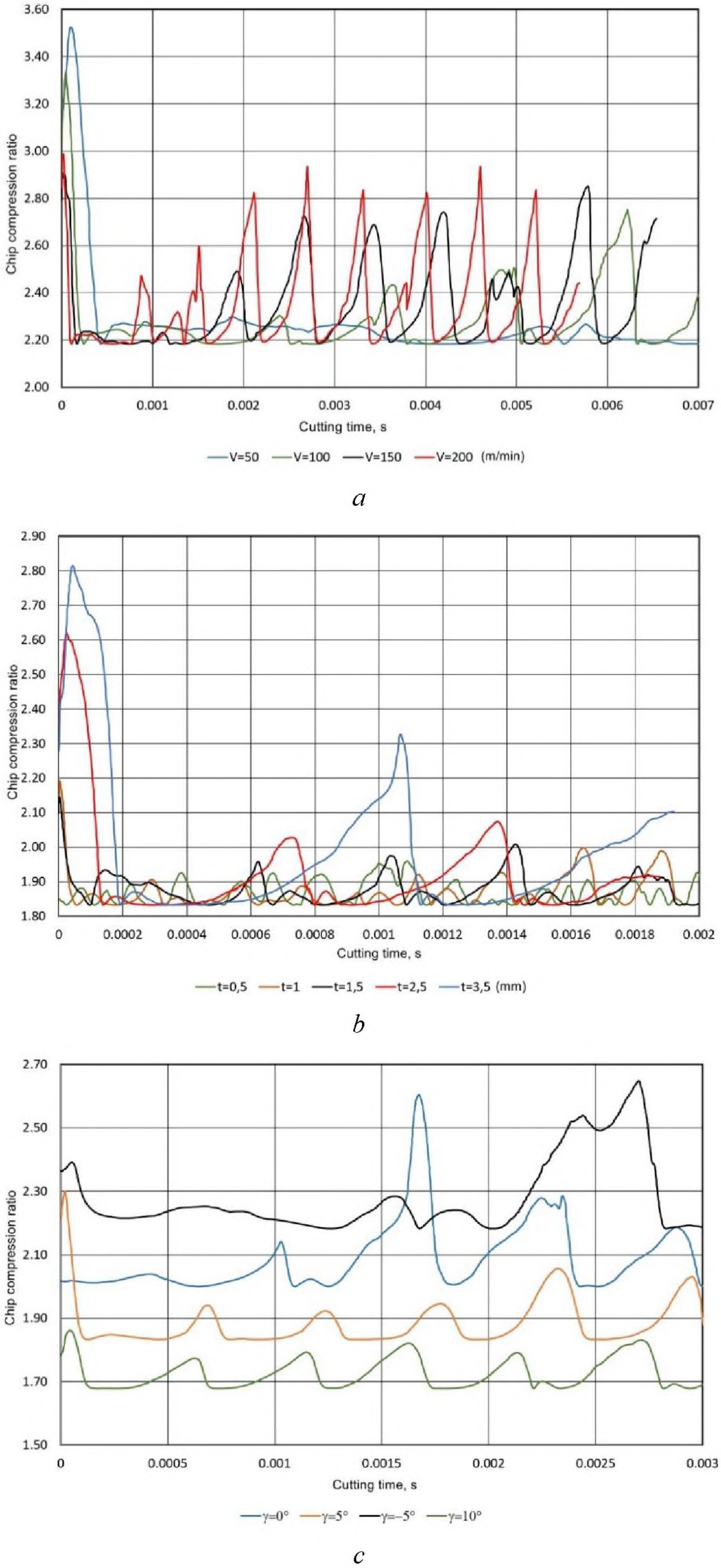


Fig. 11. Relationship between chip compression ratio and cutting speed (a), depth of cut (b) of titanium alloy, and cutting tool's rake angle (c)

