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Crack propagation in ceramic composites with layered granular structure

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Fracture experiments under conditions of subcritical crack extension were performed with double torsion and single-edge notched bend specimens of different alumina-based ceramic composites having layered granular structure. It is shown that it is possible to increase significantly the work-of-fracture as a result of layered granular structure organization. The pecularities of structure influence on the crack propagation kinetics were investigated, and the possibilities of acceleration and deceleration of subcritical crack growth are reported.

1. Introduction

The effective process of crack propagation deceleration in brittle ceramic materials is the reorientation of a crack with respect to the direction of the action of maximum tensile stresses [1]. The processes of crack reorientation occur if in the ceramic material structure there are regions of local residual stresses or regions of structure having weakened boundaries between components. It can be assumed that the crack reorientation has a substantial influence on not only the threshold values of the crack propagation resistance, but also on the kinetics of crack propagation and on the energy characteristics of the fracture resistance. This study presents some results of an investigation of the kinetic diagrams as well as the fracture resistance characteristics (including energy) for ceramic composite materials having a layered granular structure [2].

2. Experimental procedure

The presence of randomly oriented structural cells, consisting of alternating layers of thickness 100–150 μm, separated by an interlayer boundary, is characteristic of the sintered layered granular material structure. The following materials were investigated: materials with the cells structure of alternating layers of alumina, grain size 1–2 μm (material type 1); materials with alternating layers of fine-grained synthetic alumina and porous spherolites of commercial alumina (material type 2); materials with alternating layers of synthetic fine-grained alumina and hollow corundum microspheres with diameter 20–100 μm (type 3); and materials with alternating layers of fine crystalline Al_2O_3 and metallic chromium (type 4). The external layers in the structural cells of the materials of types 2–4 were layers of fine-grained alumina. The volume content of layers with fine-grained structure was 70%. For comparison, materials having the normal dense fine crystalline structure: cermet Al_2O_3–Cr with a chromium content of 30% (type 5) and Al_2O_3 (type 6), were examined. Fig. 1 shows an example of composite type 2 structure.

The layered granular materials were obtained by cold pressing layered granule batches at 200 MPa pressure and sintering in an air furnace at 1700 °C (for ceramic compositions) or *in vacuo* at 1650 °C (for ceramic–metal compositions). The maximal temperature of the sintered cycle was maintained for 1 or 0.5 h for ceramic and ceramic–metal compositions, respectively.

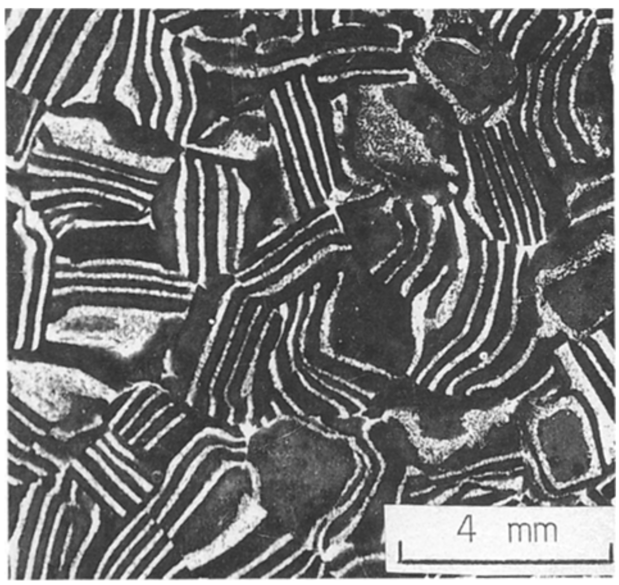

Figure 1 The structure of type 2 composite: dark layers are fine crystalline alumina, and white layers are porous layers of alumina spherolites.

The characteristics of the fracture resistance–critical stress intensity factor, K_{Ic}, and specific work of fracture, γ_F – were determined by bending prismatic cross-section specimens $8 \times 10 \times 50$ mm^3 by a concentrated force. The length of the initial notch in the specimens was half the specimen width, and the radius of curvature at the notch tip was approximately 30 μm. The tests were carried out using an Instron-type machine with displacement control at the speed of crosshead displacement 8×10^{-7} m s^{-1}.

