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Vadym STUPNYTSKYY [1], She XIANNING [1], Yurii NOVITSKYI [1], Yaroslav NOVITSKYI [1]

Comprehensive system for simulation of vibration processes during the titanium alloys machining

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Titanium alloys are difficult-to-machine materials due to their complex mechanical and thermophysical properties. An essential factor in ensuring the quality of the machined surface is the analysis and recommendation of vibration processes accompanying cutting. The analytical description of these processes for machining titanium alloys is very complicated due to the complex adiabatic shear phenomena and the specific thermodynamic state of the chip-forming zone. Simulation modeling chip formation rheology in Computer-Aided Forming systems is a practical method for studying these phenomena. However, dynamic research of the cutting process using such techniques is limited because the initial state of the workpiece and tool is a priori assumed to be "rigid", and the damping properties of the fixture and machine elements are not taken into account at all. Therefore, combining the results of analytical modeling of the cutting process dynamics with the results of simulation modeling was the basis for the proposed research methodology. Such symbiosis of different techniques will consider both mechanical and thermodynamic aspects of machining (specific dynamics of cutting forces) and actual conditions of stiffness and damping properties of the "Machine-Fixture-Tool-Workpiece" system.

1. Introduction

Titanium alloys are currently one of the most sought-after materials used in the aerospace, automotive, medical, and other high-tech industries. The widespread use of such materials is due to the unique set of properties of titanium alloys, such as high specific strength, corrosion resistance, non-magnetic properties, and high heat

✉ Vadym STUPNYTSKYY, e-mail: vadym.v.stupnytskyi@lpnu.ua

[1] Lviv Polytechnic National University, Lviv, Ukraine. ORCIDs: V.S.0000-0003-0006-9932; S.X. 0000-0003-1360-210X; Yu.N. 0000-0003-3586-9366; Ya.N. 0000-0001-9525-5951

resistance at operating temperatures of up to 500–600°C [1–3]. However, high cost significantly limits the possibility of their mass application. More efficient use of titanium alloys is only possible if product manufacturing costs are reduced. It can be explained by the fact that a significant part of the product expenses includes costs for the technological cycle of billets manufacturing (such as shaped casting and plastic deformation) as well as for welding, machining, and heat treatment operations. Thus, optimization of manufacturing costs of titanium alloy products concerning ensuring their functional properties under potential operating conditions is an essential scientific and practical task of function-oriented process planning [1]

The study of issues related to improving the quality of the surface layer of machine parts represents one of the significant challenges in an important branch of mechanical engineering science, such as Surface Integrity. The term "Surface Integrity" describes the condition and attributes of a machined surface and their relationship to functional performance. For example, surface integrity is commonly defined as "the topographical, mechanical, chemical, and metallurgical condition of a machined surface and its relationship to functional characteristics" [4]. The study of the surface layer condition of titanium alloys after machining, which affects the fatigue strength of products, is of particular relevance.

The research, modeling, simulation, and optimization of the management of machining processes of precision surfaces, including the formation of their texture, microrelief, integrity as well as high functionality, are essential objectives of mechanical engineering science [5]. The presence of different scientific interpretations of the features of the formation of the surface layer of a workpiece made of titanium alloys after machining consists in the subjectivity of the performance of the multifactorial problem, as well as due to the complexity and non-linearity of the formalization of this process of cutting [6]. It is because, depending on the cutting parameters, the strength (residual stresses and strains) and, significantly, the fatigue characteristics of products made of these alloys change significantly. Any theory, of course, relies on experimental confirmation. Therefore, many authors base their theoretical models on regression dependencies from numerous experimental studies. However, the multivariance of technological factors (different cutting parameters, tool geometry, etc.) and constant changes in the titanium alloy's nomenclature (i.e., physical and mechanical properties) cannot be taken into account in this case.

An essential aspect of the formation of microgeometry, strength, frictional, and stress-strain properties of the surface layer of products is to ensure the vibration resistance of the "Machine-Fixture-Tool-Workpiece" (MFTW) technological system [5]. Furthermore, the machine dynamics and machining process dynamics are two indispensably integrated parts that should be considered simultaneously in optimizing the MFTW system, as shown in Fig. 1.

It is especially difficult to ensure the vibration resistance of the MFTW system in manufacturing titanium-containing alloys. In this case, in addition to the apparent stiffness parameters and damping properties of the MFTW elements, an important

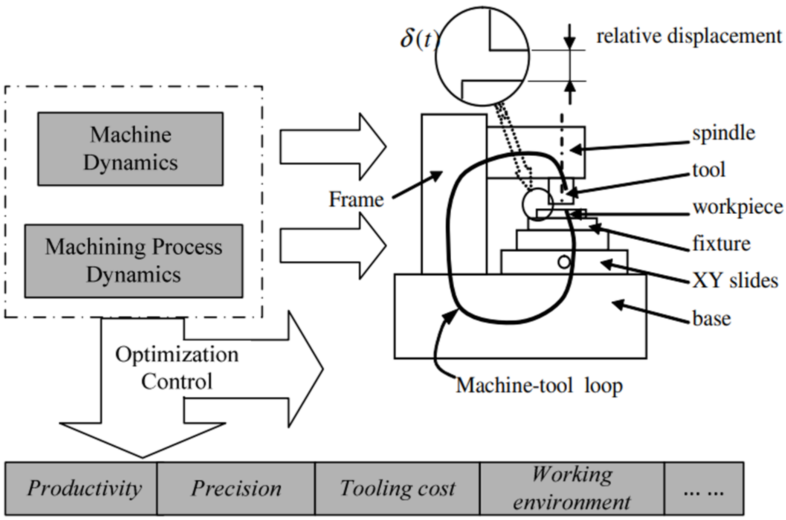


Fig. 1. The effects of the machine and machining dynamics [5]

factor in vibrations is a unique pattern of shaping due to the high plasticity of the processed material layer. This is expressed in a high-frequency change in the longitudinal and transverse cutting forces and, as a result, the formation of a serrated (segmental) chip shape [7, 8]. Depending on the physical nature of the vibration excitation mechanism acting on the flexible MFTW system, disturbance forces can create both forced and self-oscillations. In addition, other types of oscillatory processes, caused by the instantaneous application of cutting force at the entry and exit of the tool (for example, at the beginning and end of workpiece machining), sometimes become essential.

The quality of the machined surface depends equally on the machining method and cutting conditions. That is, roughness is a consequence of both the geometry of the cutting tool trace and the plastic deformations of the machined metal, as well as the vibrations of the technological system [9]. In addition, the elastic-plastic deformation during the cutting of metals (especially titanium alloys) is very complex. This is due to the interrelation with other factors and phenomena (temperature, frictional, structural-phase state, etc.) that accompany the cutting process. Therefore, a complete characterization of the physical foundations of titanium alloys cutting can be obtained only by a comprehensive study of the dominant processes, i.e., surface layer deformation, cutting forces, friction processing conditions, and the condition of the cutting tool. Analytical modeling of such methods is inadequate in this case [10].

