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ANALYSIS OF HIGHLY EFFICIENT METHODS OF TREATMENT IN DESIGN OF TECHNOLOGICAL COMPLEXES

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On the basis of an analysis of self-organization of surface phenomena, criteria for control over stability of processes of highly efficient treatment are suggested. It is recommended to develop technological complexes of highly efficient treatment in the form of flexible production modules.

One of the ways of improving efficiency of machine building is the creation of complexes of technological, transport, energy, and information machines and apparatuses realizing a technological process as a logically complete part of the production cycle. Such a combination of machines has come to be known as a technological complex [1, 2]. Therefore, comprehensive reduction of the times of creation and incorporation of new technological complexes on the basis of highly efficient is an immediate problem of modern machine building industry [3].

Principles of optimum design of a technological complex have been developed by Artobolevskii [1] and Koshkin [2]. A two-stage design was proposed: 1) structural synthesis in which principal schemes of solutions that are in conformity with initial technological conditions are considered; 2) parametric synthesis in which a schematic solution is embodied in a structural form as a combination of specific mechanisms, blocks, devices, and elements of the technological complex.

Methods of analysis of the grouping of technological complexes involve [4]: 1) a study of the structure and preliminary selection of the versions of grouping; 2) a study of the effect of the latter on the characteristics of quality, rigidity, accuracy, and wear resistance of the elements and consideration of the methods of optimization of them.

Methods of analysis and optimization of selection of groupings [5] for automated assembly technological complexes [1, 2], aggregate machines [6, 7], automatic rotor lines [2, 8], and multioperation machines [4, 6, 9] are presently known. However, the problems of structural and parametric synthesis in design of technological complexes implementing processes of highly efficient combined treatment have not been studied as yet.

By virtue of this, development of the methodology of synthesis of technological complexes of highly efficient treatment, strengthening, and recovery of articles is of primary importance. It includes:

a) substantiation of the choice of highly efficient combined methods of treatment which provide resource saving in manufacture and repair of machine building articles;

b) design of the structure of a universal technological complex of highly efficient treatment, strengthening, and recovery of parts of machines;

c) optimization of the parameters of processes implemented by a technological complex of highly efficient treatment of parts.

1. Formation of a Surface Layer by Highly Efficient Methods of Treatment. Development and incorporation into production of new methods of treatment based on combinations of different types of energy or different ways of action on the treated material is a promising trend in machine building.

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In general form, a system model of technology [10, 11] is represented by a combination of three input flows: substance, energy, information. It is expedient to consider a method of treatment in the form of energy and information subsystems. The first supplies and converts energy necessary to affect an intermediate product in order to change its physicomechanical properties, to remove or to deposit material. It is specified by the form of treatment. The second controls the flows of energy and substance, providing them in the required quantities to the prescribed place of the working volume so that certain form, size and properties of the surface of a part are ensured.

It is expedient to consider the process of treatment as some energy system affecting an intermediate product so that transition from one state to another corresponding to a new quality is provided [11, 12]. This effect is achieved in several stages. At the first stage, the supplied energy is converted to working energy, E_w, by technological equipment. At the second stage, the working energy is converted to the energy of the effect, E_{eff}, on the treated object. At the third stage, the energy of the effect leads to the formation of physicochemical mechanisms, $M_{ph.-ch}$, of treatment of the intermediate product that are a main element of formation of the parameters of the method of treatment (efficiency, energy consumption, quality of the surface, etc.).

Thus, the process of treatment (PT) represents a chain of energy conversion

$$\mathrm{PT} = \{E_w \Rightarrow E_{eff} \Rightarrow M_{ph.-ch}\} \ . \tag{1}$$

Processes of shaping (Sh) are characterized by the components [12]

$$\mathrm{Sh} = \{M_{e.s}, F_{d.e}, K_{sch.t}\} \tag{2}$$

and features of them: point, linear, surface, volumetric sources for $M_{e.s}$; continious, oscillating, pulse effect for $F_{d.e}$; rectilinear, rotary, two rectilinear, rotary-translational motion or its absence for $K_{sch.t}$.

