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Macrostructural engineering of ceramic-matrix layered composites

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Abstract

A method of computer simulation of the fracture of layered composites during a 3-point bending test is developed. A model of failure is considered which can be applied to two-component brittle layered composites (in particular ceramic-matrix composites). This particular model is executed for composites with the number of layers $N = 3$, 7 and 15. The model is applied for the description of mechanical behaviour of two-component ceramic-matrix layered composites. The trends of the theoretical calculations agree with data obtained from 3-point bending test of real ceramic-matrix layered composites.

Keywords: A. Ceramic-matrix composites (CMCs); A. Layered structures; B. Fracture; B. Strength; C. Computational simulation

1. Introduction

The strategy of ceramic strengthening is usually associated with design of ceramic composites that can enable the action of the different mechanisms of fracture energy absorption and/or dissipation. In addition to these mechanisms other properties can also be modified by suitable microstructure design in composites, including those which cannot be combined in a single-phase material. In functional gradient materials even more complex microstructural architectures have to be developed. Different structure elements such as particles, whiskers, filaments, platelets or laminates and others are combined to tailor properties in accordance with different service requirements.

Composites are complicated systems which are characterized by a host of interdependent parameters. The theoretical prediction of mechanical behaviour provides information related to the failure of such materials. The strength of a ceramic-matrix layered composite depends on the properties of the separate layers and the process of composite failure on the system of layers. Ceramic materials possess many outstanding physical and chemical properties which make them interesting objects for different engineering purposes. However, their more intensive technical application is restricted by their brittleness.

The purpose of the present work is the development of methods of fracture simulation and calculation of optimal structural parameters of two-component ceramic-matrix layered composites as systems of layers. It is necessary for an optimal design of processing parameters for fabrication of such composites.

For this purpose the method of computer simulation of the fracture of layered composites during a 3-point bending test is developed. A model of failure is considered which can be applied to two-component brittle layered composites (in particular ceramic-matrix composites). The authors attempt to solve a physical problem of the description of failure of two-component brittle layered composites as process of the cracking of separate layers. This particular model, which is executed for composites with the number of layers $N = 3$, 7 and 15, is applied for the description of mechanical behaviour of two-component ceramic-matrix layered composites (Fig. 1). The trends of the theoretical calculations agree with data obtained from 3-point bending test of real ceramic-matrix layered composites.

2. Macrostructural fracture model of two-component brittle layered composites

2.1. Initial data of model

In this work two-component brittle layered composites with symmetric macrostructure are considered (Fig. 1). The layers consisting of different components alternate one after another, but the external layers

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Fig. 1. Two-component layered composite: 1—layers of the first component including two external (outside) layers; 2—layers of the second component (internal).

consist of the same component. Thus the total number of layers, N, in such a composite sample is odd. In Fig. 1 the layers of the first component including two external (outside) layers are designated as symbol 1 ($j = 1$), and the layers of the second component (internal) are designated as symbol 2 ($j = 2$). The number of layers designated as symbol 1 is $(N + 1)/2$ and the number of layers designated as symbol 2 is $(N - 1)/2$. The layer of each component has some constant thickness, and the layers of same component have identical thickness.

Three-point bend tests are the most likely to be needed for brittle layered materials. In this work the mechanical behaviour of a layered sample as a beam with rectangular cross section under conditions of three-point bending is considered. Modeling of the flexural loading process of samples with cross–section height h and the section width b is carried out. It is supposed that the components of a layered composite have various factors of thermal expansion. Therefore the difference, ΔT, in temperature between the actual temperature and the joining temperature of layered material is the important initial parameter which determines the residual thermal stress in layers.

Characteristics of the individual structural elements also affecting composite failure process are moduli of elasticity E_j of jth components of layered composite. The effective elastic modulus of the layered sample (Fig. 1) is determined with the parameters E_j and the thicknesses of layers of jth components l_j (j=1, 2). The process of layer cracking depends on the strength of the jth component of layered composite, σ_{cj}, and the fracture toughness of the jth component, $K_{1c}^{(j)}$. The important structural parameter affecting σ_{cj} and $K_{1c}^{(j)}$ is the grain size of the jth component of a layered composite d_j. The residual thermal stress in layers also depends on the thermal expansion coefficients, α_{Tj}, of the jth component.

Normalized variables are used in the model calculations. The normalized modulus of elasticity of each component of composite is $E_j^* = E_j/E_1$ where E_1 is the elastic modulus of the component named first. The normalized stresses are $\sigma^* = \sigma/E_1$. The normalized fracture toughness is $K_{1c}^* = \frac{K_{1c}}{E_1\sqrt{l_1}}$ where l_1 is the thickness of layers of the component named first.