Modern cutting simulation systems, also called Computer-Aided Forming Systems (DEFORM 3D, LS-DYNA, AdvantEdge, Abaqus), allow for predicting the interconnected dynamics of force and stress-strain machining processes with a sure accuracy [11]. However, firstly, the results of modeling such systems, unfortunately, are not always adequate for the real parameters of the cutting process. Secondly, the initial state of the workpiece and tool is a priori assumed to be “rigid”, and the damping properties of the fixture and machine elements are not taken into account at all [12].

A new approach to studying vibrational processes occurring during the cutting of a titanium alloy is that we propose combining analytical modeling of the dynamics of the cutting process with the results of simulation modeling. After their experimental refinements and confirmation of their adequacy, such a symbiosis of various methods will make it possible to take into account both the mechanical aspects of shaping (specific dynamics of cutting forces) and the actual conditions of rigidity and damping properties of the MFTW system. This, in the final result, will contribute to the solution of two main problems: determining rational cutting conditions and choosing ways to achieve the required quality of the machined surface and the layer adjacent to it, in which the original physical and mechanical properties of the titanium alloy would be preserved or their other values would be obtained, guaranteeing the characteristics required for the product in potential operating conditions.

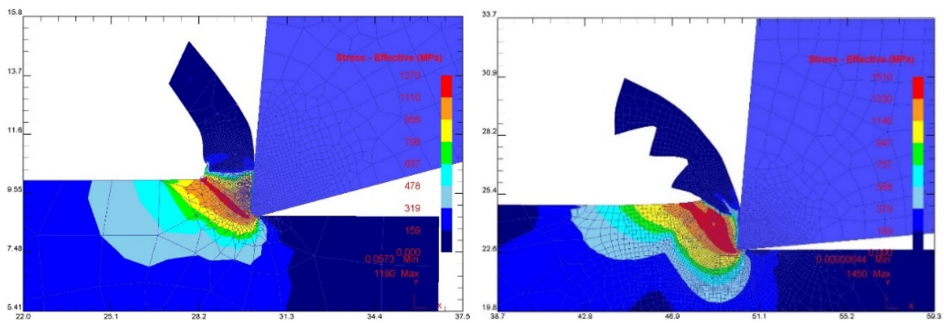
2. Analysis of recent research and publications

Literature sources [2, 10, 13] indicate that the labor intensity of machining titanium alloys is 2–2.5 times higher than for medium-carbon steels. One of the most significant reasons for this conclusion is the tool’s and workpiece’s complex thermodynamic state during the cutting process. When machining titanium alloys, a much smaller contact area exists between the chip and the tool than when machining carbon steels. Thus, the contact pressure increases and the frictional heat of the chip sliding on the rake face of the tool is concentrated in a smaller area. This leads to extremely high temperatures in the contact area of the tool with the chips since titanium has a very low thermal conductivity [14]. For example, for Ti6Al4V alloy the parameter of heat conductivity is 11 W/(m·K) whereas for steel AISI1045 of 45–40 W/(m·K). If during the cutting of medium-carbon steel the temperature in the contact zone “tool-workpiece” reaches 300–350°C, then during the cutting of titanium alloys under the same conditions the temperature exceeds 900–1200°C. Therefore, for titanium relatively low cutting speeds are used (from 20 to 60 m/min) to reduce the thermodynamic effect, which reduces the tool life as well as the accuracy of machining [2].

Forced vibrations are usually caused by an out-of-balance force associated with a component integrated with, or external to, the machine tool, whereas a self-excited vibration is spontaneous and increases rapidly from a low vibratory amplitude to a large one; the forced vibration results in an oscillation of constant amplitude. Cheng et al. summarize all kinds of machining instability and their features [5]. The instability is classified as chatter vibration, random or free vibration, and forced vibration. The random or free vibration usually includes any shock or impulsive loading on the machine tool. A typical random vibration is the tool vibration, for instance, when the tool strikes a hard spot during the cutting process. The tool will bounce or vibrate relative to the workpiece, which is the beginning of the phenomenon of self-excited vibration.

In [15], devoted to the analysis of cutting forces and vibrations arising in the process of face milling with a variable angle of surface inclination, it is proved that cutting forces and vibrations strongly depend on the surface inclination, both in the quantitative and qualitative aspects. This observation is also confirmed by the developed model.

A characteristic feature in the machining of titanium alloys is the tendency of the MFTW elastic technological system to intense vibrations. This is explained, first of all, by the large values of high-frequency oscillations of the radial, longitudinal and transverse components of the cutting force [13]. In addition, the high ductility of titanium alloys contributes to the emergence of a specific process of formation of a serrated chip shape (Fig. 2).



(a) (b)

Fig. 2. Comparison of chip formation when machining medium-carbon steel (a); titanium alloy (b)

This phenomenon is explained by the authors of [14, 16] as follows. When machining materials with normal ductility (for example, medium carbon steels such as AISI 1020), the cut layer of material is first compressed and then sheared. The process of compression of the material and shear are carried out simultaneously in the process of further cutting. That is, there is always a compressed material in front of the cut layer. A different picture occurs during the cutting of a titanium alloy. First, the cut metal layer is compressed. When the compression process reaches a sufficient limit, the shear layer is destructive-shifted. However, in contrast to cutting material of medium plasticity, the compressed material is removed along with the chips and a new layer of uncompressed metal appears in front of the tool, and the process is repeated.

This complex process is accompanied by the appearance of an "adiabatic shear" zone [17]. In this case, high-frequency oscillations of the longitudinal and transverse components of the cutting force are carried out asynchronously, which causes high-frequency vibrations in the tool and the workpiece (Fig. 3) [16]. This diagram shows the mechanism of adiabatic shear zone occurrence. This is the case: at a certain point in the simulation study (Stage 1), the transverse cutting force is of the maximum value. At the same time, the longitudinal cutting force has a minimum. This chip-forming step occurs with the prevailing process of compressing the chip formation zone with the chip root convexity over the outer surface. At the moment of cutting (Stage 2), opposite phenomena occur: transverse cutting force takes the minimum value, and longitudinal cutting force – the maximum value. This step corresponds to the complete prevalence of the shear mechanism with characteristic chip concavity over the outer surface. At the moment of cutting (Stage 3), the step of dominant compression of the chip formation zone is repeated, etc.

