STRESS INHOMOGENEITY IN A CERAMIC SURFACE LAYER UNDER ACTION OF AN EXTERNAL LOAD. PART 1. EFFECT OF COMPLEX MECHANICAL LOADING

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First results are provided for a comprehensive study of stress inhomogeneity in a ceramic surface layer. The stress-strained state of a ceramic surface layer based on zirconium dioxide under the action of a complex mechanical load is studied. High stress inhomogeneity is revealed in ceramic structural elements. A requirement is noted for considering stress inhomogeneity in describing a wear and failure mechanism, and also in designing objects of this ceramic for prescribed operating conditions.

Keywords: ceramic, inhomogeneity, stress-strained state, surface layer, modelling, zirconium dioxide, design.

Improvement of the operating properties of ceramic components is possible on the basis of a profound study of processes occurring within a surface layer [1 – 3]. It is particularly important to determine features of material inhomogeneous deformation, under action of external loads [4, 5]. However, these studies are significantly complicated by a requirement for considering boundaries between ceramic interacting structural elements having different properties [6, 7].

Analysis of the stress-strained state of structural inhomogeneous bodies makes it possible to determine features of their failure, and to formulate effective recommendations for a reduction in the intensity of a process [8, 9]. An important aspect of analysis is a study of local stresses at boundaries of interacting structural elements of inhomogeneous material and evaluation of the volumetric stress distribution in a surface layer of a component of this material with different external action [10, 11]. Solution of this complex task makes it possible to realize the idea of computer design of structurally inhomogeneous materials [12]. This approach may also be used for automation of a search for optimum sintered material compositions for manufacture of innovative objects intended for specific operating conditions.

The aim of this work is to evaluate stress inhomogeneity in a surface layer of zirconium oxide ceramic under action of a complex mechanical load. The effect of thermal and combined loading is also studied; results of these studies will be provided future articles.

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RESEARCH PROCEDURE

Solution of this problem is based on numerical modelling of deformation processes using methodology of control by ceramic component operating properties [5, 9], and a set of models [2, 6]. A design scheme is formulated on their basis for carrying out numerical experiments in a SolidWorks simulation software module (Fig. 1).

The design layout is presented in the from of a structure with a size of $38 \times 18 \times 4$ μm, consisting of fragments of components D1 and D2 made of ceramic and copper respectively. These components are in close contact, and the form of the interface takes account of real microgeometry of a ce-

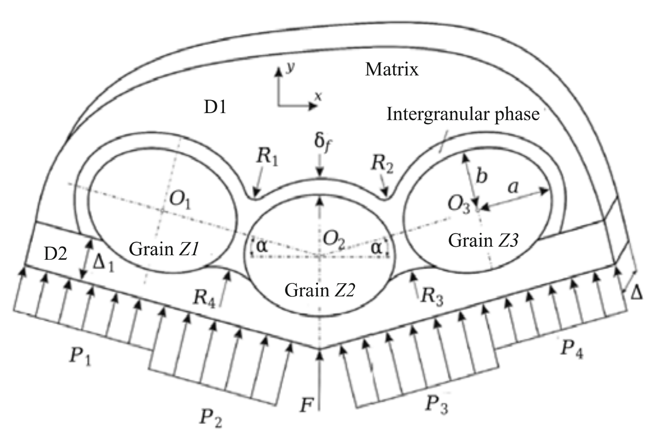

Fig. 1. Design layout.

ramic component, formed after sintering or machining. A fragment of component D1 consists of three grains $Z1$, $Z2$, $Z3$ of elliptical shape and sizes $a = 5$ μm and $b = 4$ μm, which are fixed in a matrix through intergranular phase of thickness $\delta_f = 1$ μm. The major axis of grain $Z2$ coincides with axis x, and major axes of grains $Z1$ and $Z3$ are arranged at angle $\alpha = 15°$ to axis x, and the distance between the axes of neighboring grains is 11 μm. Junctions of intergranular phase at grain boundaries have radii of contact curves $R_1 = R_2 = 1$ μm and $R_3 = R_4 = 4$ μm. At the outer side of a grains, intergranular phase, and matrix there is a fragment of component D2 of thickness $\delta_f = 2$ μm. The grain and matrix of component D1 is made of zirconium dioxide (density $\rho = 5.68$ g/cm^3, elasticity modulus $E = 180$ GPa, Poisson's ratio $\mu = 0.2$); the intergranular phase is made of MgO ($\rho = 3.4$ g/cm^3, $E = 315$ GPa, $\mu = 0.18$), and D2 is made of copper ($\rho = 8.9$ g/cm^3, $E = 110$ GPa, $\mu = 0.37$). In future this structure will be called "ceramic system ZrO_2–MgO–ZrO_2–Cu."

