CALCULATION OF FATIGUE LIFE OF CYLINDRICAL PARTS AT MULTILAYER SURFACING AND SERVICE CYCLIC THERMOMECHANICAL LOADING

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Procedure was developed for calculation of residual stress-strain and microstructural state of cylindrical part at multilayer surfacing aver lateral surface as well as calculation of its thermomechanical state and fatigue life in further service cyclic thermomechanical loading. The procedure was developed in scope of common mathematical model based on theory of growing bodies, current model of viscoplastic non-isothermic flow, thermokinetic diagrams of decay of austenite, deposited and base metals considering residual stress-strain and structural state in single- and multilayer surfacing of parts by layers of different chemical composition, structure and thickness. It allows evaluating the fatigue life of deposited parts depending on value and relationship of service cyclic thermal and mechanical loads and on consumables applied for sublayer and wear-resistant layer. 21 Ref., 7 Figures.

Keywords: *multilayer surfacing, numerical simulation, residual surfacing stresses, cyclic thermomechanical loading, fatigue life*

Hot rolls, continuous casting machine rollers, stamps for metal hot working etc. are subjected to multilayer surfacing and further cyclic service thermomechanical loading [1, 2] in manufacture or repair.

Methods for numerical simulation of thermomechanical processes are used in evaluation of stress-strain and microstructural state of deposited parts and their fatigue life in operation. The nature of surfacing process lies in deposition of molten metal on surface of part being strengthened or repaired. Such processes from point of view of mechanics of deformed solid body are described in scope of nonclassical models of such called growing bodies [3]. Such models applicable to surfacing and related technologies are represented in works [4–7].

Surfacing process is realized in a wide interval of homological temperatures, in which thermal viscoelastoplastic properties of material become apparent. Experimental and theoretical investigations showed that governing equations for inelastic deformation are developed based on unified models [8]. Bodner–Partom [9] model is one of them. It is well grounded by experiments and widely used in practice. Adapting of this model to processes, typical for surfacing, is given in work [10].

Structure of part material can be changes in manufacture and operation in thermomechanical processes. Structural changes are accompanied by change of physical-mechanical characteristics, latent heat of each of used materials, changes of volume, appearance of thermal-phase deformations etc. Thermokinetic diagrams of decay of overcooled austenite [11] in combination with Koistinen–Marburger equation [12] are used in calculation of kinetic of phase concentration.

Finite-element (FE) procedure combined with implicit time-based step schemes of integration of nonstationary equations as well as iteration methods of solving nonlinear boundary thermomechanic problems at each time step were developed for finding solution of considered class of problems in works [5–7, 13]. In whole, current level of numerical simulation of studied processes is registered in works [2, 14, 15].

Calculation of residual and current service stress-strain and microstructural state is an important, but not a final stage of problem solving. The determining is evaluation of life of deposited element of structure and its connection with selection of surfacing consumables and technological parameters of surfacing.

This work represents a procedure for evaluation of fatigue life of cylindrical parts, deposited over lateral surface, under effect of service cyclic thermomechanical loading.

An object of investigation is a hot roll (Figure 1, *a*) from 50KhFA steel, deposited by sublayer of low-carbon steel 08kp (solid wire

Sv-08A) and outer layer of martensite steel 25Kh5FMS (flux-cored wire PP-Np-25Kh5FMS) (Figure 1, *b*). Diameter of roll body makes 1435 mm. After surfacing the roll is subjected to service cyclic thermomechanical loading. It is assumed that the roll is supported by backup roll and does not suffer from bending deformation.

Problem of spiral (helical) surfacing and further cyclic loading of roll is a three-dimension (3D-problem). Such formulation can not be effective for practical calculations at present stage of computer development.

The following approach is proposed for problem solving considering double-stage nature of the process, i.e. surfacing and operation as well as axial length of bead:

1. Surfacing stage is simulated in scope of axial-symmetric problem formulation.

2. Operation stage, characterizing by highly-localized contact temperature-mechanical loads, is described in scope of problem on flat deformation for axial *A*–*A* section of cylinder (see Figure 1, *a*).

At that problem formulation for stage 2 should consider residual deformations ($\varepsilon_{zz} \neq 0$) formed at surfacing stage. In this aspect, such a formulation differs from classical problem of flat deformation, in which residual stresses are absent ($\varepsilon_{zz} = 0$).