To study the kinetics of crack propagation, tests on plane specimens with an initial notch for double torsion were carried out. The speed of specimen deformation was 8×10^{-8} m s^{-1}. To measure the velocity of crack propagation, v, over a wide range of values, both load relaxation and monotonic active loading methods were used. Values of v were calculated using the equation

$$v = (P_i l_i / P^2)(dP/dt) \quad (1)$$

under load relaxation, and

$$v = ((d\delta/dl) - \lambda_o(dP/dt))/P(\lambda_o/l_o) \quad (2)$$

under active loading, where P_i and l_i are the load and the crack length at the moment relaxation begins, P and t are the current values of load and time, l_o is the initial notch length, δ is the deflection; and λ_o is the initial specimen compliance. The increment of the crack length, Δl, was evaluated using the relations.

$$\Delta l = [(P_i/P) - 1]l_i \quad (3)$$

under load relaxation, and

$$\Delta l = (1/\lambda)\Delta\lambda \quad (4)$$

under active loading, where $\Delta\lambda$ is the increment of specimen compliance. To measure the compliance, periodic off-loadings and repeated specimen loadings were carried out during the test process. The stress intensity factor values were calculated using the formula given by Evans [3].

3. Results and discussion

The materials with fine crystalline structure (types 5 and 6) were monotonically deformed to ultimate load. The presence of a non-linear deformation stage is characteristic of layered granular materials. Deformation in materials type 1 and 3 was accompanied by load jumps with a significant decrease in load, which certified the discrete character of their fracture. The fractographic analysis carried out using optical microscopy and SEM showed that reorientation and branching of a crack along the cell boundaries in interlayer boundaries, take place during the fracture process of type 1–4 materials. Examples of crack trajectories are shown in Fig. 2. For type 2 and 3 materials, the crack propagates in the porous layers of spherolites and microspheres, respectively. The cracks

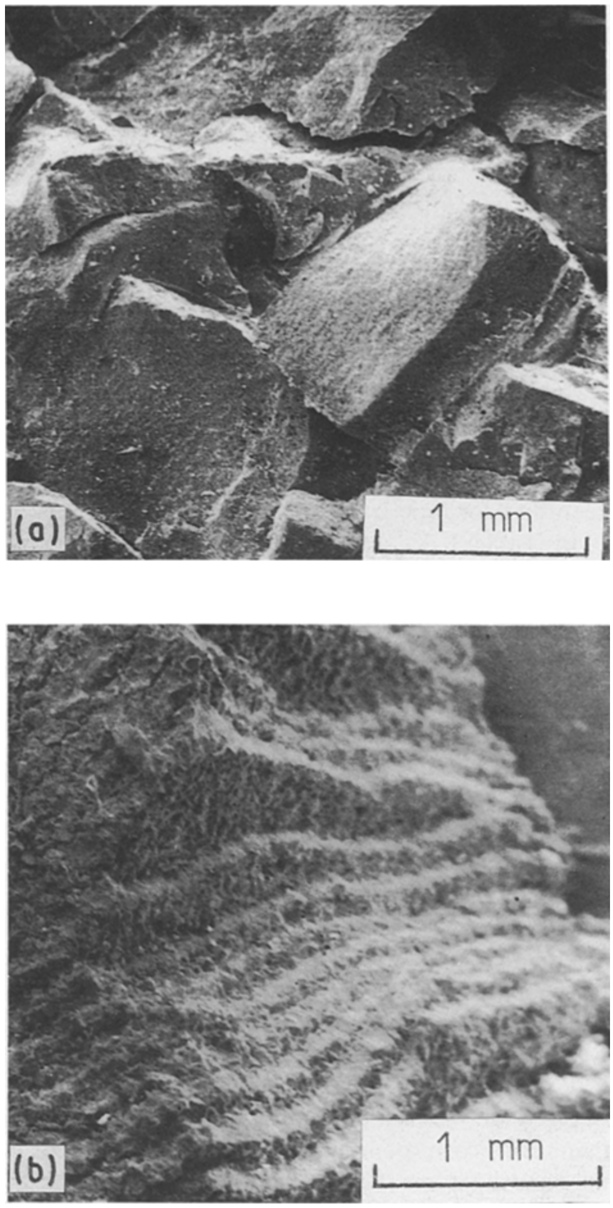

Figure 2 Scanning electron micrographs of fracture surfaces of (a) type 1 alumina layered granular ceramics and (b) type 2 alumina/alumina composite.

