The features of fracture processes of the ceramic composite

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Abstract. The phenomenon of material fracture spans many different length scales. The paper is devoted to the numerical investigation of the features of fracture processes in alumina-zirconia composite ceramics at the mesoscale subjected to uniaxial compression. A structural model of the composite mesovolume based on the experimental SEM image is adopted. The mechanical behavior of the composite is described by a constitutive model of the damageable elastic-brittle medium. Two local fracture criteria are used that are based on the limit values of damage and tensile pressure. The energy dissipation process in the ceramic composite mesovolume during damage accumulation is analyzed. It is shown that the damage accumulation results in nonlinear dissipation of potential energy and the following kinetic energy increase. The last is accompanied by the appearance and growth of cracks in matrix and inclusions at the final stages of deformation.

1. Introduction

The human bone tissue damage associated with pathological diseases, physical injuries, etc. is one of the most widespread medical problems. Therefore, the development of new materials for creating implants is an actual task of modern materials science. The biocompatibility with bone tissues and good mechanical strength are the main requirements for such materials. The porous ceramic materials have the necessary complex of physical and chemical properties and fulfill these requirements. The porous materials have a heterogeneous structure. The alumina-zirconia ceramic composite is an object of research in this paper. It is well known that the addition of unstabilized zirconia to alumina leads to an increase in fracture toughness, and, consequently, to an improvement in strength properties [1–3]. Therefore, this type of ceramic composites causes particular interest.

Both experimental and numerical methods are used for studying the mechanical behavior of structurally heterogeneous materials. Numerical modeling can significantly reduce the costs associated with both time and resources compared to experimental methods. Therefore, the method of numerical investigation of the mechanical behavior of structurally heterogeneous materials is used in this paper. It is known, that the assurance of numerical methods depends on the quality of the computer models used. Here we used a model of an isotropic elastic-brittle damaged medium, which takes into account the combined mechanism of damage accumulation due to shear stress accompanied by pressure sensitivity due to internal friction.

The aim of this paper is a numerical investigation of damage accumulation and its influence on fracture patterns and energy dissipation in ceramic alumina-zirconia composite.
2. Model description and investigation method

The porous ceramic alumina-zirconia composite for numerical studying the mechanical behaviour was used. The SEM image of a ceramic composite sample consisting of porous alumina matrix and zirconia inclusions was taken from the study by Alsebaie [4] (figure 1a). The region of 370×500 pixels was selected from the SEM image of this ceramic composite (figure 1b), after that the image was converted to a binary image using the ImageJ program (figure 1c). This selected region of SEM image was regarded as a structural model of the composite mesovolume for numerical simulation. The dark color represents the porous alumina, while white color the zirconia. The mechanical and physical characteristics of the ceramic composite components are given in table 1.

![Figure 1. The structural model of the porous composite](image)

| Material | Density ρ, g/cm³ | Cohesion Y, MPa | Bulk modulus G, GPa | Shear modulus K, GPa | Coefficient of internal friction α |
|----------|-----------------|-----------------|---------------------|----------------------|----------------------------------|
| Porous Al₂O₃ | 3.98            | 600             | 160                 | 346                  | 0.13                             |
| ZrO₂     | 5.7             | 300             | 66.5                | 143.3                | 0.13                             |
The system of equations of solid mechanics was solved using the finite-difference method for the numerical study of deformation and fracture processes in the investigated structure. The complete system of continuum mechanics equations includes the fundamental conservation laws of mass and momentum, geometrical relations and constitutive equations. In this work, constitutive equations of the damageable elastic-brittle medium are used. These constitutive equations take into account damage accumulation, which causes the degradation of elastic moduli [5].

The fracture process of the structural model was described using two local fracture criteria. These criteria correspond to two various fracture mechanisms. The first criterion is based on the local damage value \( D(t) = 1 \). The second criterion describes fractures due to the critical value of tensile pressure \( P = P_{cr} < 0 \). After meeting a fracture criterion, all components of stress tensor are equated to zero, and then the material ceases to resist tension but not compression. The simulation was performed in a two-dimensional statement under quasi-static loading conditions. The investigated structure was subjected to uniaxial compression along the horizontal axis.

