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Evaluation of the influence of the reaction rate of the thermodynamic subsystem on the dynamics of the cutting process in metalworking

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ABSTRACT

Introduction. Modern metalworking machines with CNC, allow to achieve a qualitatively new level of metal processing by cutting in metal turning. At the same time, it is possible to achieve the required shape, dimensional accuracy, as well as the relative position of the surfaces of the part, but such an indicator of the processing quality as the roughness of the treated surface, associated with the vibration activity of the tool, does not always meet the specified requirements. The factor determining the vibration mode of cutting in a metal-cutting lathe is the self-excitation factor of the cutting system, which is caused by additional feedbacks formed during the cutting process, one of which is the thermodynamic subsystem of the cutting system, which is the **subject of research**. **Purpose of the work**: due to the formation of a consistent model of the relationship between the subsystems that describe the force, heat and vibration reactions of the tool, an adequate description of the mechanism for reducing the vibration load on the cutting process is obtained. The paper studies the process of metal turning on metal-cutting machines with a detailed description of the interaction between the thermodynamic, power and vibration subsystems of the cutting system. **Research methods**: full-scale and numerical experiments in which the Matlab package of mathematical programs is used for data processing and analysis. **Results and discussion**. The results of full-scale and numerical experiments are presented, in particular, graphs of coordinate changes describing tool deformation, and data sets are obtained that reflect the dependence of the vibrational energy of tool movements on the reaction time of the thermodynamic subsystem of the cutting system. A qualitative assessment of the results of a full-scale experiment allows us to confirm the adequacy of both the model itself and the results of its modeling. The scope of application of the results obtained in the study is related to the possibility of preliminary preparation of the cutting wedge, which will provide a set value of the time constant of the thermodynamic subsystem, which in turn ensures the minimization of vibration energy. **Conclusion**: the mathematical model proposed in this paper adequately describes the mechanism of temperature influence on the vibration load of the turning process.

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Introduction

Modern technologies of metal turning on metalworking machines, due to the use of a fundamentally new element base, primarily new measuring instruments, can significantly improve the quality of metal processing. At the same time, it is possible to achieve the required shape, dimensional accuracy, as well as the relative position of the surfaces of the part, but such an indicator of the processing quality as the roughness of the surface being processed, associated with the vibration activity of the tool, does not always meet the

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specified requirements [1]. The vibration of the tool is caused by various factors, which are conveniently divided into two subgroups, the subgroup due to external influence on the processing process, here there can be both machine vibrations and vibrations associated with the malfunction of the spindle group or tool wear [1-2]. The second group of factors, affecting the vibration mode of cutting in a metal-cutting machine, is the factors of self-excitation of the cutting system, which include the regenerative nature of vibrations during cutting, as well as the thermodynamic subsystem of the cutting system, which is also able to excite tool vibrations [3-4].

In the scientific literature, it is customary to divide the vibrations that occur during cutting into three components: free vibrations, forced vibrations, and self-excited vibrations [5-7]. It should be noted that a lot has already been done to combat free and forced vibrations, and there are many positive results in this area [7-9]. As for the fluctuations associated with the self-excitation of the cutting system, that is, the fluctuations that consume energy from the external environment, today there are no unambiguous solutions. Therefore, the topic of minimizing self-excited vibrations during turning of metals is popular in scientific research conducted in the world [10-15]. In the above works, the main focus is on the evaluation of the effect on tool fluctuations, the so-called regenerative effect. It should be noted that this is quite well studied in the twentieth century and is described in the works of Hahn R. S., Tobias S. A. and Merritt H. E. [16-18]. Many more modern authors note the possibility of establishing the chaotic nature of tool vibrations during vibration regeneration [19-21]. However, in general, it is noted that the main factor affecting the regenerative effect is the so-called time delay.

For Russian scientists, the problem of trail cutting, as the basis for self-excitation of the cutting system, is not so important; many scientific schools pay more attention to the analysis of the interrelated dynamics of the cutting process [22-25]. For example, in [26], the analysis of the dynamics of deformation vibrations of the tool is based on the connection, through a force reaction, of this deformation movement with the cutting elements of the CNC machine system. In the works of Soviet and Russian scientists, studying the vibration dynamics of the cutting process [27–31], it is noted that in the cutting process, in addition to the feedback on the cutting force, which takes into account the regeneration of vibrations during cutting along the "trace", through changes in the area of the cut layer, a thermodynamic feedback is formed, which is also associated with the vibration activity of the tool, as well as with the wear of the wedge. In [32-34], the influence of various factors on the dynamics of the cutting system is considered, where the most interesting, from our point of view, is the work [34], in which an interconnected model of the cutting system is proposed, in which the thermodynamic subsystem of the cutting system plays the most important role. The mathematical model of the thermodynamic subsystem presented in this paper, and first described in [33], is based on the Volterra operator of the second kind, which, for the stationary case of the cutting system, is reduced to an aperiodic equation of the first or, in the more complex case, of the second order. The dependence of this constant on the vibration energy and tool wear along the back face, revealed in these works, allows us to make conclusion about the possible non-stationary nature of the equation describing the relationship of the thermodynamic cutting system with the subsystem describing the cutting force. That is, what is meant here is the fact that such a constant can change during the processing of metals by cutting on a metal-cutting machine. Based on the considerations of the interconnectedness of the subsystems of the cutting system, such a non-stationarity of the time constant should lead to a change in the entire cutting system. To assess the influence of changes in the time constant of the thermodynamic subsystem on the dynamics of the processing process, it is possible to simulate a simplified version of the mathematical model of the subsystem with already known models of the subsystems of deformational movements of the tool and the force response to the shaping movements of the tool from the side of the cutting process. In this regard, the aim of the work is to form a consistent model of the relationship between the subsystems that describe the force, heat and vibration reactions of the tool, which adequately describes the mechanism for reducing the vibration load on the cutting process.

Research methodology

Let us consider as an example of processing the process of longitudinal turning of a part, while the axes of deformation of the tool will be three [33].

In figure 1, the traditional scheme of decomposition of deformations on the axis is revealed: the **x** – axis is the axial direction of deformations (mm), the **y** – axis is the radial direction of deformations (mm) and the **z** – axis is the tangential direction of deformations (mm), along these axes the force reaction from the cutting process is decomposed on the shaping movements of the tool (F_x, F_y, F_z (*H*)), V_x and V_z (mm/s) of the feed and cutting speed, respectively, **ω** is the angular speed of rotation of the spindle (rad/s).

