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Modeling of the Mechanical Behavior of Fiber-Reinforced Ceramic Composites Using Finite Element Method (FEM)

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Abstract:
Modeling of the mechanical behavior of fiber-reinforced ceramic matrix composites (CMC) is presented by the example of Al_2O_3 fibers in an alumina based matrix. The starting point of the modeling is a substructure (elementary cell) which includes on a micromechanical scale the statistical properties of the fiber, matrix and fiber-matrix interface and their interactions. The numerical evaluation of the model is accomplished by means of the finite element method. The numerical results of calculating the elastic modulus of the composite dependance on the quantity of the fibers added and porosity was compared to experimental values of specimens having the same composition.
Keywords: *Alumina ceramics, Finite element method, Image analysis, Thermal shock.*

1. Introduction

Alumina silicate refractories are used in metallurgical, ceramic and glass industries. These materials are made from refractory clays. Chamotte transforms refractories into high temperature compounds which have a heterogeneous microstructure with a large grain size distribution and high porosity. The use of fiber reinforced composites has been expanded in the world because of high strength, stiffness, ductility and impact resistance. The main goal of fiber addition is to improve the mechanical properties, mainly strength. [1] Composite materials are superior to all other known structural materials in specific strength and stiffness, high temperature strength, fatigue strength and other properties. The desired combination of properties can be tailored in advance and realized in the manufacture of a particular material.

Many of modern technologies require materials with unusual combinations of properties that cannot be met by the metals, conventional metal alloys, ceramics, and polymeric materials, e.g. materials needed for aerospace, underwater, and transportation applications. All composites generally have one thing in common: a matrix or binder combined with a reinforcing material. Obviously, a composite consists of a matrix material, dispread within which is a dispersion of one or more phases of another material. If the fibers are directionally oriented and continuous, the material is termed an advanced composite.

The properties of composites mainly depend on the physical mechanical properties of their components and the strength of bonds between them. A characteristic feature of composite materials is that the merits of their components are fully utilized. Composite

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materials may acquire certain valuable properties not found in the components. For obtaining the optimal properties in composites, their components are chosen so as to have sharply different, but complementary properties.

The base, or matrix, of composites may consist of metals or alloys (metallic composites), polymers, carbon and ceramic materials (non metallic composites). [2] Technologically, the most important composites are those in which the dispersed phase is in the form of a fiber. The strong fibers embedded in a softer matrix produce products with high strength-to-weight ratios. The matrix materials transmit the load to the fibers, which absorb the stress.

The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber-reinforced composites. With respect to orientation, two extremes are possible: (1) a parallel alignment of the longitudinal axis of the fibers in a single direction, and (2) a totally random alignment. Mechanical responses of this type of composite depend on several factors to include the stress–strain behaviors of fiber and matrix phases, the phase volume fractions, and, in addition, the direction in which the stress or load is applied. [3]

In the past years ceramic materials have become increasingly important. Especially for applications which require high strength. Ceramics show a superior behavior at elevated temperatures. The problem of using ceramic materials in construction is their brittle damage behavior. A single defect can lead to the total brittle damage of the whole structure.[4]

In previous decades, finite element method (FEM) has become widely accepted numerical method, not only in computational mechanics, but in many engineering disciplines. The methodology developed this method enables solving simple linear problems in mechanics of solid bodies by demanding non-linear problems in almost all fields of applied physics, and more recently, and many other branches of science. Software packages used are: ABAQUS, ANSYS, ADINA, NASTRAN, and LUSAS. Finite element method gives an approximate distribution of the required size of the observed area, which cannot be determined analytically. Approximate solution is achieved by dividing the area (bodies) to the elements. Then the corresponding physical laws apply to each element and elements of the set of solutions to solve the observed problems. [5]

The aim of the model described below is to study the influence of important parameters on the behavior of the fiber composite. This substructure (elementary cell) takes the single components matrix, fiber, the fiber-matrix interface and their specific damage behavior into account. It is chosen in such a way that a macrostructure characteristic for the whole structure can be built-up by a suitable number of substructures. To study the influence of separate component parameters on the behavior of the total material the model has been implemented in a finite element method (FEM) code.

