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Prehodni pojavi pri postopku brušenja

Transient Phenomena in the Grinding Process

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Lokalne stične premike, ki so posledica elastičnih deformacij orodja in obdelovanca, smo proučevali z uporabo končnih elementov in s preskusi. Izdelali smo grafične in analitične prikaze rezalne sile s harmoničnimi in stohastičnimi elementi.

Predhodno objavljene raziskave stika med brusilnim kolesom in obdelovancem temeljijo na predpostavki, da predstavljajo stične deformacije neposredno funkcijo normalnih in tangencialnih sil, ki med postopkom brušenja delujejo na kolo oz. njegova zrna, brez upoštevanja obrabe in lomljenja zrn. V prispevku smo, s pomočjo metode končnih elementov in preskusa krožnega polirnega brušenja z velikimi hitrostmi, opisali postopek raziskave in grafično prikazali prehodne pojave in vzorec uničenja brusilnih zrn znotraj stične zone kot posledico impulznih obremenitev. Prej omenjeno metodo lahko uporabimo pri prožnih, togih, plastičnih in drugih nelinearnih materialih, ki jih obdelujemo z brušenjem. Uporabo nelinearnih lastnosti materiala, modul prostornine in modul pomika v stični coni med brusilnim kolesom (vrsta 24A12ПСМ28К5) in obdelovancem (jeklo 45), smo pri preskusu simulirali z uporabo tri-parametričnih elementov. S predstavljeno metodo lahko izračunamo prehodne napetosti in deformacije med krožnim polirnim brušenjem z velikimi hitrostmi ter proučujemo uničenje brusilnih zrn na dvorazsežnem modelu z nedoločenimi mejami in nelinearlnimi značilnostmi. Namen predstavljene razsikave je določitev vpliva prehodnih pojavov na sestavo rezalne sile med postopkom brušenja.

(Ključne besede: postopek brušenja, napetosti, deformacije, simuliranje, analize eksperimentalne)

Local contact displacements resulting from the elastic deformation of the tool and the blank, were studied using the finite-element and by experiments. Graphical and analytical expressions for the cutting force, with harmonical and stochastic components, were obtained.

Previously published research on the behaviour of the contact between the grinding wheel and the workpiece has been based, on the assumption that the contact deformations represent a direct function of both the normal and the tangent forces acting on the wheel or its grains during the grinding process, without taking into account the attrition and breaking of the grains. This paper covers the procedure for researching and graphically representating transient processes and the pattern of the abrasive grains' destruction within the contact zone under impulse loads, which is based on the method of finite elements and the results of a high-speed circular plunge-grinding experiment. The above-mentioned method can be applied to elastic, inelastic, plastic and other nonlinear materials machined by grinding. To introduce the nonlinear properties of the material in the experiment, the modulus of the volume and the modulus of the shift in the contact zone between the grinding wheel (grade 24A12ПСМ28К5) and the workpiece (steel 45) are simulated by three-parametric elements. The presented method makes it possible to calculate transient stress and deformations during high-speed circular plunge grinding and to study the destruction of abrasive grains in a two-dimensional medium with indefinite boundaries and nonlinear characteristics. The present research is aimed at finding out the influence of transient phenomena on the structure of the cutting force during the process of grinding.

(Keywords: grinding process, stress, strain, simulation, experimental analysis)