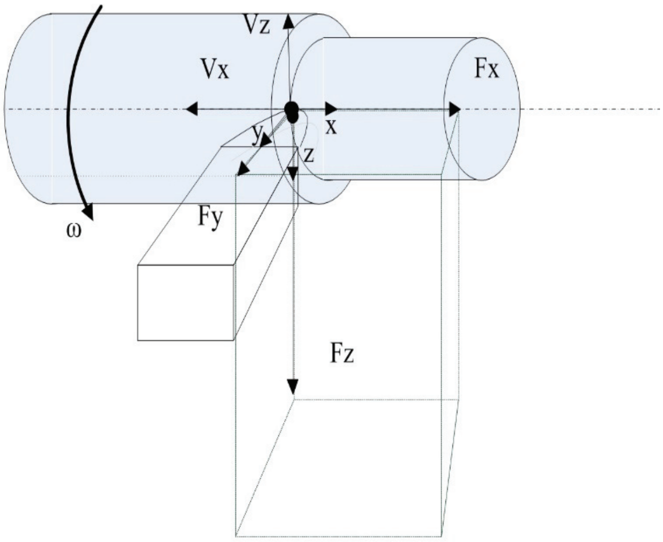


Fig. 1. Axes of deformations and forces during turning

To refine the mathematical model of the cutting process, taking into account the effects that occur in the contact zone of the tool and the part, it is considered to represent a scheme of the cutting process through the prism of the formation of thermodynamic coupling in this system. (See Figure 2).

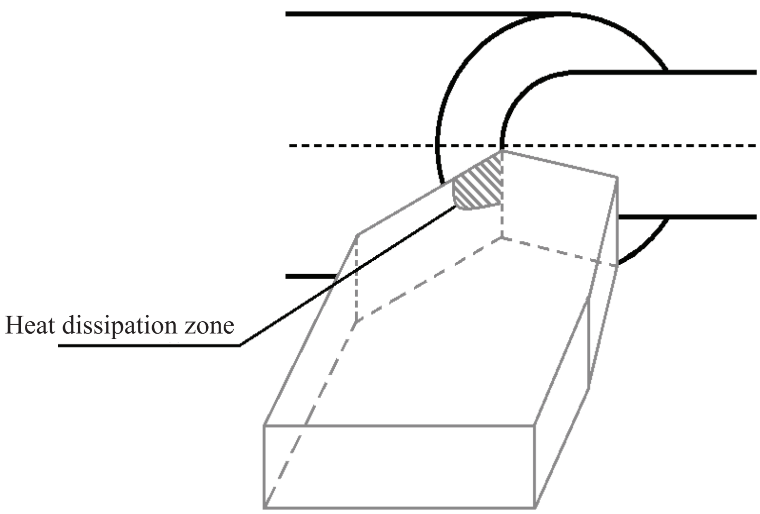


Fig. 2. Heat dissipation zone

As it can be seen from figure 2, during the cutting process, a heat transfer zone is formed, due to the formed worn place along the back face; the temperature from the previous processing stages is transmitted through it. Due to this temperature transmission channel, a thermodynamic connection is formed, which affects the force response from the cutting process to the shaping movements of the tool. The force itself, which prevents the shaping movements, can be determined because of the hypothesis of the proportionality of the cutting force to the area of the cut layer (see expression 1):

$$F = \rho(Q)[t_p - y]\int_{t-\mathrm{T}}^{t}\left(V_x - \frac{dx}{dt}\right)dt\,, \tag{1}$$

where $\rho(Q)$ is the coefficient that characterizes the chip pressure on the front face of the tool (kg/mm^2), Q is the temperature in the cutting zone (°C), t_p is the feed per revolution (mm) recorded in the CNC program, T is the rotation time of the spindle with the part fixed in it (c^{-1}), V_x is the tool feed rate (mm/s), $\frac{dx}{dt}$ is the tool vibration rate in the feed direction (mm/s), y is the tool deformation in the radial direction (mm).

The rotation time of the spindle with the part fixed in it also depends on the coordinates of the deformations of the tool, based on the relationship of the rotation time with the rotation frequency $\mathrm{T} = \frac{2\pi}{\omega}$ (ω _ rad/s), where the rotation frequency can be described in terms of the cutting speed $V_z = \omega R$ (mm/s), we get the following dependence describing the rotation period of the spindle:

$$\mathrm{T} = \frac{2\pi R}{V_z - \frac{dz}{dt}}, \tag{2}$$

where $\frac{dz}{dt}$ is the tool deformation rate in the cutting direction (mm/s), R is the radius of the work piece (mm).

Thus, a mathematical model that describes the cutting force in the coordinates of the tool deformations is obtained, but here (see expression 1), there is a temperature in the cutting zone, taking into account our previous studies published in [33-34], the dependence of the temperature in the cutting zone on the power of irreversible transformations can be represented by the following expression:

$$T_Q\frac{dQ}{dt} + (Q + Q_0) = kN, \tag{3}$$

where T_Q is the time constant of the thermodynamic subsystem (c^{-1}), Q is the current temperature in the cutting zone (°C), Q_0 is the temperature of the part to be processed before the start of processing (°C), k – the coefficient of conversion of the power allocated in the contact zone of the tool and the processed part into temperature $\left(\frac{^\circ\mathrm{C}\cdot\mathrm{c}}{\mathrm{Н}\cdot\mathrm{мм}}\right)$, N – the power of irreversible transformations in the cutting zone $(\mathrm{Н}\cdot\mathrm{мм})$.

The power of irreversible transformations, taking into account the entered coordinates of tool deformations (see Figure 1), is described by the following expression:

$$N = F\sqrt{\left(V_z - \frac{dz}{dt}\right)^2 + \left[V_x - \frac{dx}{dt}\right]^2 + \frac{dy^2}{dt}}, \tag{4}$$

Taking into account the accepted model of forming the temperature in the cutting zone (see expressions 3, 4), as well as on the basis of the metalworking dependences of the tensile strength of the metal on the temperature of the experiment, the following dependence $\rho(Q)$ is assumed:

$$\rho(Q) = \frac{\rho_0}{2}e^{-\alpha Q} + \frac{\rho_0}{2}, \tag{5}$$

where ρ_0 is the coefficient that characterizes the chip pressure on the front face of the tool at the standard temperature of the experiment (kg/mm^2).