Two forms of force were applied to the free surface of a component in the design layout (see Fig. 1); distributed of forces P_1, P_2, P_3, and P_4, were applied over the whole contact length; concentrated force F was applied to a section of contact with grain $Z2$, and this force operated over a direction towards the grain center. The specific combination of these loads was considered by a force complex, each if which is characterized by values of load provided in Table 1.

In order to analyze results of numerical experiments a control point (CP) method was used, by which we understand fixed finite structural elements. The number and location of CP was determined taking account of the purpose oft his study. Schematic arrangement and numbering of CP, and also a fragment of an actual finite element network are shown in Fig. 2. All of the CP selected for component D1 are located in surface layers of grains $Z1$ (CP1-CP25), $Z2$ (CP26-CP51), $Z3$ (CP52-CP76), and intergranular phase, adjacent to grains (CP77-CP137) and to the matrix (CP138-CP182), and also matrix surface layer adjacent to intergranular phase (CP183-CP221). Stresses in component D1 were not studied and CP in this structural element were not separated. After carrying out calculations, values of stress intensity σ_i in each CP were obtained.

Results of calculations are presented in the form of graphical image of the stress intensity field and curves connecting numerical values of stress intensity at CP. Stress inhomogeneity coefficient K_Δ is used for quantitative evaluation of stress inhomogeneity in a surface layer of a working channel of a ceramic fiber, i.e., a dimensionless index determining the level of change in stresses in a surface layer of a ceramic structural element, and expressed numerically by the ratio of the greatest value of stress intensity to the least value. Values of K_Δ were analyzed in a surface layer of each grain, layers of intergranular phase adjacent to a grain and to a matrix, and in layer of matrix adjacent to intergranular phase. Use of this procedure made it possible to study the effect in detail of a set of force loads on the stress-strained state of ceramic tools taking account of material structure and to supplement knowledge obtained in [13, 14].

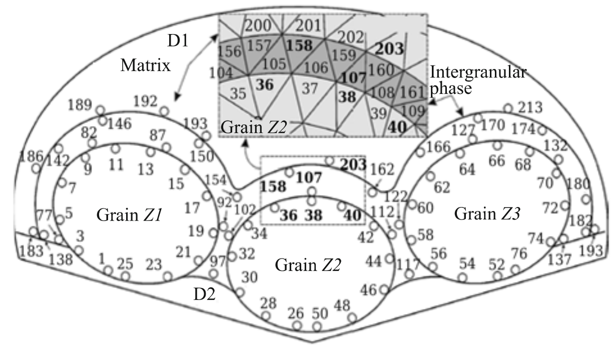

Fig. 2. CP location in object D1 surface layer of ceramic of the system ZrO_2–MgO–ZrO_2–Cu.

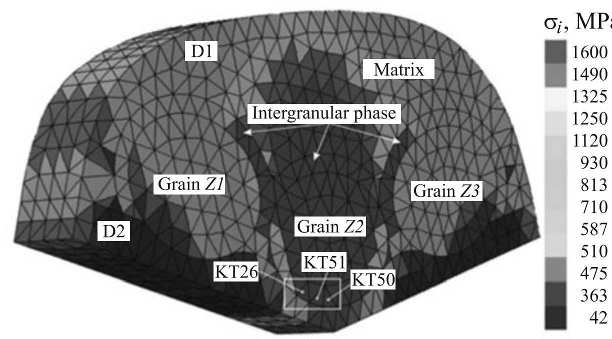

Fig. 3. Diagram of stress-strained state of structural elements of ceramic of the system ZrO_2–MgO–ZrO_2–Cu under action of force complex No. 1.

RESULTS AND DISCUSSION

An example is given in Fig. 3 of a graphical image of a stress intensity field in the surface layer of ceramic of the system ZrO_2–MgO–ZrO_2–Cu under action of a complex mechanical load. A qualitative estimate of the stress field shows that the stress-strained state of a surface layer of this ceramic differs significantly in different areas. Values of stress intensity σ_i in structural elements of ceramic of the system ZrO_2–MgO–ZrO_2–Cu under action of force complex No. 1 (see Table 1) vary from 42 to 1600 MPa. The greatest

TABLE 1. Combination of Load in Force Complexes, N

Load	Force complex number		
	1	2	3
F	0.01	0.02	0.04
$P_1 = P_4$	0.05	0.01	0.02
$P_2 = P_3$	0.01	0.02	0.04