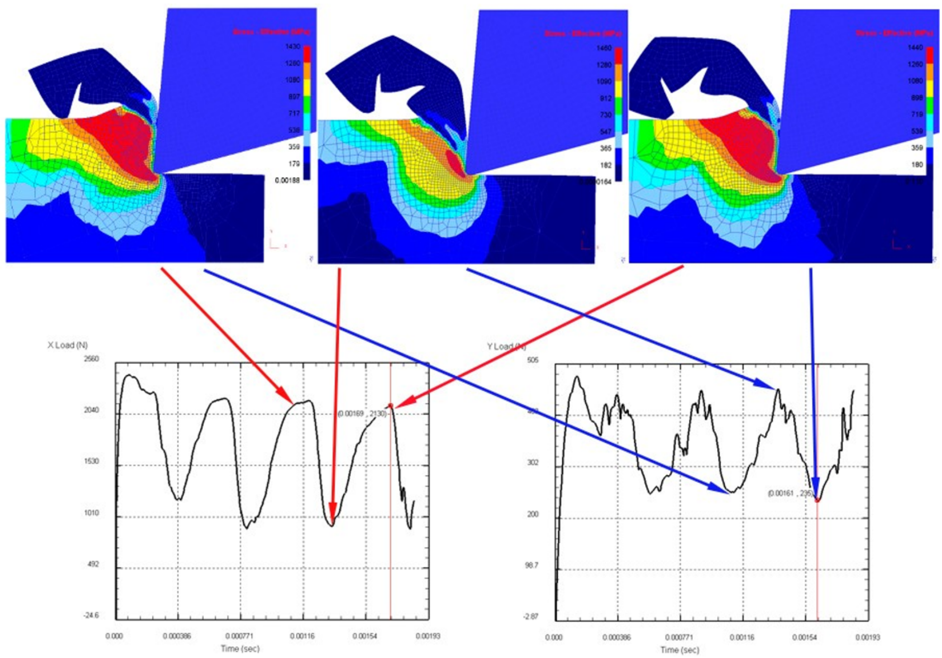


Fig. 3. Interpretation of the mechanism of an adiabatic shear formation during titanium alloy machining (Stages 1, 2, and 3 are denoted from left to right) [13]

The thermodynamic cutting pattern that confirms the adiabatic nature of chip formation during the machining of titanium alloy is shown in Fig. 4.

It is noted in [18] that a high dependence of the oscillation amplitude on the tool rigidity is typical for the machining of titanium alloys. This is due to the high speeds of the chip sliding along the rake face of the tool with simultaneously small values of the chip thickness ratio. In this case, even a small instantaneous increase in cutting speed due to vibration leads to a noticeable decrease in tool life. It is important that, unlike other processed materials, the contact of the tool in the processing of a titanium-containing alloy occurs on a smaller area and with a very

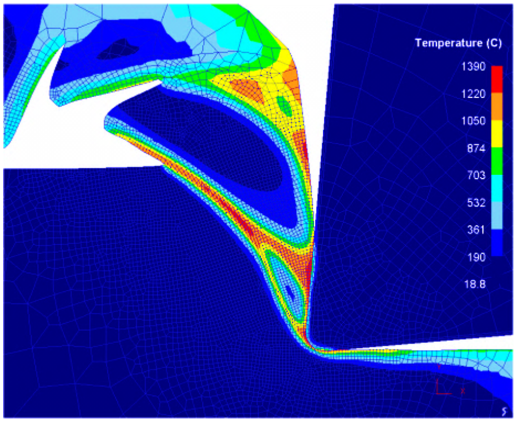


Fig. 4. Demonstration of thermodynamic state in the adiabatic shear zone when machining titanium alloy Ti6Al4V

hardened cutting surface of the chip. This phenomenon contributes to increased fatigue failure of the tool.

The physical mechanism of perturbation of the MFTW technological system oscillations operates in the following sequence [18, 19]. Any random perturbation (for example, non-uniformity of the allowance, heterogeneity of the material being processed, discontinuity in processing, radial runout of the workpiece or tool, etc.) leads to the emergence of natural damped oscillations of the technological system. These fluctuations are always accompanied by a change in the thickness of the cut and the speed of the chip sliding along the rake face of the tool. A change in these values leads to a corresponding dissonant change in the components of the cutting force of the titanium alloy (Fig. 3). And, if the change in the cutting force lags in time or is shifted in phase relative to the change in the thickness of the slice, then the damped natural oscillations can be converted into undamped self-oscillations. The energy required to maintain such self-oscillations is created by the variable component of the cutting force. A similar reason for the excitation of self-oscillations appears if, with an increase in the cutting speed, there is a decrease in the radial component of the cutting force [2].

In [19, 20] it is described that the excitation of vibrations of the MFTW technological system occurs due to the relationship of vertical and horizontal movements of the tool relative to the workpiece. Two dominant oscillatory systems during the cutting process (Fig. 5) are distinguished by the authors [21, 22]. Firstly, it is a "Workpiece-Fixture" system. This system, as a rule, performs low-frequency oscillations (50–300 Hz). However, the frequency spectrum of titanium alloy machining in this subsystem is higher (600–1800 Hz). Secondly, it is the "Tool – Tool Holder" subsystem, which performs high-frequency oscillations (800–3000 Hz). The cutting zone is the closing link in these oscillatory systems. The causal relationship of these systems is that due to vibrations of the cutter and the workpiece, the thickness of the cut layer continuously changes from the minimum (t_{min}) to the maximum (t_{max}) value (Fig. 5). Moreover, at the first stage of the cutter movement from point A to point B, the cutter moves towards the cutting force R and the system additionally consumes a part of the energy E_1. In the second stage of the reverse movement from point B to point A, the direction of movement of the cutter coincides with the direction of the cutting force. Thus, the system receives an additional energy E_2. Since the thickness of the cut layer in the second section is greater, then $E_2 > E_1$. Therefore, an excess of energy $\Delta E = E_2 - E_1$ is stored in the overall balance, supporting the fluctuations of the MFTW technological system.

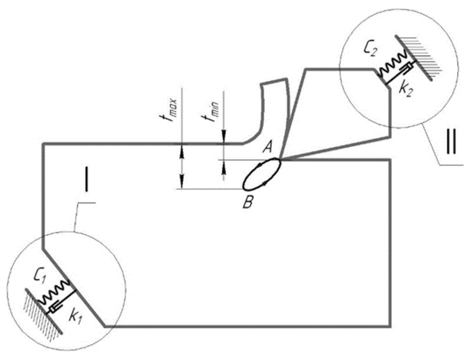


Fig. 5. Cross-sectional view of the formation of self-oscillations in the technological system MFTW: I – subsystem "Workpiece – Fixture". II – subsystem "Tool – Tool Holder"; k_1, k_2 are the generalized damping coefficients of the first and second elastic subsystems; C_1, C_2 are the stiffness of the first and second damping oscillatory subsystems

The level of intensity of self-oscillations significantly affects the tool life and machining productivity. In [23] it is indicated that for certain design and technological processing conditions, there is a certain optimal (according to the stability criterion) amplitude of self-oscillations, at which the greatest tool life takes place. When machining corrosion-resistant, heat-resistant, high-strength steels, as well as titanium and heat-resistant alloys by the hard-alloy insert of the tool, the zone of self-oscillation amplitudes optimal in terms of resistance criterion is in the range of 8–18 μm. Obviously, machining productivity is directly related to tool life. It is possible to achieve an increase in cutting time productivity by several times by controlling the intensity of self-oscillations [5].

