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DEVELOPMENT OF COMBINED HIGH-FLUX WORKPIECE SURFACING METHODS.
I. ANALYSIS OF THERMOMECHANICAL SURFACING

**M. L. Kheifets,[a] L. M. Kozhuro,[b]
A. A. Shipko,[c] and I. A. Sebchilo[d]**

On the basis of equations of phases and initial and boundary conditions, an open production and operation system is considered in the process of evolution to a steady state. Ways are outlined to increase the efficiency of combined surfacing methods. Systems analysis of thermomechanical surfacing is carried out.

1. Systems Analysis of Combined Surfacing Methods. At the present stage of science and technology, requirements on the strength, hardness, viscosity, and wear resistance of surfaces are so high that in some cases conventional surfacing methods fail to provide the necessary quality parameters of surface layers. So, in modern production, combined surfacing methods [1] employing plasma [2], electric arc [3], laser [4], electron beam [5], ion vacuum [6], and other power sources are used more and more often.

From the view point of production and operation heredity [7, 8], the conventional surfacing methods can produce efficient designs of modified layers. However, in the case of successive or parallel formation of various surface layers, the interrelatedness of the energy fluxes used makes it necessary to consider the efficient design of modified layers.

In order to describe the development of surface layers subjected to concentrated energy fluxes, it is necessary to investigate an open technological system with additional degrees of freedom and to consider the formation of dissipative structures and phases that scatter excess energy [1]. For production of modified layers with certain structures and phases, it is necessary to consider the relationship of the degrees of freedom of the system with the forming phases, to determine the optimal number and structure of the interrelationships between the degrees of freedom and as a result, to locate particular phases in the surface layers of the workpiece by optimizing the degrees of freedom.

1.1. Equation of Phases. The number of phases (structures) Φ corresponding to the number of components K in the compound and the number of variables of imposed fields (energy fluxes) Π is defined by Gibb's equation [9]:

$$\Phi = \mathrm{K} + \Pi - \mathrm{C}\,.$$

The equation is obtained for a closed equilibrium system proceeding from the fact that

$$F = U - T\varepsilon = \text{const} \quad \text{or} \quad Z = H' - T\varepsilon = \text{const}\,.$$

Moreover, these conditions can be satisfied for an open system as well, when additional energy fluxes are scattered completely by dissipative structures.

According to the second thermodynamic principle ($\Psi \geq 0$, $\sigma \geq 0$), the dissipation function and the entropy production [10] $\Psi = T\sigma = Td\varepsilon/d\tau$ increase with time τ.

Under closed conditions, in the process of evolution with $d\varepsilon \geq 0$, the system tends to an equilibrium state in which $\varepsilon = \max$; in this case the entropy production does not increase: $d\sigma \leq 0$. In the open system the condition

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[a]Polotsk State University, Novopolotsk; [b]Belarusian Agricultural Technical University, Minsk; [c]Institute of Reliability and Durability of Machines, Academy of Sciences of Belarus, Minsk, Belarus; [d]St. Petersburg State Technical University, St. Petersburg, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 6, pp. 930-942, November-December, 1995. Original article submitted September 21, 1994.

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of evolution is preserved; $d\sigma \leq 0$, and the equilibrium condition assumes $\sigma = \min d\sigma = 0$ at the time derivative $d\sigma/d\tau \leq 0$.

According to the Prigogine-Glensdorf basic theorem [11], in the case of evolution to a steady state in the τ, arbitrary systems with time-constant boundary conditions satisfy the condition of evolution ($d\sigma \leq 0$), the steady-state condition ($d\sigma = 0$), and the stability condition ($\delta\sigma \geq 0$).

Consequently, the initial conditions are satisfied for both closed and open equilibrium systems and for the latter the additional constraint $d\sigma/d\tau \leq 0$ appears, and consequently, Gibbs' equation allows consideration of open systems.