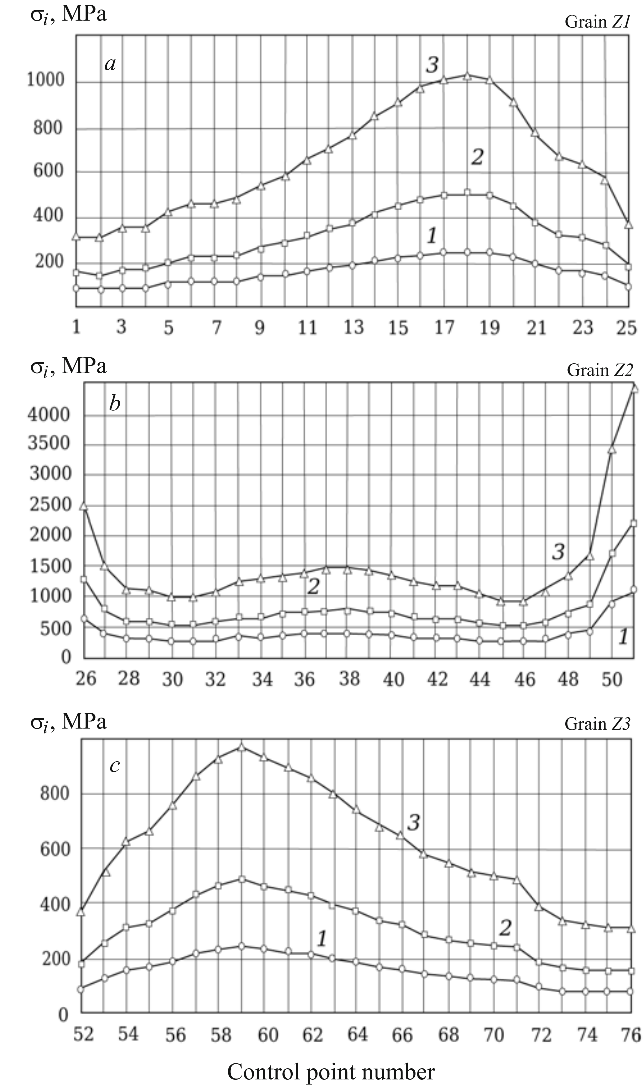

Fig. 4. Effect of complex force load on stress intensity σ_i at CP of surface layer of grain *Z*1 (*a*), *Z*2 (*b*), and *Z*3 (*c*) in ceramic of the system ZrO_2–MgO–ZrO_2–Cu. Force complex number shown on curves.

stresses arise in the central grain *Z*2, and in intergranular phase and matrix around it.

For comparison of a more detailed picture of the effect of force loads on stress-strained state in a surface layer we analyze results of calculating stress intensity in each structural element of ceramic of the system ZrO_2–MgO–ZrO_2–Cu.

The stress-strained state is shown in Fig. 4 for three grains under the action of different force complexes. The nature of change in local stresses in the surface layer of grain *Z*1 under action of a complex force load has a quite simple form (see Fig. 4*a*). The gradual increase in stress intensity σ_i recorded from CP1 to CP18, and then from CP18 to CP25 reveals a reduction in σ_i, i.e., the greatest stresses σ_i form at CP18.

An increase in force load leads to a marked increase in stress intensity σ_i at all CP of a surface layer of grain *Z*1. For example, under action of force complex No. 1 the range of change in stress intensity σ_i is 82 – 256 MPa, with load No. 2 it is 164 – 512 MPa, and with load No. 3 it is 329 – 1024 MPa. The stressed state of a surface layer of grain *Z* 1 is characterized by inhomogeneity coefficient $K_{\Delta z1} = 3.12$.

The nature of change in local stresses in the surface layer of grain *Z*2 under action of complex force loads is different, and it has a more complex form (see Fig. 4*b*). In the area from CP26 to CP31 there is a reduction in σ_i. In the section from CP31 to CP38 there is a marked increase in stress, and then in section CP38 to CP46 a reduction in stress is recorded. In the section from CP46 to CP51 there is a sharp increase in local stresses. The greatest values of σ_i are recorded at CP51, and their values are 1125, 250, and 4500 MPa under action of force complexes Nos. 1 – 3 respectively. It is seen that the greatest local stresses in grain *Z*2 form at CP26 and CP51, which are most closely placed to the area concentrated force F_i application. Analysis of the dependences obtained showed that $K_{\Delta z2}$ in a surface layer of grain *Z*2 is 4.83, which is significantly higher compared with the value in the first case.

