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PULSE HIGH-SPEED ACTION OF A HOT GAS FLOW ON A WALL OF CHROMIUM-NICKEL STEEL

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Consideration has been given to the pulse action of a hot gas flow on a wall of chromium-nickel steel; an analysis has been made of the processes and phenomena of mechanical and thermoerosive wear and fatigue failure of the wall. A structural model of thermal fatigue of chromium-nickel steel has been developed. The wear of the wall of a tube with an inside diameter of 0.03 m under the pulse action of the gas flow and thermal stresses of the second kind has been evaluated numerically. The results of short-duration mechanical tests of 12Kh18N10T steel after thermocycling have been given.

The present investigation seeks to study the problem of the physics of wear and fatigue failure of chromium-nickel steel under the multiple pulse action of a high-velocity hot gas flow on them and to numerically evaluate the wear of a tube wall and thermal stresses of the second order in it.

The action of the gas flow on the steel wall of a tube can be subdivided into the mechanical, thermal, and chemical actions. The first action manifests itself as two force components: the normal (radial) component and that tangential to the interior surface of the tube wall. Normal and tangential mechanical stresses are generated in the wall by their action. The second produces a change in the wall temperature, which in turn influences the thermophysical and strength characteristics of the material and causes the appearance of thermal stresses in the wall. The third is related to the interaction of surface and deep layers of steel with the components of gunpowder gases at high temperatures and pressures.

Change in the inside diameter of the tube is caused by wear, whereas fatigue of the wall is caused by the mechanical and thermal stresses under elastoplastic cyclic loading.

Mechanical wear manifests itself as the failure of the surface wall layer and removal of the material by a gas flow, which is caused by the intense action of "vortex motions" of the gas [1] on the tube wall. The attainment of the limiting values by equivalent stresses on the interior tube wall at a prescribed temperature is the criterion of failure under these conditions.

It is common that the strength characteristics of steel become deteriorated in heating, which contributes to the intensification of the mechanical erosion of the wall. Furthermore, the process is accompanied [1] by the high-temperature adsorption of carbon, nitrogen, and hydrogen from the gas flow by the wall material, which leads to the formation of nitrides and the carbonizing of the interior surface and hence the embrittlement of the steel.

Thermoerosive wear is observed when a material is in the low-viscosity phase or in the molten state. The attainment of the equality of the force of gas-dynamic interaction (tangential component of the gas flow) to the force of surface tension of the material is the criterion of failure of the surface layer.

The theory of thermoerosive wear has been developed based on an analysis of the thermal state of the surface layers of the wall and the dynamics of gas flow near it with consideration for the advances of metallurgy and metallography, the chemical kinetics, adsorption, and chemisorption of different gases in their interaction with the metal wall, and diffusion processes with different structural-phase nonequilibrium states of the metal (steel) layers.

We consider the foundations of this theory. The mechanical and thermophysical characteristics of a material whose basis is iron depend on the structure of the crystal lattice and the character of atomic-interaction forces. The

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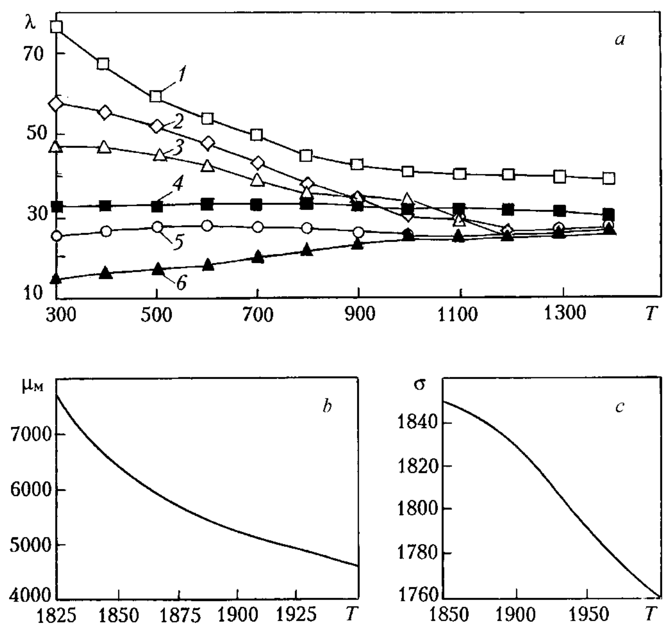

Fig. 1. Change in the thermal conductivity λ (a) of iron and steels, the kinematic coefficient of viscosity μ_m (b), and the surface tension σ (c) of steel as a function of the temperature: 1) Fe; 2) 0.8 steel; 3) 40 steel; 4) 40Kh13 steel; 5) 30Kh13 steel; 6) 17Kh18N9 steel.

thermophysical properties of the material change in heating — the heat capacity grows linearly, whereas the thermal conductivity decreases nonlinearly (Fig. 1). Iron is "softened" with increase in temperature, i.e., the viscosity and surface-tension forces decrease. Figure 1 gives the graphic dependences of the thermophysical characteristics of iron with a carbon fraction of 0.0008% and of steel on temperature.

