

THERMODYNAMIC INSTABILITIES IN MACHINING PROCESSES.

II. NUMERICAL INVESTIGATION OF STABILITY

M. L. Kheifets

UDC 536.75:621.90

A numerical investigation of methods that intensify machining by additional mechanical and thermal actions is performed. Criteria describing the formation of stagnant dissipative structures with thermodynamic instabilities of the technological system and a calculation procedure for machining regimes that ensures stable parameters of the process are proposed.

Numerical Solution. Investigation of the vector fields of distributed characteristics of machining processes in formation of vortex dissipative structures is currently difficult. Therefore, to experimentally check a mathematical model, we chose a method of machining that permits control of thermodynamic processes in the shaping zone through additional mechanical and thermal actions, i.e., rotational cutting with preheating of the cut layer (Fig. 1) [1]. Study of the components of the cutting force in free rotation of the rotational tool and comparison of the results with other methods of machining permit an analysis of the stability of the processes.

The rotation and vortices of the vector field flow for the force \mathbf{P} are described by the expression

$$\nabla \times \mathbf{P} = \mathbf{i} (\partial P_z / \partial y - \partial P_y / \partial z) + \mathbf{j} (\partial P_x / \partial z - \partial P_z / \partial x) + \mathbf{k} (\partial P_y / \partial x - \partial P_x / \partial y). \quad (1)$$

The term $\mathbf{j} (\partial P_x / \partial z - \partial P_z / \partial x)$ in expression (1) permits the description of the free rotation of the rotational tool edge in the XOZ plane by the moment \mathbf{M} (Fig. 1). The moment of the cutting force component \mathbf{P}_z relative to the arm that is formed by the travel of the cutting edge of the tool ∂x under the action ∂P_x or the force component \mathbf{P}_x relative to the travel ∂z under the action ∂P_z can be described, according to the physical meaning, by the vector product [2]

$$\mathbf{M} = C_M |\mathbf{P}_x \times \mathbf{P}_z| = C_M P_x P_z = C_M M_{xz}. \quad (2)$$

Measurements of the cutting force components P_x , P_y , and P_z were performed in machining with a regular and a round cutting tool – nonrotating, compulsory rotating, and self-rotating in different planes depending on the scheme and angles of installation [3]. To intensify cutting, use was made of plasma preheating [4] (Fig. 1). Consideration was given to machining of structural steels, titanium alloys, chromium-nickel steels, surfacings, and powder materials, which can give an idea of the influence of not only the chemical composition but also structures, pores, and inhomogeneities of materials on the stability of the cutting process. Tables 1–4 compare experimental data with the results of different authors [3–9].

Studying the experimental data shows that, to describe the process of cutting of structural steels (Table 1) with a regular tool, it is appropriate to use the approximate formula [5]

$$P_z = C_3 t S^{0.7}. \quad (3)$$

In forced cutting with a round tool the exponents x_i and y_i change due to a change in the cross section of the cut layer. Forced travel of the cutting edge of the round tool permits control of the cross section of the cut layer, and exponents of the cutting depth t and feed rate S that are close to $x_i = 1.0$ and $y_i = 0.7$ are obtained in self-rotation

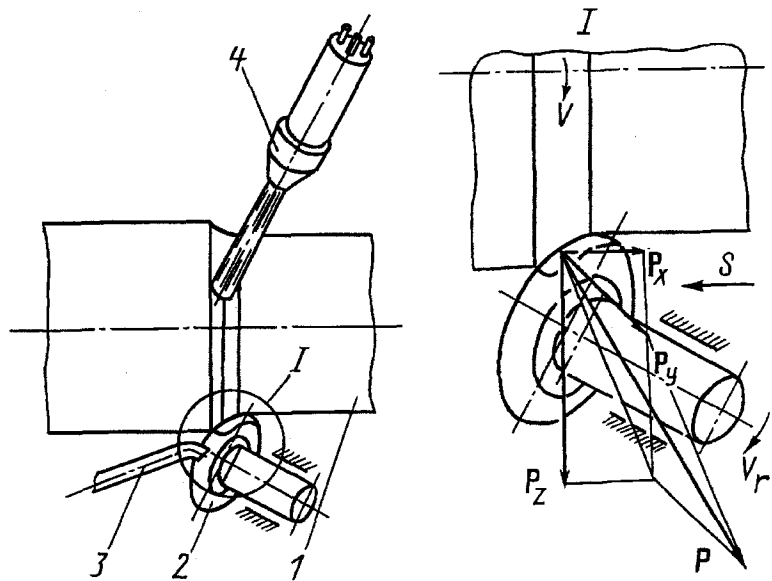


Fig. 1. Scheme of rotational machining with heating of the cut layer: 1) machined part; 2) rotational tool; 3) lubricant feed; 4) plasmatron.