2.2. Effective characteristics of layered composite under bending

There are effective residual stresses in the layers of each component in layered ceramic composite. During cooling, the difference in deformation, owing to the different thermal expansion factors of the components, is accommodated by creep as long as the temperature is high enough. Below a certain temperature, that will be called the "joining" temperature, the different components become bonded together and internal stresses appear. In each layer, the total deformation after sintering is the sum of an elastic component and of a thermal component [1]. In the case of a perfectly rigid bonding between the layers, the total deformation will be the same for all the layers, then:

$$e_j = \frac{\sigma_{rj}}{E_j'} + a_{Tj}\Delta T = \text{const} \tag{1}$$

where σ_{rj} is the residual stress in jth component, $E_j' = E_j/(1 - \nu_j)$, ν_j is Poisson's ratio of the jth component.

The force balance requires (in normal stresses):

$$\sum_j \sigma_{rj} f_j = 0 \tag{2}$$

where f_j is the volume fraction of the jth component.

For two-component material f_j is:

$$f_1 = \frac{(N - 2n_1 + 1)l_1}{2h} \quad \text{and} \quad f_2 = \frac{(N - 2n_2 - 1)l_2}{2h}$$

where n_1 and n_2 are the numbers of fractured layers of first and second components, respectively. From Eqs. (1) and (2) for two-component material, we have

$$\sigma_{r1} = \frac{E_1' E_2' f_2(\alpha_{T2} - \alpha_{T1})\Delta T}{E_1' f_1 + E_2' f_2} \tag{3}$$

and

$$\sigma_{r2} = \frac{E_2' E_1' f_1(\alpha_{T1} - \alpha_{T2})\Delta T}{E_1' f_1 + E_2' f_2} \tag{4}$$

For multi-component material we have:

$$\sigma_{rj} = E_j' \Delta T \frac{\sum_i E_1' f_1 (\alpha_{Ti} - \alpha_{Tj})}{\sum_i E_i' f_i}. \tag{5}$$

The effective elastic modulus of a layered composite under bending is the modulus of elasticity of some homogeneous material. This modulus is determined by the condition that a sample of such material has the same deflection as the layered sample with same sizes under identical bending loading.

The bending moment in cross section of a layered sample is:

$$M_z = \sum_j \int_{(F_j)} y\sigma^{(j)} \mathrm{d}F, \quad \mathrm{d}F = b\mathrm{d}y, \tag{6}$$

where y is the distance from the neutral layer of sample to the appropriate point of cross section, $\sigma^{(j)}$ is the stress at this point (j indicates that the point belongs to the jth component of composite), dF is the element of the area of cross section, F_j is the area of the jth component in cross section. The neutral layer of sample under bending is the layer without strain.

The stress distribution in the jth component layer is:

$$\sigma^{(j)} = E_j e_j = E_j \frac{y}{\rho}, \tag{7}$$

where e_j is the strain of appropriate point of cross section, ρ is the radius of curvature of neutral layer.

For a two-component material:

$$\sigma^{(1)} = \frac{E_1 y}{\rho} \text{ and } \sigma^{(2)} = \frac{E_2 y}{\rho}. \tag{8}$$

For a two-component composite the bending moment in the cross section of a layered sample is:

$$M_z = \frac{b}{\rho}\left[E_1 \int_{y^{(1)}} y^2 \mathrm{d}y + E_2 \int_{y^{(2)}} y^2 \mathrm{d}y\right] \tag{9}$$

where $y^{(1)}$ and $y^{(2)}$ are the areas of first and second components in cross section, respectively.

If the integration on areas of the first and second components is detailed, the integrals on areas $y^{(1)}$ and $y^{(2)}$ are transformed to the sums of integrals:

$$M_z = \frac{b}{\rho}\left[E_1 \sum_{i=0}^{(N-2n_1-1)/2} \int_{A_i - z_c}^{B_i - z_c} \int y^2 \mathrm{d}y + E_2 \sum_{i=0}^{(N-2n_2-3)/2} \int_{B_i - z_c}^{A_{i+1} - z_c} y^2 \mathrm{d}y\right], \tag{10}$$

where

$$A_i = i(l_1 + l_2) - \frac{h}{2}, \tag{11}$$

$$B_i = i(l_1 + l_2) + l_1 - \frac{h}{2}, \tag{12}$$

$$z_c = \frac{E_1 l_1 \sum_{i=0}^{n_1-1}(B_i + A_i) + E_2 l_2 \sum_{i=0}^{n_2-1}(A_{i+1} + B_i)}{E_1 l_1 (N - 2n_1 + 1) + E_2 l_2 (N - 2n_2 - 1)}, \tag{13}$$

A_i and B_i are the coordinates of layer boundaries (the beginning of the coordinates is the centre of the sample), z_c is the displacement of the neutral layer connected with partial destruction of layers in the stretched area of the sample under bending.

