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DYNAMIC STABILIZATION OF MACHINING PROCESS BASED ON LOCAL METASTABILITY IN CONTROLLED ROBOTIC SYSTEMS OF CNC MACHINES

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The paper describes an effective method, which permits to control the machining of hard-to-handle materials under local pre-strain and facilitates generation of structural metastability on the outer layer of the process material. Authors propose a new approach to creating local metastability in the machined material using thermal, plastic and cryogenic treatment. Changes in material properties, occurring under local deformation, are presented in a widely used graphic form of a stress-strain curve. In experimental tests, performed under local plastic strain, the authors observed normal vibration displacement of the tool in relation to the surface of the workpiece, made of medium-carbon steel (0.45 % C). Theoretical and experimental results confirmed the possibility to control the cutting process and to deliver dynamic stability for high-precision machining. The study allows to improve existing technologies for a wide range of materials and cutting modes, to implement segmentation and breaking of the chip in the shear zone, and to apply controlled robotic systems on CNC machines.

Key words: material machining, turning process, CNC machines, dynamic stabilization, chip segmentation, chip breaking

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Introduction. Russian market of robotic technologies using CNC machines is currently at its initial stage of development. In the near future demand for CNC manufacturing and machinery will entirely depend on their appeal to enterprise owners. Only provided this interest will implementation of robotic systems with CNC automatics become an irreversible process for Russian industry, same as modernization of its enterprises. Advantages of using robotic technologies will unfailingly take Russian companies to a new level and allow to improve quality of manufactured products, performance and flexibility of industrial processes.

Some technological operations, e.g. machining of geometrically complex parts, can be carried out either with production robots, or with machining centers. In general terms, the aim of both robots and machining centers is in performing relative motion of the processing tool against the workpiece according to specified requirements and with a certain degree of precision. Relative motion requirements are described in the technological program. It should be noted that robots tend to have a smaller shear zone, which is located inside of them, whereas the work zone of machining centers is larger than the robot itself.

Most modern technologies of cutting geometrically complex parts require the processing tool to move along a complex trajectory with high precision and a fixed speed. Earlier such operations were performed manually; however, the tool was often too heavy to handle. In addition, sometimes it was impossible to deliver necessary quality of tool motion – e.g., achieve specified precision or maintain constant speed. It is exactly these processing operations on CNC machines that will benefit most from the implementation of production robots.

Each stage of the machining process is associated with formation of the chip curling, which clutters the shear zone and impedes free movement of the robotic manipulator. The problem gets worse if the process parts are made of hard-to-handle materials, such as stainless steel, titanium or its alloys.

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Machining of complex parts from hard-to-handle materials results in degraded segmentation and breaking of the continuous chip, as well as in loss of stability, which leads to self-excited vibrations, increased intensity of tool wear, and reduced endurance of operating mechanisms – eventually all these factors contribute to a decrease in quality and accuracy of Russian produce [1, 6-9, 11, 12]. In order to automate and control the turning process on CNC devices, it is necessary to lay the basis for reduction of self-oscillation intensity and to develop necessary software for computer-based solutions [2, 3, 13, 14].

Currently in mechanical engineering there is a wide scope of products that require a special approach to automation and management of their machining process from the position of improving cutting efficiency. Among these are parts from corrosion-proof and heat-resistant steels and alloys, machined using high-performance automatically-controlled equipment. From the viewpoint of technology, it is preferable to obtain continuous chip because it indicates stability of the technological system, assures high quality of process surface and guaranteed tool durability, which is especially important for automation purposes. Under real time conditions of manufacturing, continuous chip can be obtained in a very narrow interval of technological parameters, which do not always correspond to recommended cutting modes and to the value of tool durability, required to reach a certain level of performance. It should be noted that continuous chip significantly obstructs operation of computer-controlled equipment, intensifies machine wear, provokes accidents and injuries, impedes processes of complex mechanization and automation of chip cleaning and its subsequent recycling [10, 14].

Methods and materials. Breaking the chip into segments of a specified length is one of the most important turning processes. Control over this operation is especially relevant for computerized machines, CNC automatics and manipulators. Fig.1 offers schemes of creating local metastability in the process material be means of thermal (Fig.1, *a*), plastic (Fig.1, *b*) and cryogenic (Fig.1, *c*) treatment.