2. Experimental procedure

Specimens were prepared using the chamotte, clay and bauxite in the quantities defined by the producer Samot Arandjelovac. [6,7] In order to compare the results of mathematical modeling to the experimental data, specimens with addition of 1 wt. % of short alumina based fibers (having the aspect ratio $l/d \approx 17$), were added to the composition. The materials were mixed in the ball mil in water to enable better distribution of components, specially fibers. The obtained composition was dried during 24 h at 100 °C and after that pressed using two different pressures (36 MPa and 50 MPa) resulting in two different porosities. Green samples were thermally treated at 1200 °C and then were tested using the compression test and the Brazilian test [8] to obtain values of strength and modulus of elasticity. The test was done usingthe servo-hydraulic testing machine Instron 1332 with load cell of 100 kN and 5kN with data acquisition system. The obtained values of modulus were used to compare to the numerically obtained values.[7] Specimens were examined using the scanning electron microscope and obtained images were used to determine the porosity of specimens. [9]

Porosity measurements were based on different gray level of the obtained images using image analysis techniques. Several SEM images of each sample were used to determine the porosity of samples. The method is based on the fact that the pore absorb more light and they occur as part of the picture darker when compared with solid material. Showing porosity of the material and method for determining the share of pores is given in Fig. 1. The SEM images were obtained using a scanning electron microscope (SEM), the Jeol JSM 5800, operated at 20 kV.

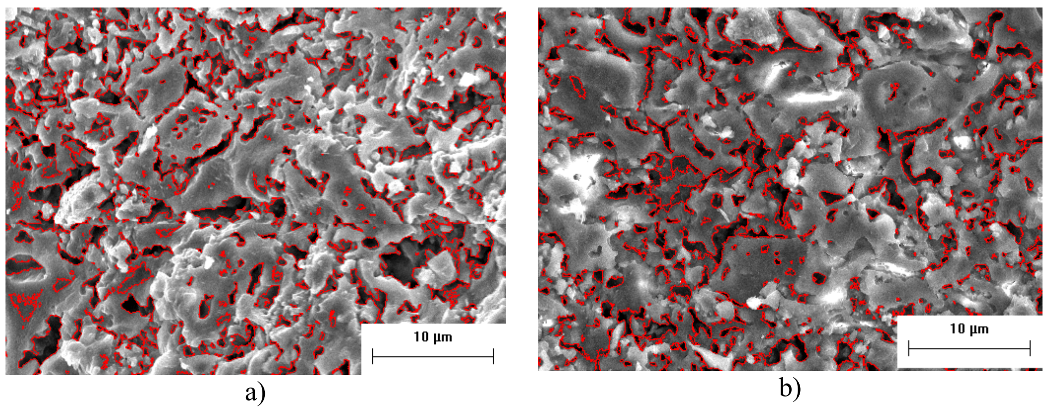

Fig. 1. SEM mocrographs with visible porosity used to obtain the values for comparation to the model.

2.1 Finite element modeling

The unit cell method assumes that the porous ceramic material is constructed of array of basic units, each with identical composition, cell geometry and material properties. A face cubic cell is considered as a representative volume element to simulate the real microstructures of porous ceramics. This model assumes that: a) the elastic property of the Al_2O_3 ceramic is linear, b) the ceramic matrix is considered as an isotropic material. [10, 11]

All the 3D FE models were produced using ABAQUS 6.7-1, finite element software package. The material data used for FE analyses were: for matrix: Young's modulus E = 10 GPa and Poisson's ratio ν = 0.2, for fibers: Young's modulus E = 145 GPa and Poisson's ratio ν = 0.25.

