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Method of investigation of the stress-strain state of surface layer of machine elements from a sintered nonuniform material

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Abstract. A microstructural model of surface layer of machine elements from a nonuniform material is developed. With using of this model a calculation scheme that includes basic structural elements is created. Each element is characterized by the following properties: density, elastic modulus, thermal conductivity, linear expansion coefficient and Poisson's ratio. A mathematical model of surface layer of machine elements from a sintered nonuniform material is formulated on the basis of solution of two-dimensional heat-conduction and elasticity problems by the finite-element method. The created algorithms for solution of these problems are used for formation of an automated system for thermal-strength calculations. This system is surrounded with some original techniques which provide the investigation of the stress-strain state of surface layer of machine elements from a sintered nonuniform material.

Introduction

The machine elements from a sintered nonuniform material (SNM) with high and stable operational characteristics have particular importance for general engineering. However, the creation of effective technologies of machining and operation of these details is hindered by imperfect understanding of mechanical processes in difficult structure material under technological and operational loads [1 – 3]. The results of investigation of the stress-strain state can considerably add this knowledge and to increase reliability of machine elements [4 – 5]. The decision of this problem complicates imperfection of methods for investigation of the stress-strain state of surface layer of machine elements with taking into account structure heterogeneity and dependence of structural elements properties from temperature.

The goal of this work is to create the method of investigation of the stress-strain state of surface layer of machine elements from a SNM on the basis of the constructed microstructural and mathematical models. The decision of the formulated goal is based on the system of representations formulated and tested in papers [6 – 8].

Microstructural model

The geometrical parameters of machine elements, the main properties of SNM and the manufacturing and operating conditions form the macro stress-strain state of the details. The microgeometry and the structure of the machine elements surface which are characterized by: (1) the grains size and shape, (2) the thickness of the intergranular phase, (3) the state of the interfaces between the grains, (4) the size and shape defects (5) the properties of the structure elements of SNM produce the local stress fields. These stresses are very dangerous for machine elements because they are formed on interface of different phases each of which has its own density, elastic modulus, Poisson's ratio, linear expansion coefficient, thermal conductivity and specific heat. The adverse combination of these properties leads to appear of technological and operational defects occurred on these interfaces. These defects are accumulated in the surface layer of machine elements for some period and they lead to wear, chipping or destruction of details. Therefore, the prevention of appearance of technological and operational defects is the main aspect in decision of the problem of reliability increase of details from a SNM and so finally we should learn to minimize the microstress in this material.

The approach of the isolation of a repeating elementary fragment of the SNM surface layer consisting of its basic elements is used [6]. Investigation of different SNM structures indicates that they consist of a set of closely packed grains of basic and strengthening phases of arbitrary shape between which the intergranular phase is distributed in a relatively uniform manner (Fig. 1, a). Of course, pores and cracks are also elements of real structure but their account complicates the mathematical model very much. Therefore, we assume that the machine elements consist of defect-free SNM. Thus, the isolated surface fragment contains the following basic components: grain 1; intergranular phase 2; and matrix 3 (Fig. 1, b). Research shows that an ellipsoid may be adopted as the equivalent configuration of the grains.

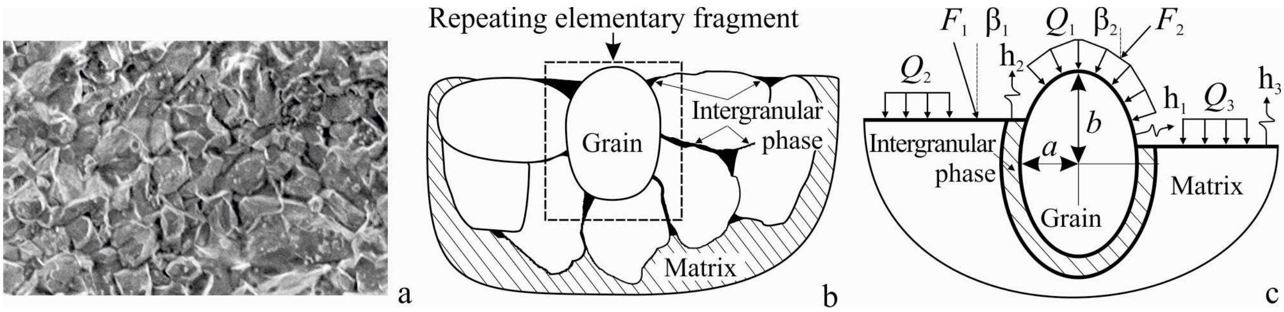

Fig. 1. Structure (a), repeating elementary fragment (b) of SNM surface layer and calculation scheme (c)

The calculation scheme is created on the basis of the microstructural model (Fig. 1, c). It includes a single ellipsoidal grain (semiaxes *a* and *b*), which is attached to the matrix by an intergranular phase (thickness b_f). Point forces F_1 and F_2 (inclined at β_1 and β_2 to the *y* axis) and heat fluxes Q_1, Q_2 and Q_3 act at arbitrary points on the external contour of grain, intergrain phase and matrix. The convective heat losses are taken into account with heat-transfer coefficients h_j (j = 1, 2, 3) at sections of the contour with no heat flux. Values of the grain size in the calculation scheme are specified on the basis of metallographic data. All the components in the calculation scheme are characterized by their density, elastic modulus, thermal conductivity, specific heat, linear expansion coefficient and Poisson's ratio.

