Journal of Engineering Physics and Thermophysics, Vol. 68, No. 4, 1995

INVESTIGATION OF THE STABILITY OF A TECHNOLOGICAL SYSTEM IN COMBINED PROCESSES OF THERMOMECHANICAL TREATMENT

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UDC 536.75:621.70:621.80:621.90

Consideration is given to combined thermomechanical methods of surface formation: rotational cutting with plasma heating and surface plastic deformation of a coating in electromagnetic welding. Unstable states of a technological system are investigated. Ways of controlling the stability and enhancing the efficiency of the combined methods of thermomechanical treatment are outlined.

Thermodynamic Instabilities. The stability of a technological system in combined processes of treatment is ensured by the scattering of excess thermal and mechanical energy through dissipative structure formation in the treated material and at the expense of the surplus degrees of freedom for the motions of a tool edge or other bodies or particles that form the surface [1, 2]. The processes of surface formation are divided into operations with the removal (cutting), $V_2 < V_1$, deposition (coating), $V_2 > V_1$, and forming of layers (deformation), $V_2 = V_1$. We consider the operations of the processes of surface formation in using different energy flows.

In cutting at small rates when the heating of the treated material is insignificant, energy dissipation leads to the formation, in addition to dislocation bending modes, of vortex ones that ensure a high degree of hardening for the material in the vicinity of the edge and outgrowth formation [3]. A fast of treatment rate or additional concentrated heating when heat removal is impossible in a narrow localized zone of the most intense deformations create high temperatures as a result of which a further growth in temperature becomes explosive and a destructive thermoplastic shear occurs [4]. A rotational tool with surplus degrees of freedom of the edge enables us to control the process of chip formation (Fig. 1a) [5]. The additional travel prevents retarded volumes of the material from fixing to the edge while renewal of the working area of the edge protects against a drastic increase in temperature in the localized volume of the treated material.

In deposition of coatings by electromagnetic welding, ferropowder particles are lined up in electrode chains in a constant magnetic field and, due to arc discharges, are welded onto the treated surface (Fig. 1b [6]). Electromagnetic welding enables us to deposit a coating only to a certain thickness, after which the layer formed loses its stability, and peaks develop on the surface which become craters upon the subsequent discharges. Electromagnetic flows that, in addition to fixing the ferropowder particles, ensure intense heat release at their contacts with the surface formed, enable us to control the process of welding.

In electromagnetic welding with surface plastic deformation of a rough surface by a ball the surplus degrees of freedom of the latter enable it, due to the interaction with projections of the treated surface, to perform spinning, in addition to rolling [7]. With no additional heating, the degree of deformation is small and the trajectory of the ball is loop-shaped in character. Intense heating converts the treated material to the plastic state as a result of which the degree of deformation and the coefficient of sliding friction increase. This hinders the spinning and decreases the trajectory of the ball, which leads to a decrease in the intensity of deformation processes. In this case, it is the concentrated heating and the additional spinning of the ball that enable us to control the process of surface deformation.

To study the principles of controlling the stability of the technological system in combined treatment, we consider stability criteria and investigate different technological processes.

Belarusian Agrarian Technical University, Minsk. Polotsk State University, Novopolotsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 68, No. 4, pp. 598-604, July-August, 1995. Original article submitted June 17, 1994.

