STRUCTURAL SCHEME OF PROCEDURE FOR CALCULATION OF STRESS-STRAIN STATE OF PARTS DURING SURFACING AND FURTHER SERVICE

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Structural scheme of calculation procedure for estimation of stress-strain and microstructural state of parts during surfacing process and further operation is presented. The procedure is based on the following mathematical models: initial condition, including stress-strain and structural state in process of production surfacing; evolution of service and structural parameters in process of operation; accumulation of damageability and reduction of fatigue life; reconstruction surfacing. In comparison with experimental methods, mathematical modelling allows evaluating stress-strain and structural state of the parts in process of surfacing and further operation with lower expenses and more efficient. 20 Ref., 3 Figures.

Keywords: *surfacing, stress-strain state, microstructural state, mathematical modelling, calculation procedure*

Development of procedure for calculation of stress-strain and microstructural state (SSMSS) of parts in process of surfacing and operation requires consideration of number of factors. Current development of mathematical apparatus and computer technologies allow eliminating number of limitations on using in calculation procedures of such characteristics of complex behavior of metal as plasticity, creep, isotropic and directed hardening, dependence of material yield strength on deformation rate, structural transformations etc. This increases safety and reliability of calculations to significant extent. As a result, experimental methods for investigation of processes of manufacture and operation of different parts of machines and mechanisms give way to more efficient and less expensive methods of mathematical modelling.

Procedures for calculation of SSMSS of parts should provide for reliable description of material behavior in area of elastic and inelastic deformation depending on time or rate of deformation. Current experimental and theoretical investigations show that models of viscoplastic behavior of materials, using concept of varying states, are the most suitable for such description. Besides, these models are convenient for computer programs [1]. As a result, deeper analysis of SSMSS of parts based on more realistic mathematical models provides for more proved evaluation of reliability of parts and safety of their operation [2, 3].

Modelling of technological processes. Uniform viscoplastic models of technological processes are more favorable in comparison with models based on separate application of plasticity and creep theory, since single system of equations can describe plasticity, creep and relaxation in a wide interval of temperatures depending on type and rate of external loading. This property is important in modelling of technological processes of manufacture of parts and their further operation. Obtained model of material behavior should be suitable for application in computer, in particular, fine-element programs.

In contrast to particular models of viscoplasticity, current models, applying varying states, describe all main phenomena such as creep, isotropic and directed hardening, dependence of material yield strength on deformation rate, relaxation etc.

This is the reason why such approaches are widely used in present time for simulation of stress-strain state of parts in welding, surfacing and other technological processes, as well as simulation of processes in deposited parts at their further operation. In particular, uniform Bodner–Partom model can be referred to such models.

Modelling of thermomechanical processes. Material of the part in thermomechanical processes can have different temperature histories in manufacture and operation. Initial structure constituents of the material, in particular, steel, are transformed in austenite at the stage of sufficiently high heating. The latter can decay for pearlite, bainite and martensite during cooling. These transformations are accompanied by physical-mechanical characteristics, latent heat, change of volume, appearance of thermal-phase deformations etc. Figure 1 shows model of interaction of thermal-mechanical processes in manufacture and operation of the part.

Figure 2 shows block diagram of monitoring of the part state at all stages of its existence. This scheme can be a basis for development of mathematical models and procedures for calculation of SSMSS of the parts in process of surfacing and further operation at different types of wear and loading. The following models are presented in the block diagram.

Model of part initial state. «Initial state» block includes initial characteristics of the deposited part when it comes into operation. These characteristics can be divided for two parts.

The first one includes actual dimensions of part and its separate layers $\{h_k\}$, their mechanical and thermal-physical characteristics, namely elasticity E, Poisson's ratio ν, heat conduction and heat capacity coefficients k and c etc.

The second part is the parameters with which part is entered into operation. Values of these parameters are determined by manufacturing technology and being specified experimentally or by means of mathematical modelling.

The set of following parameters determine initial state for the deposited part:

$$\Pi^0 = \left\{\varepsilon_{ij}^0,\ \sigma_{ij}^0,\ C_\xi^0,\ K^0,\ \beta_{ij}^0,\ w^0,\ h_k^0\right\}, \qquad (1)$$

where ε_{ij}^0 and σ_{ij}^0 are the residual deformations and stresses; C_ξ^0 is the volumetric concentration of phases: $\xi = a$ (austenite); $\xi = p$ (pearlite); $\xi = b$ (bainite); $\xi = m$ (martensite) etc.; K^0, β_{ij}^0 are the parameters of isotropic and kinematics hardening; w^0 is the damageability parameter; h_k^0, $k = 1, 2, 3$ are the initial dimension of part.