Mathematical model

A mathematical model of the stress-strain state of surface layer of machine elements from a SNM is produced on the basis of solution of two-dimensional heat-conduction and elasticity problems by the finite-element method [7]. The following assumptions are made: (1) a plane problem is considered, (2) there is no plastic deformation, (3) SNM surface layer doesn't have any defects.

Isotropic plate (thickness Δ) in the rectangular coordinate system {*x*, *y*} is considered. The corresponding nonsteady heat-conduction equation takes the form

$$\lambda(T)\left(\frac{\partial^2 T(t)}{\partial x^2}+\frac{\partial^2 T(t)}{\partial y^2}\right)-\underline{\underline{\rho c(T)\frac{\partial T(t)}{\partial t}}}=0, \qquad (1)$$

where $T(t)$ is the temperature; $\lambda(T)$ is the thermal conductivity; ρ is the density; $c(T)$ is the specific heat; *t* is the time.

Neglecting the second term in Eq. (1), we obtain the steady heat-conduction equation, which must satisfy four types of boundary conditions at the plate contour.

(1) If the temperature is known at some plate boundary, the boundary condition takes the form

$$T(t) = T_s(s), \qquad (2)$$

where *s* is the coordinate of the boundary points.

(2) If convective heat transfer occurs at the boundary (heat-transfer coefficient h), the boundary condition takes the form

$$\lambda\left(\frac{\partial T(t)}{\partial x}l_x+\frac{\partial T(t)}{\partial y}l_y\right)+h\,[T(t)-T_\infty]=0 \quad (3)$$

where T_∞ is the ambient temperature; $lx = \sin\alpha$ and $ly = \cos\alpha$ are directional cosines (Fig. 2a).

(3) If heat flux Q is specified at the boundary, the boundary condition takes the form

$$\lambda(T)\left(\frac{\partial T(t)}{\partial x}l_x+\frac{\partial T(t)}{\partial y}l_y\right)+Q=0 . \quad (4)$$

(4) If the boundary is heat-insulating, the boundary condition takes the form

$$\frac{\partial T(t)}{\partial x}l_x+\frac{\partial T(t)}{\partial y}l_y=0 . \quad (5)$$

Entry conditions at the decision of the equation of nonsteady heat conductivity take the form

$t\,(x, y, 0) = 0$

The plane elasticity theory problem takes the form

$$\varepsilon_{11}=\frac{\partial u}{\partial x};\quad \varepsilon_{22}=\frac{\partial v}{\partial y};\quad \varepsilon_{12}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}, \quad (6)$$

where ε_{11}, ε_{22}, and ε_{12} are the linear and angular strains; u, v are the displacements along the x and y axes, respectively.

The plane stress state may be described in the form

$$\sigma_{11} = E(T) / (1 - v^2)\,[\varepsilon_{11} + v\,\varepsilon_{22} - (1 + v)\,\alpha\,T] \qquad (1 \Leftrightarrow 2), \quad (7)$$

$$\sigma_{12} = [E(T) / 2\,(1 + v)]\,\varepsilon_{12}, \quad (8)$$

where α_{11}, σ_{22}, and σ_{12} are the normal and tangential stresses; E is the elastic modulus; μ is Poisson’s ratio; α is the temperature coefficient of linear expansion.

The algorithms for solution of the steady and nonsteady thermoelasticity problems are developed for the considered model. The algorithm for solution of the steady thermoelasticity problem consists of two stages: (1) solution of the heat-conduction problem and determination of the plate temperature field for the current heat flux Q_T; (2) determination of the plate stress state under the action of point forces and the steady temperature $T_T(x, y)$ at the current heat flux Q_T. The algorithm for solution of the nonsteady thermoelasticity problem also includes two stages: (1) solution of the heat-conduction problem for time t_T and determination of the plate temperature field; (2) determination of the plate stress state under the action of point forces and the steady temperature $T_T(x, y, t_T)$ at specified heat flux Q.

Automated system of thermal-strength calculations

The microstructural and mathematical models and algorithms are used to create an automated system of thermal-strength calculations for simulating stress-strain state of surface layer of machine elements from a SNM [8|. The system consists of three functional subsystems and an operative database. In the preprocessor, a calculation system and a set of finite elements are formed; initial data are introduced and diagnosed; auxiliary calculations are performed; graphical documentation from the initial data is prepared. In the processor, the steady and nonsteady thermoelasticity problems are solved. The results are transformed in the postprocessor, which also prepares the graphical documentation from the results. The constant data set corresponds to the database of mechanical and thermophysical properties of refractory compounds. Data on the construction, load, and methodological parameters form the initial data for each problem. The characteristics required for automatic generation of finite elements are also formulated.