A change in stresses in a surface layer for grain *Z*3 under action of a complex load is shown in Fig. 4*c*. It is seen that curves almost "mirror" image the dependence typical for grain *Z*1, and the least value of σ_i is recorded at CP59. With force load No. 1 the range of change in σ_i is 79 – 245 MPa, with load No. 2 it is 159 – 491 MPa, and with load No. 3 it is 319 – 982 MPa. The stressed state of a surface layer of grain *Z*3 is characterized by $K_{\Delta z3} = 3.1$.

The effect of complex force load on local stresses in layers of intergranular phase adjacent to grains and matrix is shown in Fig. 5. It is established that the nature of change in σ_i in the layer of intergranular phase under action of complex force load has a complex form with sharp changes in stress values, and curves are almost symmetrical with respect to central grain *Z*1. The range of change in σ_i in layers of intergranular phase adjacent to grains and matrix is almost the same, and under action of force complex No. 1 it is 110 – 424 MPa, for No. 2 it is 221 – 848 MPa, and for No. 3 it is 443 – 1697 MPa.

Average values of stress inhomogeneity coefficients $K_{\Delta ip1}$ and $K_{\Delta ip2}$ in layers of intergranular phase adjacent to grains and matrix comprise 3.85 and 3.62 respectively. Attention is drawn to the extremely unstable change in stresses in a layer of intergranular phase adjacent to grain *Z*2. However, in the section from CP99 to CP115 (see Fig. 5*a*) $K_{\Delta ip1} = 1.6$, which is lower by almost a factor of three than the average value of this coefficient calculated for the whole surface. It is apparent that in order to estimate instability it is necessary to use a coefficient capable of considering presence of structural stress concentration.

The nature of change in σ_i in a layer of matrix adjacent to intergranular phase under the action of a complex mechanical load is presented in Fig. 6. All curves are symmetrical with respect to CP202. Values of σ_i in the surface layer of matrix under action of force complex No. 1 change from 73 to 334 MPa, complex No. 2 from 146 to 668 MPa, and No. 3

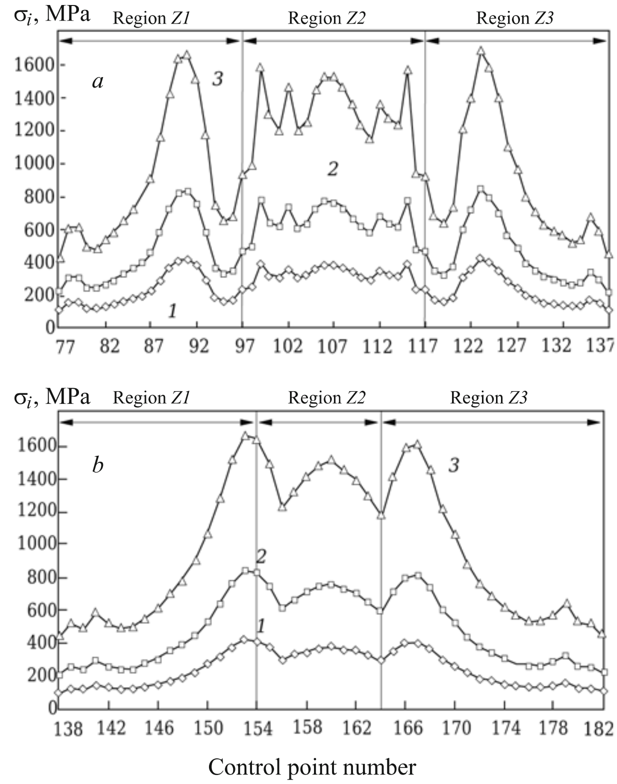

Fig. 5. Effect of complex force load on stress intensity σ_i at CP of intergranular phase surface layer, adjacent to grains (*a*) and matrix (*b*) in ceramic of the system ZrO_2–MgO–ZrO_2–Cu. Force complex number shown on curves.

from 293 to 1337 MPa. The greatest stresses form in a matrix surface layer in the area of grain *Z*2, for which there is the greatest effect of concentrated force F_i. The stressed sate of a matrix surface layer has $K_{\Delta m} = 4.6$.