0 INTRODUCTION

Factory-wide automation, the increase in machining precision and operational concentration, as well as the intensification of cutting processes, and other important factors for increasing the output and efficiency of adaptive production, constitute the objective rules of the development of technological equipment. On the whole, these trends in the development of industrial production bring forth new problems when developing grinding equipment, particularly of the spindle systems based on the intensification of cutting processes. The intensification of cutting processes is one of the basic methods of scientific and technical progress in the machine-tool building industry. An increase in the grinding speed up to 60 m/s (instead of 30 to 35 m/s) has drastically increased the efficiency of grinding equipment. Nowadays, there are all the necessary grounds for applying grinding speeds od up to 100 to 120 m/s ([1] to [3]). Despite this, a simple increase in the cutting speed by increasing the grinding wheel's velocity will not produce a tangible effect unless all the grinding system's reserves are used together, particularly the radial and circular feeds. Reference [4] shows that an increase in the circular feeding velocity of circular grinders is particularly effective when CBN grinding wheels are used. In such cases of high-speed grinding, as well as in cases of normal-velocity grinding, the quality of the work surface increases in proportion to the reduction of the cutting force. A large number of abrasive grains per unit time take part in the metal-cutting process during a high-speed grinding operation. This results in a decrease in the depth of cut-offs per abrasive grain and, consequently, in a lower stress on the grain, thus reducing its rate of wear.

At present the relative speed of the tool and the workpiece in metal machining is considered to be in the range from 25 to 500 m/s ([1] to [3]). Information is rather scarce about the phenomena occurring under such heavy-duty velocity and stress conditions. Here, theoretical physical investigations indicate that high-velocity grinding is characterized by the occurrence of the temperature field ([5] and [6]) and the field of forces during the grinding process.

At the present time there is a lot of activity to simulate the properties of abrasive tools with a particular grain and cutting-edge microgeometry in order to develop grinding wheels with new structures to operate under n-fold load and allow functional cutting speeds of up to 300-500 m/s ([1] to [3]). However the phenomena that take place during the interaction of the two elements with particular stochastic properties are still insufficiently studied. This includes the characteristics of the force field, generated during high-velocity cutting, and those of the field's stochastic components.

To make use of all the specific advantages of high-speed grinding it is necessary to clearly understand the mechanism of the wheel and workpiece interaction in the contact zone.

A number of researchers studied local elastic deformations in the contact zone between the grinding wheel and the workpiece by applying different approaches and methods. Reference [7] provides a review of this research. According to this research the deformation in the contact zone under the effect of normal and tangent forces is determined by the elastic properties of the tool and the elastoplastic properties of the workpiece.

The local elastic displacements of the abrasive grains inside an abrasive tool, caused by normal and tangent forces, are transferred to the adjacent grains thtough intergranular contacts (directly or through the binder). The intensity of these displacements depends on the geometry of an abrasive grain, the stress value, the amount and the properties of the intergranular contacts. It is common ([1], [2] and [7]) knowledge that abrasive grains have a random shape and geometry, they are also randomly oriented during the production of the abrasive tool, and the grains differ considerably from each other as regards shape, size, thickness and the number of binding ties ([2] and [7]). Because of this their displacement in the normal direction and the rotation in the tangent direction, resulting from the shock of their interaction with the billet, contributes to the activation of vibration in the cutting zone. The pulse stress waves generated in this zone spread over the material of the abrasive grains and binder ([1] and [2]). For this reason the material particles in the cutting zone vibrate at a very high frequency and produce a certain effect on the system's state and the chip-grinding process.

This paper presents a method for calculating the transient stress and the deformations in the contact zone between the grinding wheel and the workpiece, and the destruction of abrasive grains in the two-dimensional medium with indefinite boundaries and nonlinear characteristics. The suggested method and the program designed on the basis thereof ([16] and [17]) were verified with experimental data obtained during the process of grinding a steel workpiece (steel 45) with a grinding wheel (grade 24A12ПСМ28К5), which made it possible to substantiate the structure of the cutting force.

1 STRESS AND STRAIN

In order to understand the mechanism of the grinding processes and to determine the degree of system strain let us discuss local (contact) shifts resulting from the elastic deformation of the tool and workpiece during the penetration of the tool into the workpiece. Let us assume that the tools with determined geometry are not deformed whereas the grinding system undergoes eccentric deformation, though the cutting section later undergoes local thermoelastic deformations. The machining of materials using a tool with a stochastic micro-geometry is associated with local transient deformation at the contact of the interaction and the deformation of the grinding system ([1] and [8]). In the case of a rigid system the contact deformation changes the shape of the interacting bodies ([1], [8] and [9]).