Mechanical behavior of the material is described by Bodner–Partom model [9] which includes the following relationships in cylindrical coordinate system O_{rzf}:

• law of flow and equation of plastic incompressibility

$$\dot{\varepsilon}_{kk} = \dot{\varepsilon}^{p}_{ij} + \dot{\varepsilon}^{e}_{ij}, \quad \dot{\varepsilon}^{p}_{kk} = 0, \quad i, j = r, z, \varphi; \tag{1}$$

• Prandtl–Reuss law of flow

$$\dot{\varepsilon}^{p}_{ij} = \frac{D_0}{J_2^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{K_0 + K}{\sqrt{3J_2}}\right)^{2n}\right] s_{ij}, \tag{2}$$

where $J_2 = \frac{1}{2} s_{ij}s_{ij}$; $s_{ij} = \sigma_{ij} - \frac{1}{3}\delta_{ij}\sigma_{kk}$;

• equation of evolution for parameter of isotropic strengthening

$$\dot{K} = m_1(K_1 - K)\dot{W}_p, \quad K(0) = 0, \tag{3}$$

where $\dot{W}_p = \sigma_{ij}\dot{\varepsilon}^{p}_{ij}$; D_0, K_0, K_1, m_1, n are the parameters of model;

• Hook's law

$$\sigma_{kk} = 3K_v(\varepsilon_{kk} - 3\alpha(\theta - \theta_0)),$$
$$s_{ij} = 2G(e_{ij} - e^{p}_{ij}), \quad e_{ij} = \varepsilon_{ij} - \frac{1}{3}\varepsilon_{kk}\delta ij, \tag{4}$$

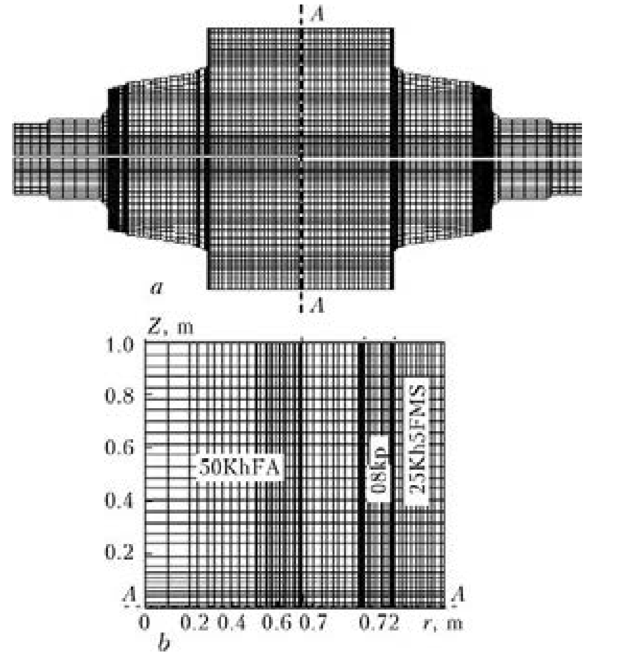

Figure 1. Finite-element layout of forming roll (*a*) and deposited roll body (*b*)

where G, K_v, α are the moduli of shear, compression and coefficient of linear heat expansion.

The relationships are supplemented with universal equilibrium quasi-static equation and equation of heat conduction for axial-symmetric problem:

$$\frac{\partial\sigma_{rr}}{\partial r} + \frac{1}{3}(\sigma_{rr} - \sigma_{\varphi\varphi}) + \frac{\partial\sigma_{rz}}{\partial z} = 0,$$
$$\frac{\partial\sigma_{rz}}{\partial r} + \frac{1}{r}\sigma_{rz} + \frac{\partial\sigma_{zz}}{\partial z} = 0, \tag{5}$$

$$c_V\dot{\theta} = \frac{1}{3}\frac{\partial}{\partial r}\left(\lambda\frac{\partial\theta}{\partial r}\right) - \frac{\partial}{\partial z}\left(\lambda\frac{\partial\theta}{\partial z}\right) + Q, \tag{6}$$

where c_V and λ are the coefficients of volumetric heat capacity and heat conduction; Q is the heat source; $\theta = \partial\theta/\partial t$, as well as boundary and initial (for temperature) conditions:

