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The finite element analysis of crack tolerance in composite ceramics

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Abstract. A finite element simulation is employed to provide a thorough investigation of fracture tolerance in ceramic materials containing lamellar inhomogeneities. The opening mode crack initiated in matrix, inhomogeneity and at interphase boundary is considered in terms of energy release rate accompanying the flaw growth to define the most feasible fracture configurations. The dependences of the crack energy release rate on sizes of crack and inhomogeneity, and elastic moduli of materials are shown and discussed. It is demonstrated that the energy release rate reaches its maximum value at certain ratios of inhomogeneity-to-matrix shear moduli and crack-to-inhomogeneity sizes.
Keywords: ceramic composites, fracture toughness, crack, energy release rate, finite element simulation

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Introduction

The development of ceramic materials endowed with less brittleness is of great interest of research in material science, especially in the way to obtain the promising composite materials with enhanced functional properties providing durability and reliability of devices under operational conditions [1-4]. These materials can be fabricated via sintering of ceramic powders with advanced compounds such as graphene [5,6]. Owing to the technological parameters of this process, the produced materials can contain high fraction of interfacial inhomogeneities mostly located at grain boundaries (GBs) [7]. Under operational conditions these inhomogeneities as the origins of stress disturbance induced by the impact of the external fields (thermal, electrical, or magnetic) can provoke the relaxation processes, either dislocation emission or crack nucleation [8-11]. The first mechanism mostly contributes to plastic deformation (yielding) phenomenon, while the second one is responsible for brittle fracture of obtained ceramic composites. The analysis of the occurrence of either relaxation mechanism is deemed to be a significant issue that could be conducted through the thorough investigation of stress disturbance in vicinity of interfacial inhomogeneities and the subsequent development of theoretical models of relaxation processes to increase the fracture resistance of ceramic materials.

For the case of ceramic/graphene composites, various toughening strategies have been suggested and realized (e.g., [12,13]), and theoretical models that considered the effects of crack deflection [13], crack bridging [14,15] and GB sliding [11,16] on fracture resistance of

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composites have been elaborated. While crack bridging and deflection expectedly lead to toughening of ceramic/graphene composites, it was demonstrated that GB sliding can reduce their fracture toughness.

Also, in our previous research, the local stress distribution in ceramics materials containing pores [17] and inclusions [18] was investigated analytically through boundary perturbation technic and verified by finite element simulation. The specific shape of triple junction inhomogeneity was approximated through the analytical equation defining a rounded triangle curve of three-fold symmetry which deviates from circle for some small variable. In the case of remote uniform tension along inhomogeneity symmetry axis, the first order analytical solution demonstrated qualitative correlation with the results of numerical simulation.

In our present research, we focused on crack initiation in the vicinity of a lamellar inhomogeneity in a ceramic matrix. The finite element analysis is employed to determine the energy release rate accompanies the increment of a Mode I crack placed in either the matrix or inhomogeneity, or at the interphase boundary. Within this approach, the fracture tolerance of crack configurations impacted by the difference of elastic moduli of materials is elucidated.

Model

We consider a plain strain of an infinite matrix containing a lamellar inhomogeneity of width d subjected to axial tension (see Fig. 1a). The applied axial tension is supposed to be perpendicular to the interphase boundary. The shear modulus and Poisson coefficient of the matrix and inhomogeneity are μ_1, ν_1 and μ_2, ν_2 respectively.