If r_i is the radius of the non-deformed tools, then the change in the curvature determined by the force F_{ij} per unit of width and acting upon the contact will be as follows [10]:

$$\frac{1}{r_i}-\frac{1}{r_i^{\prime}}=\frac{F_{ij}}{C_n l_k^2} \qquad (1)$$

where $r_i^{\prime}$ is the curvature of the deformed tool; l_n is the contact; C_n is a constant depending on the elastic properties of the tool ($C_n=\pi E_i/16\left(1-v_i^2\right)$), where ν_I is Poisson's ratio.

The dependence of the elasticity modulus on the temperature of a tool with a ceramic binder according to [11] is expressed with the exponential dependence $E_i=E_0\exp\left(\alpha_T T\right)$, where E_0 is the modulus of elasticity at room temperature ($E_0=\left(50...100\right)\cdot10^3$ MPa), E_i is the modulus of elasticity at higher temperatures, α_T is a constant dependent on temperature ($\alpha_T=\left(3...6\right)\cdot10^{-4}$), and T is the temperature. Then $r_i^{\prime}=r_i\left(1+F_{ij}/C_n l_k^2\right)$, where $l_k=\left(1+1/q^*\right)\sqrt{r_i^{\prime} t_0}$; $q^*=v_i/v_j$, v_i is the speed of the grinding wheel, v_j is the speed of the work piece, and t_0 is the real value of the depth of cut in one revolution. The transient force field F_{ij} is an unknown parameter in these expressions; it determines the degree of strain in the system. Control of the value of strain also guarantees appropriate control of the elasticity, the vibration resistance and the damping ability of the system. The shaping process strain and its field of forces are determined by the normal and tangent voltages caused by the changing characteristics of the integrating elements (instrument and part). The elastic displacements of abrasive grains at the point of interaction contact were determined by calculation and by experiment [7]. However, neither the strained state [12] nor the beginning of the transient processes with accompanying fracture of abrasive grains under the effect of impulse loads (Fig. 1) were observed. This can be explained by complicacy on account of lots of factors, particularly during the non-linear behavior of the instrument's and the part's material. The non-linear behavior of the material can be simulated by rheological equations on the basis of a three-parametrical model, including the model of Kelvin-Foight and spring (elastic materials, materials with Poisson's ratio and plastic flow). It is known from [7] that it is the removable layer that possesses the greatest elasticity, which is why it can be modulated as a spring and as a plastic flow of metal, it can also be modulated as a model of Kelvin-Foight. In this case the bulk modulus will be represented by a rigid spring, and the modulus of shear by a dashpot. Then the relation between the stress and the strain can be expressed as follows [13]:

$$\{\sigma\}=\left[\bar{C}\right]\{\varepsilon\}+\left[\overline{C_0}\right]\left\{\dot{\varepsilon}\right\}+\sum_{i=1}^{3}\left\{\left[\overline{C_i}\right]\int_0^t e^{-\left(\frac{t-\xi}{\tau_i}\right)}\left\{\varepsilon\left(\xi\right)\right\}d\xi\right\} \qquad (2).$$

Where σ is the stress; $\bar{C}$, $\bar{C}_0$, and $\bar{C}_i$ are the matrixes characterising the material properties; ξ is the integration variable; and ε is the strain.

The application of the principle of conformity [13] makes it possible to automatically calculate the ratio of the stresses and strains (i.e., to calculate the values of the matrixes $\left[\bar{C}\right]$, $\left[\bar{C}_0\right]$, and $\left[\bar{C}_i\right]$).