In concrete operations of the production process and in concrete stages of operation on a workpiece, with a constant number of components K of the compounds and supplied energy fluxes Π, the degrees of freedom C of the system allow the developing phases Φ to be controlled in accordance with Gibbs' equation.

Since the production-operation system is sensitive to initial conditions, it can be expressed rationally as a strange attractor for which three degrees of freedom are sufficient for a chaotic regime to arise [12]. Consequently, in order to avoid unpredictability of determinate matter and energy fluxes, for their dissipation the system should have no more than two degrees of freedom.

1.2. Initial and Boundary Conditions. If the production processes are classified (see Table 1) as follows: division of the surfaced material into workpieces with volume V_1 and production of the workpieces with volume V_2; coating ($V_2 < V_1$); heat treatment ($V_2 = V_1$); cutting ($V_2 < V_1$), and deformation ($V_2 = V_1$) [13], it is possible to formulate the boundary conditions of an open production-operation system. Additional degrees of freedom of conventional boundaries such as displacements and renewals make it possible to control the nonequilibrium state of the production-operation system [14]. If tribological processes involved in operation of the surface are classified as follows: running-in with the wear intensity U_0; developed friction and wear with intensity U_1 ($U_1 < U_0$), and destruction with intensity U_2 ($U_2 >> U_1$) [15], it is possible to determine the initial conditions of the changing production-operation system. Additional exposure to energy fluxes at the initial moment provides conditions leading to stabilization of nonequilibrium production and operation processes [1].

The efficiency of the combined surfacing and operation procedures [1] obtained by a combination of methods that change the boundary conditions by introducing additional degrees of freedom by displacement of the working body (the tool, production environment, the allowance to be removed, the surface to be shaped) [16-20] and methods that change the initial conditions by using additional sources with different levels of energy concentration (with volume zone I, many local zones, II, and single local III zone of heat generation) [21-25] is analyzed in Table 1.

As can be seen, at present under industrial conditions most of the up-to-date methods can be implemented and only few of them are not feasible, but these combinations of the joint actions are exhibited as side effects in shaping and operation of surfaces. Analysis has shown that the use of combined methods based on joint thermal and mechanical actions is efficient [26-30].

The distribution of the combined surfacing and operation methods in the accuracy of surface shaping was studied with the suggested table of classification according to the energy concentration level (I, II, III) for the various standard sources (Fig. 1). For deformation and cutting the surfacing accuracy was estimated from the deviation of sizes and shapes and by waviness and roughness; for heat treatment, it was estimated from the inhomogeneity of the depth of thermal strengthening or weakening and from the thickness of the defective surface layer, and for coating and separation, all the indices enumerated were take into consideration.

Analysis of the accuracy of surface shaping shows (Fig. 1) that the power density increases from the first to the third energy concentration levels (I → II → III), which, in turn, leads to a decrease in the dimensions of the heat generation zone. A decrease in the dimensions of the heat generation zones (from I' to V') and the number of operation stages (from III'' to I'') results in an increase in the concentration of stresses, whose field determines the surface to be shaped and its accuracy. It is evident that at level I the accuracy does not increase as a result of an increase in the size of the heat generation zone rather than in energy concentration. At level II the accuracy is minimal, because of forming of the surface over stress concentrators scattered in a large volume and formed by

TABLE 1. Combined Surfacing Methods Effectively Used in Industry (X) [15-30] and Low-Efficiency (–) or Unfeasible (0) Methods