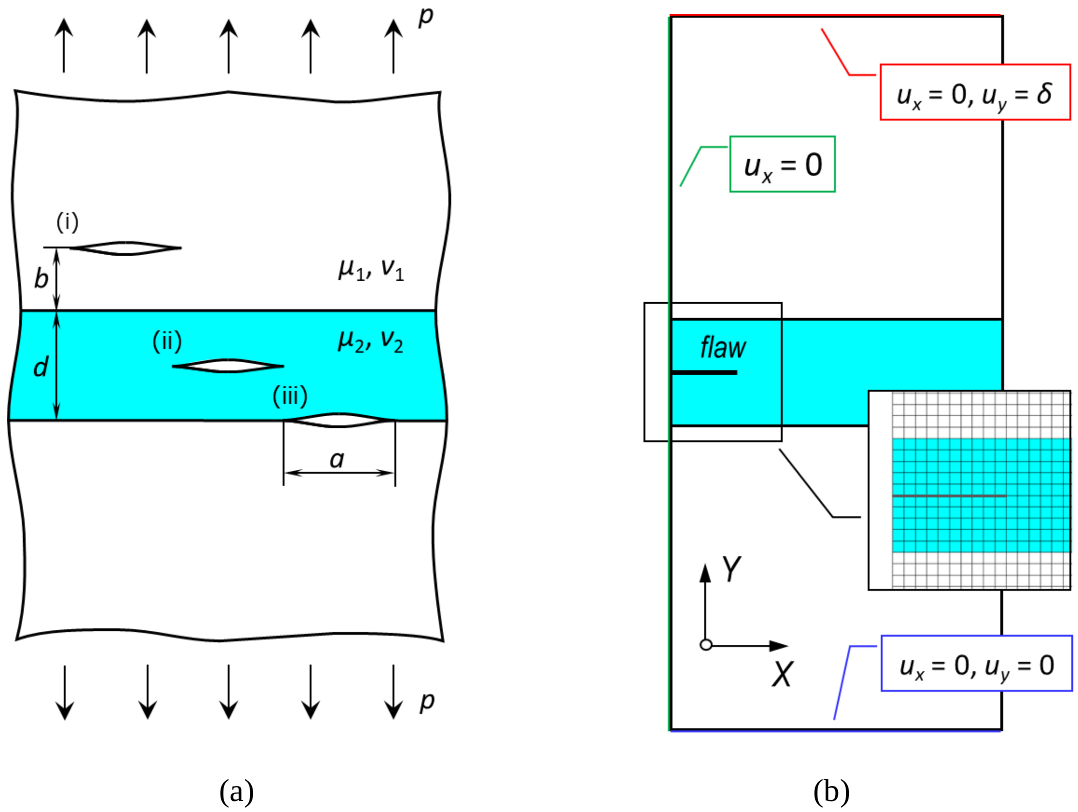


Fig. 1. a) Feasible cracking locations in a matrix containing a lamellar inhomogeneity under remote axial tension: (i) flaw in the matrix, (ii) flaw in the inhomogeneity and (iii) flaw at the interphase boundary; b) The finite element model of a flaw placed in the middle of lamellar inhomogeneity. The kinematic boundary conditions for displacement components u_x and u_y are shown

The following fracture scenarios are considered: (i) the flaw initiated in the matrix; (ii) the flaw initiated in the inhomogeneity and (iii) the flaw initiated at the interphase boundary as it is illustrated in Fig. 1a. The energetic approach is employed to provide a comparative analysis of these fracture scenarios. According to this approach [19] the fracture tolerance of aforementioned crack types can be estimated in terms of energy release rate as

$$G \approx -\frac{\Delta E_{st}}{\Delta a}, \qquad (1)$$

where ΔE_{st} is a change of the strain energy of the elastic system available for increment of crack extension Δa. Eq. 1 is valid as long as the work done by external forces vanishes.

In order to estimate an energy release rate G of the cracks, a finite element model of a body composed of the matrix and inhomogeneity domains is prepared in one of the commercial software and shown in Fig. 1b. The model is built up from 2D plane elements containing 4 nodes. The cracks are treated as a flat cut placed in the different locations: (i) in the matrix at a distance b from the interphase boundary; (ii) in the middle of the inhomogeneity and (iii) at the interphase boundary. The axial tension state is achieved due to prescribed displacement, viz. the model bottom is fixed while the top gets a vertical displacement δ. The crack faces and right border of the model are assumed to be traction free. The size of the body is considered to be big enough to neglect the screening effects of the external boundary. The symmetry of the problem is taken into account with respect to both the geometry and loading. The materials of the matrix and the inhomogeneity are supposed to be linearly elastic and isotropic.