The transient grinding process with the resulting ractures of abrasive grains during an impulse load (Fig. 1) belong to the type of problems for which no analytical solutions can be found. Therefore, in this case a widely known method of finite elements ([14] to [17]) to structurally idealize the continuous medium, to evaluate the rigidity of elements through the following node movement and

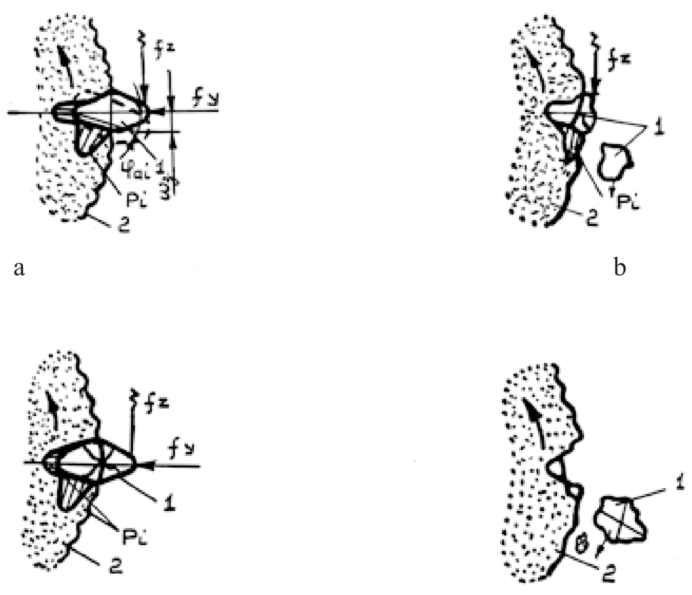

Fig. 1. *Basic types of destruction of abrasive grains: a – rotation and wear of grinding grains; b – crack-formation; c – destruction of grains with the separation of large particles; d – pull-out of grains from the binder; 1 – abrasive grain; 2 – binder of the grinding wheell; φ_{ai} - angle of rotation of the "i-th" grain in binder; ω_j – rotation value; f_z, f_y – forces; p_i – distribution of normal pressure*

velocity, to change the node movement in time and as an effective means of researching the strained state and the field of forces can be used.

2 FINITE-ELEMENT MODEL

In the model where finite elements are used every element is chosen so that a reasonable relation between load and movement (displacement) can be found. It is assumed here that the material characteristics of the element change in a known manner and the movement of any point of the element can be determined in the function of some system with generalized coordinates:

$$\{V(y)\}=[N(y)]\{q\} \tag{3}$$

and

$$\{V\}=[D]^{-1}\{q\} \tag{4}$$

where $\{V\}$ and $\{V_n\}$ are vectors of motion of the point located at "y" and the vector of nodal movement of the element; y is the vector of the position of the element point; $[N]$ is the matrix of the chosen function of displacement; $\{q\}$ is the vector of generalized coordinates; $[D]^{-1}$ is the matrix obtained after the substitution of the node vectors of the position into Equation (3).

Deformation at any point of the element is expressed by the following equation:

$$\{\varepsilon(y)\}=[B(y)]\{q\} \tag{5}$$

where the matrix $[B(y)]$ is obtainable from $[N(y)]$ by means of the equation (2). The use of the principle of virtual work and expression (2) leads to the following dynamics equation of grinding systems with non-linear materials:

$$[M]\{\ddot{\delta}\}+[C]\{\delta\}=\{F_\varepsilon(t)\}-[C_0]\{\dot{\delta}\}-\sum_j\left([C_j]\int_0^t \exp\left[-\left(\frac{t-\xi}{\tau_j}\right)\right]\{\delta(\xi)\}d\xi\right) \tag{6}$$

where $[M]$ is the diagonal matrix of concentrated masses; $F_\varepsilon(t)$ is the vector of node forces; $\{\delta\}$, $\{\dot{\delta}\}$ and $\{\ddot{\delta}\}$ are the vectors of node movement, velocity and acceleration, respectively; $[C]$, $[C_0]$ and $[C_j]$ are the matrixes of node rigidities of the system, associated with the matrixes $[C]$, $[C_0]$ and $[C_j]$.