$$\sigma_{rr} = \sigma_{rz} = 0, \quad -\lambda\frac{\partial\theta}{\partial r} = \alpha(\theta - \theta_a) + cc_0(T^4 - T_a^4),$$
$$r = R, \quad R + h, \quad 0 < z < L, \quad t \neq t^*_{1,2};$$
$$\sigma_{zz} = \sigma_{rz} = 0, \quad \pm\lambda\frac{\partial\theta}{\partial r} = \alpha(\theta - \theta_a) + cc_0(T^4 - T_a^4), \tag{7}$$
$$z = 0, \quad r = R, \quad R + \tilde{h}, \quad t > 0;$$

$$\theta = \theta_a, \quad t = 0, \tag{8}$$

where $\tilde{h} = h_1$; $h_1 + h_2$; $h_{1,2}$ are the thicknesses of first and second layers being deposited; $t^*_{1,2}$ is the time of overlaying of layers being deposited; λ is the heat conduction coefficient; c is the emissivity factor; c_0 is the Boltzmann constant; α is the coefficient of heat exchange; θ_a is the temperature of ambient atmosphere.

Let's consider surfacing process ($t = t^*_{1,\,2}$) and modification of (2)–(4) relationships taking into account build-up process. The problem is solved by FE method. The process of build-up is controlled, i.e. speed of build-up and final body configuration are known. The configuration of body being built-up is covered by fixed FE-mesh. The FE-mesh covers body being built-up in initial configuration as well as all further build-up layers. Thus, mesh (quantity of nodes) does not change in process of numerical simulation.

Properties of area, taken by initial body, are determined by body material properties. Build-up material initially receives properties of «emptiness» material which is considered as thermoelastic with $E = 0$, $\nu = 0$, $\alpha = \alpha_f$ characteristics, where E is the Young modulus, ν is the Poisson's coefficient; α_f is the coefficient of thermal expansion of the build-up material. Thermophysical properties of «emptiness» are taken the same as of material, which is built-up. Therefore, the element is «empty» only from point of view of mechanics. During filling, which is considered as a process developing in time, «empty» elements of the FE-mesh will be filled by build-up material. It should be taken into account that the whole FE-mesh, covering initial body as well as adjacent to body «empty» elements, are deformed in process of filling of the element (build-up).

It is assumed that in moment of filling t^* a certain empty element of the mesh $\Delta V(t^*)$ has ε^*_{ij} deformation, and it is filled by material having temperature θ^*. It is supposed that material of layer being built-up is unstressed up to the moment of contact with the body surface:

$$\sigma_{rr} = \sigma_{\varphi\varphi} = \sigma_{zz} = \sigma_{rz} = 0 \text{ at } t = t^*. \qquad (9)$$

Studied model of build-up contains filling of the element, which has preliminary deformation ε^*_{ij}, by build-up material of θ^* temperature. Thus, conditions (9), basically, mean that

$$\sigma_{ij}(\varepsilon^*_{ij},\ \theta^*) = 0 \text{ in } \Delta V(t^*). \qquad (10)$$

In order to match the governing equations of build-up material (2), (4) with condition (9), (10), it is necessary and quite enough to modify equations (2) and (4) in the following way:

$$s_{ij} = 2G_j(e_{ij} - \varepsilon^p_{ij} - e^*_{ij}),$$
$$\sigma_{kk} = 3K_j(\varepsilon_{kk} - \varepsilon^*_{kk} - 3\alpha_f(\theta - \theta^*)); \quad t > t^*, \qquad (11)$$
$$\varepsilon^p_{ij}(t^*) = 0, \quad K_0(t^*) = K_{0f}(\theta^*).$$

In this case, lower index f shows that parameters refer to material of build-up volume. Thus, in order to fulfill build-up condition (9), all elements, which are built-up, will have the governing equations, individualized by specific values of deformation ε^*_{ij} and temperature θ^*, at which their filling has taken place. Therefore, condition (ε^*_{ij}, θ^*) can be interpreted as «own», since it does not promote stresses.

Thermokinetic diagrams (TKD) are used for calculation of microstructural condition of metal. Figure 2 gives TKD for steel 50KhFA and 25Kh5FMS [11]. They represent transformations in steel at cooling caused by austenite decay (ξ = = A) in ferrite (ξ = F), pearlite (ξ = P), bainite (ξ = B) and martensite (ξ = M). Thick lines limit the transformation areas, and thin ones correspond to cooling curves. Digits show volume per cent of decayed austenite in the output of transformation areas.