Model of SSMSS of parts in surfacing. The calculation simulates thermal-mechanical processes in surfacing of parts using elements of theory of growing thermal viscoplastic bodies [4–7] in combination with numerical finite element method (FEM). Thermal-kinetic diagrams of austenite decay for corresponding steels [8, 9] are used in phase calculation. Thermal-mechanical behavior of materials is described using modified Bodner–Partom flow model [10–13].

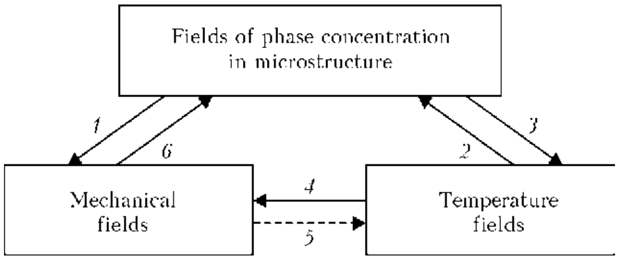

Figure 1. Relation between temperature, mechanical state and evolution of microstructure in process of manufacture and operation of part: *1* — dependence of mechanical properties on phase concentration; volumetric changes due to phase transformations; plasticity caused by phase transformations; *2* — microstructural evolution based on temperature history; *3* — microstructural evolution effecting temperature field via latent heat, and properties of materials depending on microstructure; *4* — interaction through heat expansion and properties of materials depending on temperature; *5* — mechanical heating; *6* — effect of stresses on microstructure transformations

Model of evolution of service parameters. Two aspects can be outlined in this case, namely geometry and strength. The geometry parameter, as a service factor, is related with part wearing. The strength aspect is related with damageability accumulation in places of stress concentration and can result in exhaust of part functions due to fracture. The proposed model as service parameters takes a set of critical dimensions of the parts h_k, $k = 1, 2, 3$, or parameter of damageability w, or service life N_f. They are designated by $\Omega = \{h_k, w, \ldots\}$ symbol in sum form.

Model describing structural transformations. Accurate description of structure transformations plays an important role in analysis of thermal elastoplastic stress-strain state of part in surfacing (welding) and operation [14]. Results received at that also effect evaluation of possibility of part wear resistance and cyclic loading. Today, two methods for investigation of structure transformations are used. The first one applies information from diagrams of isothermal transformation of austenite, as well as in Schaeffler–Delong diagrams [15]. The second uses thermal-kinetic diagrams also termed as CCT-diagrams (Continuous Cooling Transformation) [16, 17]. They describe austenite decay in continuous cooling mode.

Recently, synthetic models, combining advantages and results of both approaches, became widespread. Typical in this sense is a model developed in work [18].

Model of part wearing. Wearing is a process of continuous change of part dimensions taking place in friction, and wear is a result and quantitative measure of wearing.

Wearing result is loss of functional properties of the part as well as its service life due to change

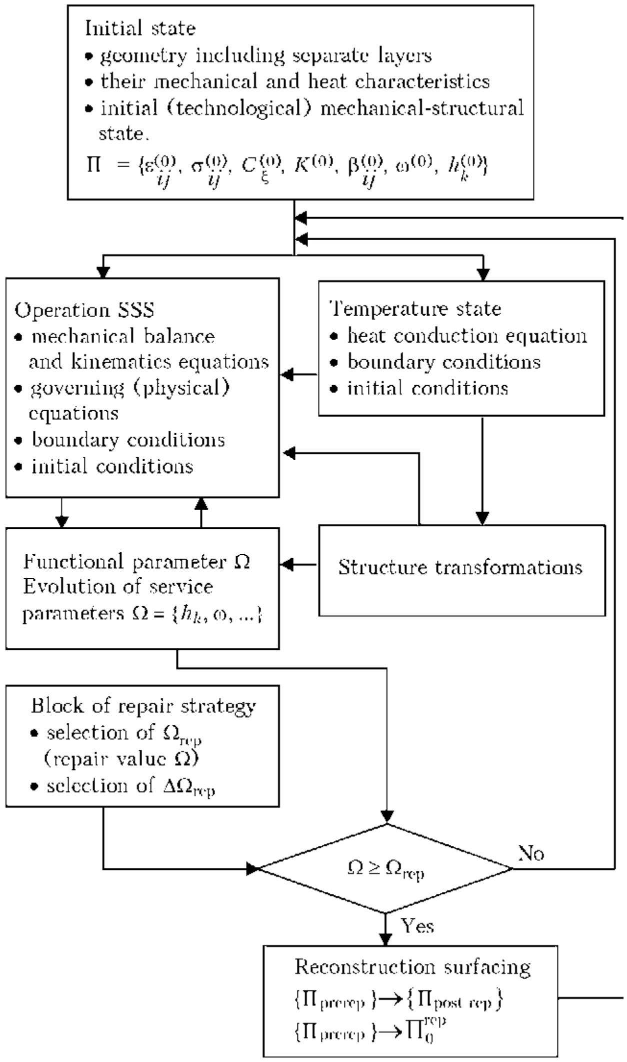

Figure 2. Scheme for monitoring of part state in process of its manufacture, operation and reconstruction surfacing