The roughness of the machined surface is also largely determined by the intensity of self-oscillations. The height parameters of the roughness always grow with an increase in amplitude and slightly decrease with an increase in the oscillation frequency [6].

The existing methods of reducing the amplitude of self-oscillations can be divided into two classes – technological and designing. Technological methods include such as the choice of appropriate cutting parameters and sharpening angles of the tool [5]. Increasing the resistance in the oscillating system and the use of dynamic vibration dampers belong to the designing methods.

Thus, the problem-oriented analysis of literary sources allows us to draw the following conclusions:

1. Machining of titanium alloys has many specific features, which are due to the mechanical and physicochemical properties of these materials. One of the most significant factors is the presence of large vibrations in the tool due to the original phenomenon of adiabatic chip shear and complex thermodynamic machining processes.
2. The control of dynamic cutting processes is of particular importance, since, firstly, it significantly affects the formation of roughness and waviness of the surface layer specifically for titanium alloys; secondly, the low cutting speed caused by dynamic instability leads to a decreased in processing productivity; thirdly, the formation of cyclic loads contributes to the appearance of local zones of residual stresses and deformations, which negatively affect the fatigue strength of the product [9].
3. To effectively influence the occurrence and nature of oscillatory processes during the titanium alloys machining, it is necessary to analyze the priority of factors affecting the real pattern of the physical processes of the elastic dynamic system "Machine-Fixture-Tool-Workpiece". This system, on the one hand, is described by the known equations of mechanical dynamics [5, 23]. However, in the analytical description of the system of dynamic equations in the classical form, it is impossible to take into account the features of physical phenomena in the processing of titanium alloys (adiabatic shear conditions, specific dynamics of thermodynamic cutting processes, etc.). This influence can be taken into consideration only with the use of simulation modeling of the cutting process. But, on the other hand, the results of such modeling do not take into account the elastic-strain state of the MFTW system.

Therefore, the combination of analytical modeling of vibration processes in the titanium alloy cutting system and simulation modeling will help one to take into account both the main features and specifics of this process. The results of such a study should be subject to analysis for adequacy as a result of comparison with the results of experimental research.

3. Research methodology

3.1. Simulation of dynamic cutting processes of titanium alloys in DEFORM 2D

The first stage of the above research is the rheological simulation of the titanium alloy cutting process in DEFORM 2D. The results of such research will make it possible to estimate the dynamics of force, stress-strain, and thermodynamic state of the tool taking into account the given cutting parameters and changing properties of the machined material.

A phenomenological model of the properties of the machined titanium alloy is used in the widely known Johnson-Cook model [24]. This model takes into account both kinematic hardening and thermodynamic adiabatic shear of titanium alloy in the form of stress dependence on strain rate and temperature. In this model, the equivalent plastic stress is defined by the expression:

$$\sigma = \left(A + B\varepsilon_2^n\right)\left[1 + Ch\left(\frac{\dot{\varepsilon}_2}{(\dot{\varepsilon}_2)_0}\right)\right]\left(\frac{\dot{\varepsilon}_2}{(\dot{\varepsilon}_2)_0}\right)^{\alpha}\left(D - E\left(\frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}}\right)^{m}\right), \tag{1}$$

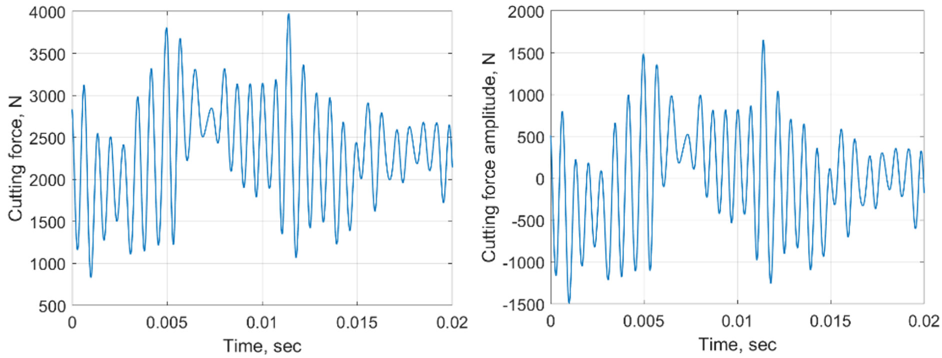
where A is the yield strength under slow loading ($A = 862$ MPa for Ti-6Al-4V [25]); B is the static hardening, which describes the deformation property of the material ($B = 331$ MPa); ε is the equivalent plastic strain; n is the coefficient characterizing the hardening property ($n = 0.34$); C is the strain rate coefficient ($C = 0.012$) [25]; $\dot{\varepsilon}_2$ is the plastic strain rate; $(\dot{\varepsilon}_2)_0$ is the strain rate in static state; T_{room}, T_{melt} are the initial room temperature and melting temperature of the material, respectively; m is the degree index, which takes into account the phenomenon of thermal softening of the material. In Eq. (1), the first part of the equation describes the static hardening phenomenon, the second part characterizes the dynamic hardening, and the third part formalizes the phenomenon of thermal softening.

The main initial data for the stimulation of cutting in DEFORM are the following machining parameters, such as cutting speed, depth, and feed rate. The geometry of the cutting edge is: the rake angle is 5°, the flank angle is 10°, and the cutting edge radius is 0.1 mm. The Newton-Raphson method was used as an iterative research method. The type of deformation process in the simulation model of cutting was considered according to the Lagrangian Incremental Model. The main solver of the system (computational kernel) was the Sparse Matrix Method [26]. The strength parameters, physical-mechanical, and thermal-physical characteristics of the titanium alloy Ti-6Al-4V were taken according to [25]. The defined model to calculate tool wear was the Usui model [27]:

$$w = \int apVe^{-b/T}\,\mathrm{d}t, \tag{2}$$

where P is the interface pressure; v is the sliding velocity; T is the interface temperature (in degrees absolute); $\mathrm{d}t$ is the time increment; a and b are the experimentally calibrated coefficients ($a = 1 \cdot 10^{-5}$; $b = 1150$).