3. Discussion of simulation results

The results of numerical modeling of deformation and fracture of the porous ceramic composite are shown in figures 2, 3. The macroscopic stress-strain curve of the porous ceramic composite in uniaxial compression is presented in figure 2a. Here averaged stress is plotted versus engineering strain. It can be noted that the linear correlation between the averaged stress and the strain is finished when the strain value reaches 0.14 %. Then the stress-strain curve reaches a short plateau with the strain increasing, after which the drop of the stress-strain curve is observed. The presence of this short plateau on the stress-strain curve is caused by the microdamage accumulation in the investigated structure of the composite.

![Figure 2. Stress-strain curve (a) and the change of the energies with the strain increasing (b)](image)

To analyze the energy dissipation processes during damage accumulation in the ceramic composite, the graphs of the potential, kinetic, and total energies of the mesovolume were plotted as a function of the mesovolume engineering strain (figure 2b). One can note that at first, the potential energy increases with the growth of the strain. The presence of the microdamage and their accumulations in the volume of the composite leads to a slowdown in the growth of potential energy. When a fracture criterion is satisfied a crack appears which causes an increase in kinetic energy and corresponding a
headlong drop of potential energy. Later on, the total energy of the system begins to fall with the development of macroscopic fractures.

The fracture patterns in the investigated mesovolume of the ceramic composite in compression along the horizontal axis are shown in figure 3. Figure 3a illustrates the structure of the composite in an undamaged state at the initial stage of deformation. When strain value reaches 0.122 %, microdamages nucleate in the material and cracks appear in the fracture patterns. Microdamage nucleation occurs in the location of strong stress concentrators caused by the structure of the composite. With the growth of strain, the damages are accumulated and propagate in both matrix and inclusions of the composite along the loading axis, forming cracks.

At a strain of 0.145 %, macroscopic fracture of the composite occurs, and the drop of the stress-strain curve is observed (figure 2a). Consequently, fracture regions are propagated almost in the entire structure of the composite (figure 3c). It should be noted that the fracture occurs only according to the fracture criterion based on the damage limiting value.

![Fracture patterns of ceramic composite at various engineering strain values](image)

**Figure 3.** Fracture patterns of ceramic composite at various engineering strain values

### 4. Conclusion

In the results of the numerical simulation, the mesoscale fracture patterns in a porous ceramic composite mesovolume loaded in compression were analyzed for various stages of deformation. Also, the mesovolume energy dissipation during damage accumulation and the fracture was studied.

The analysis of the results showed that the presence of the microdamage and their accumulation in the bulk of the composite leads to a slowdown in the potential energy growth. Fracture and crack appearance cause an increase in kinetic energy and the corresponding drop of potential energy. The total energy of the system begins to fall with the development of macroscopic fractures. Also, it was shown that cracks are originated in the softer matrix near the matrix-inclusion interfaces and then propagate along the loading axis both in the matrix and inclusions of the composite. This propagation of cracks is accompanied by the growth of the kinetic energy of the sample. The above-mentioned features of the mesoscale fracture process in composite ceramics agree with experimental results in the form of the stress-strain curve and SEM observations [6].

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References

[1] Zhukov I, Buyakova S P and Kulkov S S 2016 Éptőanyag-JSBCM 68 (3) 74 http://dx.doi.org/10.14382/epitoanyag-jsbcm.2016.13

[2] Buyakov A S, Levkov R V, Buyakova S P, Kurovics E, Gomze L A and Kulkov S N 2018 Éptőanyag-JSBCM 70 (1) 27 https://doi.org/10.14382/epitoanyag-jsbcm.2018.6

[3] Wakily H, Mehrali M, Metselaar H S C 2010 World Academy Sci., Eng. Technol. 46 140

[4] Alsebaie A M 2005 Characterisation of Alumina-Zirconia Composites Produced By Micron-Sized Powders. M. Eng. Thesis (Dublin: Dublin City University) p 115

[5] Mikushina V A, Smolin I Yu 2019 Vests. Tomsk. Gos. Univ. Mat. Mekh. 58 99 https://doi.org/10.17223/19988621/58/8

[6] Savchenko N L, Sablina T Yu, Sevostyanova I N, Buyakova S P and Kulkov S N 2016 Russ. Phys. J. 58 1544 https://doi.org/10.1007/s11182-016-0680-4