3. Results and discussion

The geometry of the elementary cell was obtained by calculation using elements obtained from image analysis applied to the SEM images of the material and some calculations based on the composition of the material. Volume fraction of fibers was chosen during the preparation of the material and was fixed on 1% volume. The fiber dimensions were obtained from measurements of short fibers using the image analysis program. The fiber diameter was measured to be about 7,5 µm and the average fiber length was 134 µm. So the volume of the unique fiber was,

$$\text{Fiber volume: } V_f = \frac{d^2\pi}{4}\cdot l = \frac{7{,}56^2\,\pi}{4}\cdot 134{,}4 = 6028\,\mu m^3$$

The volume of material corresponding to the average fiber was calculated using the simple proportion and the cell volume of 301442,7 μm^3, was obtained which will give the length of the edge of 67 μm. Since the fiber length is 134 μm and the unit cell should be large enough so the fiber can fit in the cell. The assumption that 8 fibers belong to one elementary cell gives a cube of dimensions 0,14mm x 0,14mm and depth 0,14mm and the fiber diameter r = 0,003925 mm and length l = 0,137388 mm are the same for all fiber volume fractions. Fibers were randomly inserted into the matrix 4 and 8 fibers. The matrix with 8 fibers is shown in Fig. 3. This model elementary cell is made from the matrix in which the pores are not included.

To analyze the influence of porosity on mechanical properties, elementary cell is made with fibers without pores and cells that are inserted into the pores. Fig. 2 shows the unit cell: a) with fiber without pores and b) the fibers and pores.

It is found that established contact between fibers and matrix is surface to surface contact with friction coefficient 0.1. In software it is defined that friction formulation is a penalty and surface to surface contact is described as finite sliding.

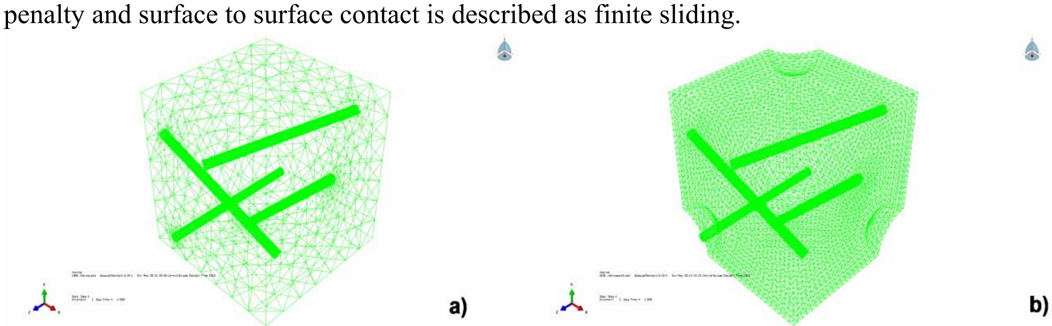

Fig. 2. Elementary cells: a) with fiber without pores and b) the fibers and pores.