of the rotating tool if one describes the process by the cutting moments M of (2) in the plane in which the rotation occurs:

$$M = C_M t S^{0.7}. \quad (4)$$

To describe the process of cutting of titanium alloys (Table 2) with a regular tool, Eq. (3) is also suitable. For forced cutting with a round tool, even in self-rotation of it, the exponents x_i and y_i change in the force and moment equations, since in tool rotation the cutting speed increases, which leads to the formation of a step (cyclic) chip, which fails to be removed by the rotating tool.

In cutting chromium-nickel steels (Table 3) with a regular tool, especially in using additional plasma heating, the cross section of the cut changes periodically, which does not permit the use of Eq. (3) to describe cutting processes with heating. A rotational tool makes it possible to rapidly remove the chip and permits a description of cutting processes by the moment equations (4). The exceptions in this case are materials containing pores and inclusions, for example, surfacings, in machining of which with a rotating tool we observe no stabilization of the process of chip formation.

In cutting steel and chromium-nickel powder materials (Table 4) with a regular tool the presence of pores alters the cross-sectional area of the cut. In rotational cutting of powder materials there is no such intense pore crumpling and, to describe it, it is appropriate to use moments of cutting whose exponents x_i and y_i are close to the exponents in Eq. (4).

Analysis of the experimental data on the components of the cutting force P_x , P_y , and P_z in machining different materials showed that, to describe stable cutting processes with small corrections for the material (its physicomechanical properties, structure, and chemical composition), it is appropriate to use the force equation (3) and moment equation (4).

We consider processes that occur in the zone of chip formation. For this we investigate parameters similar to stresses in machining with a regular tool: $\sigma_e = P_z / Stk_l$ [10] – similar to effective stresses at which plastic flow of the metal commences; $s_v = P_z / St$ [11] – similar to conventional stress that characterize the intensity of the process, and $\sigma_u = \sigma_e \sigma_v / (\sigma_e + \sigma_v) = P_z / (St(k_l + 1))$ [12] – similar to the ultimate strength of the material.

Results of the investigations (Table 5) showed that in machining with a self-rotating round tool it is appropriate to describe the stressed state in the cutting zone by parameters that characterize stresses on portions of unit length in the directions of the fundamental motion v , i.e., by σ_z , and the travel of the cutting edge v_r , i.e.,

TABLE 1. Values of the Coefficients and Exponents of the Components of the Cutting Force $P = C_i t^{x_i} S^{y_i} v^{z_i} u^{k_i}$, Roots of the Characteristic Equation p_1 , p_2 , and Stability of the Cutting Process in Machining 45 Steel