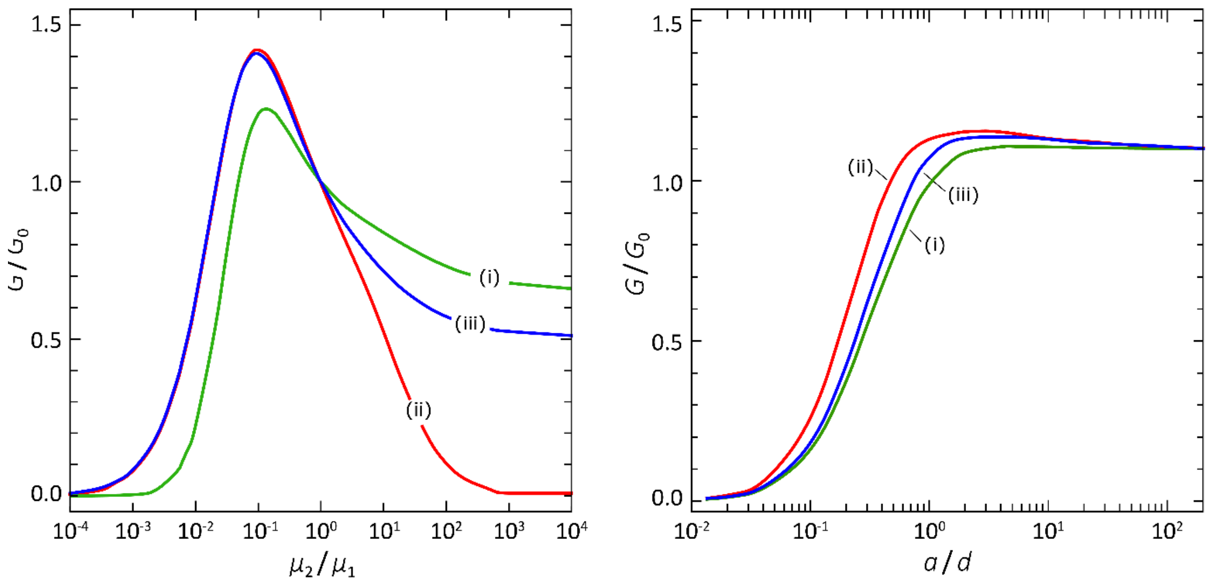
The couple of separate numerical simulations are performed for cracks of length a and $a + \Delta a$ to calculate the strain energy increment in the Eq. 1. The crack increment Δa is considered to be in the order less then crack length a ($\Delta a \approx a / 10$).

Results

Let us first investigate the effect of elastic moduli of the matrix and the inhomogeneity on the energy release rate of the cracks. Fig. 2a shows the curves $G(\mu_2 / \mu_1)$ obtained numerically for $a = d / 2$ and $b = d / 2$. As is seen, there are peaks at $\mu_2 / \mu_1 \approx 0.1$ with the values of $G \approx 1.2G_0$ for the crack located in the matrix region (curve (i)) and $G \approx 1.4G_0$ for the cracks located in the inhomogeneity and at the interface (curves (ii) and (iii), respectively). Hereafter G_0 is the crack energy release rate in a homogeneous material (when $\mu_1 = \mu_2$). One can note that the peak value of the crack energy release rate reduces with the increase of the distance between flaw and inhomogeneity b. Besides, with the increase of b the value of μ_2 / μ_1 corresponding to the maximum of G rises.

In the case of relatively soft inhomogeneities ($\mu_2 / \mu_1 < 1$), the curves (ii) and (iii) practically coincide, while curve (i) goes significantly lower than these ones. In the limiting case of an infinitely soft inhomogeneity ($\mu_2 / \mu_1 \to 0$), the energy release rate vanishes for all crack locations under consideration.

In the case of relatively rigid inhomogeneity ($\mu_2 / \mu_1 > 1$), the crack in the matrix takes the highest energy release rate, while the crack in the inhomogeneity takes the lowest one. In the limiting case of a rigid inhomogeneity ($\mu_2 / \mu_1 \to +\infty$), the crack energy release rate tends to some constant values: $G \approx 0.65G_0$ for the crack in the matrix, $G \approx 0.5G_0$ for the interface crack, and $G \approx 0$ for the crack in inhomogeneity.