The results of the simulation of titanium alloy Ti-6Al-4V cutting are shown in Fig. 6. The machining parameters used as input data are as follows: cutting speed is 60 m/min, the feed rate is 0.095 mm/rev, and cutting depth is 1.0 mm. The research time in the steady-state cutting mode was 20 µs. The average value of the main cutting force is 2500 N (Fig. 6a), and the amplitude of high-frequency oscillations is shown in Fig. 6b.



(a) dynamics of cutting force (b) amplitude of cutting force variations

Fig. 6. Results of modeling the machining process in DEFORM 2D

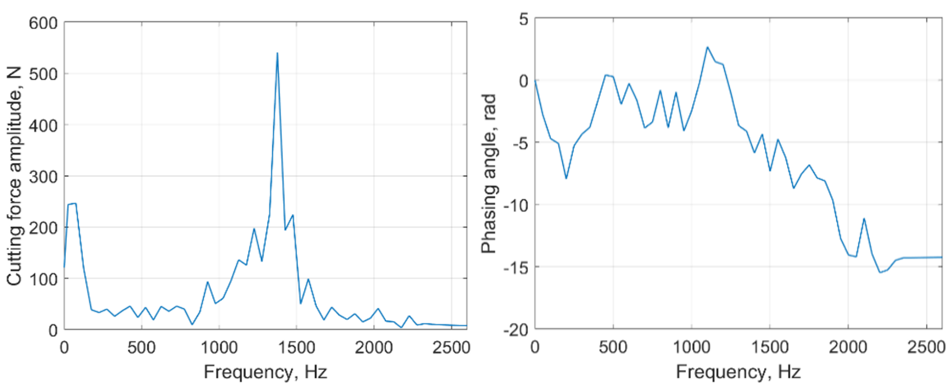
The Fourier transform method (FTM) [28] in MATLAB/SIMULINK software was used to determine the amplitude-phase frequency spectrum of the dynamic analysis of the cutting process. The results of this transformation are shown in Fig. 7 by amplitude characteristics (Fig. 7a) and phase response (frequency response) (Fig. 7b).

As can be seen from the analysis of Fig. 7a, the time dependence of the cutting force is multifrequency in the range of frequencies up to 2250 Hz with pronounced maxima in the range of low (25–200 Hz) and medium (1200–1400 Hz) frequencies.

Using the dependences shown in Fig. 6, we can get an approximation of the cutting force by an equation of the type:

$$P_x = A_0 + A_1 \sin(\omega_1 t + \varphi_1) + A_2 \sin(\omega_2 t + \varphi_2) + \ldots + A_n \sin(\omega_n t + \varphi_n), \quad (3)$$

where $A_0, A_1, \ldots, A_n$ are the amplitude values of the signal; $\omega_1, \omega_2, \ldots, \omega_n$ are the corresponding frequencies; $\varphi_1, \varphi_2, \ldots, \varphi_n$ are the initial phase angles.



(a) amplitude-frequency spectrum (b) phase-frequency spectrum

Fig. 7. Results of FTM conversion of high-frequency cutting force oscillations relative to the average value when machining titanium alloy Ti-6Al-4V

The cutting force approximation is represented by Eq. (3), where, to reduce the expression, only terms with amplitude values greater than 50 N are displayed.

$$P_x = 2385 + 55\sin(2\pi\,25t + 4.17) + 140\sin(2\pi\,50t + 5.57) + \ldots \\ \ldots + 71\sin(2\pi\,1575t - 9.23) + 62\sin(2\pi\,1600t - 11.6). \tag{4}$$

3.2. Analytical modeling of dynamic cutting processes of titanium alloys

To study the vibrations in the MFTW system, the system of differential equations of the four-mass vibrational scheme consisting (Fig. 8) of a tool (index is t), support (index is h), the workpiece (index is w), and spindle (index is s), which are connected between themselves and the machine bed by elastic ties with dampers.

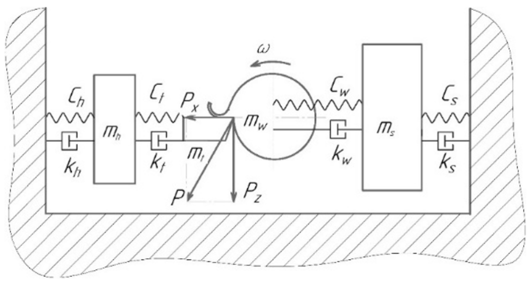


Fig. 8. A four-degrees-of-freedom mass-spring system of turning tool machine

Such a scheme corresponds to the design of a classical lath; the mass of its bed is much greater than the mass of its elements. So, their vibrations will be considered relative to the stationary base of the machine. The four-mass oscillating circuit is characterized by its versatility, since if we replace the mass of the spindle with the mass of the table, and the mass of the tool holder with the mass of the spindle, it will be the circuit of a milling machine. The oscillating contour of a machining center can be described similarly.

For simplicity, let us consider the scheme of vibrations along only one coordinate, namely x since it is the vibrations in this direction that form the roughness indicators and create residual stresses and strains of the machined surface:

$$\begin{aligned}
\frac{d^2x_h}{dt^2}m_h - C_h x_h - k_h\frac{dx_h}{dt} - C_t(x_h - x_t) - k_t\left(\frac{dx_h}{dt} - \frac{dx_t}{dt}\right) &= 0,\\
\frac{d^2x_t}{dt^2}m_t + C_t(x_h - x_t) + k_t\left(\frac{dx_h}{dt} - \frac{dx_t}{dt}\right) + P_x &= 0,\\
\frac{d^2x_w}{dt^2}m_w - P_x - C_w(x_w - x_s) - k_w\left(\frac{dx_w}{dt} - \frac{dx_s}{dt}\right) &= 0,\\
\frac{d^2x_s}{dt^2}m_s + C_w(x_w - x_s) + k_w\left(\frac{dx_w}{dt} - \frac{dx_s}{dt}\right) - C_s x_s - k_s\frac{dx_s}{dt} &= 0,
\end{aligned} \tag{5}$$

where x_i is the displacement of the i-th element of the scheme (tool holder (h), tool (t), workpiece (w), and spindle (s), respectively); m_i is the reduced mass of the i-th element; C_i – stiffness of the i-th element; P_x is the radial component of the cutting force; k_i is the damping of the i-th element of the scheme:

$$k_i = \frac{m_i \delta_i \omega}{\pi}, \tag{6}$$

where δ_i is the logarithmic decrement of oscillations of the i-th element of the scheme, which characterizes the intensity of the damping of the oscillatory process; ω is the angular frequency of oscillations. The radial component of the cutting force P_x is determined as a result of simulation (Fig. 6a) and is described by Eq. (4).

The initial data for the numerical solution of the system of differential Eqs. (5) are the following parameters of the four-mass oscillatory system MFTW: m_t = 0.15 kg; m_w = 0.2 kg; m_s = 25 kg; m_h = 125 kg; $C_i = 2 \cdot 10^9$ N/m; $C_w = 45 \cdot 10^6$ N/m; $C_s = C_h = 1.5 \cdot 10^8$ N/m.