P	C_i	x_i	y_i	z_i	k_i	p_1	p_2	Stability	Ttjectories
Regular tool									
P_x	4750	0.50	0.50	-0.40					
P_y	2130	0.90	0.60	-0.30					
P_z	2940	1.00	0.75	-0.15		-0.045	1.645	US	P_y/P_z
Round tool, nonrotating									
P_x	560	1.00	1.01	1.99					
P_y	1064	0.86	0.65	0.52					
P_z	1736	0.70	0.65	0.26		-0.073	1.423	US	P_y/P_z
Compulsory rotating in the XOY and YOZ planes $u = v_r/v = 0.2-0.7$									
P_x	614	0.88	0.61	0.08	0.54				
P_y	1297	0.60	0.72	-0.26	0.60				
P_z	1968	0.66	0.68	-0.40	-0.43	0.050	1.329	UN	P_y/P_z
$P_x P_y$	796358	1.48	1.33	-0.18	1.14	-0.062	2.053	US	M_{xy}/P_z
$P_y P_z$	2552496	1.26	1.40	-0.66	0.17	-0.145	2.735	US	M_{xy}/M_{yz}
Self-rotating in the XOY and YOZ planes									
P_x	2382	0.67	0.43	-0.19	0.50				
P_y	1821	0.46	0.35	-0.43	0.77				
P_z	1783	0.64	0.44	-0.28	-0.69	0.22	0.968	UN	P_y/P_z
$P_x P_y$	4337622	1.13	0.78	-0.62	1.27	0.001	1.419	UN	M_{xy}/P_z
$P_y P_z$	3246843	1.10	0.79	-0.71	0.08	-0.018	1.898	US	M_{xy}/M_{yz}
Self-rotating in the XOY plane									
P_x	520	0.45	0.65	-0.36					
P_y	190	0.45	0.25	0.00					
P_z	700	1.00	0.47	-0.33		0.032	1.218	UN	P_y/P_z
$P_x P_{yy}$	98800	0.90	0.90	-0.36		0.298	1.602	UN	M_{xy}/P_z
$P_y P_z$	133000	1.45	0.72	-0.33		-0.336	1.956	US	M_{xy}/M_{yz}
Self-rotating in the YOZ and XOZ planes									
P_x	680	0.60	0.39	0.02					
P_y	440	0.51	0.27	0.03					
P_z	750	0.41	0.33	-0.04		-0.076	0.756	US	P_y/P_z
$P_y P_z$	330000	0.92	0.60	-0.01		-0.070	1.350	US	P_y/M_{xz}
$P_x P_z$	510000	1.01	0.72	-0.02		-0.034	1.644	US	M_{yz}/M_{xz}

TABLE 2. Values of the Coefficients and Exponents of the Components of the Cutting Force $P = C_i t^{x_i} S^{y_i} v^{z_i}$, Roots of the Characteristic Equation p_1 , p_2 , and Stability of the Cutting Process in Machining Titanium Alloys

p	C_i	x_i	y_i	z_i	p_1	p_2	Stability	Trajectories
Regular tool VT14 alloy								
P_x	45	1.05	0.40	-0.10	-0.110	1.710	US	P_y/P_z
P_y	90	1.05	0.60	-0.10				
P_z	173	1.00	0.75	-0.09				
Round tool Self-rotating in the XOY plane VT1-0 alloy								
P_x	790	0.42	1.00	-0.30	0.127	1.474	UN	P_y/P_z
P_y	490	0.54	0.80	-0.10				
P_z	480	0.80	0.84	-0.10	0.272	2.328	UN	M_{xy}/P_z
$P_x P_y$	387100	0.96	1.80	-0.40	0.294	2.846	UN	M_{xy}/M_{yz}
$P_y P_z$	235200	1.34	1.64	-0.20				

by σ_x , and, with allowance for the interdependence of the motions v and v_r through the cutting moment M , by the parameters $\sigma_{xz} = \sigma_x \sigma_z$ [2]. For structural steels it is appropriate to describe approximately the parameters of stresses in machining with additional travels of the edge as follows:

$$\sigma_{xz} = C_\sigma S^{-0.3}, \tag{5}$$

and in machining with a regular tool [10] as follows:

$$\sigma_z = C_\sigma = \text{const}. \tag{6}$$

We represent the quantity $tS^{0.7}$ in the force equation (3) and moment equation (4) as numbers by using the stresses (5) and (6): the Reynolds number $Re = vt/\nu$, which describes the laminar-to-turbulent transition, and the Prandtl number $Pr = \nu/\omega$, which describes the ability of heat to propagate in a given medium, where the kinematic viscosity factor ν describes the tangential stresses:

$$Re^* = tS^{0.7} = \frac{vtS}{\nu S^{0.3}} = \frac{vt}{(C_\sigma/\sigma_{xz})(v/S)} = \frac{vt}{(\sigma_z/\sigma_{xz})(v/S)} = \frac{vt}{\nu^*} = \frac{vt}{\omega Pr^*} = \frac{Pe}{Pr^*}, \tag{7}$$

$$\nu^* = (C_\sigma/\sigma_{xz})(v/S).$$

Equation (7) shows that for constant removal of material per unit time $vt = \text{const}$ upon increase in Re^* and decrease in Pr^* to a critical value vortices form. This occurs as a result of a decrease in C_σ , i.e., the constant of the machined material, owing to heating of the cutting zone when the material has no way of traveling freely in the cutting zone $\sigma_{xz} \rightarrow 0$ or as a result of an increased cutting speed v , which also involves heating of the cutting zone, when there is no way for the tool to additionally travel in a direction of S not coinciding with the direction of the fundamental motion v .