As a result, all methods are first subdivided into three classes: with removal, without removal, and with deposition of the material. Second, subclasses which characterize the types of energy used in treatment of the material are distinguished for each class. Third, there exist differences in the character of the physicomechanical effect and, fourth, in the type of instrumentation used and the kinematics of treatment [10, 11].

On the basis of this classification, suggested are generalized models of the method of treatment (MT), which are usually represented [12, 13] by analytical expression of the form

$$\mathrm{MT} = \{N_{m.t}, RA_{m.t}, E_w, E_{eff}, M_{ph.-ch}, K_{sch.t}, F_{d.e}, M_{e.s}, S, G\} \ . \tag{3}$$

Formulas (1)-(3) give a rather complete and clear idea about the structure and composition of components of the processes of treatment and shaping. It is convenient to use them in the development of new technological procedures and methods of shaping, but they do not allow one to conduct any logical operations and transformations. To formalize the conditions of target-oriented formation of new methods of treatment, each aggregate of like components r_i is described as some set of technological solutions R_i. This approach [13] allows each method of treatment $r_{m.t}$ to be represented in the form of a procession

$$r_{m.t} = (r_{surf}\ , r_{mat}\ , r_r\ , r_{eff.mat}\ r_{e.s}\ , r_{m.e.s}\ , r_{c.sour}\ , r_{e.m}\ , r_t\ , r_k\ , r_{st}) \ . \tag{4}$$

Each element of procession (4) is a component of the corresponding set of technological solutions, i.e., $\{r_i\} = R_i$ or $r_i \in R_i$.

The presence of a specific property α in a technological solution r_i is expressed by the corresponding predicate

$$E_\alpha\,(r_i)\ , \tag{5}$$

which confirms that the technological solution r_i possesses the property α.

Each property α can acquire many values θ_α. Then the expression

$$E_\alpha\,(r_i) \wedge \theta_\alpha \tag{6}$$

indicates that the technological solution r_i possesses the property α and the value of the latter is θ_α.

Predicate (5) allows one to choose a technological solution with a given property, the value of which is determined by formula (6).

In general, a technological solution r_i is characterized by a number of properties α, δ, ..., γ, each of which can acquire different values; this is expressed by the formula

$$\forall r_i \exists \alpha \exists \delta \ldots \exists \gamma \left\{ \left[E_\alpha(r_i) \wedge \left(\bigvee_{j=1}^{n} \theta_{\alpha j} \right) \right] \wedge \left[E_\delta(r_i) \wedge \left(\bigvee_{k=1}^{m} \theta_{\delta k} \right) \right] \wedge \ldots \wedge \left[E_\gamma(r_i) \wedge \left(\bigvee_{p=1}^{q} \theta_{\gamma p} \right) \right] \right\}. \tag{7}$$

Certain relationships can exist between the values of the properties of the solution r_i and not every combination of them is admissible, i.e., the technological solution r_i possesses the property α with the value $\theta_{\alpha n}$ and the property δ, the value of which is determined by the set $\theta_{\alpha pj}$. This situation is described by the relation

$$\exists \alpha \exists \delta \forall r_i \left[E_\alpha(r_i) \wedge \theta_{\alpha n} \rightarrow E_\delta(r_i) \wedge \left(\bigvee_{j=1}^{k} \theta_{\delta pj} \right) \right]. \tag{8}$$

We assume that if any two components of the method of treatment possess at least one common property, then a relationship of commonnality of properties exists between them. This makes it possible to organize the selection of technological solutions by equivalency and preference [13]. Unlike solutions the combinations of whose properties correspond to each other are chosen by the first characteristic:

$$\exists \alpha \forall r_i \forall r_j \left[E_\alpha(r_i) \wedge E_\alpha(r_j) \wedge (\theta_\alpha^{r_i} = \theta_\alpha^{r_j}) \rightarrow (r_i \approx r_i) \right], \tag{9}$$

and like solutions possessing the best values of the required properties are chosen by the second characteristic

$$\exists \theta_\alpha \forall r_{i1} \forall r_{i2} \left[E_\alpha(r_{i1}) \wedge E_\alpha(r_{i2}) \wedge (\theta_\alpha^{r_{i1}} \, h \, \theta_\alpha^{r_{j2}}) \rightarrow (r_{i1} \approx r_{i2}) \right]. \tag{10}$$