Local metastability, characterized by depth h_m and width b_m, is generated on the workpiece surface in the area of planned machining allowance and follows a specified trajectory. This metastability causes local changes in material structure and encourages development of elastic and dissipative properties, which cannot be encountered in the initial material.

Changes in material properties, occurring under local strain, are presented in Fig.2 in a widely used graphic interpretation of a dependency between stress (σ) and deformation (ε). Stress-strain curves allow to come to a conclusion that in the first approximation

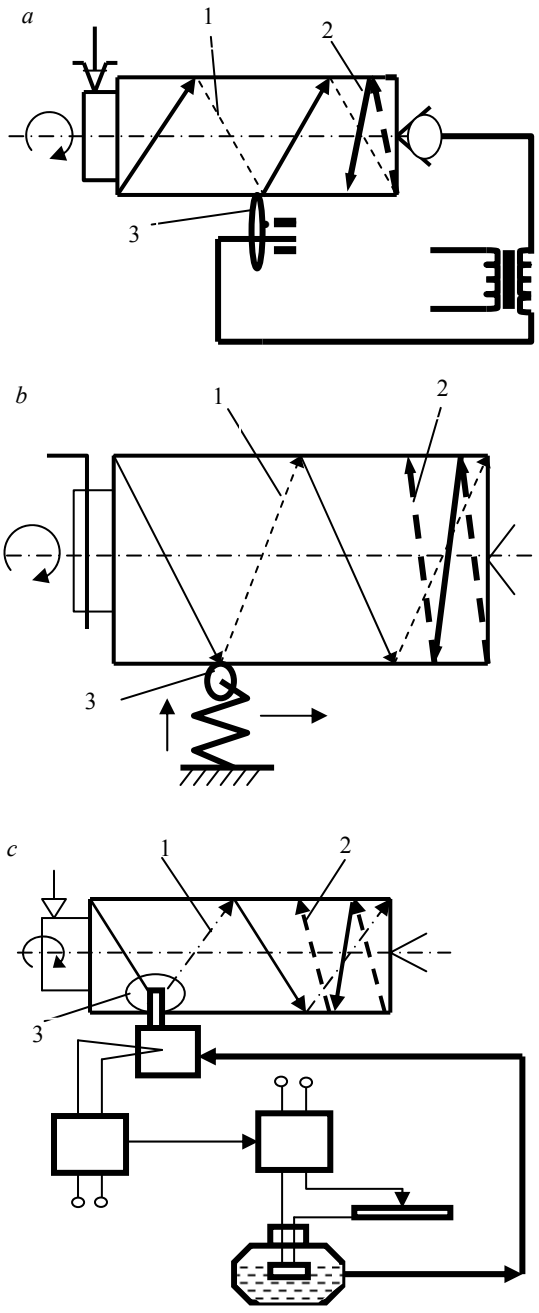


Fig.1. Schemes of creating local metastability in the process material
1 – mark of the local strain; 2 – mark of the shear plane; 3 – local strain source

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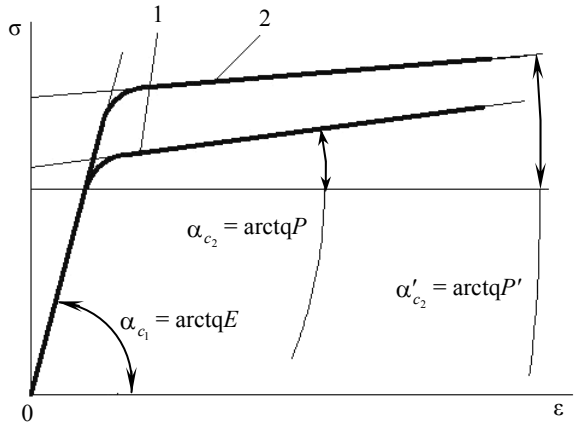


Fig.2. Stress-strain curves under local deformation
1 – initial material; 2 – after local deformation

elasticity modulus E, both in the initial structure of the material and in the local strain zone, reflects quasi-elastic properties of stiffness coefficients c_1 and c_1^1; besides it correlates with stiffness coefficients c_2 and c_2^1, and damping ratios β_2 and β_2^1 [2, 4]. It should also be mentioned that stiffness coefficients behave almost identically in the zone of plastic strain and in subsequent processes of chip formation.