To synthesize a model of the system of tool deformation movements' dynamics, the following system of equations is taken:

$$\begin{cases} m\dfrac{d^2x}{dt^2} + h_{11}\dfrac{dx}{dt} + h_{12}\dfrac{dy}{dt} + h_{13}\dfrac{dz}{dt} + c_{11}x + c_{12}y + c_{13}z = \chi_1 F \\ m\dfrac{d^2y}{dt^2} + h_{21}\dfrac{dx}{dt} + h_{22}\dfrac{dy}{dt} + h_{23}\dfrac{dz}{dt} + c_{21}x + c_{22}y + c_{23}z = \chi_2 F, \\ m\dfrac{d^2z}{dt^2} + h_{31}\dfrac{dx}{dt} + h_{32}\dfrac{dy}{dt} + h_{33}\dfrac{dz}{dt} + c_{31}x + c_{32}y + c_{33}z = \chi_3 F \end{cases} \quad (6)$$

where c1, c2, c3 are the coefficients that take into account the decomposition of the cutting force on the axis of tool deformation.

Thus, a mathematical model of the cutting system, described by a set of equations 1–6 is obtained. To conduct an experiment with the resulting model, several programs in the Matlab and Matlab/Simulink environments are developed. The initial data for these models are obtained based on analyses of experiments conducted earlier and published in [32, 33].

For all experiments, it is denoted that the system of equations of instrument motion is described by the following parameters:

$$m = \begin{bmatrix} 0{,}0065 & 0 & 0 \\ 0 & 0{,}0065 & 0 \\ 0 & 0 & 0{,}0065 \end{bmatrix} \text{ kg} \times \text{s}^2/\text{mm}, \qquad h = \begin{bmatrix} 0{,}844 & 0{,}39 & 0{,}37 \\ 0{,}39 & 0{,}77 & 0{,}36 \\ 0{,}37 & 0{,}36 & 0{,}75 \end{bmatrix} \text{ kg} \times \text{s/mm},$$

$$c = \begin{bmatrix} 1390 & 190 & 165 \\ 190 & 795 & 150 \\ 165 & 150 & 970 \end{bmatrix} \text{ kg/mm}.$$

Coefficients of expansion of the cutting force on the tool deformation axis: $\chi_x = 0{,}3369$, $\chi_2 = 0{,}48$, $\chi_3 = 0{,}81$. Parameters of the process mode: depth $t_p = 2$ mm, feed $S = 0.1$ mm, spindle speed $n = 1000$ rpm, $\rho = 400$ kg/mm^2, radius of the work piece $R = 50$ mm.

Results and discussion

The results of the experiments carried out in the Matlab/Simulink environment are shown below in a series of pictures, the first of which is to consider the dynamics of the cutting system at a time constant of the thermodynamic subsystem of the cutting system equal to 0.7 seconds (see Figure 3).

As it can be seen from figure 3, after the tool deformations increase by 0.1 seconds of the experiment, there is a certain stabilization of the deformation coordinates and even a subsequent decrease; this is due to the influence of the operator being introduced in expression 5, which displays the dependence of the cutting force on the temperature in the cutting zone. Taking into account the time constant of the thermodynamic subsystem of the cutting system introduced in the experiment of 0.7 seconds, the reaction of the system to the change in the cutting force is approximately 2/3 of this time, that is, the process of temperature stabilization of the change in the deformation coordinates takes about 1.05 seconds. To assess how the state coordinates of the deformation subsystem of the cutting system react to the increase in temperature during cutting, consider the phase trajectories of the deformation coordinates shown in figure 4.

As it can be seen from figure 4, the tool deformation coordinates in the *x* direction are contracted from a maximum value of 0.0075 mm to 0.005 mm, in the y direction from 0.034 to 0.024 mm, and in the *z* direction from 0.059 to 0.04 mm. As it was pointed out earlier, this is due to a drop in the cutting force with

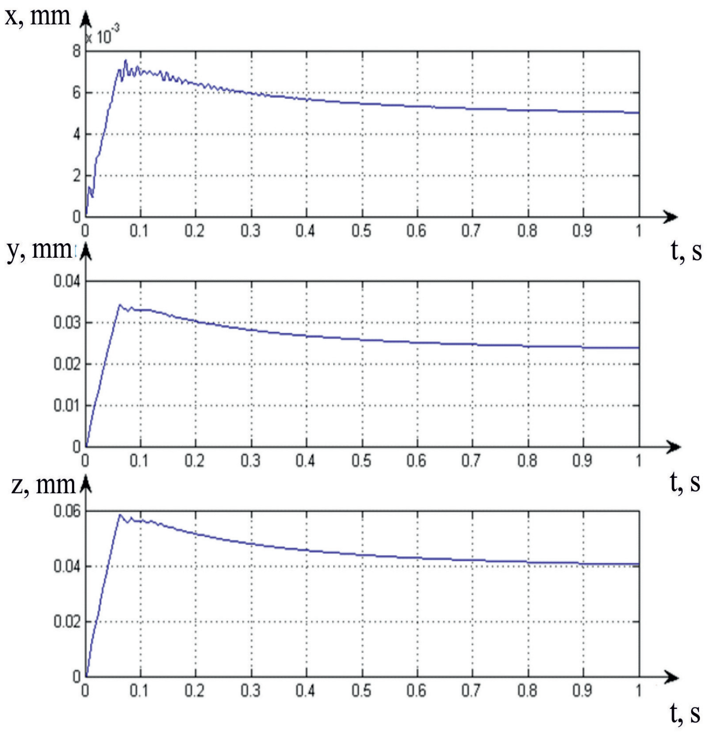


Fig. 3. Graphs of tool deformation coordinates during embedding (T_Q = 0.7)