Law of new phase ξ accumulation in corresponding areas along the cooling path is represented by phenomenological Koistinen–Marburger equation [12]:

$$p_\xi = \left[1 - \exp\left(-k\,\frac{\theta_s - \theta}{\theta_s - \theta_e}\right)\right] p_{\xi e}, \qquad (12)$$

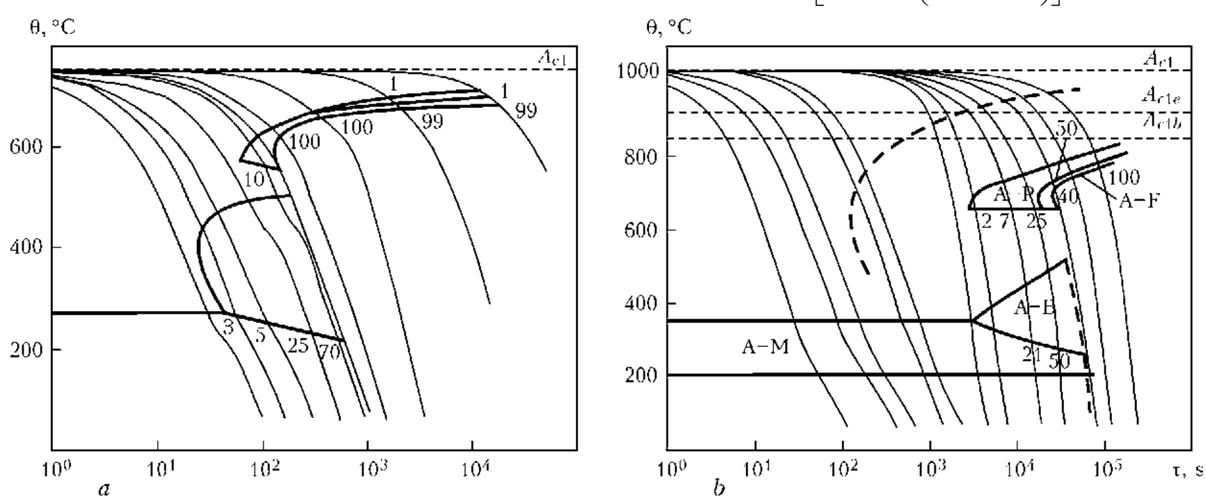

Figure 2. Thermokinetic diagrams for steels 50KhFA (*a*) and 25Kh5FMS (*b*)

where θ_s, θ_e are the temperatures of start and ending of transformation; $p_\xi = C_\xi \cdot 100$ %; $p_{\xi e}$ is the maximum value of new phase for given path; C_ξ is the volumetric fraction of phase; $0 \le C_\xi \le 1$; $\sum_\xi C_\xi = 1$.

The properties of each phase Y_ξ are calculated considering dependence on temperature $Y_\xi = Y_\xi(\theta)$. Linear rule of mixtures is used for calculation of Y macrocharacteristics for random phase composition. The general formula looks like

$$Y(\theta, t) = \sum_\xi C_\xi(\theta, t) Y_\xi(\theta). \quad (13)$$

Physical values, calculated by rule of mixtures, are as follows: c_V is the coefficient of volumetric heat capacity; k is the heat conduction; E is the Young modulus; α is the coefficient of linear thermal expansion; ν is the Poisson's coefficient. The rule of mixtures (13) for wide interval of temperatures is used and matched with experiments described in [5, 15, 16].

Manson–Birger model [17] is used for evaluation of fatigue life. The following is received at asymmetric cycle of loading considering Goodman equation [18]:

$$\Delta\varepsilon = \left(\ln \frac{1}{1-\psi}\right)^{0.6} N^{-0.6} + \frac{2\sigma_{-1}}{E}\left(1 - \frac{\sigma_m}{\sigma_t}\right)\left(\frac{N}{N_0}\right)^k, \quad (14)$$

where ψ is the plasticity at fracture; σ_{-1} is the fatigue limit; E is the Young modulus; σ_m is the mean value of stress in the cycle; σ_t is the tensile strength; N_0 is the base for determining fatigue limit; k is the parameter, determining slope of fatigue curve.

The first summand in (14) can be neglected in absence of cyclic plastic deformation $\Delta\varepsilon^p = 0$.