Determination of the natural frequencies of the MFTW components was carried out most of all by the method of free oscillations [29, 30]. This methodology consists in recording the damped acoustic oscillations excited in the MFTW system component, followed by the analysis of the resonance frequencies and damping decrements of the natural mechanical vibrations.

The method of free oscillations uses the accumulation of time series of measurements at the i-th moment of damped oscillations:

$$\begin{aligned} A_i &= A e^{-\delta_i t_i} \sin(\omega_1 t_i + \alpha), \\ A_{i+1} &= A e^{-\delta_i (t_i + T_1)} \sin\left(\omega (t + T_1) + \alpha\right), \end{aligned} \tag{7}$$

where A is the maximum amplitude of oscillations; α is the initial phase; t_i is the time corresponding to the i-th extremum of oscillations; δ_i is the damping coefficient, characterizing the properties of the product; T_1 is the period of damping oscillations.

The damping coefficient is determined from the known values of logarithmic decrements of vibration: $\delta_w = 0.01$ (for steel AISI 1045); $\delta_w = 0.005$ (for titanium alloy Ti-6Al-4V) $\delta_s = \delta_h = 0.15$ (with the actual damping in the connections of lathe elements [4]).

The natural frequencies of the MFTW system: f_s = 176 Hz; f_h = 393 Hz; f_w = 2493 Hz (for workpiece 60 mm diameter and 350 mm long is clamped in a 3-jaw self-centering lathe chuck (MAC AFRIC Spare 3 Jaw Chuck)); f_t = 18451 Hz.

The solutions of the system of differential Eqs. (5) are presented in Fig. 9. In Fig. 9a, there is shown the displacement of the machine support in time, in Fig. 9b – displacement of the tool, in Fig. 9c – displacement of the workpiece, and in Fig. 9d – displacement of the spindle.

As can be seen from the graphical dependencies shown in Fig. 9, the support with the tool cutter is displaced in frequency antiphase to the workpiece and the

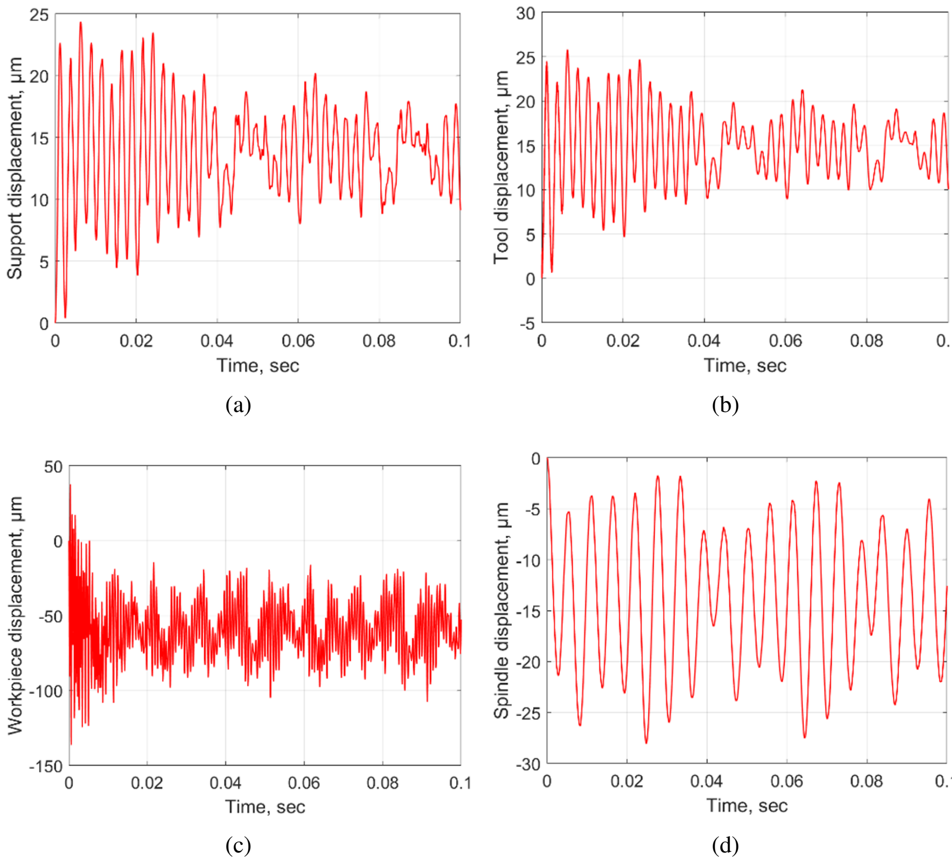


Fig. 9. Graphs of oscillations of the tool machine working bodies and the workpiece

spindle due to the action of cutting force on them. The magnitude of this displacement is directly proportional to the cutting force and inversely proportional to the stiffness of the MFTW system component. The response of individual elements of the MFTW system is different at varied excitation frequencies and is known to depend on the proximity to the resonance of its elements. The amplitude of oscillations of the workpiece in the steady-state cutting mode of titanium alloy is 80 µm.

For additional research, it is proposed to change the workpiece clamping from a 3-jaw self-centering lathe chuck to a center clamping. In this case, the stiffness of the part decreases by about 3 times: from $C_w = 45 \cdot 10^6$ N/m to $C_w = 15 \cdot 10^6$ N/m. In this example, the calculated frequencies of the vibrating system will be as follows: $f_s = 176$ Hz; $f_h = 393$ Hz; $f_w = 1552$ Hz; $f_t = 18451$ Hz. As can be seen from Fig. 10, the natural frequency of the workpiece decreased from 2493 Hz to 1552 Hz, which brought it closer to the local maximum of the magnitude-frequency characteristic of the excitation force (approximately 1400 Hz – Fig. 7a).