Heat generation zones	Standard energy sources and their power q, W/cm^2	I. Separation				II. Coating application				III. Heat treatment				IV. Cutting by tool				V. Deformation by			
		Tthermal spalling	Outflow of melt	Flowing off melt	Evaporation	Facing	Fusion (rendering amorphous)	Sputtering	Alloying	Heat shock	Quenching	Annealing	Tempering	By cutting edge	With forced displacement	Self-displaced	By abrasive	Block head	Plate	Roller	Ball
I. Volume zone	Destruction processes (DP), $3{\cdot}10...10^3$ III″	–	0	0	0	0	0	0	0	0	0	0	0	×	×	×	×	×	×	×	×
	Induction heating (IH), $(10^2)...10^3...10^4$	–	–	0	0	×	×	×	–	–	×	×	×	×	×	×	–	×	×	×	×
	Gas flame (GF), $10^2...10^3...(3{\cdot}10^3)$	–	×	×	–	×	×	×	–	–	×	×	×	×	×	×	–	×	×	×	×
	Plasma arc (PA), $5{\cdot}10^2...3{\cdot}10^4$	×	×	×	–	×	×	×	–	–	×	×	×	×	×	×		×	×	×	×
II. Many local zones	Friction processes (FP), $10^3....3{\cdot}10^4$ II″	–	0	0	0	×	–	–	–	–	–	–	×	×	×	×	×	–	×	×	×
	Electric contact heating (EH), $10^3....5{\cdot}10^4$	–	–	0	0	×	–	–	–	–	–	–	–	×	×	×	×	–	×	×	×
	Welding arc (WA), $10^3...10^5...(10^6)$	–	–	×	×	×	×	×	–	–	×	×	×	×	×	×	×	–	×	×	×
	Spark discharge (SD), $5{\cdot}10^8...8{\cdot}10^8$	–	–	–	–	×	×	×	×	–	–	–	–	–	–	–	–	–	–	–	–
III. Single local zone	Running-in processes (RP), $(10^3)...3{\cdot}10^4...8{\cdot}10^8$ I″	–	0	0	0	–	×	–	×	–	–	–	×	×	×	×	×	×	×	×	×
	Electron (ion) beam (EB), $(10^3)...10^6...8{\cdot}10^8$	×	×	×	×	×	×	×	×	×	×	×	×	–	–	–	–	–	–	–	–
	CW laser (CL), $(5{\cdot}10^3)...10^6...10^9$	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	–	×	×	×	×
	Periodic pulsed laser (PL), $(10^7)...10^{10}...10^{14}$	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	–	×	×	×	×

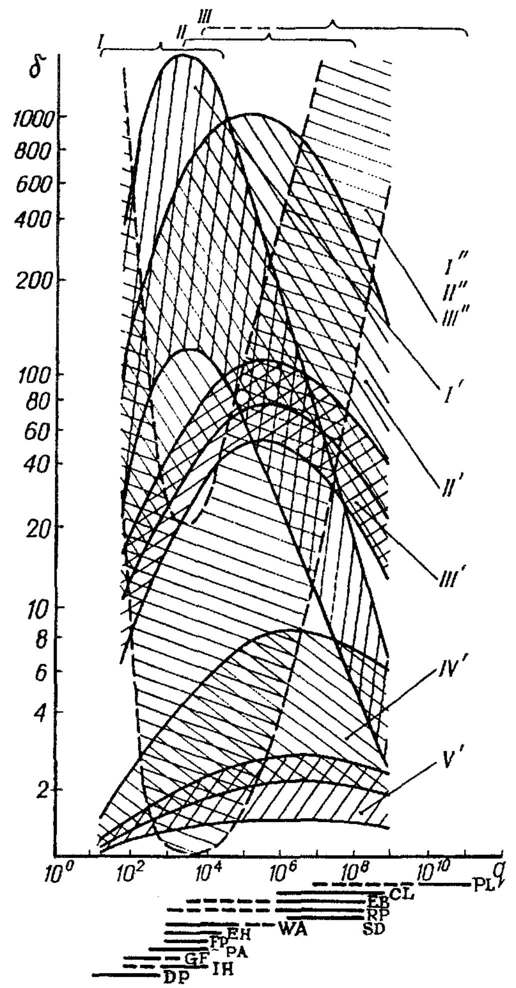


Fig. 1. Distribution of surfacing operations and operational stages according to surfacing accuracy δ (μm) and surface quality as a function of power density of q (W/cm^2) of standard sources with various levels of energy concentration. See notation in Table 1.

many local heat generation zones. At level III the accuracy does not decrease but subsequently rises abruptly due to focusing of the local heat generation zone accompanied by enhanced growth of the stress concentration.