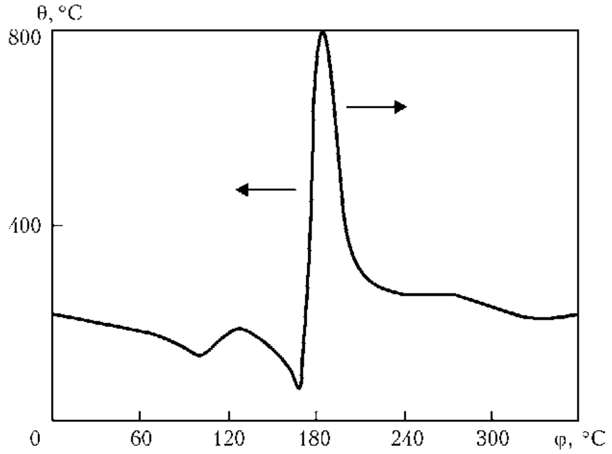

Figure 3. Distribution of temperature along circumferential coordinate on roll surface at $\theta_{max} = 800$ °C

Then $\Delta\varepsilon = \Delta\sigma / E$ and $\Delta\sigma = 2\sigma_{amp}$ are received as a result considering relationships:

$$\ln N = \frac{1}{k} \lg\left[\frac{\sigma_{-1}}{\sigma_t}\left(\frac{\sigma_t - \sigma_m}{\sigma_{amp}}\right)\right], \quad (15)$$

where σ_{amp} is the amplitude value of stress in the cycle.

Transfer from uniaxial equation (15) to multiaxial stressed state is performed using equivalent stress $\sigma_1 = \sqrt{3} s_i = (2/3 s_{ij} s_{ij})^{1/2}$ [17].

Taking into account $\sigma_{iamp} = \sqrt{3} s_{ia}$ and $\sigma_m = 3 s_{im}$ relationships, the following is received after several transformations:

$$\ln N = \frac{1}{k} \lg\left[\chi\left(\frac{\sigma_t - \sqrt{3} s_{im}}{s_{ia}}\right)\right], \quad (16)$$

where

$$\chi = \frac{\sigma{-1}}{\sigma_t} \frac{N_0^k}{\sqrt{3}}. \quad (17)$$

Values $\sigma_t = \sigma_t(\theta)$, $\sigma_{-1} = \sigma_{-1}(\theta)$, $N_0(\theta)$ and $k(\theta)$ for each material were taken from reference literature [18–21], and s_{ia}, s_{im} and θ values were

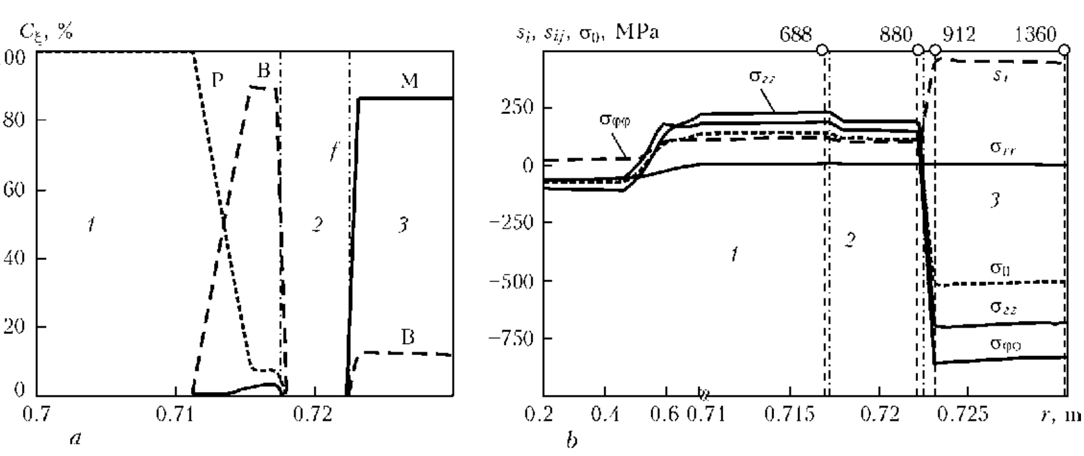

Figure 4. Residual microstrucutural (*a*) and stress-strain (*b*) state of deposited cylinder: *1* — base layer; *2* — deposited sublayer; *3* — deposited wear-resistant layer (digits in upper part of Figure 4, *b* correspond to numbers of points in Figure 5, *b*; $\sigma_0 = 1/3\sigma_{kk}$)