According to (9), (10), this approach allows one to formalize the search for a technological solution r_i by the specific value of the determined criterion of selection t_q:

$$\theta_\alpha^{r_i} \, h t_q . \tag{11}$$

Then a combination of predicates of the type (11) allows one to select the solution r_i by several criteria of selection t_{q1}, t_{q2}, ..., t_{qn}, which correspond to n different properties of the solution r_i. In this case the condition of selection of the solution r_i takes the form

$$\bigwedge_{j=1}^{n} (\theta_{\alpha j}^{r_i} \, h_i \, t_{qi}) . \tag{12}$$

Use of expression (12) in problems of selection of unlike technological solutions possessing different but mutually dependent properties α and δ (i.e., the condition $E_\alpha(r_i) \rightarrow E_\delta(r_j)$ is valid) allows one to organize the selection of solutions

$$\exists \theta_\alpha \forall r_i \forall r_j \left[E_\alpha(r_i) \wedge E_\delta(r_j) \wedge (\theta_\alpha^{r_i} \, h_1 t_1) \wedge (\theta_\delta^{r_j} \, h_2 t_2) \rightarrow (r_i \approx r_j) \right]. \tag{13}$$

However, in general, condition (13) is not valid, since the interrelations of the properties $E_\alpha(r_i) \rightarrow E_\delta(r_j)$ of the solutions r_i and r_j are often unknown. Moreover, in substantiating the selection of technological solutions and the synthesis of combined methods one must allow for stability of formation of the parameters of the quality of treatment and consider the mechanisms of control over stability of the technological process using feedback [14]. Therefore, it is suggested to use criteria of self-organization as an object function instead of specific values of the combination of the criteria of selection t_{q1}, t_{q2}, ..., t_{qn} [15], since the conditions providing self-organization of surface phenomena and stabilization of formation of the parameters of the quality of treatment are a consequence of an excess structural composition of the considered technological system [1].

2. Analysis of Self-Organization of Surface Phenomena in Processes of Treatment. Interrelated processes of motion and exchange of material and information flows in a technological system are described by the entropy [16, 17]

$$\varepsilon = -\kappa \int_0^\infty p \ln p dp .$$

The equation of balance of local density of entropy $\rho\varepsilon$ in time τ is

$$\partial (\rho\varepsilon)/\partial\tau + \nabla \cdot (\rho\varepsilon \cdot \mathbf{v}) + \nabla \cdot \mathbf{F}_\varepsilon = \sigma . \qquad (14)$$

The production of entropy $\sigma = d\varepsilon/d\tau$ makes it possible to consider the criteria describing different states of the working zone of the technological system.

A study of the state of the working zone and investigation of self-organization of technological processes in combined methods of treatment [15] allowed one to consider the model of an analysis of processes of formation of articles

$$\partial\rho/\partial\tau + \nabla \cdot (\rho\mathbf{v}) = 0 ; \qquad (15)$$

$$\partial (\rho\mathbf{v})/\partial\tau + \nabla \cdot (\rho\mathbf{v} \cdot \mathbf{v}) + \nabla \cdot \mathbf{P} = \rho \sum_{i=1}^{K} \mathbf{F}_{\mathrm{m}i} . \qquad (16)$$

$$\partial (\rho e)/\partial\tau + \nabla \cdot (\rho e \cdot \mathbf{v}) + \nabla \cdot \mathbf{F}_q = \sum_{i=1}^{K} \mathbf{F}_{\mathrm{m}i} \mathbf{F}_{\mathrm{d}i} - \mathbf{P} \cdot \nabla \cdot \mathbf{v} ; \qquad (17)$$

$$\partial C_i/\partial\tau + \nabla \cdot (C_i \mathbf{v}) + \nabla \cdot \mathbf{F}_{\mathrm{d}i} = \sum_{r=1}^{R_0} \nu_{i,r} \omega_r , \qquad (18)$$