Analysis of the results of the study (Fig. 10) has shown that the approximation of the natural frequency of the MFTW system to the frequency of the forced load at a significant value of the amplitude (local maximum) leads to a major increase in the amplitude of tool movement relative to the workpiece (about 12 times). This significantly affects the accuracy and quality of machining (especially the vibration component of roughness). Moreover, this conclusion applies not only to the vibrations in the "tool-workpiece" subsystem but also to any element of the MFTW system. As can be seen from the analysis of Fig. 10, the maximum range of spindle vibrations is twice as large as the maximum range of support vibrations. The reason for this is the different ratio of the values of natural frequencies of the support and tool holder – spindle (f_s = 176 Hz; f_h = 393 Hz) to the local maximum of the amplitude-frequency characteristic of the cutting force (f = 150 Hz – Fig. 7a). The purpose of the theoretical studies is to confirm the possible reaction of the machine tool to the polyharmonic excitation of oscillations (Fig. 7a), where a change in the stiffness of the MFTW system (increase or decrease) causes an approach to resonance and, as a result, an increase in the amplitude of relative vibrations of the cutter and workpiece at medium frequencies, which is shown in Fig. 10. That is, the results of simulation studies of the titanium alloy cutting process in DEFORM 2D should be compared with the spectrum of machine vibration frequencies, and if possible, move away from the resonance in one direction or another, or change the cutting parameters. In the process of experimental studies, the frequency of oscillations of the cutting tool was close to the lower resonance region of the cutting characteristics obtained during the simulation in DEFORM (Fig. 7a). Moreover,

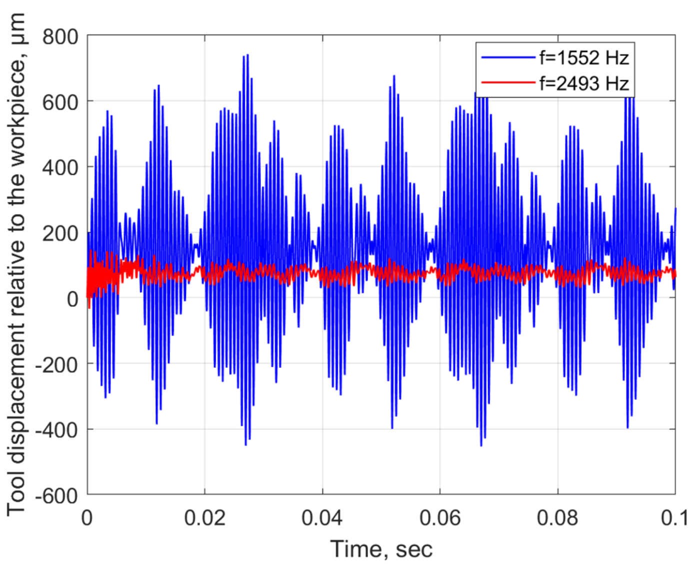


Fig. 10. Amplitude-frequency characteristics of oscillations of the tool machine bodies and the workpiece under different conditions of clamping the part (in red – clamp in 3-jaw self-centering lathe chuck, in blue – clamp in the centers)

the workpiece had high rigidity, namely, it was fixed in a 3-jaw chuck and supported by the center of the tailstock. In this case, we obtained near-resonant vibrations, which caused a significant increase in the amplitude of vibrations.

An increase in the amplitude of the support oscillations will similarly lead to an increase in the amplitude of the tool's oscillations. Therefore, for effective and high-quality machining of the workpiece, it is necessary to ensure that such natural frequencies of the MFTV elements are far enough from the maximum amplitude-frequency values of the cutting force. This is especially important when machining titanium alloys since the cutting force dynamics have a pronounced sinusoidal character. Therefore, there are several extreme values. To solve this problem, it is necessary to apply an algorithm for solving design and technological problems: changing cutting parameters, ways of workpiece locating and clamping, tool design, use of lunettes or other design solutions, and so on. The main idea of the described scientific approach is to ensure the accuracy and quality of processed surfaces as a result of machining. We determined the dynamics of cutting force in one of the simulation systems (DEFORM, LS-DYNA, Abaqus) and the amplitude-frequency characteristics of forced and natural vibrations of the MFTW system.

4. Experimental studies

The above-mentioned methodology of the combination of theoretical and simulation results of titanium alloy cutting process dynamics research is based on some simplifications and empirical assumptions. This can create errors that significantly affect the quality of the research results and create prerequisites for false recommendations and conclusions. Therefore, this article proposes an approach based on the processing of experimental data obtained in a series of experiments, which allows one to identify the vibration response to the shaping movements of the tool. To process and analyze the experimental data obtained, the Matlab mathematical software package was used, in which a subroutine was developed to perform the spectral analysis of vibration signals, as well as the graphic interpretation of the measured values.

To conduct experimental studies on the dynamics of the cutting process of titanium alloys, an experimental device was designed and developed. The design of this apparatus includes the following components (Fig. 11): 1 – workpiece (material – Ti-6Al-4V); 2 – tool with tungsten carbide insert WC8; 3 – vibration sensor model UC 507-I (frequency range 100...5000 Hz); 4 – 3-jaw self-centering lathe chuck; 5 – 2-channel USB oscilloscope model OWON VDS1022 (25 M Hz); 6 – computer.

Fig. 12 shows the results of the experimental study of the cutting process of titanium alloy Ti-6Al-4V (spindle speed 500 rpm, feed rate 0.095 mm/rev, cutting depth 1.0 mm). Fig. 11a illustrates the accelerometer output signal – vibration acceleration. Fig. 11b presents a twice-integrated signal, which is the vibration of the milling cutter. The amplitude-frequency characteristic of the vibration signal