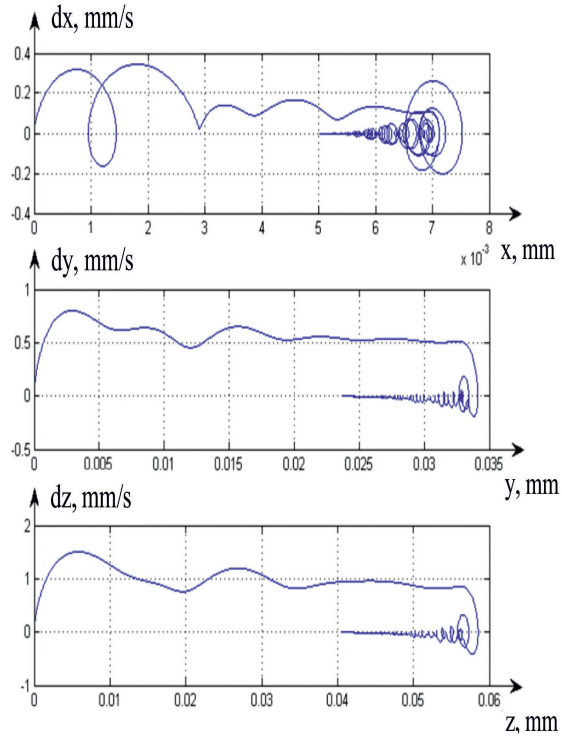


Fig. 4. Phase trajectories of strain coordinates at T_Q = 0.7

an increase in temperature, for an adequate consideration of this issue; graphs of changes in the cutting force, temperature, and ρ(Q) are provided (see Figure 5).

As it can be seen from Figure 5, in fact, the cutting force, depending on ρ(Q), falls in about 1.05 seconds from almost 80 N to a value of less than 60 N, that is, by a quarter, which affects the coordinates of the tool deformation (see Figures 3 and 4). However, of interest is the relationship between the reaction time of the thermodynamic subsystem and the vibrations of the instrument, which can be conveniently, measured using the following integral indicator:

$$VA = \sqrt{\frac{1}{T_v}\left(\int_0^{T_v} \frac{dy}{dt}^2 dt\right)} \qquad (6)$$

where VA – shows the vibration energy of the instrument for the period of observation (experiment) – T_v.

For the case shown in figure 4, the value VA = 2 mm/s, for example, for the variant TQ = 1.0009 mm/s. The graph of changes in the state coordinates for this case is shown in figure 6.

As can be seen from the comparison of Figures 6 and 3, the difference in the oscillations is not visually observed, but as it was indicated earlier, it is convenient to consider for such an analysis the graphs of the phase trajectories, which are shown in figure 7.

As can be seen from the comparison of figures 7 and 4, the graphs of the phase trajectories actually became smaller in amplitude, almost without changing in the direction of the coordinates of the deformations.

The series of experiments made it possible to obtain a curve that characterizes the changes in the calculated value of the vibration signal energy when the reaction time of the thermodynamic subsystem of the cutting system changes, this curve and the curve approximating the obtained studies.

The calculated curve is based on the synthesis of a second-order polynomial by the least squares method. As can be seen from Figure 8, the calculated curve differs significantly from the curve obtained on the basis of a series of numerical experiments. The deviations are maximum at the left and right ends of the graph, in the center of the graph, these deviations are minimal, we did this on purpose in order to obtain maximum convergence in the center of the graph, where the minimum point of the characteristic is. The enlarged area of the chart with the minimum point is shown in Figure 9.

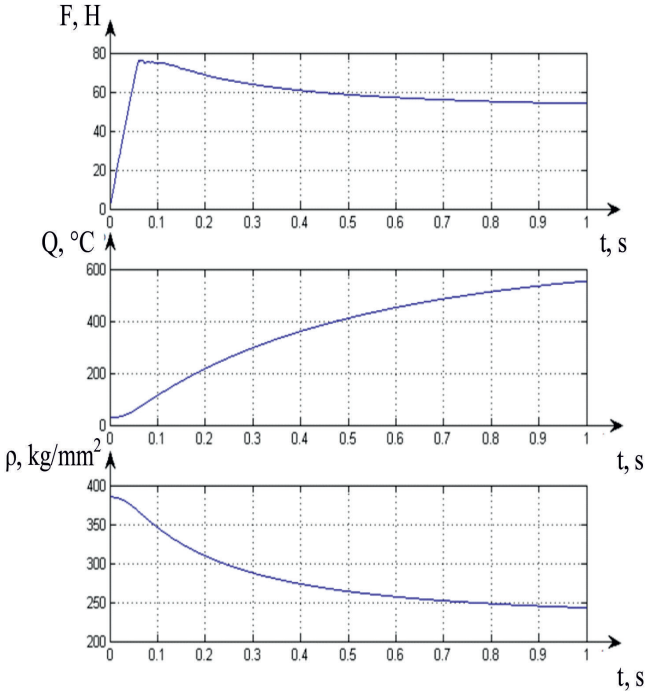


Fig. 5. Graphs of force, temperature, and the coefficient that characterizes the chip pressure on the front face of the tool

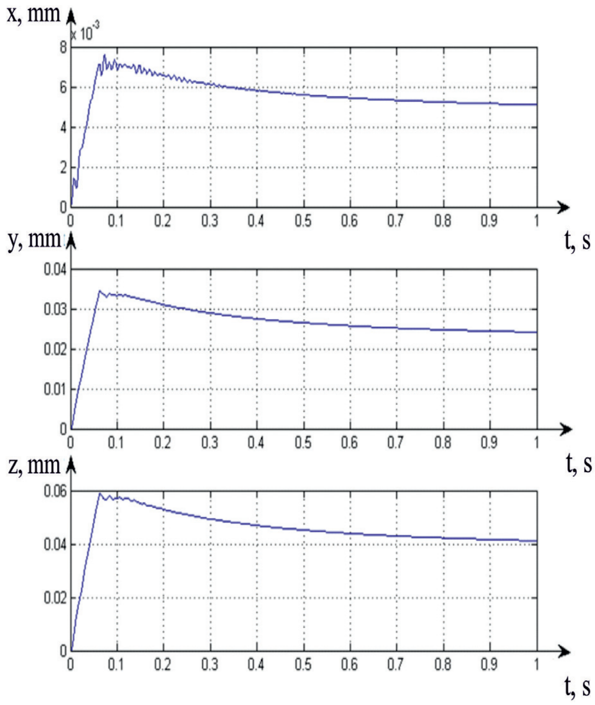


Fig. 6. Graphs of the coordinates of the tool deformation when cutting $T_Q = 0.85$