where

$$\rho = \sum_{i=1}^{K} M_i C_i ; \qquad (19)$$

$$\mathbf{F}_\varepsilon = \left(\mathbf{F}_q - \sum_{i=1}^{K} \mathbf{F}_{\mathrm{d}i} W_i \right) / T ; \qquad (20)$$

$$\sigma = \mathbf{F}_q \cdot [\nabla (1/T)] - \sum_{i=1}^{K} \mathbf{F}_{\mathrm{d}i} \cdot [\nabla (W_i/T) - (1/T) \mathbf{F}_{\mathrm{m}i}] -$$

$$- (1/T) \mathbf{P}_{\mathrm{dis}} \cdot \nabla \cdot \mathbf{v} + (1/T) \sum_{i=1}^{K} W_i \sum_{r=1}^{R_0} \nu_{i,r} \omega_r . \qquad (21)$$

Analytical model (14)-(18) of the structural changes and phase conversions of the treated material in formation of the surface, which is described by the state (19)-(21), establishes the sequence of formation of structures and phases with an increase of the power of effects by the criteria of transfer

$$\mathrm{Pe} \rightarrow \mathrm{Re} \rightarrow \mathrm{Mr} \rightarrow \mathrm{Gr} \rightarrow \mathrm{Ra},$$

where

$$\mathrm{Pe} = vl/\omega\,; \tag{22}$$

$$\mathrm{Re} = vt/v\,; \tag{23}$$

$$\mathrm{Mr} = \sigma_{\mathrm{surf}} \nabla T t^2/(\rho\omega v)\,; \tag{24}$$

$$\mathrm{Gr} = \beta g \nabla T t^3/v^2\,; \tag{25}$$

$$\mathrm{Ra} = \beta g \nabla T t^4/(\omega v)\,. \tag{26}$$

Use of the criteria of formation of structures and phases (22)-(26) greatly decreases the volume of experimental studies of the processes of formation of a surface layer in highly efficient methods of treatment.

In cases when the physicochemical mechanisms of formation of a surface layer are unknown, it is suggested to describe the processes by the laws of distribution of randon quantities rather than by a system of balance equations (14)-(18) [15].

The Romanowski relation [18]

$$\mathrm{R} = (\lambda_{\mathrm{P}}^2 - k)/\sqrt{2k}\,. \tag{27}$$

allows one to judge the degree of correspondence of the statistical data to the selected law of distribution.

A statistical analysis of the parameters of quality of the studied methods of treatment makes it possible to distinguish the most substantial technological factors and to reveal the interrelations between them. Formation of technological rules of the studied methods of treatment only from narrow ranges of the modes restricted by the conditions of self-organization provides conditions for stabilization of the parameters of quality of a surface layer.

In selecting the number of elements and processes realized by a technological complex it is expedient to consider the interrelation of conflicting requirements to a production system on its reliability and plausibility. The reliability–stability and flexibility–adaptiveness relationship can serve as a criterion which allows one to decide on a rational structure of a technological complex.

In self-organizing systems one can control flexibility and reliability by changing the number of subsystems [17]. Each subsystem i has a strictly defined q_1 and a fluctuating with scattered characteristics q_2. The total yield of the system to a first approximation with account for the additivity of the material and information flows is

$$q^{(i)} = q_1^{(i)} + q_2^{(i)}\,. \tag{28}$$

Assuming that under the conditions of production $q^{(i)}$ is an independent random quantity, we present the total yield as

$$Q = \sum_{i=1}^{n} q^{(i)}\,. \tag{29}$$

Total yield (29), according to the central limit theorem [17], increases in proportion to the number of subsystems n, whereas the degree of scattering increases in proportion to the square root $\sqrt{n}$, similar to relation (27). These estimates are based on an analysis of linear relation (28); in fact, the feedback inherent in Eqs. (14)-(18) leads to even more substantial suppression of scattering of the characteristics.

Thus, it is expedient to create technological complexes of highly efficient treatment providing stabilization of the parameters of quality of a part and automation of control over technological processes on the basis of the fulfillment of conditions for self-organization of surface phenomena.