The dynamic action of the gas flow on the surface of a molten metal manifests itself as shear deformations leading to the failure of this layer and the removal of metal particles by the gas flow and further fragmentation under the action of inertia forces in accordance with the Weber criterion [1]. The condition of separation of the metal from the molten surface has the form $Q_\tau \geq \sigma$.

In the course of the heating–cooling cycle, the thermophysical characteristics of iron change due to the structural-phase transformations and as a result of the interaction of different phases with the components of the gas flow, which variously influences the formation of different zones in the metal. Temperature transformations in steel are described by phenomenological isothermal theory [2]. At the same time, the thermal action of the gas flow on a very thin surface layer of metal is nonisothermal and nonstationary in character. In this connection, thermally the metal wall can be considered as a multilayer structure in which the thermophysical characteristics depend not only on the temperature but also on the degree of structural-phase transformations of the metal in the heating–cooling cycle (Fig. 2). The number of transformation zones over the wall thickness depends on the entire prehistory of cyclic heating–cooling of individual layers of the wall experiencing thermal action in a medium that consists either of a mixture of carbon, oxygen, hydrogen, and nitrogen and their oxides or of light gases — hydrogen or helium.

At high temperatures and pressures, the surface layers of steel are saturated with the above components of the gas flow due to the processes of adsorption and chemisorption. An increase in the concentration of carbon in the surface steel layers leads to a drop in the temperature of the beginning and the end of melting in accordance with the iron–cementite diagram. Implementation of nitrogen in the steel contributes to the formation of brittle nonmetallic compounds, i.e., nitrides, which serve as concentrators of stresses, and reduces the viscosity and plasticity of the steel. The adsorption of hydrogen into the steel structure contributes to the appearance of the hydrogen erosion of metals [3]. The hydrogen absorbed by the steel combines with carbides (primarily with cementite). The ultimate strength of the steel is reduced as a result of failure of cementite. After the saturation of the crystal lattice, the hydrogen begins to accumulate in microcracks, hollows, and pores. The phenomenon of "hydrogen corrosion (stratification and failure of ma-

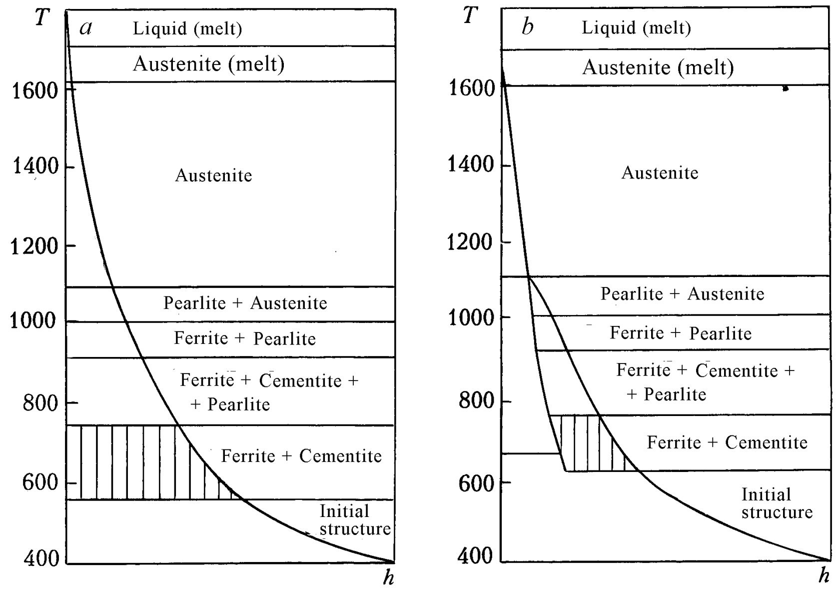

Fig. 2. Diagram of the structural-phase transformations in heating–cooling of the steel wall: a) heating; b) cooling; dashed region, zone of formation of martensite.