Thus, the force equation (3) and moment equation (4) as well as the stresses (5) and (6) in the zone of chip formation permit the description of stable processes and make it possible to determine from Re^* and Pr^* the formation of thermodynamic instabilities such as outgrowths, adiabatic shifts, and others.

TABLE 3. Values of the Coefficients and Exponents of the Components of the Cutting Force $P = C_i t^{x_i} S^{y_i} v^{z_i} w^{k_i}$, Roots of the Characteristic Equation p_1 , p_2 , and Stability of the Cutting Process in Machining Chromium-Nickel Steels

P	C_i	x_i	y_i	z_i	k_i	p_1	p_2	Stability	Trajectories
Regular tool 18Kh2N4MA									
P_y	2100	0.44	0.54	0.01		0.061	1.229	UN	P_y/P_z
P_z	4200	0.75	0.75	-0.19					
With plasma heating, 18Kh2N4MA									
P_y	8100	0.29	0.85	0.01	-0.24	0.143	1.347	UN	P_y/P_z
P_z	8300	0.64	1.21	0.20	-0.36				
With plasma heating, 30Kh2N2MA steel									
P_y	7475	0.70	0.50	-0.10	-0.70	0.067	1.633	UN	P_y/P_z
P_z	3753	1.20	0.70	-0.06	-0.30				
With plasma heating, 12Kh18N10T steel									
P_y	2019	0.95	1.10	-0.60	-0.45	0.113	1.937	UN	P_y/P_z
P_z	3826	0.95	0.87	-0.39	-0.30				
Round tool, self-rotating in the YOZ and XOZ planes, Np-30KhGSA wire surfacing									
P_x	1560	0.90	0.18	0.06					P_y/P_z
P_y	1690	0.78	0.13	0.05		-0.055	1.015	UN	
P_z	2560	0.83	0.21	-0.11					
Self-rotating in the XOY plane, 2Kh13 steel									
P_x	97	0.37	0.51	-0.43					P_y/P_z
P_y	1000	0.65	0.28	-0.30		-0.001	1.230	US	
P_z	1100	0.95	0.41	-0.38		0.218	1.522	UN	M_{xy}/P_z
$P_x P_y$	97000	1.02	0.79	-0.73		0.263	2.127	UN	M_{xy}/M_{yz}
$P_y P_z$	1100000	1.60	0.69	-0.68					

Investigation of Stability. To investigate thermodynamic instabilities in machining processes, we consider the changes in the cutting force components P_z and P_y :

$$dP_z/d\tau = C_3 t^{x_3} S^{y_3} v^{z_3} (x_3/t + y_3/S + z_3/v) \approx P_z (x_3/t + y_3/S),$$

$$dP_y/d\tau = C_2 t^{x_2} S^{y_2} v^{z_2} (x_2/t + y_2/S + z_2/v) \approx P_y (x_2/t + y_2/S)$$

owing the smallness of z_2 and z_3 . Special equilibrium points $\{(1/t)_c; (1/S)_c\}$ at which P_z and $P_y = \text{const}$ permit, from the character of the trajectory

TABLE 4. Values of the Coefficients and Exponents of the Components of the Cutting Force $P = C_i t^{x_i} S^{y_i} v^{z_i}$, Roots of the Characteristic Equation p_1, p_2 , and Stability of the Cutting Process in Machining Powder Materials

P	C_i	x_i	y_i	z_i	p_1	p_2	Stability	Trajectories
Regular tool 20Kh9p powder								
P_x	180	0.78	0.00	-0.09	0.261	1.489	UN	P_y/P_z
P_y	1580	0.40	0.91	-0.05				
P_z	5700	0.84	0.94	-0.12				
Round tool self-rotating in the YOZ and XOZ planes PG-10N-01 powder								
P_x	2850	0.47	0.14	-0.03	-0.058	0.678	US	P_y/P_z
P_y	4200	0.48	0.10	-0.02				
P_z	2770	0.52	0.19	-0.12	-0.052	1.142	US	P_y/M_{xz}
$P_y P_z$	11634000	1.00	0.29	-0.14	-0.033	1.313	US	M_{yz}/M_{xz}
$P_x P_z$	7894500	0.99	0.33	-0.15				

TABLE 5. Values of the Coefficients and Exponents of $C_i t^{x_i} S^{y_i} v^{z_i}$, the Chip Shrinkage k , and the Parameters of the Stresses σ in Cutting 45 Steel with a Round Tool, Self-Rotating in the YOZ and XOZ Planes