According to the classification of the methods of treatment, we consider self-organization in the processes of deposition, thermal treatment, deformation, and cutting of surface layers of articles and also in combinations of deposition of coatings and thermal treatment with deformation and cutting in combined methods of treatment.

3. Matching of Processes in Combined Methods of Highly Efficient Treatment. Simultaneous use of several energy fluxes transferred to the working zone by both a technological medium and instrumentation with control elements sharply increases the efficiency of technological operations [19]. However, in the combined use of several fluxes there arise technological limits to stability of combined processes. Therefore, principally new technological complexes for combined treatment can now be created on the basis of processes of self-organization in technological systems [20].

To produce articles by technological complexes, it is expedient to use thermomechanical and electromagnetic flows of substance and energy, since the processes of formation of surfaces of production objects, up to micron accuracy, have basically a thermomechanical character, and electromagnetic flows (due to their simplicity of formation and convenience of monitoring) are most technological [19, 21].

We consider the whole range of technological operations: deposition of coatings, thermal treatment, deformation and cutting of surface layers of treated articles, and the principal combinations of them [10, 11, 19] which should be realized by technological complexes in combined electromagnetic and thermomechanical treatment of articles. The method of electromagnetic fusion is used for deposition of a surface layer [21], in which particles of ferromagnetic powder are alligned with electrode chains in a constant magnetic field, and, as a result of electric-arc discharges, are welded to the surface of the blank. This method makes it possible to deposit coatings of only a certain thickness; then the formed layer looses stability, and protrusions are formed on the surface that are destroyed in subsequent discharges. The processes of surface formation are controlled by electromagnetic flows, which, besides the fixation of ferropowder particles, provide intense heat release at the places of their contact and, regardless of the expenditure of powder, control the thickness of the weld layer, changing its electric resistance [22].

Local inductive electric-contact heating or electric-spark discharge, which allow one, besides heating, to alloy the surface layer of the treated articles using ferropowder particles or introducing additives to the lubricating and cooling fluids, are used for surface thermal treatment of products. Electromagnetic flows in the working zone are mainly those that allow control of both the depth and degree of strengthening of the surface layer in processes of thermal treatment [22].

Ball rollers are used in technological complexes for deformation strengthening and changing of the form of surface layers. In surface plastic deformation, additional degrees of freedom allow the ball, as a result of interaction with the treated surface, to rotate as well as to swing. Without additional heating, the degree of deformation is small and the trajectory of the ball has a loop-like character. In heating, the treated material passes over to a plastic state, due to which the degree of deformation and the coefficient of friction increase. This impedes rotation and decreases the length of, first, the peak-like and, then, sinusoidal trajectory of the ball, thus leading to a decrease in the intensity of plastic deformation. Thus, the process of surface plastic deformation can be controlled by a thermal effect and additional rotation of the ball [22].

A technological complex realizes cutting by traditional cutters, milling cutters, emery disks, and a free abrasive in a magnetic field [23, 24].

In cutting by traditional cutting tools during treatment with preheating, the equilibrium of intensities of temperature weakening and deformation strengthening is violated, and the zone of chip formation loses stability and begins to shift, changing the shear angle. In this case the process of chip formation can be controlled by additional displacement of the rotating tools, which do not allow frozen volumes of metal to fasten to the blade and restores the working part of the cutting edge, thus preventing a sharp increase of temperature in a localized volume of the zone of chip formation [25].

In grinding by an emery disk, with an increase in the depth of cutting in incision or oscillations of the allowance, the forces of cutting and friction increase, which facilitate active crumbling-out of abrasive particles of the disk. Due to this, the intensity of wear of the disk and the velocity of transfer of crumbled particles accompanied by heating increase. As a result the forces of cutting and friction decrease, thus leading to a decrease in the intensity of the process of crumbling-out. These oscillations of intensity make it possible, by restoring the abrasive particles of the disk, to control the process of grinding [26].

Treatment of viscous and plastic materials by an emery disk leads to its greasing, thus impeding self-sharpening. In this case the process of grinding is controlled by electromagnetic flows in magneto-abrasive treatment in which mechanical-chemical removal of metal is performed by unfastened grains of abrasive powder with a ferromagnetic coating under the effect of a constant magnetic field [23, 24].