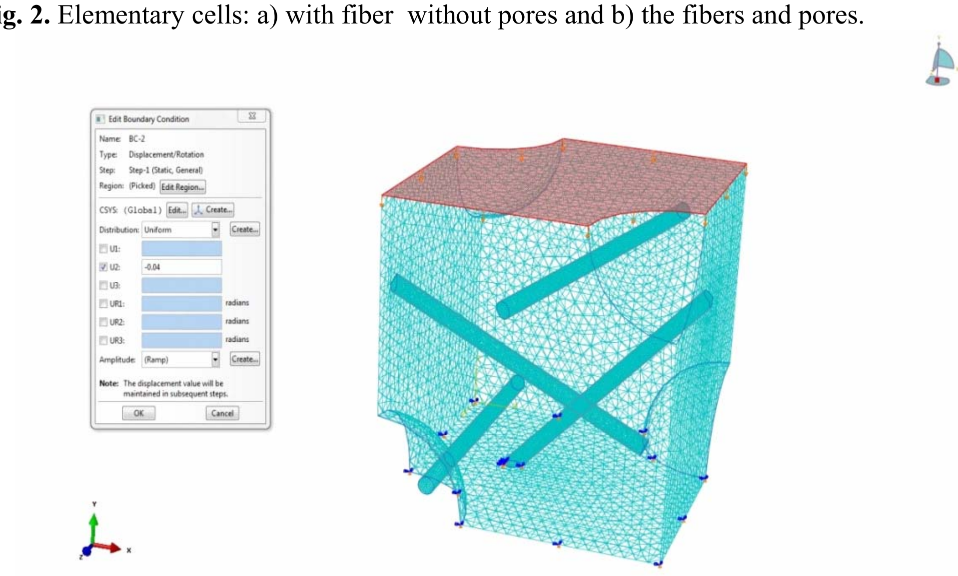

Fig. 3. Showing how the load is acting on the elementary cell.

3.1 Comparation of experimental and calculated values of elastic modulus

To compare the obtained numerical results the data obtained from mechanical testing were used. The calculated values of elastic modulus for different compositions having only pores and having simultaneously pores and fibers are given in Fig. 4. The data obtained experimentally were also added to the data presentation and they fit to the model developed in this paper.

When the material contains pores and fibers, the value of Young's modulus decreases with increase of porosity. The value of Young's modulus of improved material containing fibers has higher values compared to the material without fiber and having the same porosity.

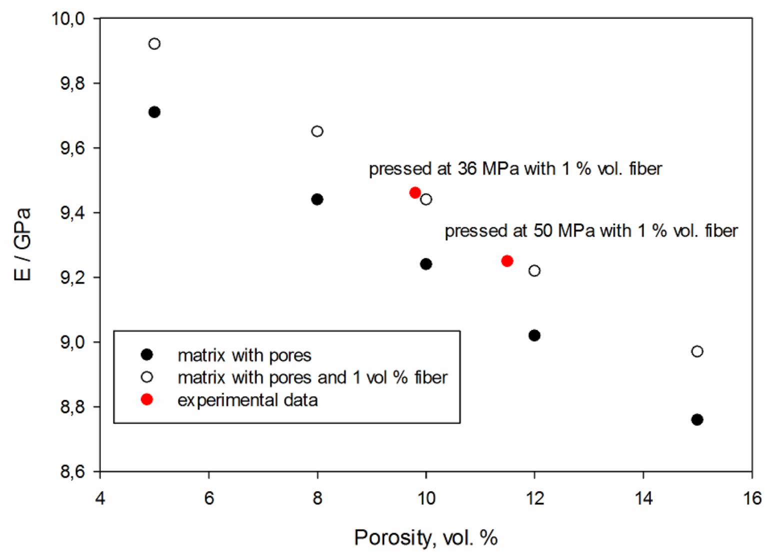

Fig. 4. Dependence of Young's modulus of elasticity vs. the share of porosity.

The comparison to experimental values obtained from mechanical testing gives good accordance of those values to calculated values of the model.

4. Conclusion

The model based on the analysis of mechanical behavior of the unit element cube having the length of 0,140 mm and consisting of a number of pores that correspond to measured porosity characteristics is developed. The number of fibers in the cube corresponds to the composition of the material prepared in the experiment. Prepared materials were tested mechanically in order to obtain the values of elastic modulus and the structure was examined using the SEM. Obtained pore sizes and porosity were the basis to calculate the appropriate elementary cube for numerical simulation. The experimental and numerical results values are in good accordance.

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Садржај: *Моделовање механичког понашања влакнима ојачаних керамичко – матричних композита представљен је на примеру композита са влакнима од Al_2O_3 и матрицом на бази Al_2O_3. Полазна тачка моделовања је подструктура (јединична ћелија) која обухвата микромеханичке статистичка својства влакна, матрице и међуповршине влакно – матрица и њихове интеракције. Нумерички прорачун модела се остварује помоћу методе коначних елемената. Резултати израчунавања зависности модула еластичности композита од удела додатих влакана и порозностисупоређени са експерименталним вредностима узорака са одговарајућим саставом.*

Кључне речи: *керамика на бази алуминијум оксида, метода коначних елемената, анализа слике, термошок*