Local plastic strain provokes changes in mechanical properties of the process material: yield stress σ_y, flexural strength σ_E, actual breaking stress S_k, percentage elongation δ, strengthening coefficient k_n. It is this strain that is responsible for periodical changes in the parameters of the technological system.

Research on system behaviour in the machining process was carried out on a four-contour dynamic model with the help of local strain method. Contact interaction between the process part and the machining tool was described by a multi-element rheological model of chip formation [2, 3], taking into account not only primary plastic deformation in the shear zone, but also secondary deformation and friction, occurring as the chip moves along the tool face. Modelling of the chip breaking process, based on piecewise linear approximation, allowed to formulate differential equations that describe dynamic properties of the machining system.

In accordance with the adopted rheological model of chip formation, behaviour of the selected dynamic four-contour model can be conveniently expressed in a vector-matrix form:

$$T\dot{q} + N(q)\,q = 0, \tag{1}$$

where $q(n\times 1)$ – vector function of system's generalized coordinates; T – diagonal matrix of order $(n\times n)$; $N(q)$ – matrix of order $(n\times n)$. In the given model $n = 10$, the number of contours n corresponds to the model order.

The system of differential equations (1) describes dynamics of the machining system with a regard to rheological distinctions of chip formation process in the local strain zone and elastoplastic properties, exhibited in the contact interaction between the tool and the process part. Basing on this system of equations, it is possible to solve the problem of controlling the chip breaking process.

Analysis of the machining process under local strain was carried out using a dynamic model (1), where control function ψ, responsible for the introduction of local strain, was represented by the following equation:

$$\psi(G_i) = \begin{cases} G_1 \ for \quad T_{p_m} \le t < m \quad T_{p_m} + T_p, \\ T_p = \text{const}, T_{p_m} = \text{const}, \\ G_2 \ for \quad T_{p_m} + T_p \le t < (m+1)T_{p_m}, \\ T_{p_m} - T_p = T_m = \text{const}, \end{cases} \tag{2}$$

where $G_1\{c_1, c_2, \beta_2\}$ and $G_2\{c_1^1, c_2^1, \beta_2^1\}$ – state parameters, reflecting the process of chip formation in the initial material and in the local strain zone; T_{p_m} – period of local strain; T_p –period of machining in the initial material; T_m –period of machining in the local strain zone; m – number of local strains, in the first approximation defined by dynamic properties of the technological system and length of the chip curl.

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Following the method described in publication [7], the authors modelled quasi-elastic and dissipative characteristics of the chip formation process in the initial material $G_1\{c_1, c_2, \beta_2\}$ and in the local strain zone $G_2\{c_1^1, c_2^1, \beta_2^1\}$ (Fig.3).

Dependence between stress σ_x and deformation ε over time t (Fig.4) is presented for the workpiece made of medium-carbon steel (0.45 % C), in its initial state and under local strain.

Solution to the equation system (1) under conditions of deformation and phase transitions (see Fig.2), as well as to the control function (2) allowed to plot stability boundary in $b_c - V_s$ coordinates (Fig.5) for the case of preprocessed surface machining under plastic strain (see Fig.1, *b*).

It is essential to understand the impact of unstable machining on the chip breaking, especially if process parts are subject to local plastic strain – under actual turning conditions stability of the technological system depends on a whole variety of factors, and any changes can disturb the balance.

Discussion of results. Analysis of the oscillogram allows to state that self-excited vibrations do not affect stability of the chip breaking, neither does local plastic strain cause self-oscillation.

In the experiments, performed on 1K62 lathe machine with a special dynamic measuring bench, the authors observed normal vibration displacement of the tool in relation to the surface of the workpiece, made of medium-carbon steel (0.45 % C), under local plastic strain. The tests confirmed that in the area of unstable cutting process there are clusters of stable machining and reliable chip breaking.