σ	C_i	x_i	y_i	z_i
$k_l = k_a$	2.47	0.42	-0.39	-0.24
$\sigma_{ex} = P_x k_a / t$	1680	0.02	0.00	-0.22
$\sigma_{ez} = P_z / S k_l$	304	-0.01	-0.28	-0.20
$\sigma_{exz} = M_{xz} k_a / S t k_l$	510000	0.01	-0.28	-0.02
$\sigma_{vx} = P_x / S$	680	-0.40	0.39	0.02
$\sigma_{vz} = P_z / S$	750	0.41	0.67	-0.04
$\sigma_{vxz} = M_{xz} / S t$	510000	0.01	-0.28	-0.02
$\sigma_{uxz} = M_{xz} / (S t (k_l / k_a + 1))$	255000	0.01	-0.28	-0.02

$$\frac{dP_y}{dP_z} = \frac{P_y (x_2/t + y_2/S)}{P_z (x_3/t + y_3/S)}$$

judgment of the stability of an equilibrium with the relative deviations [13]

$$(1/t)_\Delta = (1/t) - (1/t)_c, \quad (1/S)_\Delta = (1/S) - (1/S)_c.$$

To investigate the stability, we linearize derivatives of the relative deviations, assuming that the changes in $(1/t)_\Delta$ and $(1/S)_\Delta$ are proportional to the changes in P_z and P_y :

$$d(1/t)_\Delta / d\tau = x_3 (1/t)_\Delta + y_3 (1/S)_\Delta \quad \text{and} \quad d(1/S)_\Delta / d\tau = x_2 (1/t)_\Delta + y_2 (1/S)_\Delta.$$

The solutions of the equations in the form

$$(1/t)_{\Delta} = A_1 \exp(p_1\tau) + A_2 \exp(p_2\tau) \quad \text{and} \quad (1/S)_{\Delta} = B_1 \exp(p_1\tau) + B_2 \exp(p_2\tau)$$

are determined by the roots of the characteristic equation

$$p^2 - (x_3 + y_2)p + (x_3y_2 - x_2y_3) = 0. \quad (8)$$

The type of equilibrium at the point $\{(1/t)_c; (1/S)_c\}$ depends on the roots p_1 and p_2 of Eq. (8).

Investigation of the stability of cutting processes for different machined materials was performed from experimental data (see Tables 1–4). Consideration was given to characteristic equations for the components of the cutting forces and moments that determine the behavior of the trajectories in machining with a regular and a round tool – nonrotating, compulsory rotating, and self-rotating in different planes – as well as in using preheating of the cut layer. As a result of calculations two types of equilibrium states are obtained among the six possible [13].

p_1 and p_2 Are Real Positive Numbers – Unstable Node (UN). With an unstable regime of nodal type the system moves away from the equilibrium position, performing aperiodic self-exciting motion, which may become periodic vibrations with an increasing amplitude under the known conditions. This indicates the regime of self-exciting vibrations whose phase trajectory has the form of an untwisting spiral. In real systems the increase in the amplitude is limited by physical processes, as a result of which stable periodic motion with a time-constant amplitude arises. The phase trajectory twists on an isolated closed curve corresponding to stable autooscillations and is the limiting cycle. This type of phase trajectory, as was shown earlier, is realized in periodic outgrowth formation, step (cyclic) chip formation, and formation of other thermodynamic instabilities.

p_1 and p_2 Are Real Numbers with Different Signs – Unstable Saddle (US). With small deviations from the equilibrium position in an unstable saddle-type regime the system begins to move away in a prescribed direction. There are always two new stable states that the system approaches. Instability of this type in metal cutting has a qualitatively different structural level and is manifested in a stable process in the form of shifts on the planes of chip formation by a dislocation mechanism [11] or other mechanisms [14].

Study of instabilities in processes of cutting structural steels (see Table 1) showed that in the absence of rotation of the tool stable chip formation is described by phase trajectories of cutting force components. Forced rotation and self-rotation of the tool call for a description of the process by trajectories of cutting moment components, which the cutting force components can be confined just to a plane that is perpendicular to the additional travel of the cutting edge.

Stable chip formation in cutting of titanium alloys (see Table 2) is disturbed owing to the formation of step (cyclic) chips at high cutting speeds, as demonstrated by the phase trajectories of the components of forces and moments.