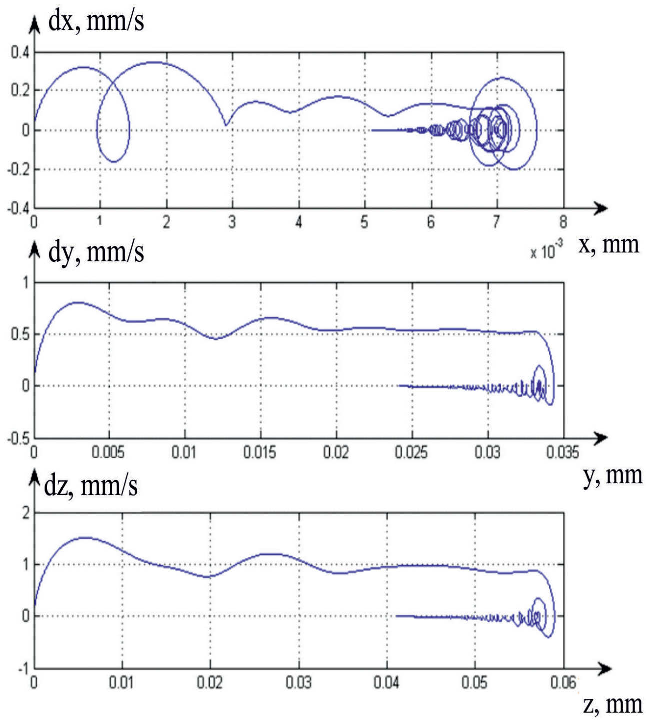


Fig. 7. Phase trajectories of strain coordinates at $T_Q = 0.85$

As can be seen from figure 9, the conducted studies have indeed shown the presence of a local minimum of the curve reflecting the dependence of the vibration energy of the instrument on the reaction time of the thermodynamic subsystem. Figure 9 also shows that the constructed calculated curve accurately reflects the local minimum obtained as a result of the experiment in the Matlab system.

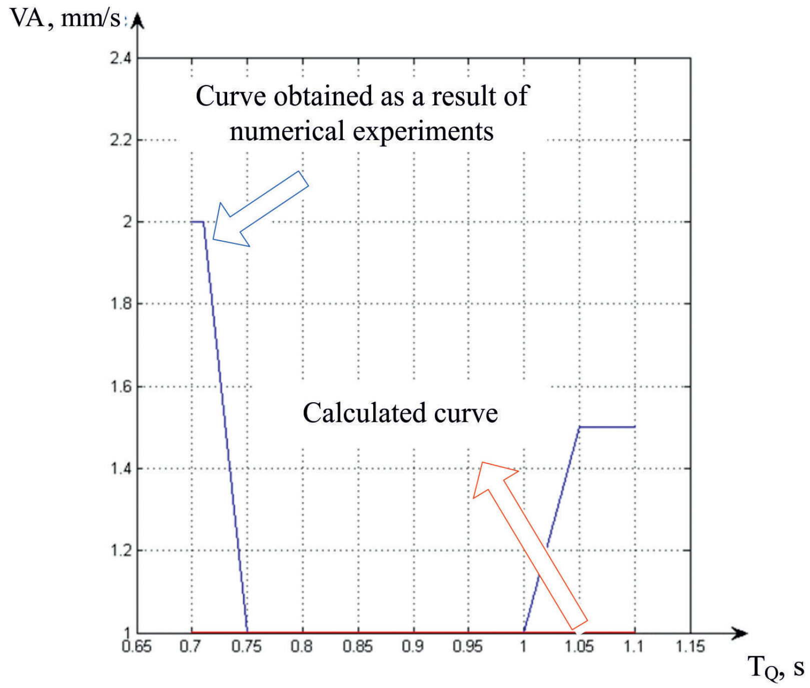


Fig. 8. The curves obtained in numerical experiments and calculated on the general scale

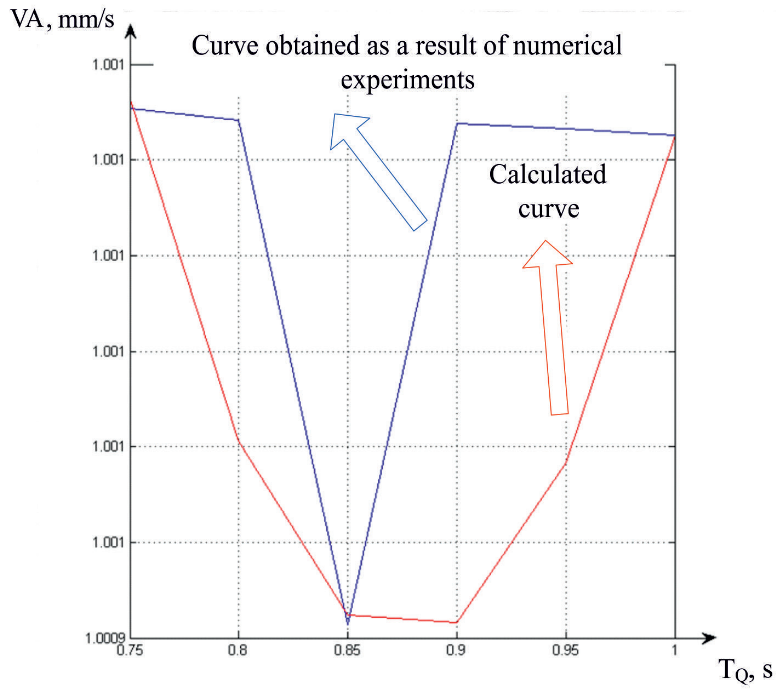


Fig. 9. The curve obtained because of numerical experiments and the calculated curves