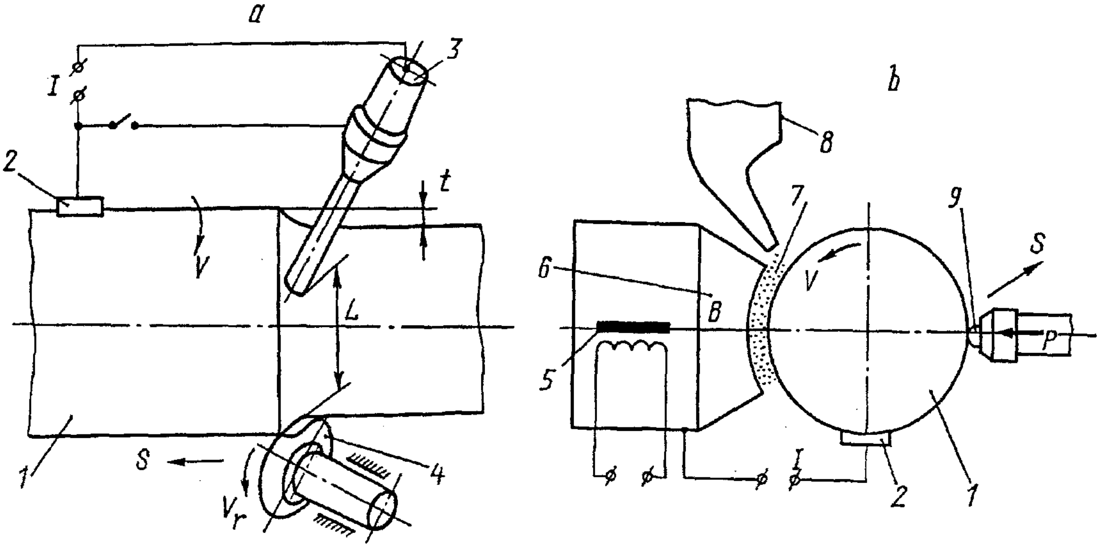

Fig. 1. Diagrams of rotational treatment with plasma preheating (a) and electromagnetic welding with surface plastic deformation (b): 1) treated workpiece, 2) sliding contact, 3) plasmatron, 4) rotational cutting tool, 5) electromagnet, 6) pole piece, 7) ferropowder, 8) metering device, 9) ball rolling tool.

Stability Criteria. It is appropriate to describe the formation of thermodynamic instabilities in the technological system by the Reynolds, Prandtl, and Peclet numbers. In removing the layers (by cutting) and forming the surface (by deformation) in the processes of mechanical treatment, these numbers can be represented by the expressions

$$\mathrm{Re}^* = \frac{v' t}{(\sigma_z/\sigma_{xz})\,(v/S)} = \frac{v' t}{\nu^*} = \frac{v' t}{\omega\,\mathrm{Pr}^*} = \frac{\mathrm{Pe}}{\mathrm{Pr}^*},$$

$$\nu^* = (\sigma_z/\sigma_{xz})\,(v/S),$$

$$v' \approx v, \quad \text{since} \quad v >> S.$$

Similarly we describe the process of electromagnetic-field deposition of a coating by the expressions

$$\mathrm{Re}^{**} = \frac{v' t}{(\sigma_y/\sigma_{yz})\,(v/S)} = \frac{v' t}{\nu^{**}} = \frac{v' t}{\omega^*\,\mathrm{Pr}^{**}} = \frac{\mathrm{Pe}^{**}}{\mathrm{Pr}^{**}},$$

$$\nu^{**} = (\sigma_y/\sigma_{yz})\,(v/S), \quad \omega^* = 1/\rho.$$

In electromagnetic welding, these numbers will be proportional to the relation

$$Ra \sim \frac{v' \,[Q/(1 - \Delta HRC_e/HRC_e)]}{(B/I)\,(v/S)}.$$

The thickness t is proportional to the increment in the coating Q with account taken of its compaction that enhances the hardness HRC_e of the surface: $t \sim Q/(1 - \Delta HRC_e/HRC_e)$. The stresses σ_y/σ_{yz} are proportional to the values of electromagnetic induction that hinder the travel and rotation of ferropowder particles in the technological zone [6]: $\sigma_y/\sigma_{yz} \sim B/I$.

We use the numbers and expressions obtained for investigating the stability of the technological system in combined processes.