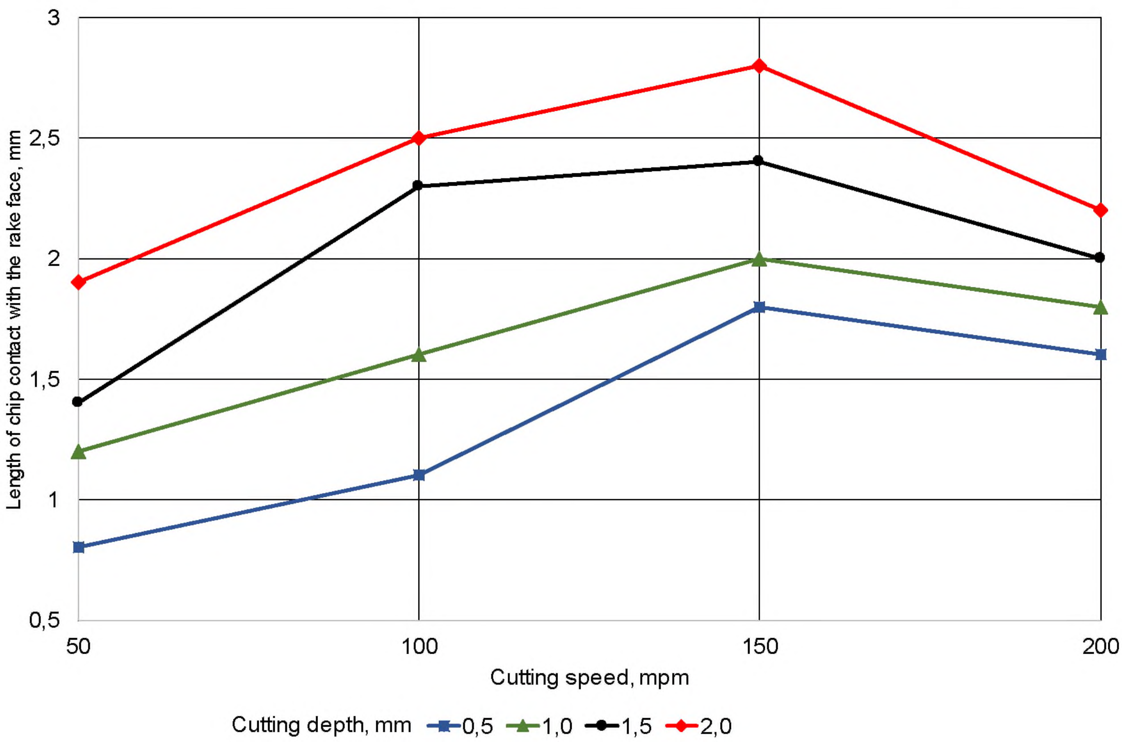


Fig. 12. Graphical dependence of the chip contact length on the cutting speed of the titanium alloy TI6AL4V

The above results of simulation and analytical studies of machining titanium alloys have proved, firstly, the adequacy of the proposed research methodology as a consequence of the qualitative coincidence of the results obtained and the data known from the literature; secondly, it allows us to establish the most loaded cutting parameters in terms of the formation of contact interaction in the "chip-rake face" subsystem.

Conclusions

1. The results of simulation and experimental studies of the chip formation process during the machining of titanium alloys indicate that the geometric shape of the chips formed during adiabatic shearing is determined by the conditions of resistance to plastic deformation, the cyclicity of the cutting forces and the geometric change in the shear angle. The proportion of deformed chip parts determines the frequency of cutting force fluctuations during contact. Changes in metal resistance in the shear zone at high cutting temperatures and high deformation rates determine the amplitude of the cutting load. Thus, chip formation during titanium alloy machining occurs under unstable cutting conditions, which contributes to the release of large amounts of heat, high residual stresses, intense tool wear, and dynamic instability in the cutting zone. A rational choice of titanium alloy cutting parameters, cutting-edge geometry, and cooling environment should be aimed primarily at reducing the dynamic activity of the MFTW technological system. This is a feature of the functionally oriented approach to technological process planning.
2. The analysis of the relationship between chip compression ratio and changes in cutting speed showed that with an increase in cutting speed, the average value of the compression ratio practically does not change, but its amplitude of oscillation increases significantly, which is equivalent to a change in the shear angle, which changes dynamically due to the adiabatic character of chip formation.

3. Based on the results of simulation modeling of the machining process of the titanium alloy TI6AL4V, it has been proved that the length of contact between the chip and the rake face of the tool has a certain tendency to change: the contact length first increases and then decreases with increasing cutting speed. The following conclusions can be drawn: the cutting speed of approximately 150 m/min, at maximum contact length, is within the transitional range between the normal and high-speed machining of titanium alloys. Such an initial increase and then decrease in the contact length for Ti6Al4V alloy at higher feed rates can be explained by changing chip geometry due to the adiabatic shear phenomenon. The above results of simulation and analytical studies of machining titanium alloys have proved, firstly, the adequacy of the proposed research methodology as a consequence of the qualitative coincidence of the results obtained and the data known from the literature; secondly, it allows us to establish the most loaded cutting parameters in terms of the formation of contact interaction in the "chip-rake face" subsystem.

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