For the sample of homogeneous material the bending moment in cross section is:

$$M = \frac{E^*}{\rho} \frac{bh^3}{12} \tag{14}$$

where E^* is the effective elastic modulus. Integrating (10) and comparing (10) and (14) we can obtain:

$$E^* = \frac{4}{h^3}\left[E_1 \sum_{i=0}^{(N-2n_1-1)/2} \left((B_i - z_c)^3 - (A_i - z_c)^3\right) + E_2 \sum_{i=0}^{(N-2n_2-3)/2} \left((A_{i+1} - z_c)^3 - (B_i - z_c)^3\right)\right]. \tag{15}$$

For the composite without fractured layers ($n_1 = 0$, $n_2 = 0$, $z_c = 0$) expression (15) can be transformed to:

$$E^* = \left(1 - f_2^*\right) E_1 + f_2^* E_2 \tag{16}$$

where

$$f_2^* = \frac{2l_2^3}{h^3}\left[N - 1 + \frac{6}{l_2^2} \sum_{i=0}^{(N-3)/2} A_{i+1} B_i\right] \tag{17}$$

is the effective volume fraction of the second component under bending layered sample.

The distributions of normal stresses in the critical cross section of a two-component composite specimen under bending are:

$$\sigma^{(1)} = \frac{E_1 \sigma}{E^*} = \sigma_n \frac{2E_1}{hE^*} y \tag{18}$$

for the first component and

$$\sigma^{(2)} = \frac{E_2 \sigma}{E^*} = \sigma_n \frac{2E_2}{hE^*} y \tag{19}$$

for the second component, where

$$\sigma = \frac{12 M_z}{bh^3} y = \sigma_n \frac{2y}{h}$$

is the distribution of normal stresses in the critical cross section of effective material sample and

$$\sigma_n = \frac{6M}{bh^2}$$

is the effective normal stress. The effective normal stress is the maximal normal tensile stress in homogeneous sample of effective material with elastic modulus E^*. This stress is determined by the condition that the sample of such material has the same deflection as the layered sample with same sizes under identical bending loading.

The observable fracture toughness of each component in layered composite is dependent on the residual stresses in layers. Let the observable fracture toughness of component be called the effective fracture toughness of layer. There is the well-known relationship for fracture toughness:

$$K_{1c}^{(j)} = \xi\sigma_{cj}\sqrt{d_j}, \tag{20}$$

where ξ is the geometrical factor depended on shape and location of crack. A relationship similar to (20) takes place for the effective fracture toughness of the jth component layer in composite:

$$K_{1c}^{(je)} = \xi\sigma_{cj}^{(e)}\sqrt{d_j}, \tag{21}$$

where $\sigma_{cj}^{(e)}$ is the normal stress at the point of sample of effective material corresponding to the point with the maximal normal tensile stress in the jth component layer at the moment of its fracture in layered sample. This stress is:

$$\sigma_{cj}^{(e)} = \frac{E^*}{E_j}\left(\sigma_{cj} - \sigma_{rj}\right), \tag{22}$$

because the total working stress in the jth component layer at the moment of its destruction is the sum of applied stress $E_j\sigma_{cj}^{(e)}/E^*$ and residual stress σ_{rj} and the sum is equal to the jth component strength σ_{cj}.

Then comparing (21) and (20) in view of (22) we can obtain:

$$K_{1c}^{(je)} = \frac{E^*}{E_j}K_{1c}^{(j)}\left(1 - \frac{\sigma_{rj}}{\sigma_{cj}}\right). \tag{23}$$

2.3. Model of layered composites fracture

Consider the procedure of determination of the effective normal stress for a given deflection of the layered sample under bending. A certain effective elastic modulus E^* corresponds to some n_1 and n_2. Then the effective normal stress is:

$$\sigma_n = E^*\varepsilon \tag{24}$$

where ε is the effective normal strain. The effective normal strain is the maximal normal positive strain in homogeneous sample of effective material with elastic modulus E^*. This strain is determined by the condition that the sample of such material has the same deflection as the layered sample with same sizes under identical bending loading. A certain given effective strain corresponds to the given deflection of the layered sample under bending. Further it is necessary to determine new n_1 and n_2 corresponding to the effective normal stress σ_n. For this purpose the criterion of fracture of layers of the stretched area in composite sample should be checked up under the given conditions.