Theoretical and experimental research of the system's behaviour in the process of plastic strain turning demonstrated that asynchronous influence of the variable components of quasi-elastic and dissipative parameters, caused by differences in the structure and mechanical properties of the metal and the local strain zone, allows to break the chip into segments of a specified length. This finding is applicable to a wide scope of process materials and can significantly increase productivity and precision of machining. Deviation of theoretically estimated stability boundary (Fig.5) from experimental data amounts to 17-23 %.

Breaking of curling chip into segments with length L_c was accomplished for preprocessed surface machining under local strain. Among other results, the authors proposed a brand new dynamic model of machining system that takes into account rheological distinctions of the chip formation

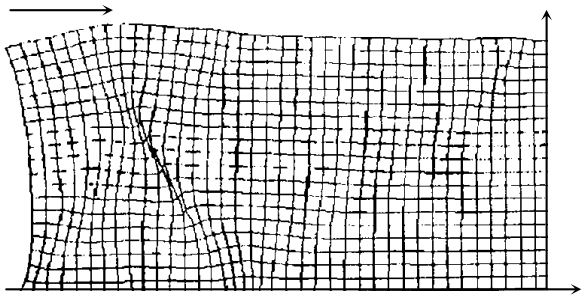


Fig.3. Fragment of deformation ε dynamics along the section of deformed material under local plastic strain

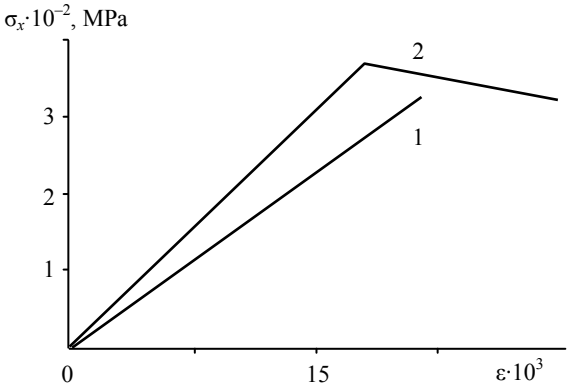


Fig.4. Dependence between stress σ_x and deformation ε
1 – initial state; 2 – local plastic strain

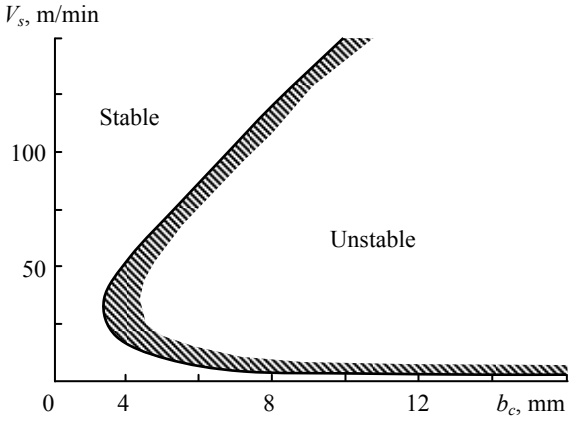


Fig.5. Estimated stability boundary of machining system in $b_c - V_s$ coordinates