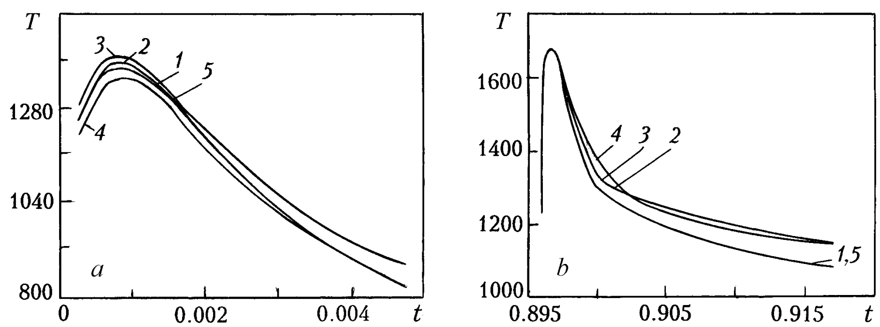

Fig. 3. Change in the temperature of the steel-wall surface with time for the first (a) and fortieth (b) pulses.

terial) is caused by the decarbonization of steels as a result of the combination of carbon with hydrogen to form methane. The mechanism of failure of the metal can be represented as follows. Atomic hydrogen, arriving at the metal surface, begins to diffuse inward. In the intercrystalline space, there accumulates hydrogen whose pressure can generate stresses in the metal which exceed its ultimate strength; this leads to intracrystalline damage in the form of breaks called flocs. Figures 3 and 4 give the results of calculations of the pulse heating of the tube wall with the use of the STRIZh software system [1].

Figure 3 gives the change in the wall-surface temperature with time for the tube with an inside diameter of 0.03 m with a loading frequency of 40 pulses/sec for the first (a) and fortieth (b) pulses in the case where the thermophysical characteristics have been computed for martensite (1), the running state of structural-phase transformations (2), the γ phase (3), the equilibrium composition (4), and the α phase (5).

Figure 4 gives the dependence of the wear and the maximum temperature of the tube-wall surface on the pulse repetition frequency. Under loading conditions where the temperature of the interior surface fails to attain its critical value (lies below the liquidus line), thermoerosive wear is absent but mechanical wear occurs.

Knowledge of cyclic force and temperature loads on the tube wall enables us to pass to consideration of fatigue failure of material.

Mechanical stresses generated in the wall by the action of the normal (radial pressure) and tangential components of the force of the gas flow attain their extremum values on the tube surface, which determines the position of

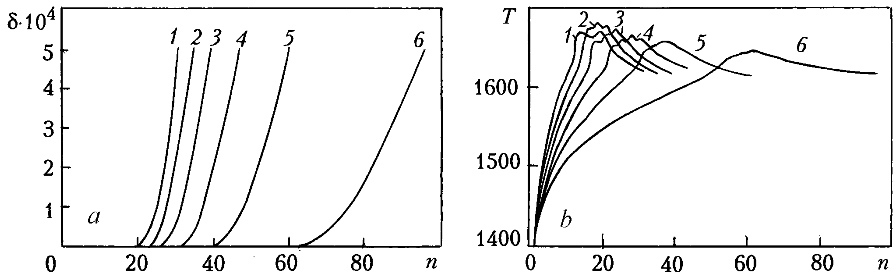

Fig. 4. Influence of the pulse repetition frequency on the wear (a) and the value of the maximum temperature of the interior tube surface (b): 1) 40; 2) 35; 3) 30; 4) 25; 5) 20; 6) 15 pulses/sec.

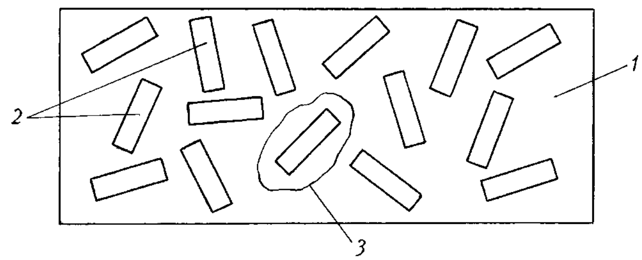

Fig. 5. Hypothetical structural model of chromium-nickel steel: 1) matrix (Fe, Cr, Ni); 2) carbides of metals and silicon; 3) volume element of the material.

a dangerous point [4, 5]. The principal stresses at the dangerous point are $\sigma_1 = \sigma_\theta > 0$ and $\sigma_3 = \sigma_r < 0$. In thermal cyclings, as a result of the alteration of the thermal action of the gas flow and cooling of the wall, temperature stresses are generated in the wall, whose nature is related to the temperature gradients over its thickness. Compressive thermal stresses act in the most heated layers of the wall, whereas tensile stresses act in less heated layers (inside the wall), i.e., dangerous points shift from the interior surface to the exterior surface.