The given n_1 and n_2 should be analysed. Starting from $n_1 = 0$ and $n_2 = 0$ the following condition should be checked up:

$$\sigma_B \geqslant \sigma_{c1} - \sigma_{r1}, \tag{25}$$

where

$$\sigma_B = \frac{2E_1\sigma_n(Bk - z_c)}{E^*h} \tag{26}$$

is the normal stress at the point with coordinate B_k. Except for the points of crack tips the greatest normal stress in layers of the first component is reached in this point. This coordinate is:

$$B_k = k_1(l_1 + l_2) + l_1 - \frac{h}{2}, \tag{27}$$

where

$$k_1 = (N - 2n_1 - 1)/2 \tag{28}$$

is the index of critical layer of first component. If the condition (25) is carried out, then the number n_1 is increased by unit. Further the new effective elastic modulus E^*, the new residual stresses in layers and the new effective normal stress σ_n corresponding to new n_1 should be calculated and the new n_1 and n_2 should be analysed. If the condition (25) is not carried out, then the following condition should be checked up:

$$\sigma_A \geqslant \sigma_{c2} - \sigma_{r2}, \tag{29}$$

where

$$\sigma_A = \frac{2E_2\sigma_n(A_k - z_c)}{E^*h} \tag{30}$$

is the normal stress at the point with coordinate A_k. Except for the points of crack tips the greatest normal stress in layers of the second component is reached in this point. This coordinate is:

$$A_k = (k_2 + 1)(l_1 + l_2) - \frac{h}{2}, \quad (31)$$

where

$$k_2 = (N - 2n_2 - 3)/2 \quad (32)$$

is the index of the critical layer of the second component. If the condition (29) is carried out then the number n_2 is increased by unit. Further the new effective elastic modulus E^*, the new residual stresses in layers and the new effective normal stress σ_n corresponding to new n_2 should also be calculated and the new n_1 and n_2 should be analysed again. If the condition (29) is not carried out the effective normal stress σ_n corresponds to the given effective normal strain ε.

If $n_1 = 0$ and $n_2 > 0$ the layers of the first component are not destroyed and there are only internal cracks in layers of the second component in sample. The critical crack is the crack which is the nearest to a stretched side of the sample and is in the field of the greatest normal tensile stress. Then, the following condition should be checked up:

$$K_{1in} \geqslant K_{1c}^{(1e)}, \quad (33)$$

where

$$K_{1in} = Y_{in}\sigma_n\sqrt{l_2} \quad (34)$$

is the stress intensity factor of internal critical crack. The layers of the second component are internal by definition. The factor Y_{in} for such a crack is:

$$Y_{in} = Y_{in}\left(\frac{l_1}{h}, \frac{l_2}{h}\right),$$

where l_1 determines the distance from the critical tip of internal crack to the stretched side of sample, l_2 determines the length of the critical crack. The calculation of Y_{in} for the cross internal crack in sample under bending is considered in Refs. [2,3]. If the condition (33) is carried out, then the number n_1 is increased by unit. Further the new effective elastic modulus E^*, the new residual stresses in layers and the new effective normal stress σ_n corresponding to new n_1 should be also calculated and the new n_1 and n_2 should be analysed again. If the condition (33) is not carried out, then the condition (25) should be checked up.

If $n_1 > 0$ and $n_1 \leqslant n_2$ the external edge crack consists of n_1 cracks in layers of the first component and n_1 cracks in layers of the second component. The external edge crack is the critical because this crack is in the field of the greatest normal tensile stress. Then, the following condition should be checked up:

$$K_{1ou1} \geqslant K_{1c}^{(1e)}, \quad (35)$$

where

$$K_{1ou1} = Y_{ou1}\sigma_n\sqrt{n_1(l_1 + l_2)} \quad (36)$$

is the stress intensity factor of the external edge critical crack. The calculation of Y_{ou1} for the external edge crack in sample under bending is considered in Ref [4]. The factor Y_{ou1} for such crack is:

$$Y_{ou1} = 1.93 - 3.07w_1 + 14.5w_1^2 - 25.1w_1^3 + 25.8w_1^4$$

and

$$w_1 = \frac{n_1(l_1 + l_2)}{h},$$

where $n_1(l_1 + l_2)$ determines the length of critical crack. If the condition (35) is carried out, then the number n_1 is increased by unit. Further the new effective elastic modulus E^*, the new residual stresses in layers and the new effective normal stress σ_n corresponding to new n_1 should also be calculated and the new n_1 and n_2 should be analysed again. If the condition (35) is not carried out, the effective normal stress σ_n corresponds to the given effective normal strain ε.