The matrixes of rigidity included in Equations (6) can be obtained by summing up the matrix of element rigidity $[C_i]=[D]^T\int_s[B(y)]^T[\bar{C}][B(y)]ds[D]$, where s is the volume of the element. If an element fractured, its quality characteristics and node rigidities also get changed. A set of ordinary differential equations is solved by means of digital integration using the Hamming forecast and correction method. While solving Equation (6) the strain is being checked in every element and in the case when the maximum strain exceeds a critical value all the terms pending to this element are cancelled from the matrix of rigidity. If witnesses about the facture of the abrasive grain. As to the processed part, changing the characteristics of damping, modulus elasticity, etc., simulates the transition from an elastic band to a plastic one. The transition from one type of material behavior to another shows that all the following changes of the element's shape will be accompanied by new materials characteristics. In reference to the above-mentioned equation (6) it is considered in the increments on the step of integration Δt. It guarantees the absence of sudden load changes, typical of any

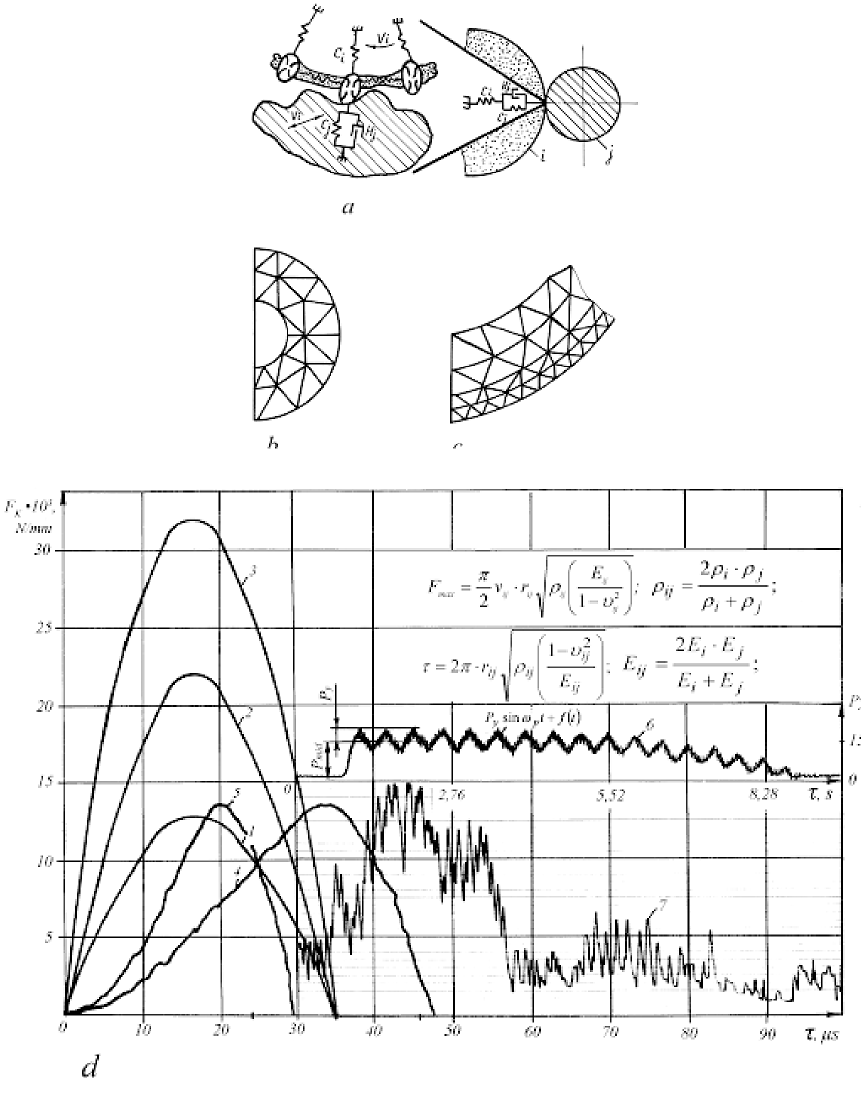

Fig. 2. *Numerical simulation and experimental results: a – a schematic diagram of the rheological model of the grinding process; b – partitioning of the grinding wheel and workpiece into final elements (39 nodes, 54 elements for contact zone); c – enlarged image of the contact zone; d – results of numerical simulation; 1,2,3 – according to the Hertz theory when V_{ij} – 30, 50 and 75 m/s, respectively; 4,5 – according to the rheological model; 6 – cutting force obtained from strain measurement; 7 – vibrations at the moment of cutting-in of the grinding wheel into the workpiece.*