As the calculations show, the equivalent stresses at the dangerous points of the cross section of the tube, which are determined with allowance for the temperature stresses whose nature is represented by temperature gradients, do not exceed the limiting values of the strength characteristics of materials determined under normal conditions. However, deterioration of the strength characteristics in heating of a material can give rise to plastic deformations in it under cyclic loading.

It is noteworthy that, in addition to the thermal stresses in question that are due to the temperature gradients and are called stresses of the first kind, thermal microstresses (called stresses of the second kind) are generated in metals because of their inhomogeneity caused by the polycrystalline structure [6]:

(a) the anisotropy of the coefficient of thermal expansion in an individual crystallite surrounded by a nearly isotropic material;

(b) the difference in the coefficients of thermal expansion and thermal conductivity of neighboring phases in multiphase systems;

(c) phase transformations in individual small volumes, which occur with change in the phase density.

Irreversible shaping, temperature aftereffect, a pronounced acceleration of creep, and the occurrence of thermal fatigue of the second kind are observed in materials as a result of cyclic thermal action [7].

We have tested free (unfastened) rod-type specimens in thermal cyclings with the aim of evaluating the appearance of fatigue of steels under the action of thermal microstresses [8]. The thermal stresses of the first kind in the specimens amounted to 20–30% of the yield strength of the material. Such a level of stresses is sufficient not only for small-cycle fatigue failure but also for multicycle failure in mechanical tests of such specimens. However, the inspection of the specimens after 100 thermocycles enabled us to detect (with a 10–50-fold magnification) numerous fatigue cracks scattered throughout the volume of the material. It is noteworthy that a main fatigue crack (macrocrack) was revealed in none of the specimens tested even after 5000 thermocycles or more. The appearance of microcracks with a low level of stresses of the first kind is attributable to the action of relatively high stresses of the second kind. The

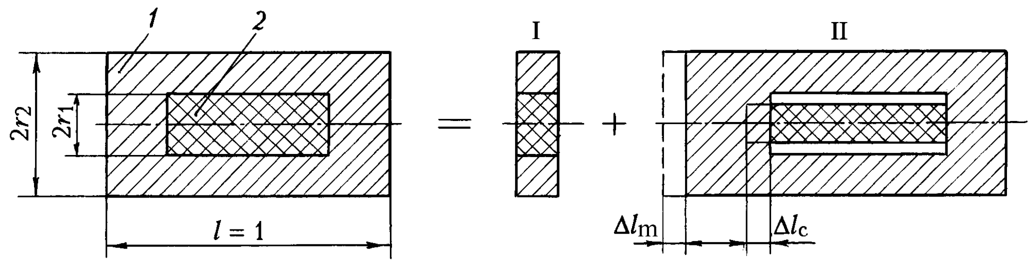

Fig. 6. On the calculation of the stressed state of the element of a material: 1) cylinder (metal); 2) core (carbides); I, disk with a core; II, rod-type system.

latter had the order of the yield strength σ_y, since small-cycle fatigue damage is possible upon the attainment of this level of stresses.

Let us evaluate the order of thermal stresses in chromium-nickel steel in isothermal heating because of the difference in the thermal-expansion coefficients of the phase components. For this purpose we represent chromium-nickel alloy as a dispersion-hardened composite material (CM) consisting of a metallic (m) matrix and a filler in the form of carbides (c) (Fig. 5). From the material, we separate a volume element 3 (Fig. 5), representing it in the form of a cylinder of unit length l with a rod-type core 2 (Fig. 6). In calculating the stressed state, we subdivide the element into two constituent parts: disk with a core I and rod-type system II. The stressed state of the element will be considered as the sum of plane axisymmetric and linear stressed states with components σ_r, σ_θ, and σ_x. As a first approximation, the coefficient of thermal expansion of the matrix will be assumed to be equal to the coefficient of thermal expansion of iron as its basic component, and the averaged (for any carbide) value of the coefficient of thermal expansion will be taken as the coefficient of thermal expansion of the filler. The coefficients of thermal expansion α of the matrix and the filler versus the temperature are plotted in Fig. 7 from the data of [9].