Results of the study of self-organization in the processes of deposition, thermal treatment, deformation, and cutting of surface layers of articles and also in combinations of deposition of coatings and thermal treatment with deformation and cutting in combined methods of treatment allow one to conclude that a technological complex can work stably in an automatic mode over a long period of time and does not require external control actions. This indicates the expediency of designing technological complexes in the form of autonomous flexible production modules of combined electromagnetic and thermomechanical treatment of articles.

NOTATION

E_{w}, working energy; $\mathrm{E}_{\mathrm{eff}}$, energy of effect; $\mathrm{M}_{\mathrm{ph.-ch}}$, physicochemical mechanism; $\mathrm{M}_{\mathrm{e.s}}$, means of energy supply in space; $\mathrm{F}_{\mathrm{d.e}}$, form of distribution of energy in time; $\mathrm{K}_{\mathrm{sch.t}}$, kinematic scheme of treatment; $\mathrm{N}_{\mathrm{m.t}}$, name of treatment method; $\mathrm{RA}_{\mathrm{m.t}}$, range of application of treatment method; S, scheme of location and fastening of intermediate product; G, treating instrument; R_i, set of technological solutions; r_i, technological solution; $r_{\mathrm{m.t}}$, type of treatment method; r_{surf}, treated surface of part; r_{mat}, treated material; r_{r}, type of range of application of treatment method; $r_{\mathrm{eff.mat}}$, means of effect on material of intermediate product; $r_{\mathrm{e.s}}$, type of energy supplied to treatment zone; $r_{\mathrm{m.e.s}}$, means of energy supply to treatment zone; $r_{\mathrm{e.sour}}$, energy source; $r_{\mathrm{e.m}}$, energy mode of treatment; r_{t}, treating instrument; r_{k}, type of kinematic scheme of treatment; r_{st}, static scheme of treatment; E, predicate; α, δ, ..., γ, properties of technological solution r_i; θ_α, set of values of property α; $\forall$, quantifier of generality; $\exists$, quantifier of existence; h, symbol of preference ratio, which can acquire values $>$, $\geq$, $<$, $\leq$; t_q, criterion of selection; ε, entropy; κ, constant factor; p, density of distribution of probable states of subsystem; $\rho\varepsilon$, local density of entropy; τ, current time; $\mathbf{F}_\varepsilon$, flux density of entropy; $\mathbf{v}$, velocity of flow; σ, production of entropy; ρ, mass density of treated material; $\rho\mathbf{v}$, density of momentum; ρe, density of energy; $\mathbf{P}$, tensor of pressure; K, number of components; $\mathbf{F}_{\mathrm{m}i}$, force of masses affecting i-th component; $\mathbf{F}_q$, density of heat flux; $\mathbf{F}_{\mathrm{d}i}$, density of the diffusion flow of i-th component; R_0, number of reactions; $\nu_{i,r}$, stoichiometric coefficient of i-th component of r-th reaction; M_i, molecular mass of i-th component; ∇, Laplace operator; C_i, concentration of i-th component; W_i, chemical potential of i-th component; T, absolute temperature; $\mathbf{P}_{\mathrm{dis}}$, dissipative part of pressure tensor, which describes viscous forces; Pe, Peclet number; Re, Reynolds number; Mr, Marangoni number; Gr, Grashof number; Ra, Rayleigh number; l, characteristic size in direction of motion of heat source; ω, coefficient of thermal diffusivity; t, thickness of treated surface layer; ν, kinematic viscosity; σ_{surf}, coefficient of surface tension; β, coefficient of volumetric expansion; g, acceleration of gravity; R, Romanowski relation; λ_{p}^2, Pierson criterion; k, number of degrees of freedom used in calculation of theoretical distribution of statistical characteristics; $q^{(i)}$, total yield of subsystem; $q_1^{(i)}$, deterministic yield; $q_2^{(i)}$, fluctuating yield; Q, total yield of system. Mathematical symbols: $\Rightarrow$, consequently; $\wedge$, conjunctively; $\vee$, dissipatively; $\rightarrow$, image; $\approx$, approximately equal.

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