A change in the cross section of a chip and its packing [4] at the cutting edge in machining of chromium-nickel steels with heating (see Table 3) have an effect on the phase trajectories of the cutting force components. Rotation of the tool alters the type of cutting process instability but it stabilizes chip formation insufficiently.

Rotation of the tool in machining steel and chromium-nickel powder materials (see Table 4) stabilizes completely the process of chip formation, as confirmed by the phase trajectories of the components of cutting forces and moments.

A small difference of the roots p_1 of the characteristic equations from zero demonstrates low structural stability of the cutting system, for which the structure of the phase portrait changes with small changes in parameters of the process. This is especially noticeable with a scheme of the installation that provides low stability of self-rotation for the tool in the XOY and YOZ planes (Table 1) and with insufficient stabilization of chip formation by a stably rotating tool in the XOY plane or in the YOZ and XOZ phases (Table 3).

Thus, low structural stability of the technological system demonstrates the need for a detailed investigation of thermodynamic instabilities in developed processes of machining of both new and traditional materials.

NOTATION

P and P_x , P_y , P_z , cutting force and its components; M and M_{xy} , M_{xz} , M_{yz} , cutting moment and its components; C_M , proportionality factor between a cutting force component and the travel of the cutting edge under the action of and in the direction of this component; C_i , empirical coefficient taking account of machining conditions; x_i , y_i , z_i , and k_i , empirical exponents; t , cutting depth; S , rate of the tool feed; u , ratio of the velocity of the additional travel of the cutting edge v_r to the velocity of the fundamental motion of machining v ; w , plasmatron power; σ_e and σ_v , effective and conventional stresses; σ_u , ultimate strength; σ_x , σ_z , and σ_{xz} , parameters of stresses in the directions of v_r , v , and M ; k_l and k_a , longitudinal and traverse shrinkage of a chip; C_σ , empirical coefficient, i.e., constant of the machined material; Re , Pr , and Pe , Reynolds, Prandtl, and Peclet numbers; ν , kinematic viscosity; ω , thermal diffusivity of the material; A_1 , A_2 , B_1 , B_2 , integration constants in solving differential equations; p_1 and p_2 , roots of the characteristic equation; τ , current time.

REFERENCES

1. P. I. Yashcheritsyn, A. V. Borisenko, N. N. Popok, and M. L. Kjeifets, Dokl. Akad. Nauk Belarusi, 36, No. 5, 429-432 (1992).
2. P. I. Yashcheritsyn, A. V. Borisenko, and M. I. Kheifets, Izv. Akad. Nauk Belarusi, No. 1, 48-53 (1992).
3. P. I. Yashcheritsyn, A. V. Borisenko, I. G. Drivotin, and V. Ya. Lebedev, Rotational Cutting of Materials [in Russian], Minsk (1987).
4. A. N. Reznikov (ed.), Cutting with Plasma Heating [in Russian], Moscow (1986).
5. B. S. Balakshin (ed.), Adaptive Control of Machine Tools [in Russian], Moscow (1973).
6. Yu. A. Novoselov and N. N. Popok, Mashinostroenie, No. 12, 33-37, Minsk (1987).
7. E. P. Konovalov and G. F. Shaturov, Vestsi Akad. Navuk BSSR, Ser. Fiz.-Tekhn. Navuk, No. 2, 56-60 (1973).
8. N. S. Zhuchkov, P. D. Bepakhotnyi, A. D. Chubarov, et al., Raising the Efficiency of Cutting of Blanks of Titanium Alloys [in Russian], Moscow (1989).
9. Ye. E. Fel'dshtein and V. A. Nikolaev, Finish Machining of Parts of Powder Materials [in Russian], Minsk (1987).
10. V. D. Kuznetsov, Solid State Physics, Vol. 3 [in Russian], Tomsk (1944).
11. V. K. Starkov, Dislocation Concepts of Metal Cutting [in Russian], Moscow (1979).
12. P. A. Gorezko, Interrelationship of the Processes of Metal Cutting and Stretching [in Russian], Minsk (1959).
13. V. Ebeling, Structure Formation in Irreversible Processes: Introduction to the Theory of Dissipative Structures [Russian translation], Moscow (1979).
14. B. A. Kravchenko, Vestnik Mashinostr., No. 10, 53-56 (1991).