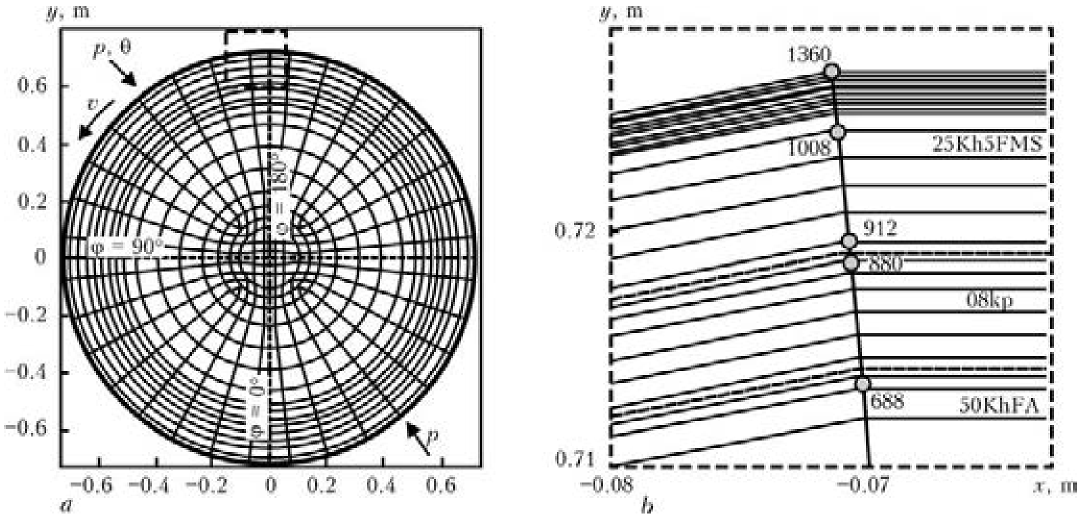

Figure 5. FE-mesh and scheme of roll loading: *a* — full circle; *b* — fragment of circle and numbers of points

calculated using numerical methods in each point of cylinder.

The following assumptions were used for specification of relationship (16): $\sigma_{-1}(\theta)/\sigma_t(\theta)$ = const, k = const, N_0 = const for all temperatures; σ_t depends on temperature and in relationship (16) is calculated for maximum value of temperature in the cycle. Indicated assumptions result in some generalization of multicycle variant of Manson universal equation. Values of parameters in (16) and (17) are given below.

Problem of service loading of the cylinder is formulated in scope of flat deformation for middle section $z = L/2$. In polar coordinate system $O_{r\varphi}$ the typical distribution of temperature and pressure in involute $\varphi^* = \varphi - \omega t$ (where ω is the circular frequency of roll rotation) is shown in Figure 3.

Boundary conditions are taken in the following form in area of contact with hot strip:

$$\sigma_{rr} = \sigma(\varphi^*), \quad \sigma_{rz}(\varphi^*) = 0, \quad |\varphi^*| < \varphi_0^*. \qquad (18)$$

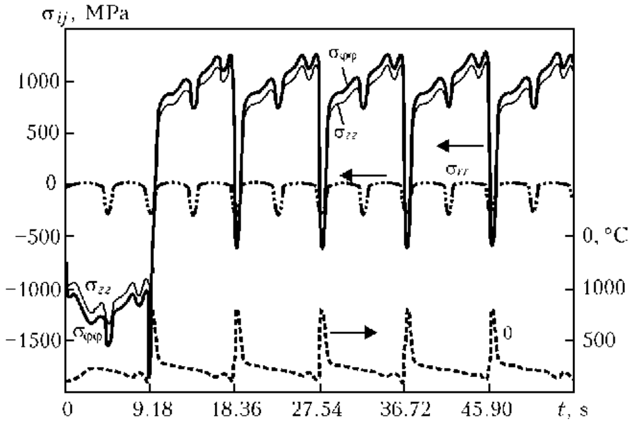

Figure 6. Operating stress-strain state in point 1360 in external deposited layer at p_0 = 300 MPa and θ_{max} = 800 °C

In this case $\varphi^* = \varphi - \omega t$; $\theta(\varphi)$ distribution is given in Figure 3; $\sigma(\varphi^*) = p_0\sqrt{1 - (\varphi^*/\varphi_0^*)^2}$ (where $2\varphi_0^*$ is the area of loading effect).