If $n_1 > 0$ and $n_1 > n_2$ the external edge crack consists of $(n_2 + 1)$ cracks in layers of the first component and n_2 cracks in layers of the second component. Such external edge crack is also the critical because it is in the field of the greatest normal tensile stress. Then, the following condition should be checked up:

$$K_{1ou2} \geqslant K_{1c}^{(2e)}, \quad (37)$$

where

$$K_{1ou2} = Y_{ou2}\sigma_n\sqrt{n_2(l_1 + l_2) + l_1} \quad (38)$$

is the stress intensity factor of external edge critical crack. The calculation of Y_{ou2} for the external edge crack in sample under bending is considered in Ref. [4]. The factor Y_{ou2} for such a crack is:

$$Y_{ou2} = 1.93 - 3.07w_2 + 14.5w_2^2 - 25.1w_2^3 + 25.8w_2^4$$

and

$$w_2 = \frac{n_2(l_1 + l_2) + l_1}{h},$$

where $n_2(l_1 + l_2) + l_1$ determines the length of critical crack. If the condition (37) is carried out, then the number n_2 is increased by unit. Further the new effective elastic modulus E^*, the new residual stresses in layers and the new effective normal stress σ_n corresponding to new n_2 should be also calculated and the new n_1 and n_2 should be analysed again. If the condition (37) is not carried out, the effective normal stress σ_n corresponds to the given effective normal strain ε.

The possible variants of failure process of two-component brittle layered composite (number of layers $N = 5$) are illustrated in Fig. 2. The proposed model enables to predict the dependence of the normalized stress on the strain for two-component ceramic-matrix layered composites and the mechanical behavior of loaded laminar structures.

3. Strength of ceramic-matrix layered composites

3.1. Calculated stress–strain dependence of ceramic-matrix layered composites

The mechanical behaviour of layered samples with number of layers $N=3$, 7 and 15 under bending was simulated. The stress–strain dependences were calculated. For simulation the component A and component B were selected. The structural characteristics of component A correspond to TiN-ceramic. The structural characteristics of component B correspond to Al_2O_3-ceramic. The mechanical characteristics of components of layered composite are presented in Table 1. The difference ΔT in temperature between the actual temperature and the joining temperature of layered material was taken 800 K. It corresponded to many real cases. The height h of calculated sample was 3 mm.

The dependence of the normalized effective stress $\sigma_n^* = \sigma_n/E_1$ on the effective normal strain for a two-component brittle layered composite with the number of layers $N=7$ are shown in Fig. 3. The first component is component A. The second component is component B. The curve 1 corresponds to the macrostructural parameter $l_2/l_1 = 0.2$. The curve 1 has no stress jumps caused by partial destruction of layers. The curve 2 corresponds to the macrostructural parameter $l_2/l_1 = 0.5$. The curve 3 corresponds to the macrostructural parameter l_2/l_1. The curve 2 and the curve 3 have stress jumps caused by partial destruction of layers.

The dependence of the normalized effective stress $\sigma_n^*/\sigma_n/E_1$ on the effective normal strain for a two-component brittle layered composite with the number of layers $N=15$ are presented in Fig. 4. The first component is component A. The second component is component B. The curve 1 corresponds to the macrostructural parameter $l_2/l_1 = 0.2$. The curve 1 has no stress jumps. The curve 2 corresponds to the macrostructural parameter $l_2/l_1 = 0.5$. The curve 2 has many stress jumps caused by partial destruction of layers. The curve 3 corresponds to the macrostructural parameter $l_2/l_1 = 1$. There are also stress jumps on this curve.

The dependence of the normalized effective stress $\sigma_n^* = \sigma_n/E_1$ on the effective normal strain for a two-component brittle layered composite with the number of layers $N = 7$ are shown in Fig. 5. The first component is component B. The second component is component A. The curve 1 corresponds to the macrostructural parameter $l_2/l_1 = 0.2$. This curve has no stress jumps. The curve 2 corresponds to the macrostructural parameter $l_2/l_1 = 1.5$. The curve 3 corresponds to the macrostructural parameter $l_2/l_1 = 2$. The curve 4 corresponds to the macrostructural parameter $l_2/l_1 = 4$. The curves 2, 3 and 4 have stress jumps caused by partial destruction of layers.

The stress–strain dependence of ceramic-matrix layered composites has no stress jumps caused by partial destruction of layers when the condition (37) is carried out after the fracture of the first layer of the first component.

3.2. Strength–layer thickness dependence of two-component brittle layered composite

The dependences of the normalized strength $\sigma_c^* = \sigma_c/E_1$ on l_2/l_1 for a two-component brittle layered composite with number of layers $N=7$ are presented in Fig. 6. The curve 1 corresponds to the case when the first component is component A and the second component is component B. The curve 2 corresponds to the case when the first component is the component B and the second component is component A. The curves 1 and 2 have minima at l_2/l_1 from 1 to 2. There is the strength of first component at $l_2/l_1 = 0$ for both dependences. The strength of the layered composites in which the first component is component A and the second component is component B is higher than the strength of the layered composites in which the first component is component B and the second component is component A at $l_2/l_1 > 1$.