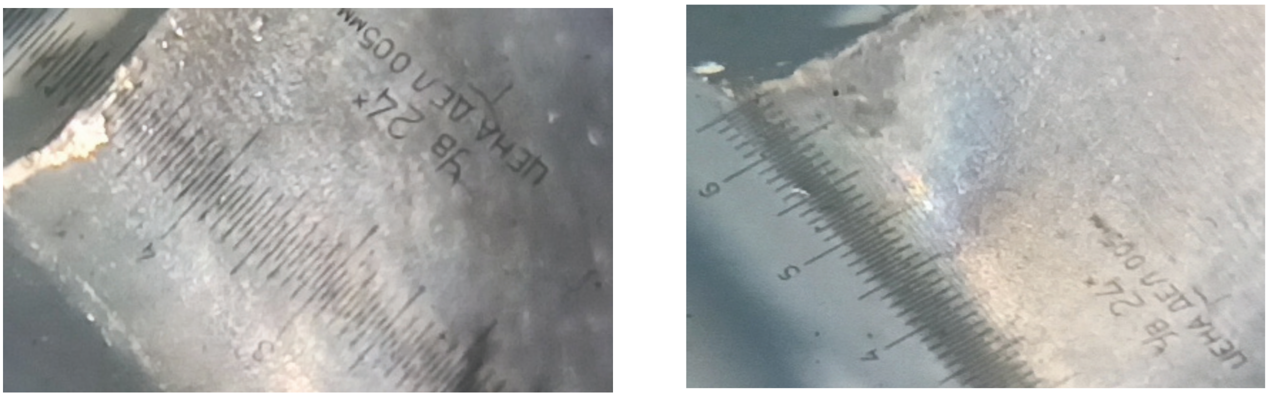
Consider, for example, the results of a full-scale experiment conducted on a 1K625 lathe with a measuring complex developed by the authors that allows registering the vibration the activity of the tool in the direction of the axes of deformation. As well as the temperature near the contact zone of the back face of the tool (replaceable plate 6 gr. "broken triangle" WNUM 120612 (02114-120612) H30 (T5K10) KZTS) and the work piece (see Figure 10).

a *b*

Fig. 10. Machine with equipment (*a*), measuring complex on the tool (*b*)

As can be seen from figure 10, the experimental tool contains three vibration accelerometers and an artificial thermocouple built into the wedge in the immediate vicinity of the contact zone of the back face of the tool with the work piece. To embed the thermocouple in the wedge, it was previously cut by the method of electroerosive metal cutting, in the prepared hole the thermocouple is fixed with hot glue.

During the experiment, a part made of round rolled steel (45 steel) with a diameter of 50 mm was processed, the spindle speed was 810 rpm, the cutting depth was 1 mm, and the feed was 0.11 mm/rev. Photos of the back surface of the instrument under a microscope are shown in figure 11.



a *b*

Fig. 11. Pre-burn tool (*a*), tool with a formed back face (*b*)

As can be seen from figure 11, the experiment was carried out until the tool wear area was formed along the back face (see Figure 11 (b)), at which, according to the approach proposed in this paper, a value of the time constant *TQ* is formed at which the turning process is stabilized. When the cutting process is stabilized, the SCR (root mean square value) of the signals taken from the vibration accelerometers installed along the axes of the tool deformation decreases sharply, but the most obvious reduction in the vibration load can be seen on the surface of the processed part, the photo of which is shown in figure 12.

As can be seen from figure 12, the area of stabilization of the vibration activity of the tool is visually observed on the processed part, after which the quality of the processed surface is significantly improved. To understand the relationship between the time constant of the thermodynamic subsystem of the cutting