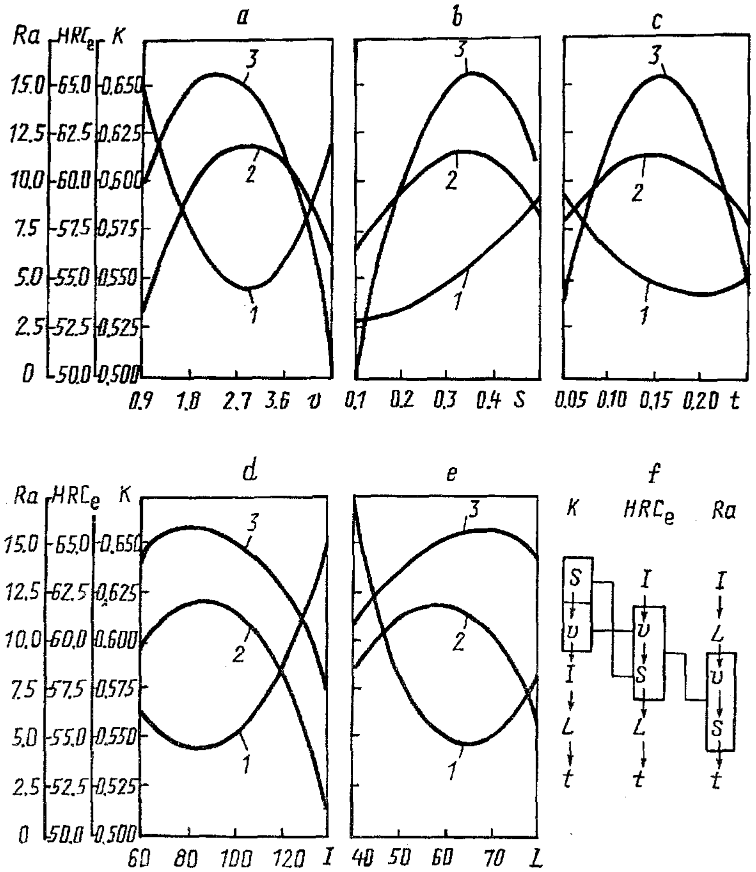

Fig. 2. Parameters of quality of the surface in rotational plasma-heating treatment of the welding with PG-SR4 powder (1, *Ra*, 2, HRC_e, 3, K) vs technological factors and the diagram of the degree of influence of the technological factors. *Ra*, μm; *v*, m/sec; *S*, mm/rev; *L*, *t*, mm; *I*, A.

Removal and Forming of the Layers. We consider the combined process of cutting, i.e., that of removal of a defective surface layer by the rotational tool with the additional arc and plasma heating when the rotating tool plastically deforms the heated surface (Fig. 1a) [8]. We investigate the process depending on the basic technological factors *v*, *S*, and *t* that enter in the stability criteria and the additional factors *I* and *L* that affect the stress parameters entering in the criteria. We consider the quality indexes *Ra* and HRC_e that characterize the stability criteria and the coefficient *K* that describes the surplus degree of freedom of the tool and affects the criterion in terms of the relation v/S [1]. The experiments performed [8] show (Fig. 2a-e) that changes in the quality indexes *Ra* and HRC_e and the coefficient *K* occurring as the intensity of heating *I* increases are similar to changes from a reduction in the rate *v* and a decrease in the distance to the source of heating *I*. The changes in *Ra*, HRC_e, and *K* with growing *I* are also similar, but to a lesser degree, to the changes with change in feed *S* and depth of cut *t* due to the fact that *S* and *t* govern the cut cross section whose constancy $St = vt(v/S) = \text{const}$ ensures to a large extent the constant criterion. We also note that the rate *v* has a greater effect on the change in the intensity of heating *I* than the feed *S* while the heating alters more the vortex σ_{xz} stress component than the translation σ_z one, which makes it possible to enhance the stability of cutting and deformation with additional heating in using the rotation tool.

Investigating the experimental results (Fig. 2a-e) and the arrangement of the technological factors *v*, *S*, *t*, *I*, and *L* according to the degree of the influence on the indexes of the stability of the process *K* and the quality of the surface HRC_e and *Ra* (Fig. 2f) performed by statistical methods [8] enable us to judge the stability of the combined process.

Thermodynamic instabilities like outgrowths and thermoplastic shears formed in treatment with heating as well as structures of the surface that reduce its hardness HRC_e are eliminated using the additional travel of the