From the conducted analysis it is possible to conclude that initial conditions can be provided efficiently by suitable selection of concentrared energy sources with preset boundary conditions for the various surfacing operations and operational stages. Standard sources of level I can be used most efficiently for shaping large volumes in the case of deformation, substantial allowances in cutting and layers in application of coats, bulk heat treatment, separation, and destruction of large-sized workpieces. Sources of level II decrease the surfacing accuracy most strongly, so they can be used effectively in combination with cutting and deforming tools and also in the case of coating and heat treatment. Use of these sources does not greatly damage the surfaces and has a strong effect on the friction of the surfaces. In all technological surfacing operations, sources of level III give the best results. In operation of surfaces these sources are most efficient in running-in processes. The data of [16-30] (see Table 1) confirm this conclusion and studies of the surfacing accuracy indicate that the classification of combined surfacing methods suggested earlier here is effective [1].

1.3. Ways of Increasing the Efficiency of Surfacing. The present survey is useful for outlining the ways of increasing the efficiency of surfacing and operation of surfaces with a preset accuracy and other quality parameters. The production and operation system of combined surfacing is open mainly for thermal and mechanical energy fluxes that determine the changing initial and boundary conditions for surfacing and operation of surfaces up to micrometer accuracy. An excess of the supplied energy above a certain limit at which the system maintains dynamic

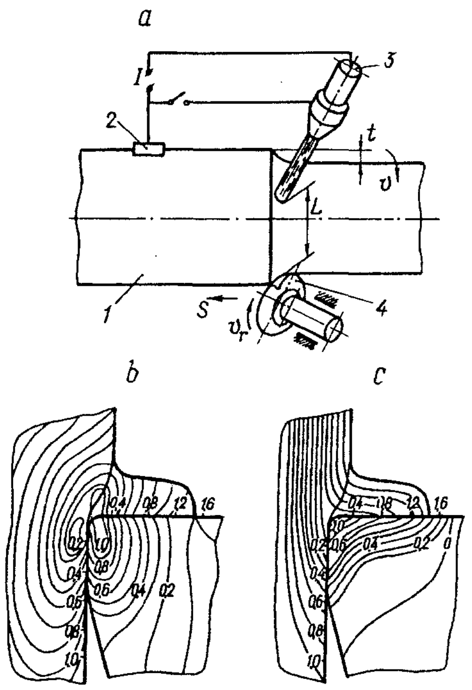


Fig. 2. Scheme of rotary cutting with plasma heating (a) [1) workpiece to be surfaced; 2) sliding contact; 3) plasma generator; 4) rotary cutting tool] stress field (b) (1.0 is equivalent to 1000 MPa), and thermal field (c) (1.0 is equivalent to 1000 K) in the surfacing zone (dimensions in mm).

equilibrium should be able to be scattered and absorbed due to additional degrees of freedom of the system with the boundary formed in this or a previous surfacing operation or stage of operation of the surface. In a thermomechanical system the additional degrees of freedom are expressed in terms of displacements, rotations, or other motions of the working body (tools, production and operation media and materials) as well as the presence of additional structures, phases, and an increase in the number of surfaces that separate them, absorbing the excess energy and simultaneously preserving the surfacing or operation process in one or several certain states.

Consequently, the efficiency of surfacing and operation of the surface is increased by using additional energy fluxes and degrees of freedom of the components of the system. As the energy concentration increases, as a result of evolution, the zone of interaction of the energy flux with the surface is transformed from a volume-distributed system to many local systems, which are focused subsequently to a single spot. Because of the additional degrees of freedom of the components of the system, surfaces, phases, and structures can be renewed, thereby preserving the processes of interaction between the energy fluxes and the surface under certain conditions.