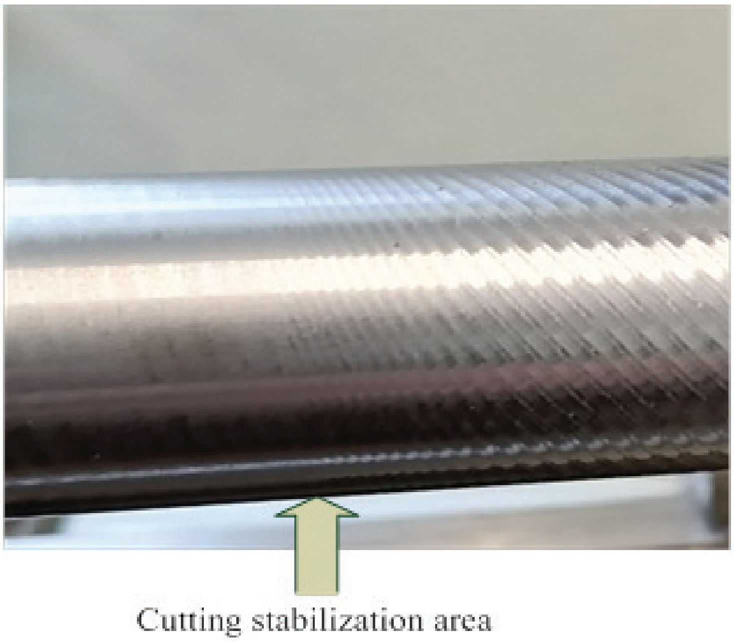


Fig. 12. Photo of the processed part

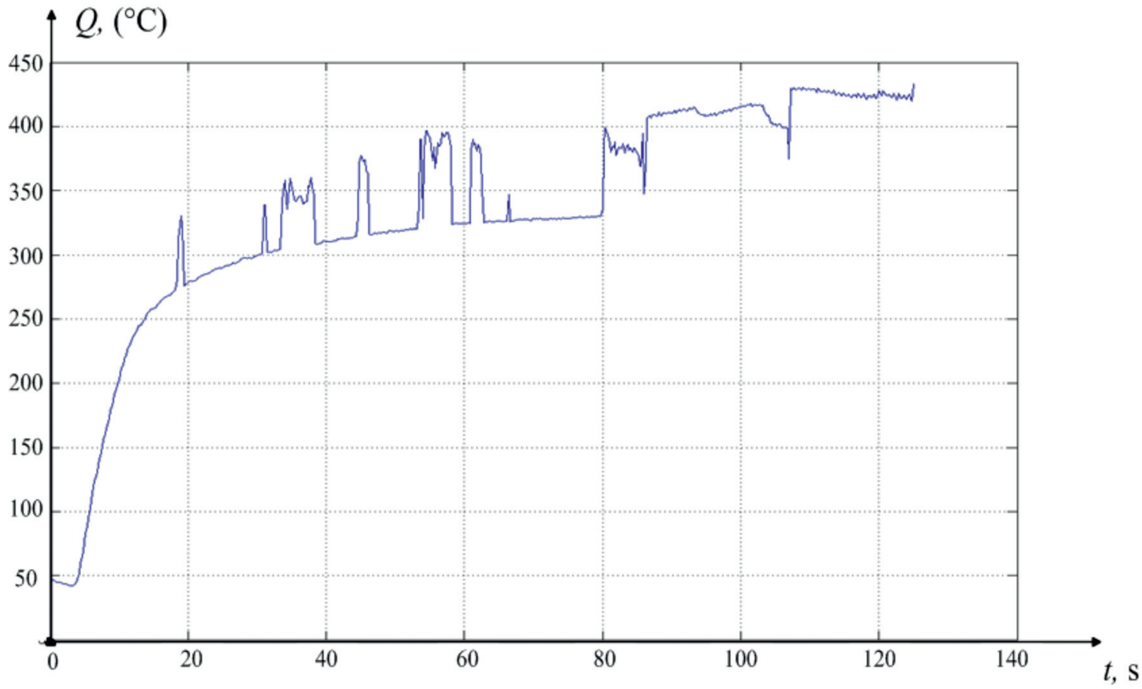


Fig. 13. Diagram of the temperature change of the thermocouple being removed from the thermocouple.

system and the fact of improving the quality of the surface to be treated, consider the graph of temperature changes taken from an artificial thermocouple (see Figure 13).

As can be seen from Figure 13, in the area of stabilization of the processing process, there is an increase in temperature in the processing zone, which on average amounted to a value greater than 50 ^{0}C. Taking into account the mechanism of temperature formation in the cutting zone, or rather its connection with the reaction time constant of the thermodynamic subsystem of the cutting system, described in detail in (33-34), it is the growth of the time constant that leads to an increase in the temperature itself in the tool contact zone and the work piece.

Thus, the earlier conclusions based on numerical analysis of the developed mathematical model are experimentally confirmed.

The conducted studies have shown that the time constant of the thermodynamic subsystem of the cutting system significantly affects the dynamics of the deformation movements of the tool. In addition, studies have shown that there is some optimal range of acceptable values of such a time constant, in terms of ensuring a minimum of energy spent on the vibration of the instrument. All this is quite well correlated with the results of experimental studies conducted by us, as well as other authors, in particular, this is confirmed the existence of an optimal cutting mode from the point of view of ensuring maximum tool life. Continuing these arguments, and taking into account the fact that the dynamics of the processing process is continuously related to the dynamics of temperature changes in the cutting zone, which in turn depends on the time constant of the thermodynamic subsystem, the optimal temperature is largely determined by the value of the constant we have introduced.

Conclusion

The paper reveals the mechanism of self-organization of the cutting process, through the prism of the interaction of the three subsystems of the cutting system, the subsystem describing the deformation movements of the tool, the subsystem of the force reaction of the cutting process to the shaping movements of the tool, as well as the thermodynamic subsystem of the cutting system. The paper proposes and confirms the hypothesis that there is a minimum vibration energy of the tool, which is functionally dependent on the variation of the time constant of the thermodynamic subsystem of the cutting system. The mechanism of minimizing the tool vibration activity during cutting, considered in the work, allows to optimize the process of turning metals in terms of the roughness of the treated surface, due to the advance preparation of the tool, by which we mean the formation of a preliminary contact area of the tool and the part, taking into account the selected cutting elements, at which its vibrations during turning are minimal.

References

1. Grabec I. Chaos generated by the cutting process. *Physics Letter A*, 1986, vol. 117, no. 8, pp. 384–386. DOI: 10.1016/0375-9601(86)90003-4.

2. Lapshin V.P., Tyunyaev R.A., Khristoforova V.V. [Evaluation of the effect of the feed rate on the equilibrium modes of the drive providing milling of the workpiece of variable thickness]. *Dinamika tekhnicheskikh sistem*, *DTS-2015* [Dynamics of technical systems], Rostov-on-Don, 2016, pp. 180–184. (In Russian).

3. Reznikov A.N., Reznikov L.A. *Teplovye protsessy v tekhnologicheskikh sistemakh* [Thermal processes in technological systems]. Moscow, Mashinostroenie Publ., 1990. 288 p.

4. Ryzhkin A.A. *Teplofizicheskie protsessy pri iznashivanii instrumental'nykh rezhushchikh materialov* [Thermophysical processes during wear of tool cutting materials]. Rostov-on-Don, DSTU Publ., 2005. 311 p. ISBN 5-7890-0348-6.

5. Huang S.N., Tan K.K., Wong Y.S., De Silva C.W., Goh H.L., Tan W.W. Tool wear detection and fault diagnosis based on cutting force monitoring. *International Journal of Machine Tools and Manufacture*, 2007, vol. 47, iss. 3–4, pp. 444–451.

6. Arsla H., Er A.O., Orhan S., Aslan E. Tool condition monitoring in turning using statistical parameters of vibration signal. *International journal of acoustics and vibration*, 2016, vol. 21, iss. 4, pp. 371–378.

7. Alonso F.J., Salgado D.R. Application of singular spectrum analysis to tool wear detection using sound signals. *Proceedings of the Institution of Mechanical Engineers*, *Part B: Journal of Engineering Manufacture*, 2005, vol. 219 (9), pp. 703–710.

8. Dimla Sr D.E., Lister P.M. On-line metal cutting tool condition monitoring. I: force and vibration analyses. *International Journal of Machine Tools and Manufacture*, 2000, vol. 40 (5), pp. 739–768. DOI: 10.1016/S0890-6955(99)00084-X.

9. Orhan S., Er A.O., Camuşcu N., Aslan E. Tool wear evaluation by vibration analysis during end milling of AISI D3 cold work tool steel with 35 HRC hardness. *NDT & E International*, 2007, vol. 40 (2), pp. 121–126.

10. Tobias S.A. *Vibraciones en Máquinas-Herramientas* [Machine tools vibrations]. Bilboa, Spain, Ediciones Urmo, 1961.

11. Sri Namachchivaya, Beddini. Spindle speed variation for the suppression of regenerative chatter. *Journal of Nonlinear Science*, 2003, vol. 13, no. 3, pp. 265–288. DOI: 10.1007/s00332-003-0518-4.

12. Wahi P., Chatterjee A. Regenerative tool chatter near a codimension 2 Hopf point using multiple scales. *Nonlinear Dynamics*, 2005, vol. 40, no. 4, pp. 323–338.