Calculation of residual stresses. Simplified scheme of instantaneous surfacing by layers was realized in the following mode. Surface of the roll body was heated up to 1800 °C during 2.8 s, then the first layer of steel 08kp (sublayer) of h_1 = 5 mm thickness was deposited on it. After

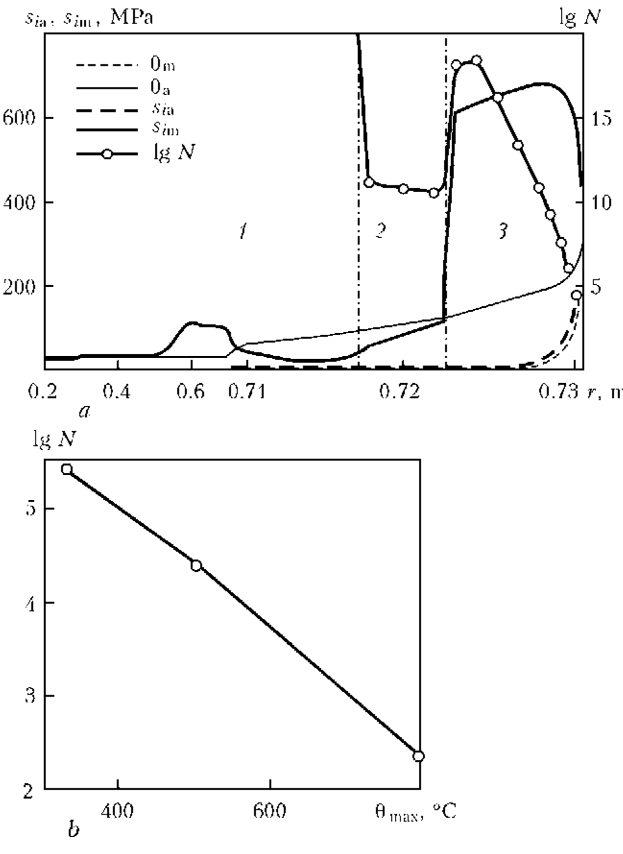

Figure 7. Radial distribution of life lg N, mean s_{im} and amplitude s_{ia} values of stress intensity s_i for p_0 = 0, θ_{max} = = 500 °C cycle (*a*), and dependence of life of external deposited layer on temperature (*b*): *1* — base layer; *2* — deposited sublayer; *3* — deposited wear-resistant layer

part cooled to 300 °C its surface was again heated up to 1800 °C during 2.8 s, and the second layer of h_2 = 8 mm thickness from steel 25Kh5FMS was deposited. Then part cooled to room temperature 20 °C.

Figure 4 shows microstructural and stress-strain state of the deposited cylinder. Dashed lines indicate boundaries of the layers. It is seen that structure of external layer is mainly martensite, and near-boundary zones of the base metal is bainite. Since the martensite phase has maximum volume, then residual stresses in the external layer are compressive ones and that in sublayer and base metal are tensile ones (Figure 4, *b*).

Calculation of service stresses. Figure 5, *a* shows the FE-mesh of cylinder section $z = L/2$ (section *A–A* in Figure 1), and Figure 5, *b* is the mesh fragment, extracted in Figure 5, *a* by dashed square. Digits in this case as in Figure 4 show numbers of points, for which indices of stress-strain state were calculated. Arrows show mobile loading, v is the linear speed of surface points.

Figure 6 shows the time dependencies of components of stresses and temperature for point 1360 close to cylinder surface at v = 0.5 m/s. It is seen that stresses in surface layer of roll in area of contact with hot strip ($\theta = \theta_{max}$) are compressive ones and in cooling they transform into tensile ones. Calculations show that effect of mechanical constituent of loading is insignificant at p_0 < 300 MPa and stress-strain state is formed due to heat loading.

Life evaluation. Life is calculated by formula (16), (17) in each point of cylinder section (see Figure 5, *b*). Figure 7, *a*, as an example, shows a radial distribution of life lg$N$ as well as mean s_{im} amplitude s_{iamp} values of stress intensity s_i for $p_0 = 0$, θ_{max} = 500 °C cycle. It can be seen that surface layers of external deposited layer of the roll has minimum life $N \approx 10^4$. At that, life of the surface layer significantly depends on temperature (Figure 7, *b*). Sublayer and base metal under these conditions have fundamentally higher life.