The dependences of the normalized strength $\sigma_c^* = \sigma_c/E_1$ on l_2/l_1 for two-component brittle layered composites with number of layers $N=3$, 7 and 15 are shown in Fig. 7. The first component is component A. The second component is component B. The curve 1 corresponds to $N=3$. The curve 2 corresponds to $N=7$. The curve 3 corresponds to $N=15$. The point A is a boundary between a region where the residual stresses are higher than the strength of component B and a region where the residual stresses are lower than the strength of component B. The spontaneous initial cracking of layers of the second component takes place to the left of this point.

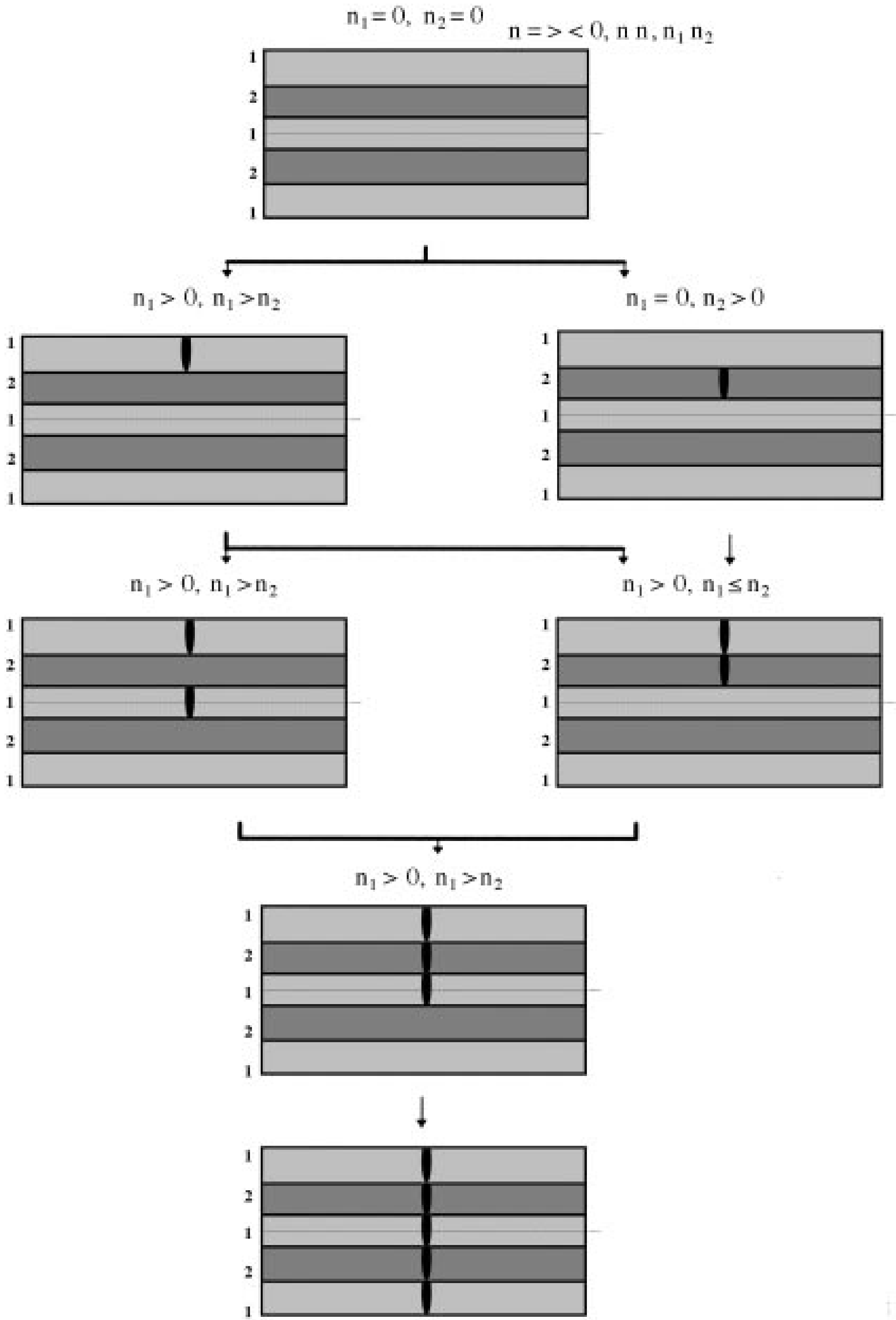

Fig. 2. Possible variants of failure process of two-component brittle layered composite (number of layers $N = 5$).