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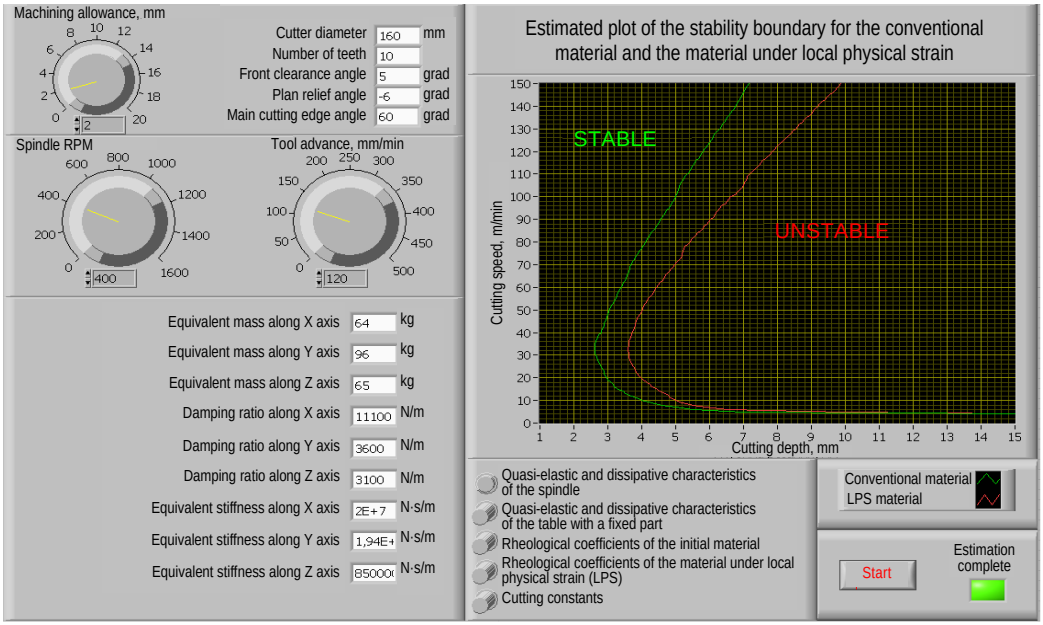


Fig.6. Stability boundaries of the machining system,
calculated in LabVIEW software basing on innovative solutions in material engineering

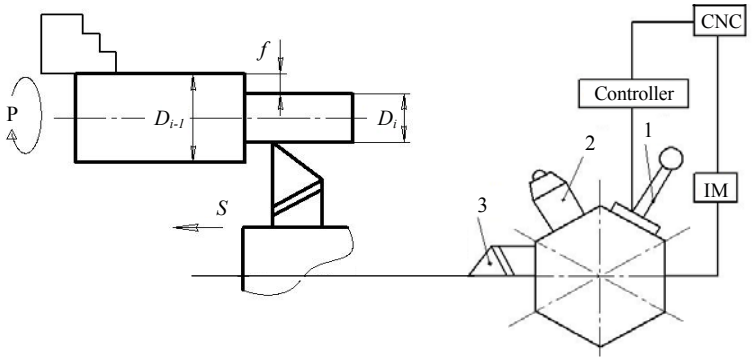


Fig.7. CNC software system, designed to control the machining process using local metastability

process [7]. This model allows to study dynamic characteristics not only in the zone of stable machining, but also in self-oscillation zone (Fig.6). The model is realized in LabVIEW software and focuses on innovative solutions in material engineering.

Application of metastable material properties allows to propose a new method of controlling CNC turning (Fig.7) and to formulate recommendations regarding automation of the machining process through the control of chip formation.

Conclusion

1. The authors designed a method that can be used in controlled robotic systems for processing hard-to-handle materials on CNC machinery. The method is based on local treatment of the material surface, which changes its crystal structure and leads to formation of high-energy configurations with increased metastability. All this creates periodical changes in machining conditions of the local strain zone as compared to the initial material, and facilitates segmentation and stable breaking of the chip.

2. Theoretical research of periodically changing parameters, caused by local deformation, was carried out with a frequency much lower (by factor of 50-100) than the one of self-excited vibrations. This assures stability of the system in case of changes in the frequencies of local strains and self-oscillations within technologically possible limits.

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3. Low-frequency local strain on the potentially self-oscillating system, characterized by a much higher frequency, can also be regarded as a superposition of additional forced vibrations – with a frequency equal to the one of local strain and an amplitude amounting to the difference between statistical shear forces, the latter being caused by the contrast of material properties in the mentioned zones.

4. Theoretical and experimental research led to an understanding that one of the most efficient methods, based on generation of local structural metastability on the outer layer of the process part, offers reliable control over the cutting process of hard-to-handle materials and permits to forecast dynamic stabilization for the machining of high-precision products. In its own turn, it creates opportunities for further improvement of machining technologies in a wide range of materials and cutting modes.

5. Mentioned results are based on dynamic modelling of the technological system by means of developed software and an algorithm of turning automation under local strain. All the findings add knowledge to the theory of automation and control of the turning processes, allow to develop its practical aspects and lay the methodological basis for engineering solutions.

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