We will consider some methods combining the various surfacing operations and stages of operation of surfaces, in each of which one energy source from group I, II, and III is used. A three-dimensional source such as a plasma arc can be used for application of a coating of powder or wire and for preheating in the case of cutting and deformation by a freely rotating rotary tool. Many local sources are used for electromagnetic facing of powder followed by plastic surface deformation and smoothing of the heated surface. A single focused surface is used for electron beam heating of surfaces with coatings, for modification of surfaces by ion implantation and ion sputtering and also allows surfacing operations to be combined with running-in in operation of the workpiece.

Since the space and time scales of the considered processes involved in the use of the combined methods differ substantially, different equipment and methods are used for their investigation. Now we will describe results of interaction of the various matter and energy fluxes involved in surfacing and surface operation by the combined methods, successively extending and specifying recommendations for development of the next of the methods considered. On the basis of the obtained results, general conclusions will be formulated for the combined methods, irrespective of their specific features.

2. Rotary Cutting with Plasma Heating. Rotary cutting with plasma heating is a technological process combining application of coatings and heat treatment of the coatings with removal of the defective surface layer by cutting and deforming the treated surface (Fig. 2a). The method is used for hardening and restoration of machine elements by wear-resistant and very strong coatings [2]. For a temporary decrease in the strength of the defective surface layer of the coatings, use is made of preheating or technological heating of the facing, which changes the initial conditions of the process. The allowance is removed by a rotary tool that changes the boundary conditions by additional displacements of the tool edge. The combined thermomechanical action decreases the variation amplitudes of thermal and dynamic loads, thereby stabilizing the surfacing process.

2.1. Methods. First, from the experimental data obtained for the components P_z, P_y, and P_x of the cutting force, contact sites l and h, and shrinkage of chips k, the stress fields were determined (Fig. 2b) in the cutting tool and the cut and surface layers of the workpiece.

For the treated material the normal σ_z, σ_y, and tangential τ_{xy} stresses at an instantaneous point with the coordinates (z, y) were calculated in terms of the Airy stress functions for the half space [31]:

$$\sigma_z = \int_{\Theta_1}^{\Theta_2} - \frac{2g(\Theta)}{\pi} \cos^2 \Theta d\Theta , \quad \sigma_y = \int_{\Theta_1}^{\Theta_2} - \frac{2g(\Theta)}{\pi} \sin^2 \Theta d\Theta , \quad \tau_{zy} = \int_{\Theta_1}^{\Theta_2} - \frac{g(\Theta)}{\pi} \sin 2\Theta d\Theta .$$

In the cutting wedge the stresses σ_z, σ_y, and τ_{yz} were determined by the method of compensatory loads [32] suggested by Hétenyi for a quarter-space [33].

The stress fields (Fig. 2b) were constructed for the equivalent stresses σ_ε, which were determined by the Coulomb-Mohr universal strength theory [34] at different values of the coefficient $\chi = \sigma_0^+/\sigma_0^-$, depending on the heating temperature:

$$\sigma_\varepsilon = (1 - \chi)(\sigma_z + \sigma_y)/2 + (1 + \chi)\sqrt{(\sigma_z - \sigma_y)^2/4 + \tau_{zy}^2} .$$

Then, in terms of the temperatures T of the contact sites l and h and the surfaces of the tool and workpiece, the temperature fields (Fig. 2c) in the tool and the cut and surface layers of the workpiece were determined.

For the treated material the temperature at an instantaneous point with the coordinates (z, y) was calculated by the method of heat sources [35]. The thermal field from a uniformly distributed source with intensity q, length l, and contact width B moving at a high velocity v was described for the half-space by the expression [36]