of part size, formation of stress concentrators in places of wearing, fatigue microcracks etc.

Intensity of wearing is often used for process characterization:

$$I_h = \Delta h/\Delta s = \dot{h}/v, \qquad (2)$$

where $\dot{h}$ is the rate of change of part linear size; v is the slip velocity.

Model of damageability accumulation. Concept of damageability introduced by Kachanov [19] simulates acceleration of creep in metals which results in material fracture. At more general approach, the damageability reflects defects in material such as microdefects and microcracks. When these microdefects are uniformly distributed and have random orientation, then the damageability can be considered as scalar quantity. If orientation of the damageability defects is important then the latter is treated as tensor parameter [20].

Model of reconstruction surfacing. Change of Ω service parameter (see Figure 2) is controlled by simulation of time process of part operation. At each time step it is compared with some «repair» value, reaching which the part is transferred from operation step in reconstruction (repair) surfacing step. From point of view of mathematical modelling, the repair is a transformation of set of pre-repair parameters Π_{prerep} in a set of after repair parameters:

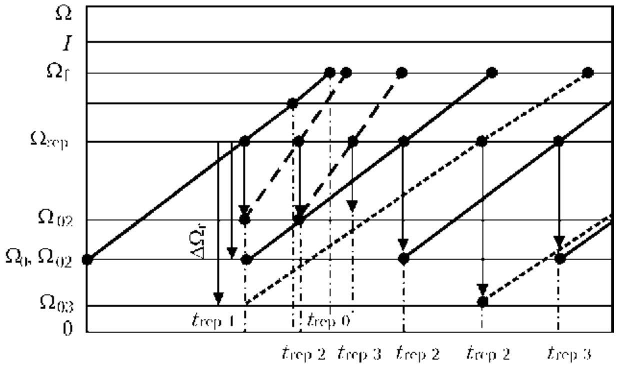

Figure 3. Change of Ω service parameter (SP) in process of operation and reconstruction by different schemes: Ω_f — SP value in part fracture; Ω_{rep} — «repair» value of SP reaching of which determines necessity of part surfacing; Ω_0 — SP value before operation start; Ω_{0n} — SP value after n-th surfacing; $\Delta\Omega_r$ — change of SP as a result of surfacing; $t_{rep\ 0}$ — time during which part works before fracture; $t_{rep\ 1}$ — time of part operation before first repair surfacing; $t_{rep\ n}$ — time before n-th surfacing

$$\Pi^n_{\text{prerep}} \to \Pi^n_{\text{post rep}}, \qquad (3)$$

where $n = 1, 2, 3$ are the repair numbers.

Graphical interpretation of reconstruction surfacing is given by curves of Ω parameter change in time (Figure 3).

The first stage of part operation is finished when Ω parameter reaches Ω_{rep} value at moment of time $t = t_{\text{rep 1}}$. Stepwise change of Ω parameter by $\Delta\Omega_r$ value corresponds to reconstruction stage. There are three types of reconstruction surfacing from point of view of quality:

- *identical on quality*, at which Ω falls to initial value of $\Omega_{01} = \Omega_0$, and after surfacing Ω rises with the same rate as before it;
- *low on quality*, at which Ω falls to $\Omega_{02} > \Omega_0$ value and further increases faster then at initial stage;
- *high on quality*, which results in achievement of Ω_{03} value being lower then Ω_{01} and it rises lower in after surfacing operation.

Surfacing of more wear-resistant material or additional strengthening of deposited metal correspond to the latter case.

Conclusion

Procedure for calculation of stress-strain and microstructural state of parts during surfacing process and further operation was developed. The procedure is based on the following mathematical models, initial condition including SSMSS in process of production surfacing; evolution of service and structural parameters in process of operation; accumulation of damageability and reduction of fatigue life; reconstruction surfacing. In comparison with experimental methods, mathematical modelling allows evaluating SSMSS of the parts in process of surfacing and further operation with lower expenses and more efficient.

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