The stresses in disk I will be determined as a function of the pressure on the surface of the metal–carbide (m–c) contact. For the multilayer disk we have the dependence [10] $[a_{ij}] \times [P_i] = [L_i]$, where $[a_{ij}]$ is the pliability matrix, $[P_i]$ is the matrix of contact pressures along the boundaries of the layers, and $[L_i]$ is the load matrix. For the two-layer disk we obtain

$$[a_{11}] \times [P_1] = [L_1]\,, \tag{1}$$

where

$$a_{11} = \frac{r_1^2}{r_2^2 - r_1^2}\left(1 + \frac{r_2^2}{r_1^2}\right) - \mu\,\frac{r_1^2}{r_2^2 - r_1^2}\left(1 - \frac{r_2^2}{r_1^2}\right) + 1 - \mu\,; \quad L_1 = (\alpha_c - \alpha_m)\,E\Delta T\,.$$

Since the matrix volume is much larger than the filler volume, it may be assumed in calculating the stresses that the disk has an infinite thickness, i.e., $r_2 \to \infty$, and $\lim a_{11}\big|_{r_2 \to \infty} = 2$. From (1) we have

$$P_1 = \frac{\alpha_c - \alpha_m}{2}\,E\Delta T\,. \tag{2}$$

The stresses in the disk of infinite thickness are determined by the expression

$$\sigma_{r,\theta} = \pm\,P_1\,\frac{r_2^2}{r^2}$$

or with account for (2) when $r = r_1$ by

$$\sigma_{r,\theta} = \pm\,\frac{(\alpha_c - \alpha_m)}{2}\,E\Delta T\,. \tag{3}$$

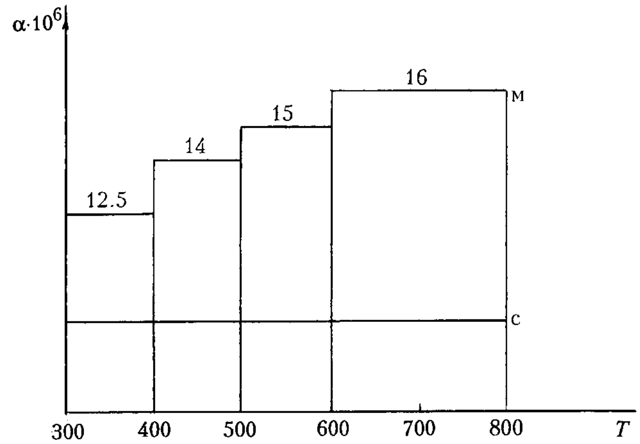

Fig. 7. Coefficient of thermal expansion of steel vs. temperature (m, metal; c, carbide).

The stresses in the core [5] are determined by $\sigma_{r,\theta} = -P_1$ or, with account for (2), by

$$\sigma_{x,\theta} = \pm \frac{(\alpha_c - \alpha_m)}{2} E\Delta T .$$

The axial stresses in rod-type system II (see Fig. 6) will be determined on condition of equality of the axial displacements of its elements ($\Delta l_m = \Delta l_c$):

$$\sigma_x^c = \frac{N}{A_c}, \quad \sigma_x^m = \frac{N}{A_m},$$

where

$$N = \frac{(\alpha_m - \alpha_c)}{A_m - A_c} A_m A_c .$$

For the cylinder of infinite thickness we have lim $N\big|_{A_m \to \infty} = (\alpha_m - \alpha_c)EA_cT$; then we will have $\sigma_x^c = (\alpha_m - \alpha_c)E\Delta T$ and $\sigma_x^m \approx 0$. The stresses on the contact surface of the element of the material are $\sigma_x^c = (\alpha_m - \alpha_c)E\Delta T$, $\sigma_{r,\theta}^c = 0.5\sigma_x^c$, $\sigma_x^m = 0$, and $\sigma_r^m = \pm 0.5\sigma_x^c$.