Table 1
Mechanical characteristics of components of layered composite

Property	A (TiN)	B (Al_2O_3)
Modulus of elasticity, GPa	440	400
Strength, MPa	400	400
Fracture toughness, MPa $m^{1/2}$	4.4	4
Thermal expansion factor, K^{-1}	$7.2 \cdot 10^{-6}$	$8.6 \cdot 10^{-6}$
Poisson's ratio	0.25	0.23

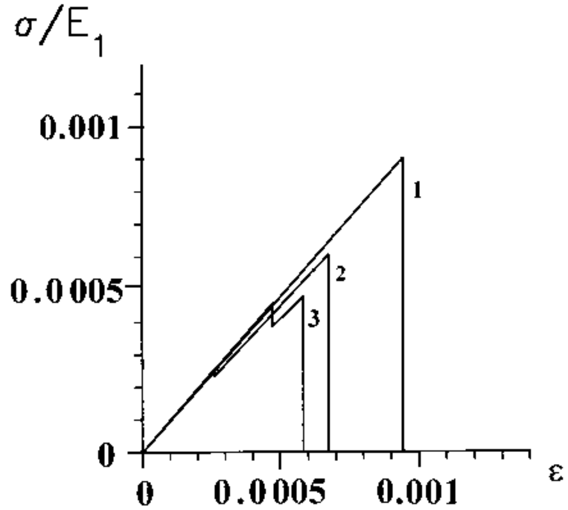

Fig. 3. The dependence of the normalized stress on the strain for two-component brittle layered composite (number of layers $N=7$; the first component is component A; the second component is component B) with: 1—$l_2/l_1=0.2$; 2—$l_2/l_1=0.5$; 3—$l_2/l_1=1$.

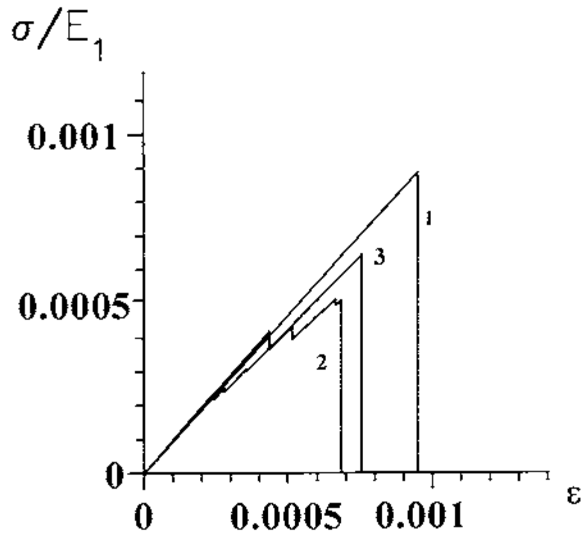

Fig. 4. The dependence of the normalized stress on the strain for two-component brittle layered composite (number of layers $N=15$; the first component is component A; the second component is component B) with: 1—$l_2/l_1=0.2$; 2—$l_2/l_1=0.5$; 3—$l_2/l_1=1$.

A certain ratio between strengths of the first and second components should be obtained to reach optimum properties of a layered material. Structural parameters of a component to reach its given strength can be appreciated by methods offered in Refs. [5,6].

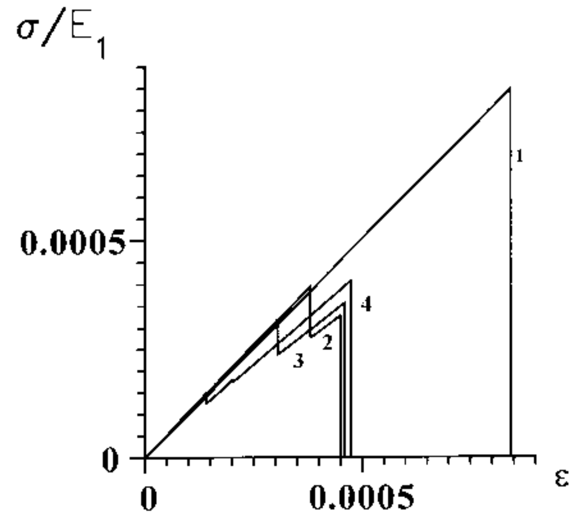

Fig. 5. The dependence of the normalized stress on the strain for two-component brittle layered composite (number of layers $N=7$; the first component is component B; the second component is component A) with: 1—$l_2/l_1=0.2$; 2—$l_2/l_1=1.5$; 3— $l_2/l_1=2$; 4—$l_2/l_1=4$.