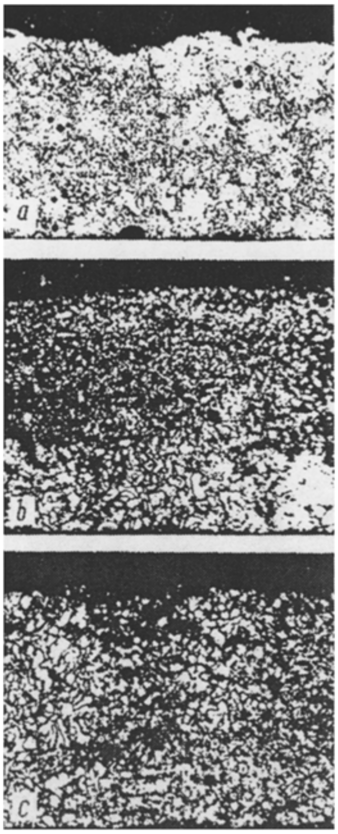
$$T = \exp\left[-(az)^2\right]\left\{(\mathrm{erf}\left[a(l + y)\right] + \mathrm{erf}\left[a(l - y)\right])\right\} q\omega a/(\sqrt{\pi}\lambda v) , \quad a = \sqrt{v/(4\omega B)} .$$

In the cutting wedge the temperature at an instantaneous point (Fig. 2c) was determined for a quarter space by superposition of the sources on the front and rear surfaces of the tool [36].

Finally, calculated results for the stress and temperature fields were compared with the distribution of microstructures (Fig. 3) and the hardness HV of the surface layer over depth H (Fig. 4). The calculations were also compared with the total hardening $\Sigma HV \cdot \Delta H$ over the entire depth determined by graphic integration of the relation of ΔHV versus H and with the change in the hardening $\Delta HV/\Delta$ as the distance from the upper surface of the surface layer determined by graphic differentiation increases.

2.2. Results and Discussion. The obtained stress and temperature fields show that under the joint action of high dynamic and temperature loads, complicated thermomechanical processes in the allowance to be cut should bring about new peculiarities of the kinetics of chip formation, changes in the forms of wear and destruction of the cutting edge, and structures providing hardening of the workpiece can be formed in the surface layer of the coating at depths of up to 0.2–0.3 mm.

Studies of chip formation show that additional heating by the plasma electric arc transforms the material to a more plastic state, and, instead of spalling chips produced as a result of the leading crack in the material, articulated chips are produced in chrome-nickel facing powders PG 10N-01 and PG-SR4. In the case of surfacing with preheating, additional displacements of the cutting edge of the rotary tool prevent the braked amounts of the surfaced material produced as a result of heat and deformation hardening of the worked plastic material by stagnant dissipative structures from fixing as outgrowths [37] on the cutting edge. It provides stable chip formation in facing



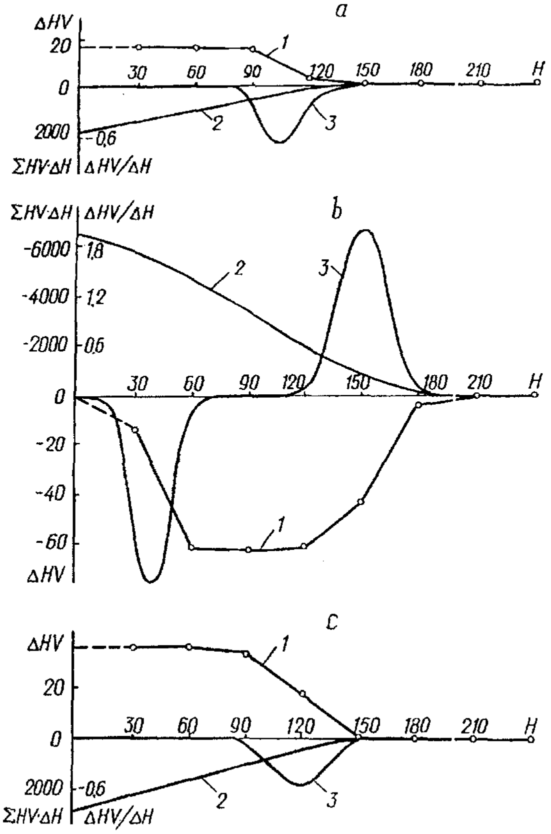


Fig. 3. Microstructures of powdered chrome-nickel facing with plasma heating at insufficient (a), excessive (b), and optimal (c) rates (×300).