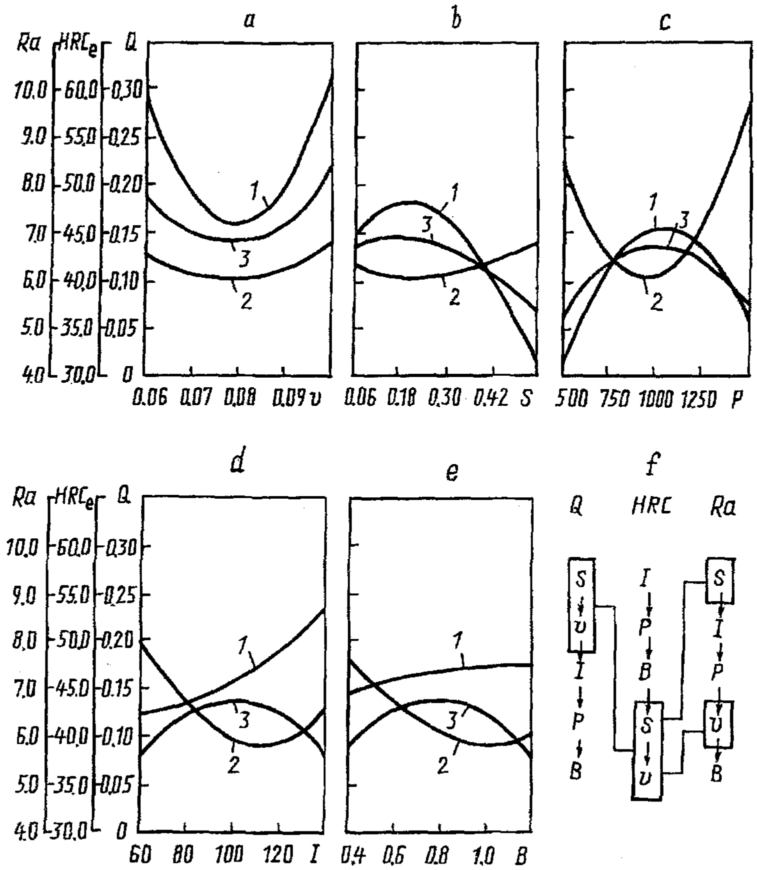

Fig. 3. Parameters of quality of the surface in electromagnetic welding of FeV powder with surface plastic deformation [1) Ra, 2) HRC_e, 3) q] vs technological factors and diagram of the degree of influence of the technological factors. P, N; Q, g; B, T.

edge. Self-organization of the processes of cutting and friction [1] ensures such an index K for which there are no instabilities, and deviations of the microrelief of the surface Ra are minimum. Thus, in the formation of the relief Ra (Fig. 2f) the influence of the components of the regime of cutting v, S, and t is small as compared to the indexes of heating I and L due to the formation of various structures in the surface layer, which is indicated by measurements of its hardness HRC_e. However, additional motion of the rotational tool described by the index K (Fig. 2f) ensures feedback of Ra with HRC_e in terms of K and enables us, by varying S, v, and v_r, to enhance the stability of the system.

Deposition and Formation of the Layers. We consider the combined process of coating deposition by electromagnetic welding with the additional surface plastic deformation of the heated surface by a ball (Fig. 1b) [9]. We study the process depending on the basic technological factors v, S, and I that enter in the stability criteria and the additional factor P that affects the quality indexes and the efficiency of the process. We consider the quality indexes Ra and HRC_e and the efficiency of the process Q.

The experiments performed [9] show (Fig. 3a-e) that the rate v and the feed S in welding affect Ra, HRC_e, and R similarly to the strength of the current I and the magnetic induction B; thus the changes in v and S are proportional to the changes in I and B. On this basis we can infer that the relation $(v/I)(B/S) = (B/I)(v/S) = v^{**}$ tends to constancy and ensures the stability of welding in fixing of the ferropowder particles in the electromagnetic field. At the same time it is pertinent to note that the efficiency Q increases in proportion to the decrease in $\Delta HRC_e/HRC_e$, the relative increment in hardness, as a result of which the expression $Q/(1 - \Delta HRC_e) \sim t$ becomes stabilized and a coating of a certain thickness t forms in electromagnetic welding.

Investigating the experimental reasults (Fig. 3a-e) and the arrangement of the technological factors σ, S, P, I, and B according to the degree of the influence on the indexes of the efficiency of the process Q and quality of the surface HRC_e and Ra (Fig. 3f), performed by statistical methods [9], make it possible to assess the stability of the combined process.

Thermodynamic instabilities that form peaks and craters in electromagnetic welding and changes in the structure of welded layers that reduce the coating hardness HRC_e are eliminated due to the drop in the cutting efficiency Q. Self-organization of the process of electromagnetic welding ensures such a minimum efficiency Q that form the coating of a certain thickness t with which unstable structures do not form, the coating hardness HRC_e increases, and the deviations of the surface microrelief Ra are minimum. Thus, in the welding of a coating of hardness HRC_e (Fig. 3f), due to the formation of various structures in the combined treatment the influence of the technological factors S and v that govern the efficiency is small as compared to the characteristics of the electromagnetic field I and B and the subsequent deformation forces P. The formation of the surface relief Ra is governed both by the motions of the workpiece in welding S and v and by the characteristics I and B of the electromagnetic field. The welding efficiency Q (Fig. 3f) described by the product Sv, through fixing ferropowder particles in the electromagnetic field and the additional motions of the surface-deforming ball, performs feedback of HRC_e with Ra and enables us, by changing I, B, and P, to enhance the stability of the technological system.

Control of Stability. The criteria proposed and the considered processes of combined treatment in removal and deposition of layers and formation of the surface enable us to determine the means of controlling the stability of the technological system and enhancing the efficiency of combined methods of treatment [10].

In removal of the defective layer and formation of the surface when the Reynolds number exceeds permissible values, vortex structures form in the cut-off, deformed layer. This occurs as a result of the reduction in the resistance of the treated material by the shear σ_z due to the high-intensity heating of the cutting zone when the material is unable to travel freely in the technological zone ($\sigma_{xz} \to 0$) or as a result of the increased rate of treatment v when the tool is unable to travel additionally in a direction S that does not coincide with the direction of the main motion v. Consequently, using tools with surplus degrees of freedom in directions v_r and S that do not coincide with the main motion of treatment v enables us to enhance the stability of the technological system in the processes of thermomechanical treatment when concentrated sources of energy are used.