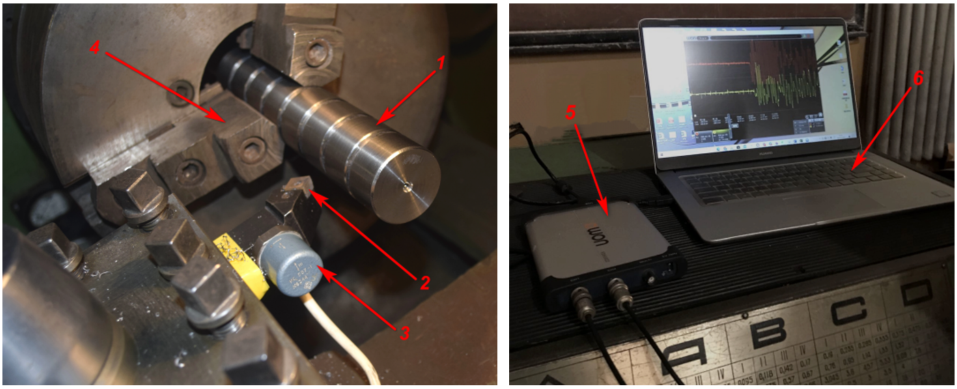


Fig. 11. Main components of the experimental setup

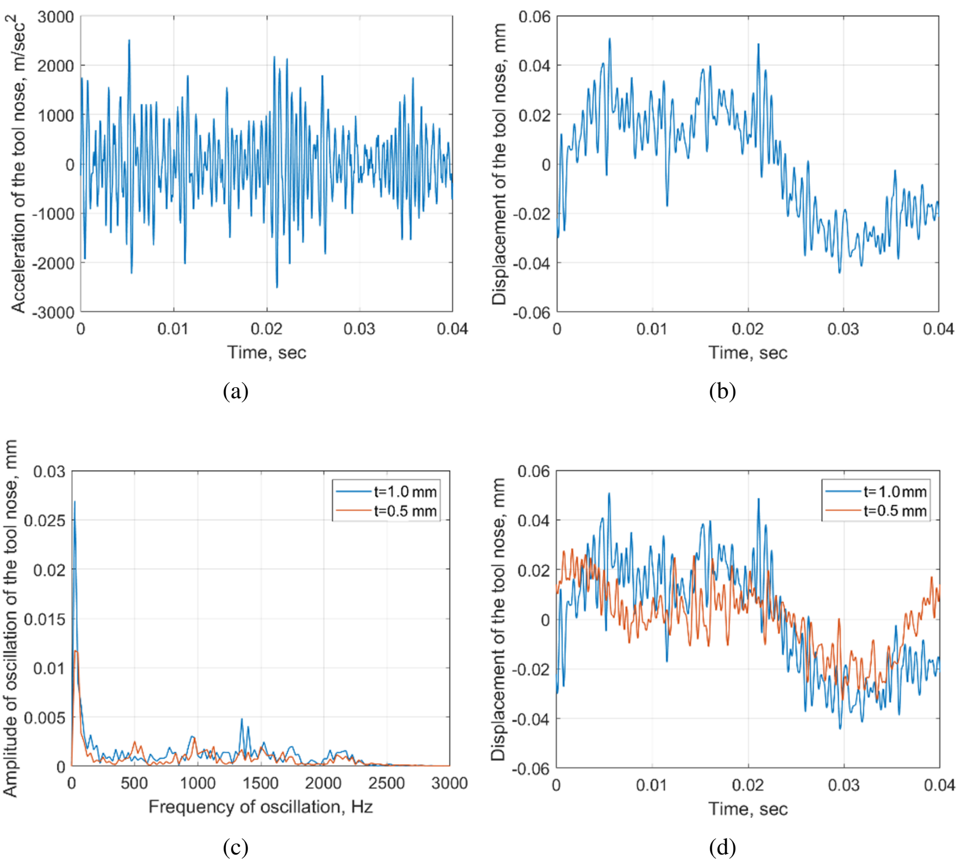


Fig. 12. Graphical representation of the experimental studies results of the amplitude-frequency characteristics for titanium alloy machining

obtained by the direct Fourier transformation method is shown in Fig. 11c. Experimental studies were conducted for the roughing mode (cutting depth 1.0 mm – on the blue line) and finishing mode (cutting depth 0.5 mm – on the red line). Analysis of graphic dependences showed that the maximum amplitude of oscillations corresponds to a frequency of about 25 Hz. Increasing the cutting depth leads to an increase in the amplitude at the same frequency (Fig. 11c).

The mean vibration amplitude of the cutting tool is 0.043 mm at a cutting depth of 1.0 mm and 0.022 mm at a cutting depth of 0.5 mm (Fig. 11d). Comparison of simulation results (Fig. 9) and experimental data (Fig. 12) allowed us to establish a high level of adequacy of theoretical and real results of vibration processes during titanium alloy machining.

5. Conclusions

1. Titanium alloys are difficult-to-machine materials due to their complex mechanical and thermophysical properties. In addition, the complex thermodynamic cutting pattern causes adiabatic shear during cutting. This is accompanied by the occurrence of high-frequency oscillatory processes of longitudinal, tangential, and radial components of cutting forces, acting under conditions of frequency dissonance. This effect leads to intensive vibrations of the tool and, as a result, to the appearance of a significant value of the vibrational component of surface roughness. In addition, high-frequency vibrations of the technological system “Machine-Fixture-Tool-Workpiece” contribute to the appearance of local zones of residual stresses on the machined surface and intensive wear of the cutting tool.

2. Classical research models of vibrations during cutting processes (construction and solution of differential equation system of multi-mass MFTD systems) work exactly when machining titanium alloys do not account for complex stress-strain and thermodynamic processes of shaping. Such studies can be implemented using simulation modeling. In turn, rheological simulation results in CAF systems (DEFORM 2/3D, Abaqus, LS-DYNA, AdvantEdge) do not take into account the fact that the initial state of the workpiece and tool are a priori assumed to be “rigid”, and the damping properties of the fixture, tool and machine elements in the initial simulation model are not taken into account at all. Therefore, combining the results of analytical modeling of the dynamics of the cutting process with the results of simulation modeling is the underlying basis of the proposed research methodology. Such symbiosis of different techniques will make it possible to take into account both the mechanical aspects of machined surface forming with the real conditions of stiffness and damping properties of the MFTD system.

3. A mathematical model of a four-mass auto-oscillating scheme of a metal-cutting machine has been developed and investigated taking into account the results of simulation modeling of titanium alloy cutting. Problem-oriented studies of the dynamics of the cutting process are carried out, and the resonance

amplitude-frequency characteristics during machining of such materials with different machining conditions and workpiece fixturing schemes are revealed. Fourier transform method in MATLAB/SIMULINK program was used to determine the amplitude-phase frequency spectrum of dynamic cutting analysis. It is proved that the amplitude displacement of the carriage with the cutter is shifted in frequency antiphase concerning the workpiece and spindle as a result of the cutting force impact on them. The magnitude of this displacement is directly proportional to the cutting force and inversely proportional to their stiffnesses. Moreover, the response of the individual elements of the MFTW system is variable for different excitation frequencies and depends on the proximity to the natural resonance of its elements.

4. Analysis of the amplitude-frequency characteristics of vibrations of the machine tool and workpiece under different fixturing conditions (clamping in 3-jaw self-centering lathe chuck versus clamping in centers) has shown that approximation of the frequency of natural vibrations of the MFTW system element to the frequency of the exciting force (local maximum) leads to a significant increase in the amplitude of tool-to-workpiece vibrations (approximately twelve times). This has a significant effect on the accuracy and quality of machining (first of all, on the vibration component of roughness). Moreover, such a conclusion concerns not only the vibrations in the "tool-workpiece" subsystem but also every element of the MFTW system. In this case, the maximum amplitude of the spindle vibrations is twice as large as the maximum amplitude of the support vibrations. The reason for this is the different ratio of the values of the natural frequencies of the support and spindle vibrations (f_s = 176 Hz; f_h = 393 Hz) to the local maximum of the amplitude-frequency characteristics of the cutting force (f = 150 Hz).

5. To carry out experimental studies to study the dynamics of the cutting process of titanium alloy, an experimental setup was developed and created. Experimental investigations were performed for the roughing machining mode (cutting depth 0.5 mm) and the finishing mode (cutting depth 0.2 mm). The analysis of graphic dependences showed that the maximum amplitude of oscillations corresponds to a frequency of about 25 Hz. Enlargement of the depth of cutting leads to an increase in the amplitude at the same frequency. A comparison of simulation results and experimental data is shown a high level of adequacy of the theoretic and real representation of vibration processes during the machining of titanium alloys.

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