Fig. 4. Plot of hardness ΔHV (1), total hardening $\Sigma\, HV\cdot\Delta H$ (2), and the rate of change in the hardening ($\Delta HV/\Delta H$) (3) versus depth H of surface layer of PG-SR4 chrome-nickel powder after rotary cutting with plasma heating at insufficient (a), excessive (b), and optimal (c) rates. H, μm.

by Np-30KhGSA and Np-65G steel wires. A high heating rate at which even additional displacement of the rotary tool does not provide adequate heat removal induces a high temperature in a narrow localized zone of the most intense deformations. Further decrease in the temperature is abrupt and induces destructive thermal and plastic shear [38], forming steplike chips.

Wear resistance tests of hard-alloy tools in rotary cutting with preheating show that with heating at an insufficient rate in PG-10N-01 and PG-SP4 facing powders the cutting edge is destroyed after the wear of the rear surface reaches 0.15 mm as a result of intense microflaking.In the case of facing by Np-30KhGSA wires and Np-65G destruction occurs after wear of 0.3 mm (Fig. 2b) as a result of thermal fatigue cracks caused by high amplitude thermal cycles in rotation of the tool. Plasma heating at an optimal rate decreases the amplitudes of thermal cycles because of a temperature rise as a result of accumulation of heat by the cutting edge in the first seconds of the operation increases the contact length of chips on the front surface 2–3 times and decreases the contact stresses on the working surfaces of the cutting edge. In this case the admissible wear can be 0.7 mm (Fig. 2b) and failure results from loss of strength by the cutting edge.

Rotary surfacing with preheating at insufficient rates results in high waviness $Sm = 1.2$ mm and roughness $Ra = 8$ μm since the surface bears traces of failure due to forming spalling chips. The hardness 58 HRC_e and hardening degree μ for pulsed dynamic loading with self-oscillations of the rotary tool are small and inhomogeneous, and the hardening depth H is low (Figs. 3a and 4a, curve 1). If the preheating rate is optimal, the waviness Sm is 0.7 mm and the roughness Ra is 3 μm, which are substantially lower. The hardness is 63HRC_e and the hardening degree μ is 0.3%, as they increase noticeably due to heat and deformation hardening of the plastic surface layer because of flaring-out of pores, fine division of grains, and formation of a certain texture, and in this case the hardening depth increases (Figs. 3c and 4c, curve 1). In the case of an excessive heating rate, the waviness Sm is 1.1 mm and the roughness Ra is 15 μm, which are sufficiently high, since craters resulting from the action of the plasma arc remain on the surface. The hardness 53 HRC_e and the weakening degree $\mu = 0.8\%$ show that the rotary tool does not provide deformation hardening of the thermally weakened surface layer, at least equivalent to the initial state, to the depth H, which is small in comparison with the zone of thermal effects (Figs. 3b and 4b, curve 1).

Investigation of the succession of the actions of thermal and mechanical energy fluxes and analysis of kinetics of the processes and quality of the surface to be formed indicates that it is necessary to investigate the production and operation heredity [7, 8] of thermodynamically unstable dissipative structures in the process of combined surfacing.

Studies of thermal and mechanical fluxes in the surface layer show that concentrated heating disorders the surface layers due to an increase in the grain size and dissolution of boride and carbide phases in a γ-solid solution of nickel. The depth of phase transformations determines the boundary of propagation of the heat flux (Fig. 3b). The rotary tool cuts the defective layer and hardens the surface by knurling, flaring out cracks and pores, and grinding grains. Mechanical actions also penetrate to a certain depth (Fig. 3b, c).