element. A diagrammatic representation of the rheological model and the subdivision into the final elements of the grinding wheel, part and some results of the numerical simulation in a graphic view are shown in figure 2. However, the pulse of the force according to the static theory of grains is not show there, and the experimental results. It is worth mentioning that the static theory of Hertz does not reflect the free time of contact.

The time of contact depends on the velocity of the grinding process, and of the contact and the force of resistance against the grinding process. A high-frequency pulse force [2] is characteristic of the high-frequency grinding process, which is a vibration system of grinding, this is confirmed by experimental results (Fig. 2).

The cutting force will change according to the expression

$$P_y = P_{cp} + P\sin\omega_p t + f\left(t\right) \qquad (7)$$

where P_{cp} is the average component of the cutting force; P is the amplitude of the variable component; ω_p is the frequency of the harmonic component of the cutting force; and f(t) is the zero average stochastic process of noise with dispersion σ_p^2.

3 EXPERIMENTAL ANALYSIS

The above-mentioned was proved by experimental analysis. Oscillograms of the cutting forces (Figs. 2, 3) and the high-frequency components show random oscillations, which can be noticed early while the fracture and the micro-fracture of the abrasive grains takes place during their wearing out.

These effects can be detected only in grinding systems with components that register and analyze the force field. Such components can be created if one has knowledge about the physical phenomena that occur during grinding and within grinding systems. Fig. 3a shows a diagram using physical phenomena for an estimation of the force field. The cutting forces are measured at the spindle, at the tensometric centers and directly at the sample mandrel by means of inductive converters. The contact between the workpiece and the sample mandrel is realized through a heat-insulation material. This arrangement is useful for avoiding any thermal expansion of the sample mandrel. The results obtained are presented in the form of an analogue oscillogram in Fig. 3b. A comparison of these results (Fig. 3b) shows that time changes in the force value are expressed by determined and stochastic components.

The cutting forces P_y and P_z were obtained by feeding the grinding wheel to a distance of 6.7 microns per revolution of the workpiece. The movements of the spindle with a grinding wheel in hydrodynamic bearings were obtained at a grinding depth of t_1 = 50 microns and t_2 = 20 microns. The vibrations of the sample chuck can reach approximately 10 microns. The obtained results show that the cutting force P_y is almost twice as large as the force P_z. The shape of the curves obtained from the spindle bearings corresponds to the shape of the cutting forces obtained by strain-gauging, but it is different as a result of the absence of the harmonic and stochastic components, which are damped by the oil film in the bearing. Such components are present in the oscillograms of the sample chuck.

These low-frequency and high-frequency components of the cutting force together with the vibrations in the system of the drive feed, and with oscillations of the spindle heats, lead to a transient radial shear of the axis rotating the spindle and the part, and to a low quantity of macro-geometry, micro-geometry and the structure of the surface layer of the processed part. The relationship between the radial shear and geometrical accuracy, the waviness and roughness of the surface under processing should be analyzed by considering the autoevaluational and cross-correlation functions and spectral densities of the processes. Therefore, it is necessary to carry out simultaneous measurements of all the above-mentioned factors. Such a treatment of the field of forces can help determine the influence of every component on the state of the system and in this case program-adaptive control of the strain of the system is indispensable. It also requires appropriate algorithms of control. However, algorithms of the program-adaptive control require a determined dependence between the cutting forces and temperatures that are occurring in the process of grinding. Analytical dependencies between the cutting force and contact temperature, arising in the process of grinding, show that the contact temperature reaches the melting temperature very soon when the specific intensity of material removal is increased. Analytical dependencies were determined on the basis of Kelvin's fundamental solution and half-empirical model [1]. This is identical