13. Stépán G., Insperger T., Szalai R. Delay, parametric excitation, and the nonlinear dynamics of cutting processes. *International Journal of Bifurcation and Chaos*, 2005, vol. 15, no 9, pp. 2783–2798. DOI: 10.1142/S0218127405013642.

14. Moradi H., Bakhtiari-Nejad F., Movahhedy M.R., Ahmadian M.T. Nonlinear behaviour of the regenerative chatter in turning process with a worn tool: Forced oscillation and stability analysis. *Mechanism and Machine Theory*, 2010, vol. 45, no. 8, pp. 1050–1066. DOI: 10.1016/j.mechmachtheory.2010.03.014.

15. Gouskov A.M., Voronov S.A., Paris H., Batzer S.A. Nonlinear dynamics of a machining system with two interdependent delays. *Communications in Nonlinear Science and Numerical Simulation*, 2002, vol. 7, no. 4, pp. 207–221. DOI: 10.1016/S1007-5704(02)00014-X.

16. Hahn R.S. On the theory of regenerative chatter in precision grinding operation. *Transactions of American Society of Mechanical Engineers*, 1954, vol. 76, pp. 356–260.

17. Tobias S.A., Fishwick W. Theory of regenerative machine tool chatter. *The Engineer*, 1958, vol. 205, no. 7, pp. 199–203.

18. Merritt H.E. Theory of self-excited machine-tool chatter: contribution to machine-tool chatter research. *Journal of Engineering for Industry*, 1965, vol. 87, pp. 447–454. DOI: 10.1115/1.3670861.

19. Balachandran B. Nonlinear dynamics of milling process. *Philosophical Transactions of The Royal Society A: Mathematical Physical and Engineering Sciences*, 2001, vol. 359 (1781), pp. 793–819.

20. Stepan G. Modelling nonlinear regenerative efects in metal cutting. *Philosophical Transactions of The Royal Society A: Mathematical Physical and Engineering Sciences*, 2001, vol. 359, pp. 739–757. DOI: 10.1098/rsta.2000.07537.

21. Litak G. Chaotic vibrations in a regenerative cutting process. *Chaos Solitons and Fractals*, 2002, vol. 13, pp. 1531–1535. DOI: 10.1016/S0960-0779(01)00176-X.

22. Guskov A.M., Voronov S.A., Kvashnin A.S. Vliyanie krutil'nykh kolebanii na protsess vibrosverleniya [Influence of torsion vibrations on process of vibration-drilling]. *Vestnik MGTU im. N.E. Baumana. Seriya: Mashinostroenie = Herald of the Bauman Moscow State Technical University. Series: Mechanical Engineering*, 2007, no. 1 (66), pp. 3–19.

23. Vasin S.A., Vasin L.A. Sinergeticheskii podkhod k opisaniyu prirody vozniknoveniya i razvitiya avtokolebanii pri tochenii [Synergetic approach to describing the nature and development of self-oscillations in turning]. *Naukoemkie tekhnologii v mashinostroenii = Science Intensive Technologies in Mechanical Engineering*, 2012, no. 1, pp. 11–16.

24. Voronin A.A. Vliyanie ul'trazvukovykh kolebanii na protsess rezaniya zharoprochnykh splavov [Influence of ultrasonic vibrations on the cutting process of heat-resistant alloys]. *Stanki i instrument = Machines and Tools*, 1960, no. 11, pp. 15–18.

25. Zakovorotny V.L., Lukyanov A.D., Gubanova A.A., Khristoforova V.V. Bifurcation of stationary manifolds formed in the neighborhood of the equilibrium in a dynamic system of cutting. *Journal of Sound and Vibration*, 2016, vol. 368, pp. 174–190. DOI: 10.1016/j.jsv.2016.01.020.

26. Zakovorotny V.L., Lapshin V.P., Babenko T.S. Modeling of tool wear: irreversible energy transformations. *Russian Engineering Research*, 2018, vol. 38, no. 9, pp. 707–708.

27. Zharkov I.G. *Vibratsii pri obrabotke lezviinym instrumentom* [Vibrations when processing with a blade tool]. Leningrad, Mashinostroenie Publ., 1986. 184 p.

28. Markov A.I. *Ul'trazvukovoe rezanie trudnoobrabatyvaemykh materialov* [Ultrasonic cutting of hard-to-process materials]. Moscow, Mashinostroenie Publ., 1968. 367 p.

29. Makarov A.D. *Optimizatsiya protsessov rezaniya* [Optimization of cutting processes]. Moscow, Mashinostroenie Publ., 1976. 278 p.

30. Zakovorotny V.L., Flek M.B. *Dinamika protsessa rezaniya. Sinergeticheskii podkhod* [Dynamics of the cutting process. Synergetic approach]. Rostov-on-Don, Terra Publ., 2006. 880 p. ISBN 5-98254-055-2.

31. Ryzhkin A.A. *Sinergetika iznashivaniya instrumental'nykh rezhushchikh materialov (triboelektricheskii aspekt)* [Synergetics of wear of tool cutting materials (triboelectric aspect)]. Rostov-on-Don, DSTU Publ., 2004. 323 p. ISBN 5-7890-0307-9.

32. Lapshin V.P., Turkin I.A., Khristoforova V.V., Babenko T.S. Influence of the temperature in the tool–workpiece contact zone on the deformational dynamics in turning. *Russian Engineering Research*, 2020, vol. 40, no. 3, pp. 259–265.

33. Bordachev E.V., Lapshin V.P. Matematicheskoe modelirovanie temperatury v zone kontakta instrumenta i izdeliya pri tokarnoi obrabotke metallov [Mathematical modeling of the temperature in the contact zone of the tool and product during metal turning]. *Vestnik Donskogo gosudarstvennogo tekhnicheskogo universiteta = Vestnik of Don State Technical University*, 2019, vol. 19, no. 2, pp. 130–137. DOI: 10.23047/1992-5980-2019-19-2-130-137.

34. Lapshin V.P., Khristoforova V.V., Nosachev S.V. Vzaimosvyaz' temperatury i sily rezaniya s iznosom i vibratsiyami instrumenta pri tokarnoi obrabotke metallov [Relationship of temperature and cutting force with tool wear and vibration in metal turning]. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2020, vol. 22, no. 3, pp. 44–58. DOI: 10.17212/1994-6309-2020-22.3-44-58.

Conflicts of Interest

The authors declare no conflict of interest.