CONCLUSION

By summarizing results of numerical experiments it may be noted that the stress-strained state of a surface layer of ceramic based on zirconium dioxide under action of a complex mechanical load is characterized by high inhomogeneity. The greatest local stresses under action of a complex force load form within grain *Z*2 and intergranular phase around it, which is determined by action of a concentrated force. The inhomogeneity coefficient $K_{\Delta z}$ for stresses in a surface layers of grains *Z*1, *Z*2, *Z*3 equals 3.12, 4.83, and 3.1 respectively. The stress inhomogeneity coefficient in layers of intergranular phase adjacent to grains comprises 3.85 and 3.62 respectively. The stressed state of a surface layer of matrix adjacent to intergranular phase is characterized by $K_{\Delta z1} = 4.6$.

Results of this study also point to a requirement for considering stress inhomogeneity forming a surface layer of a ceramic component based on zirconium dioxide under action of a complex mechanical load, in describing their wear and failure mechanisms, and also in designing components for prescribed operating conditions.

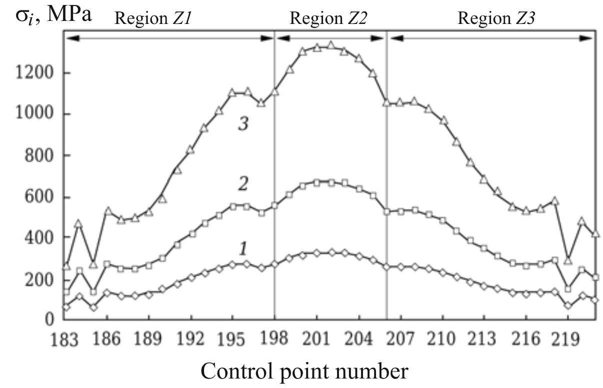

Fig. 6. Effect of complex force load on stress intensity σ_i at CP of intergranular phase surface layer, adjacent to intergranular phase of ceramic of the system ZrO_2–MgO–ZrO_2–Cu. Force complex number shown on curves.

REFERENCES

1. V. S. Bakunov and A. V. Belyakov, "Ceramic strength and structure," *Ogneupory Tekhn. Keram.*, No. 3, 11 – 15 (1998).
2. V. V. Kuzin, S. N. Grigor'ev, S. Yu. Fedorov, et al., "Model of fiber operation during fiber manufacture," *Zagatovit. Proizvod. Mashniostroenie*, No. 2, 24 – 28 (2013).
3. V. V. Kuzin, "Effective use of high density ceramic for manufacture of cutting and working tools," *Refr. Indust. Ceram.*, 51, No. 6, 421 – 426 (2011).
4. V. É. Vil'derman, Yu. V. Sokolkin, and A. V. Zaitsev, "Evolution of structural damage and macrofailure of an inhomogeneous medium for a critical deformation stage," *Mekhan. Kompozit. Materialov*, 33, No. 3, 329 – 339 (1997).
5. B. V. Kuzin, "Methodological approach to improving the operating capacity of ceramic tools," *Vestn. Mashinostroeniya*, No. 9, 87 – 88 (2006).
6. V. V. Kuzin, "Microstructural model of ceramic cutting plate," *Vestn. Mashinostroeniya*, No. 5, 72 – 76 (2011).
7. G. G. Gnesin, "Main study areas and development of nonoxide ceramic materials," *Ogneupory Tekhn. Keram.*, No. 5, 2 – 7 (2000).
8. Yu. V. Sokolkin and A. A. Tashkinov, *Structurally Inhomogeneous Body Deformation and Failure Mechanics* [in Russian], Nauka, Moscow (1984).
9. S. N. Grigor'ev and V. V. Kuzin, "Promising application of tools with ceramic cutting plates in contemporary machining," *Steklo Keram.*, No. 8, 17 – 22 (2011).
10. T. D. Shermergor, *Microinhomogeneous Media Elasticity Theory* [in Russian], Nauka, Moscow (1977).
11. G. A. Vanin, *Composite Material Micromechanics* [in Russian], Naukova Dumka, Kiev (1985).
12. V. E. Panin, et al., (editors), *Physical Mesomechanics and Computer Construction of Materials, Vol. 2* [in Russian], Nauka, Novosibirsk (1995).
13. S. N. Grigor'ev, V. V. Kuzin, D. Burton, et al., "Effect of force loads on stress-strained state of ceramic oxide cutting plates," *Vestn. Mashinostroeniya*, No. 1, 67 – 71 (2012).
14. S. N. Grigor'ev, V. V. Kuzin, D. Burton, et al., "Effect of ceramic properties on stress-strained state of a cutting plate under steady-state thermal conductivity conditions," *Vestn. Mashinostroeniya*, No. 4, 76 – 70 (2012).