TABLE I. Values of fracture toughness and work-of-fracture for composites investigated

Structural type of composite	volume content of open pores (%)	Fracture toughness K_{Ic} (MPa m$^{1/2}$)	Work-of-fracture, γ_F (J m^{-2})
1	2	4.0	50
2	12	2.4	100
3	15	2.6	250
4	5	6.0	1000
5	5	6.0	400
6	0	3.0	10

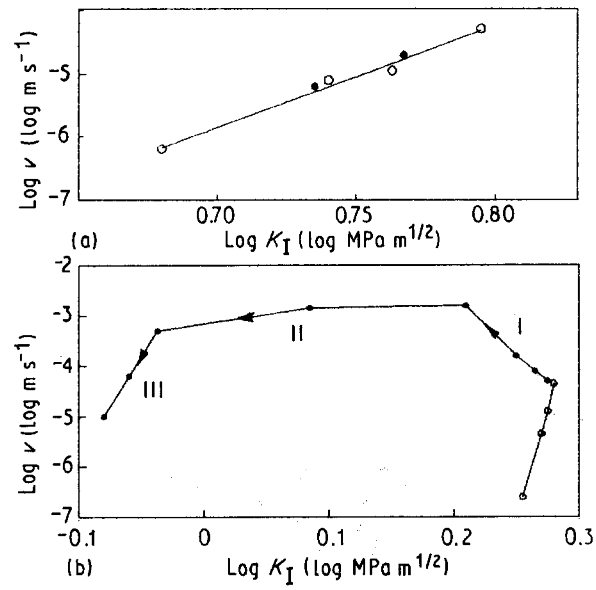

Figure 3 The kinetic diagrams of crack propagation in (a) type 6 alumina ceramics, and (b) type 2 alumina/alumina composite. (●) Load relaxation tests; (○) active loading.

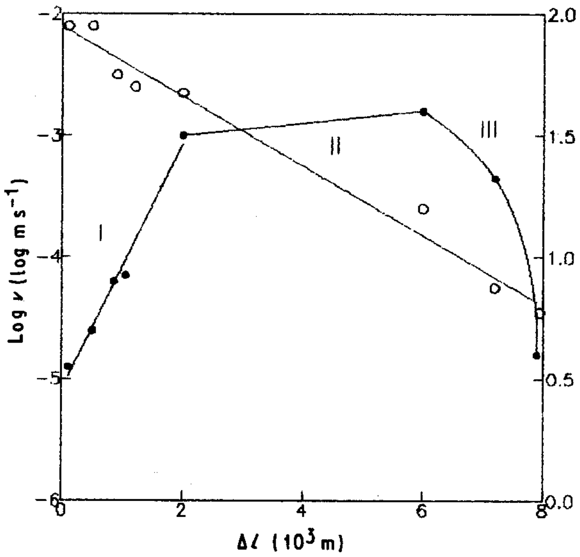

Figure 4 The dependence of (●) crack velocity and (○) stress intensity factor on the crack increment in type 2 alumina/alumina composite.

localization on the interlayer boundaries have been identified for type 2 material.

In Table I K_{Ic} and γ_F values for the materials studied are given. The cermet materials have the largest values of K_{Ic} and γ_F. However, with equal chromium content, the specific work of fracture of the layered granular composite is 2.5 times greater than that of the material with a fine crystalline structure. On the whole, the layered granular structure organization allows the fracture toughness value to increase up to 1.3 time, and work-of-fracture to increase 25 times.

Fig. 3 shows the K_I–v plots of the type 2 and 6 materials. A linear increase of log v with increasing log K_I for type 6 material can be seen. The value of exponent n in the v (K_I) dependence is 12.8. For the layered granular ceramics, three periods of load relaxation are noted after attainment of maximal load. In region I the crack propagates with a positive acceleration, in Region II with an insignificantly changed velocity, and in Region III with a high negative acceleration.

Fig. 4 shows the log v and K_I dependences on crack increment, corresponding to Regions I, II and III of the K_I–v diagrams (Fig. 3). Despite the monotonically decreasing K_I, the fracture process of the material is characterized by the presence of crack propagation acceleration and deceleration stages. According to estimates using Equation 4, the extent of each of Stages I, II and III approximately corresponds to the cells size in the material structure. Thus we can assume that the crack propagation kinetics in such a material is determined by the cell orientation with respect to the front of a propagating crack and the direction of the maximum tensile stresses in action.

4. Conclusion

The features of crack propagation in ceramic composites with a layered granular structure were investigated. It was shown that it was possible to significantly increase the ceramic materials work-of-fracture as a result of the layered granular structure organization. The reasons for this effect are the processes of crack reorientation accompanied by its acceleration and deceleration resulting in crack tip interaction with the intergranular and interlayer boundaries in the structure of a ceramic composite. The work-of-fracture value for alumina-based materials with a layered granular structure is up to 25 times greater than for the material with a fine crystalline structure.

Acknowledgements

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