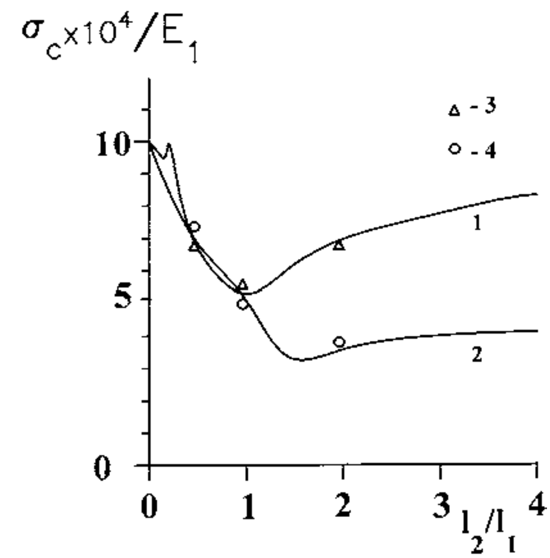

Fig. 6. The dependences of the normalized strength on l_2/l_1 for two-component brittle layered composite (number of layers $N=7$): 1—the first component is component A, the second component is component B; 2—the first component is component B; the second component is component A; 3—the experimental data corresponding to the case when the first component is TiN-ceramic and the second component is Al_2O_3-ceramic; 4—the experimental data corresponding to the case when the first component is Al_2O_3-ceramic and the second component is TiN-ceramic.

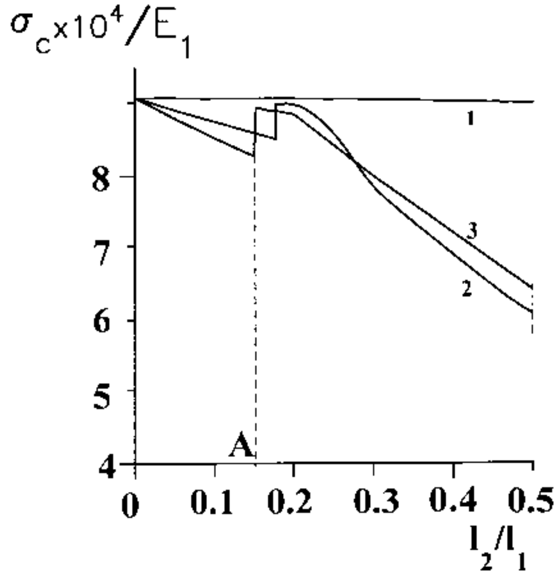

Fig. 7. The dependences of the normalized strength on l_2/l_1 for two-component brittle layered composite (the first component is component A; the second component is component B) with the number of layers: 1 $-N=3$; 2 $-N=7$; 3 $-N=15$.

3.3. Experimental strength of ceramic-matrix layered composites

The three-point bending tests of layered samples were executed. The span of tests was 20 mm. The layered samples were beams with rectangular section with height $h=3$ mm and width $b=5$ mm. Each sample consists of seven layers. There were samples in which the first component is TiN-ceramic, the second component is Al_2O_3-ceramic and in which the first component is Al_2O_3-ceramic, the second component is TiN-ceramic. The layered samples were made by hot pressing. The effective difference ΔT in temperature between the actual temperature and the joining temperature during manufacturing of layered samples was 800 K. Delamination on boundaries between layers was not observed.

The experimental data of the three-point bending tests of layered samples are presented in Fig. 5. The experimental data 3 corresponding to the case when the first component is TiN-ceramic and the second component is Al_2O_3-ceramic. The experimental data 4 corresponding to the case when the first component is Al_2O_3-ceramic and the second component is TiN-ceramic. The trends of the theoretical calculations agree with data obtained from 3-point bending tests of real ceramic-matrix layered composites.

4. Conclusions

A method of computer simulation of layered composites fracture during 3-point bending test was developed. A model of failure was considered which can be applied to two-component brittle layered composites (in particular ceramic-matrix composites). The particular modeling was executed for composites with the number of layers $N=3$, 7 and 15. The above mentioned model was applied for the description of mechanical behaviour of two-component ceramic-matrix layered composites. The trends of the theoretical calculations agreed with data obtained from 3-point bending tests of real ceramic-matrix layered composites.

The proposed model enables to predict the dependence of the normalized stress on the strain for two-component ceramic-matrix layered composites and the mechanical behavior of loaded laminar structures.

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References

[1] Chartier T, Merle D, Besson JL. Laminar ceramic composites. J Europ Ceram Soc 1995;16:101–7.
[2] Kaya AC, Erdogan F. Stress intensity factors and COD in an orthotropic strip. Int J Fract 1980;16(2):171–90.
[3] Nied HF, Erdogan F. A cracked beam or plate transversely loaded by a stamp. Int J Solids and Struct 1979;15(12):951–65.
[4] Ejike UBCO. Single-edge cracked strip under three-point load. Int J Eng Sci 1977;15(7):413–20.
[5] Podrezov YN, Lugovoy NI, Slyunyaev VN, Minakov NV. Statistical failure model of materials with micro-inhomogeneity. Theoretical and Applied Fracture Mechanics 1997;26:35–40.
[6] Lugovy M, Orlovskaya N, Berroth K, Kubler J. Microstructural engineering of ceramic-matrix layered composites: effect of grain size dispersion on single-phase ceramic strength. Compos Sci Technol 1999;59(2):283–9.