Conclusions

1. Procedure was proposed for calculation of residual stress-strain and microstructural state of cylindrical part (of forming roll) in multilayer surfacing over lateral surface, as well as calculation of its fatigue life in further service cyclic thermomechanical loading.

2. Developed procedure allows evaluating fatigue life of deposited parts depending on value and relationship of service cyclic thermal and mechanical loads and on surfacing consumables applied for sublayer and wear-resistant layer.

1. Ryabtsev, I.A. (2004) *Surfacing of machine and mechanism parts*. Kiev: Ekotekhnologiya.
2. Ryabtsev, I.A., Senchenkov, I.K. (2013) *Theory and practice of surfacing works*. Kiev: Ekotekhnologiya.
3. Arutyunyan, N.Kh., Drozdov, A.D., Naumov, V.E. (1987) *Mechanics of growing viscoelastoplastic bodies*. Moscow: Nauka.
4. Senchenkov, I.K., Lobanov, L.M., Chervinko, O.P. et al. (1998) Principles of relative longitudinal displacements of plates in butt electric welding. *Doklady NANU*, 66–70.
5. Senchenkov, I.K. (2005) Thermomechanical models of growing cylindrical bodies from physically nonlinear materials. *Prikl. Mekhanika*, 41(**9**), 118–126.
6. Senchenkov, I.K., Chervinko, O.P., Banyas, M.V. (2013) Modeling of thermomechanical process in growing viscoplastic bodies with accounting of microstructural transformation: *Encyclopedia of Thermal Stresses. Springer Ref.*, Vol. 6, 3147–3157.
7. Senchenkov, I., Chervinko, O., Turyk, E. et al. (2008) Examination of the thermomechanical state of cylindrical components deposed with layers of austenitic and martensitic steels. *Welding Int.*, 22(**7**), 457–464.
8. Krempl, E. (2000) Viscoplastic models for high temperature applications. *Int. J. Solids and Structures*, **37**, 279–291.
9. Bodner, S.R. (2000) *Unified plasticity — an engineering approach* (Final report). Haifa: IIT.
10. Senchenkov, I.K., Zhuk, Ya.A., Tabieva, G.A. (1998) Thermodynamically consistent modifications of generalized models of thermoviscoplasticity. *Prikl. Mekhanika*, 34(**4**), 53–60.
11. Senchenkov, I.K., Chervinko, O.P., Dolya, E.V. (2014) Modeling of residual stress-strain and micro–structural state of cylinder in growing along lateral surface with melted metal layers. *Teoriya i Prikl. Mekhanika*, Issue 8(**54**), 34–44.
12. Popov, A.A., Popova, L.E. (1961) *Handbook of heat-treater. Isothermal and thermokinetics diagrams of overcooled austenite decay*. M.-S.: GNTI Mashinostrit. L-ry.
13. Koistinen, D.R., Marburger, R.E. (1959) A general equation prescribing the extent of austenite-martensite transformation in pure iron-carbon alloys and carbon steel. *Acta Metall.*, **7**, 56–60.
14. Radaj, D. (2003) *Welding residual stresses and distortion: Calculation and measurement*. Dusseldorf: DVS.
15. Makhnenko, V.I. (2006) *Safety life of welded joints and assemblies of modern structures*. Kiev: Naukova Dumka.
16. Inone, T. (2011) Mechanics and characteristics of transformation plasticity and metallo-thermo-mechanical process simulations. *Proced. Eng.*, **10**, 3793–3798.
17. Dulnev, P.A., Kotov, P.I. (1980) *Thermal fatigue of metals*. Moscow: Mashinostroenie.
18. Troshchenko, B.T., Sosnovsky, L.A. (1987) *Fatigue resistance of metals and alloys*: Refer. Book, Pt 1. Kiev: Naukova Dumka.
19. Bezukhov, N.I., Bazhanov, V.L., Goldenblat, I.I. et al. (1965) *Calculations of strength, stability and vibration under high-temperature conditions*. Moscow: Mashinostroenie.
20. (2003) *Reference book on grades of steels and alloys*. Ed. by A.S. Zubchenko. Moscow: Mashinostroenie.
21. Johnson, K.L. (1989) *Contact mechanics*. Moscow: Mir.

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