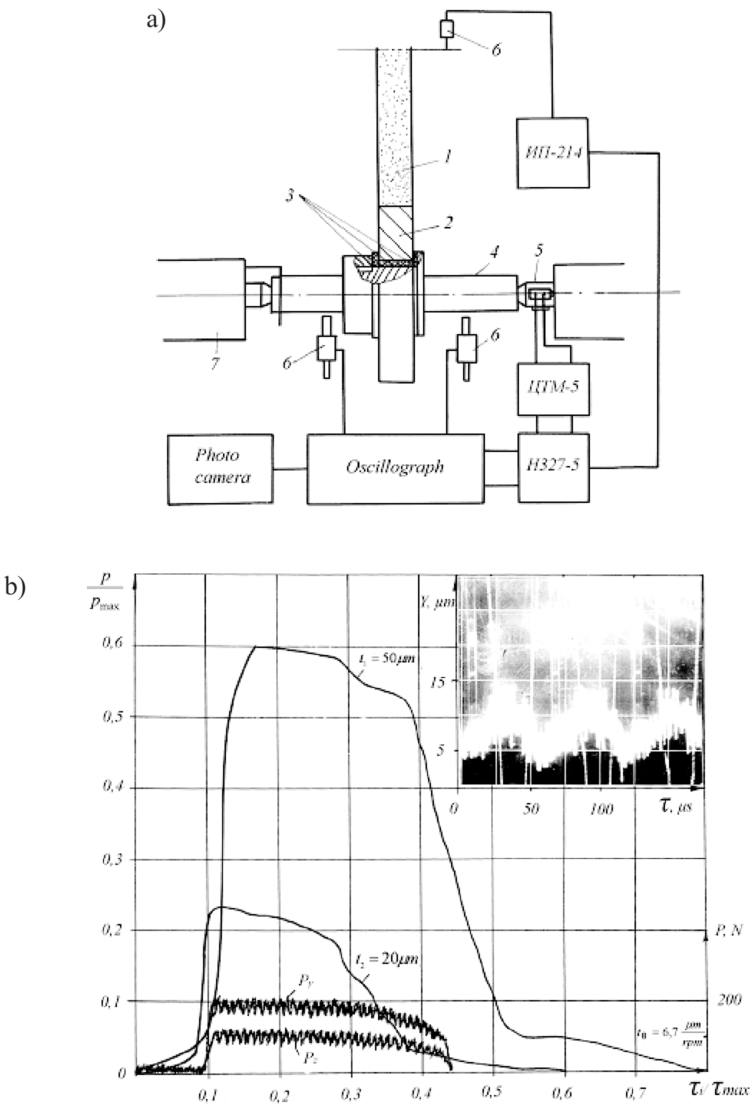

Fig. 3. *Diagram of the measurement of the force field (a) and results of the measurement (b): 1 – grinding wheel; 2 – workpiece; 3 – heat-insulation material; 4 – sample mandrel; 5 – strain-measuring centre; 6 – shift sensors; 7 – headstock.*

to the velocity change of the force pulse. Thus, it proves the expediency of measuring the cutting forces applied in flexible manufacture. Therefore, it is also necessary to analyze the influence of lubricants and cooling on the strained state of components of the grinding systems, stochastic state and the possibility of its application as a diagnostic and control means of the system. Thus, local stability mainly depends on revealing the lows and physical phenomena of the grease of the grinding process systems. The above-mentioned and other items will be discussed further in future papers.

4 CONCLUSION

Deterministic grinding systems change into deterministically stochastic ones. In this sense high-velocity grinding is rather important. Therefore, if it is clearly seen that the intensification of grinding modes requires appropriate decisions with reference to the major standards of accuracy and the quality of processing. It can be achieved by the implementation of various types of sensors, controlling the temperature and the field of forces in real-time and processing quality maintained by active control devices.

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