Traditional finite-element methods are used to establish the reliability of the algorithms and verify the accuracy of the calculations: (1) the symmetry principle is verified (Fig. 2), (2) the reactions in the supports (fixed points) are analyzed, (3) the temperature at the fixed point is analyzed by solving the steady and nonsteady heat-conduction problems, (4) the influence of the finite elements selected on the accuracy of the calculations is considered. All the iterative processes are found to converge and an error of the putting in algorithms $\varepsilon = 10^{-6}$ is obtained after 10 – 12 iterations.

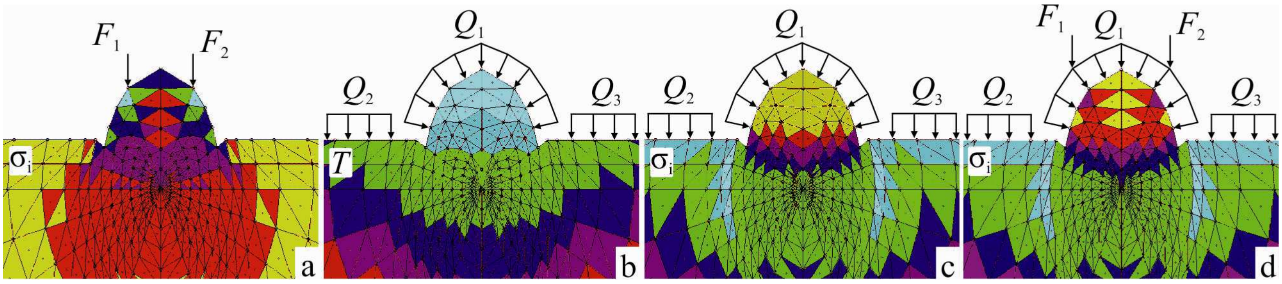

Fig. 2. Stress intensity (*a*, *c*, *d*) and temperature (*b*) fields in TiC (grain) – MgO (intergrain phase) – S_3N_4 (matrix) plate under the action of point forces $F_1 = F_2 = 0.003$ N (*a*), heat fluxes $Q_1 = Q_2 = Q_3 = 7 \cdot 10^9$ W/m^2 (*b*, *c*) and the complex external loading $F_1 = F_2 = 0.003$ N; $Q_1 = Q_2 = Q_3 = 7 \cdot 10^9$ W/m^2 (*d*)

This system is surrounded with some original techniques. For example, a method of control points which has allowed to compare the calculations results to investigate structural concentrators of stresses in surface layer of machine elements from a SNM is developed.

Conclusion

1. Microstructural model of surface layer of machine elements from a SNM is developed on the basis of repeating elementary fragment which include all the structural elements which are characterized by their density, elastic modulus, thermal conductivity, specific heat, linear expansion coefficient, and Poisson's ratio. The calculation scheme is created on the basis of microstructural model.
2. Mathematical model of surface layer of machine elements from a SNM is constructed on the basis of the solution of two-dimensional heat-conduction and elasticity problems by the finite-element method.
3. The proposed automated system for thermal-strength calculations of surface layer of machine elements from a SNM permits the simulation of the stress-strain state under the action of external loads with allowance for the material structure. Numerical experiments show the reliability of the proposed algorithms and the high precision.

References

[1] Jing kun Guo, Stress design of the ceramic grain boundary, *Materials Chemistry and Physics*, 1996, Vol. 47. pp. 99-102.

[2] Kuzin, V.V., Technology for machining high-refractory ceramic parts based on silicon nitride, *Refractories and Industrial Ceramics*, 2006, Vol. 47, No. 4, P. 204-208.

[3] Kuzin, V. A model of forming the surface layer of ceramic parts based on silicon nitride in the grinding process, *Key Engineering Materials*, 2012, Vol. 496, Precision Machining, pp. 127-131.

[4] Haiyan Liu, Stephen M. Hsu, Modeling of microfracture-induced wear and wear transition in sliding of polycrystalline alumina ceramics, *Wear*, 1996, Vol. 195, pp. 169-177

[5] Daxu Zhang, Hayhurst, D.R., Stress-strain and fracture behaviour of 0/90 and plain weave ceramic matrix composites from tow multi-axial properties, *International Journal of Solids and Structures*, 2010, Vol. 47, pp. 2958–2969.

[6] Kuzin, V.V., Microstructural model of ceramic cutting plate, *Russian Engineering Research*, 2011, Vol. 31, no. 5, pp. 479-483.

[7] Kuzin V.V., Myachenkov, V.I. Stress-strain state of ceramic cutting plate, *Russian Engineering Research*, 2011, Vol. 31, no. 10, pp. 994-1000.

[8] Grigor’ev, S.N., Myachenkov, V.I., Kuzin, V.V., Automated thermal-strength calculations of ceramic cutting plates, *Russian Engineering Research*, 2011, Vol. 31, no. 11, pp. 1060-1066.