Let us evaluate thermal stresses of the second kind in the wall of chromium-nickel steel in isothermal heating in the interval of temperatures 300–800 K: $\sigma_x^c = \sum_{i=1}^{k} (\alpha_{m_i} - \alpha_c)E\Delta T_i$, where k is the number of temperature intervals and i is No. of the temperature interval. In accordance with Fig. 8, we take the number of temperature intervals to be four; then we will have $\sigma_x^c = ((12.5 - 8) + (14 - 8) + (15 - 8) + (16 - 8)\cdot 2)\cdot 2\cdot 10^{11}\cdot 10^2 = 670$ MPa and $\sigma_{r,\theta}^c = 0.5\sigma_x^c = 335$ MPa.

The equivalent stresses, according to the theories of maximum tangential stresses for the cylinder σ_e^m and the largest deformations for the core σ_e^c are, respectively, $\sigma_e^m = \sigma_1 - \sigma_3 = \sigma_r - \sigma_\theta = \sigma_x^c = 670$ MPa and $\sigma_e^c = \sigma_1 = \sigma_x^c = 670$ MPa.

Thus, in chromium-nickel steels at temperatures much lower than T_{melt}, high tensile thermal stresses of the second kind are generated, attaining their extremum values along the metal–carbide phase boundaries. In the microlayer of the material of the interior tube surface, the tangential stresses of the second kind, combining with the tensile tangential (largest) stresses from the mechanical action of the gas flow, can give rise to plastic deformations and to subsequent fatigue failure of the material.

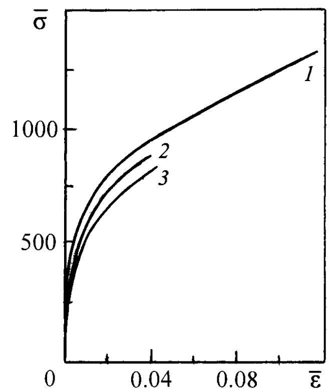

Fig. 8. True diagrams of deformation of 12Kh18N10T steel: 1) N_{tc} = 0; 2) 1500; 3) 5000.

Tensile tests of 12Kh18N10T steel after the thermocycling of cylindrical specimens in the interval 300–900 K (under stresses of the first kind $(0.2–0.3)\sigma_y$) have shown a substantial (of 60–70%) deterioration of the strength characteristics and the plasticity characteristics (of 2.5–3 times) after 1500–2500 thermocycles (Fig. 8). This is attributable to the large number of cases of damage in the specimen volume [11]. Thus, the experiments conducted have confirmed the fact that fatigue damage can appear in the wall material under the thermomechanical action of the gas flow.

CONCLUSIONS

1. The processes and phenomena related to the action of a high-velocity hot gas flow on a steel wall have been analyzed; wear under operating conditions has been evaluated numerically.

2. The nature of the fatigue damage to the wall of chromium-nickel steel under thermomechanical loading has been established.

3. The level of thermal stresses of the second kind in chromium-nickel steels in isothermal heating has been evaluated numerically.

NOTATION

A_m and A_c, cross-sectional areas of the cylinder and the core, m^2; a_{11}, coefficient of the pliability matrix, dimensionless quantity; E, Young modulus, MPa; h, depth of heating; σ, surface tension of the melt, kN; l, cylinder length, dimensionless quantity; Δl_m and Δl_c, axial displacements of the cylinder and the core, m; L_1, coefficient of the load matrix, MPa; n, pulse repetition frequency; N, normal force, kN; N_{tc}, number of thermocycles; P_1, pressure on the surface of core–cylinder contact, MPa; Q_τ, tangential component of the force of the gas flow, kH; r_1 and r_2, internal and external radii of the cylinder, m; t, time, sec; T, temperature, K; ΔT, temperature increment, K; α, coefficient of thermal expansion of the material, α_m and α_c, coefficients of thermal expansion of the matrix (metal) and the filler (carbide), K^{-1}; δ, wear of the tube wall, m; $\bar{\varepsilon}$, true relative elongation at rupture, dimensionless quantity; λ, thermal-conductivity coefficient, W/(m·grad); μ, Poisson coefficient, dimensionless quantity; μ_m, kinematic coefficient of viscosity, Pa·sec; σ, surface tension; $\bar{\sigma}$, true stress, MPa; σ_1, σ_2, and σ_3, principal stresses $(\sigma_1 \geq \sigma_2 \geq \sigma_3)$, MPa; σ_r, σ_x, and σ_θ, radial, axial, and tangential stresses, MPa; σ_y, yield strength, MPa. Subscripts and superscripts: c, carbide; m, metal; r, x, and θ, radial, axial, and tangential directions; y, yield; τ, tangential stresses; tc, thermocouple; melt, melting; e, equivalent.

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