In coating deposition by electromagnetic welding, the formation of unstable thermodynamic structures is governed by electromagnetic processes and arc discharges in the technological zone. The stresses σ_y and σ_{yz} in the powder medium depend mainly on the magnetic induction of the field B and the strength of the current I in arc discharges. Consequently, the change in the parameters of the electromagnetic field B and I that govern the fixing and melting of powder particles reduces the electrical resistance ρ of the coating in electromagnetic welding and enables us to enhance the stability of the technological system by stabilizing the thickness of the layer formed.

In the formation of the surface, the hardness HRC_e of the treated surface increases as the deformation force P grows due to which the velocities of additional travels of the rotating rotational tool or the ball grow. Excess heating ensures increased degree of deformation and reduces the velocities of the additional travels, which leads to increased deviation of the surface microrelief Ra. The joint coordinated actions of the additional travels of the tool and the heating on the treated material enhance the stability of the technological system and ensure the greatest hardness HRC_e and the smallest deviations of the microrelief of the surface Ra at maximum velocities of the additional travels for different combined processes of thermomechanical treatment.

Therefore, in an open technological system, by the use of mechanical, thermal, electromagnetic, and other actions in terms of the surplus degrees of freedom of tools or other bodies and particles, one can control the stability of the processes of combined treatment and obtain the required quality indexes of the surface.

NOTATION

V_1 and V_2, volumes of the ingot and the workpiece respectivy; Re = vt/ν, Reynolds number; Pr = ν/ω, Prandtl number; Pe = vt/ω, Peclet number; v, rate of treatment; t, treated layer thickness; ν and ω, coefficients of kinematic viscosity and thermal diffusivity; S, feed rate; v', resultant velocity of motions; σ_z and σ_{xz}, stresses of the treated material in the direction of the main motion v and in the direction of the moment of shaping that takes account of the interdependence of the motions v and S [1]; σ_y and σ_{yz}, stresses of a ferropowder medium in the direction perpendicular to the surface formed and in the direction of rotation on a plane perpendicular to it [2]; ω^* and ρ, specific electrical conductivity and electrical resistance of the powder medium; Ra, mean arithmetical deviation of the profile of the microrelief of the surface; Q, welding efficiency (the increase in the coating mass); HRC_e, Rockwell hardness; B, magnetic induction; I, current strength; L, distance from the heating source to the tool; $K = v_r/v$, kinematic coefficient of the rotational tool; v_r, self-rotational speed of the tool; P, forces of deformation of the surface.

REFERENCES

1. P. I. Yashcheritsyn, A. V. Borisenko, and M. L. Kheifets, Izv. Akad. Nauk Belarusi, Ser. Fiz. Tekh. Nauk, No. 1, 48-53 (1992).
2. P. I. Yashcheritsyn, , G. A. Deev, L. M. Kozhuro, and V. S. Shchukin, Izv. Akad. Nauk Belarusi, Ser. Fiz. Tekh. Nauk, No. 3, 36-40 (1993).
3. Yu. G. Kabaldin and O. I. Medvedeva, Vestn. Mashinostr., No. 5, 37-39 (1989).
4. N. V. Talantov, Physical Processes in Metal Cutting [in Russian], Volgograd (1984), pp. 3-37.
5. P. I. Yashcheritsyn, A. V. Borisenko, I. G. Drivotin, and V. Ya. Lebedev, Rotational Cutting of Materials [in Russian], Minsk (1987).
6. P. I. Yashcheritsyn, M. T. Zabavskii, L. M. Kozhuro, and L. M. Akulovich, Diamond-Abrasive Machining and Strengthening of Products in Magnetic Field [in Russian], Minsk (1988).
7. K. L. Johnson, Contact Interaction Mechanics [Russian translation], Moscow (1988).
8. P. I. Yashcheritsyn, A. V. Borisenko, L. M. Kozhuro, and M. L. Kheifets, Dokl. Akad. Nauk Belarusi, **36**, No. 5, 429-432 (1992).
9. P. I. Yashcheritsyn, G. A. Deev, L. M. Kozhuro, and M. L. Kheifets, Dokl. Akad. Nauk Belarusi, 37, No. 4, 114-117 (1993).
10. M. L. Kheifets, Izv. Vyssh. Uchebn. Zaved., Mashinostr., Nos. 7-9, 121-125 (1992).