(a) (b)

Fig. 2. The energy release rate G of cracks located in the matrix (i), in the inhomogeneity (ii) and at the interphase boundary (iii) in dependence on: a) the ratio of inhomogeneity-to-matrix shear moduli μ_2/μ_1 for $d = a/2$ and $b = d/2$; b) the crack-to-inhomogeneity size ratio a/d for $\mu_1 = 2\mu_2$ and $b = a/2$. G_0 is the crack energy release rate for $\mu_1 = \mu_2$

Consider now the dependence of the energy release rate on the ratio a/d at $\mu_1 = 2\mu_2$, $\nu_1 = \nu_2 = 0.3$, and $b = a/2$. As it seen from Fig. 2b, the crack energy release rate tends to zero if the flaw length is negligibly small with regard to the inhomogeneity width ($a << d$). The curves $G(a/d)$ first rapidly increase, achieving their maximum values (~$1.15G_0$ for the crack in the inhomogeneity at $a \approx 2d$) and then gradually decline to their constant values ~$1.1G_0$ for $a >> d$. It means that the energy release rate of relatively matured cracks ($a >> d$) doesn't depend on the aforementioned fracture locations.

Thus, the results of the simulations demonstrate that in the case of relatively rigid inhomogeneities (when $\mu_2 > \mu_1$), cracks in the matrix are characterized by higher values of the energy release rate than similar cracks inside the inhomogeneity or at the interphase boundary. This promotes crack propagation inside the matrix. In contrast, for relatively soft inhomogeneities ($\mu_1 > \mu_2$), the cracks in the inhomogeneity or along the interphase boundary have higher values of the energy release rate than similar cracks in the matrix. This facilitates crack propagation inside the inhomogeneity or along the interface. At the same time, along with the energy release rate, crack propagation is strongly affected by the local fracture resistance G_c, which can be defined as the critical value of the energy release rate G for the catastrophic crack growth inside the specified phase or along the interphase boundary. For example, for the case of a brittle ceramic matrix and a ductile metallic inhomogeneity (whose value of G_c is much larger than that in the matrix), cracks are expected to advance inside the matrix even if the metallic inhomogeneity is softer than the ceramic matrix. Thus, the preferred pathway of crack propagation (inside the matrix, inside the inhomogeneity or along their interface) is determined by both the ratio of the shear moduli of the matrix and the inhomogeneity (crack advance is preferable in a softer phase) and the fracture toughness of the two phases (crack propagation is promoted in the phase with a smaller value of G_c).

Conclusions

In summary, a finite element analysis is provided to consider different fracture phenomena in composite ceramics with lamellar filler. A composite ceramic is modeled as an elastic body containing matrix and lamellar inhomogeneity domains. It is assumed that a Mode I crack is opened in either the matrix in close vicinity to the inhomogeneity, or in the middle of the inhomogeneity, or at the interphase boundary. The numerically obtained energy release rate accompanying the crack extension is employed to implement the comparative analysis of the crack configurations through the finite element simulations with varying the elastic moduli of materials, the crack and inhomogeneity sizes. It is shown that if the critical values of the energy release rate in the matrix and the inhomogeneity are the same, such cracks are more feasible to open in the matrix region near the interface in the case of relatively rigid inhomogeneities (when $\mu_2 > \mu_1$). As for relatively soft inhomogeneities ($\mu_1 > \mu_2$), the cracks are expected to occur in either the inhomogeneity or the interphase boundary. The energy release rate of the aforementioned cracks tends to a constant value if the crack length is much larger than the inhomogeneity width ($a >> d$) and vanishes in the opposite case ($a << d$). One of the main results to emerge in this study is that, for all crack configurations under study, the energy release rate reaches its maximum value at certain ratios of inhomogeneity-to-matrix shear moduli and crack-to-inhomogeneity sizes.

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