When an energy pulse is transferred to the treated surface, the rate and acceleration of propagation of the energy are reflected in all parts where the pulse passes. In particular, the rate of propagation can be inferred from the distribution of hardening ΔHV along the depth H of the surface (Fig. 4, curves 1). Then, the pulse energy will be determined by the area above the hardening curve, which can be determined by graphic integration ($\Sigma\, HV \cdot \Delta H$) (Fig. 4, curves 2). In passing, the acceleration of the pulse can be determined by graphic differentiation ($\Delta HV/\Delta H$) of the hardening curve (Fig. 4, curves 3). The results of differentiation describe the depth to which the pulse penetrates, and, consequently, the second derivative of the energy pulse, which characterizes the magnitude and position of the force that decelerates the energy flux in the surface layer, can be defined as a technological barrier.

The technological barriers (Fig. 4, curves 3) are described with sufficient accuracy by the normal distribution law. In the case of hardening and weakening, the barriers are located in different sides of the abscissa.

When the technological barriers are sufficiently close to each other, preheating increases plasticity of the surface layer and deformations penetrate to a greater depth. An increase in the area and degree of deformation accompanied by enhanced absorption of heat hinders transmission of the heat flux and brings the boundary of heat propagation closer to the surface. As a result, the cooperative action of mechanical and thermal fluxes results in coincidence of the technological barriers, and the thermomechanical pocesses occur along the whole depth of the action.

It should be noted that the thermomechanical processes are stable whenever dissipation of the excess energy is possible in surfacing. In particular, for heat fluxes dissipation occurs in phase transitions at the moment preceding development of the melting groove, and for mechanical fluxes it is provided by a rotary tool with an additional degree of freedom in motion of the cutting edge. In this case it is desirable that the process of combined surfacing be stabilized since the thermodynamically unstable structures in the regions of chip formation can change the direction of dissipation of mechanical and thermal fluxes, thereby affecting the surfacing process.

CONCLUSIONS

1. Changes in the initial conditions, such as preheating to weaken the cut layer and deformation for thermomechanical hardening of the surface layer, require appropriate changes in the boundary conditions by additional displacements of the cutting edge and motion of the heat source at a certain velocity, changing the position of the boundaries of propagation of mechanical actions and heat fluxes.

2. Boundary conditions can be expressed as positions of technological and operational barriers and the initial conditions, as the area of these barriers, and the barriers themselves can be defined as the second derivative of the active pulse of thermal, mechanical, or some other energy with respect to time or the penetration depth.

3. Technological and operational barriers can be created by special inheritable structures which could dissipate energy, preserving, if possible, the initial and boundary conditions, thereby making the surfacing and operation processes approach the adiabatic conditions.

NOTATION

Φ, number of phases (structures); K, number of components; Π, number of variables of imposed fields (energy fluxes); C, number of degrees of freedom of system; F, free energy of system; U, internal energy; T, absolute temperature; ε, entropy; Z, thermodynamic potential; H, enthalpy; Ψ, dissipation function; σ, entropy production; τ, time; V_1 and V_2, volumes of blank and workpiece; U_0, U_1, and U_2, rates of running-in, wear, and destruction; δ, surfacing accuracy; q, power density of source; t,cutting depth; S, feed rate; v, velocity of main motion and heating rate; I, strength of current of electric arc; L, distance from heating spot on workpiece surface to cutting edge of tool; v_r, rotational velocity of rotary tool; P_z, P_y, and P_x, components of cutting force; l and h, lengths of contact areas on front and rear surfaces of tool; B, width of the contact areas; k, shrinkage of chips; x, y, and z, coordinates of instantaneous point; σ_z and σ_y, normal stresses; τ_{zy}, tangential stresses; Θ, polar coordinate of instantaneous point; $g(\Theta)$, distribution of contact loads; σ_ε, equivalent stresses; $\chi = \sigma_0^+/\sigma_0^-$, factor in universal strength criteria; σ_0^+ and σ_0, limiting stresses for material with single-axis expansion and compression; ω and λ, thermal diffusivity and thermal conductivity; Sm and Ra, waviness and roughness of surface; HRC_e and HV, Rockwell and Vickers hardnesses; $\mu = \Delta HV/HV$, hardening of surface layer; H, depth of hardened layers.

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