NUMERICAL INVESTIGATION OF DEFORMATION AND FRACTURE IN ALUMINUM-ALUMINA AT THE MESOSCALE

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ABSTRACT

Mesovolume deformation of aluminum-alumina metal-matrix composite is investigated within the plane-strain formulation. Numerical solutions were performed in terms of Lagrangian variables using the finite-difference method. Hierarchical simulation presumes the use of different models for describing a mechanical behaviour of the plastic metal matrix and brittle ceramic inclusions: elasto-plastic formulation with the strain hardening and a cracking model using a fracture criterion of Huber type, respectively. The criterion takes into account the difference in critical values for different local stress-strain states: tension and compression.

It has been shown that the composite mesovolume exhibits complex mechanical behaviour controlled by both shear band formation in the matrix and cracking of inclusions. The computational results have been analysed in details and compared with those experimentally observed.

1 INTRODUCTION

According to the physical mesomechanics approach an occurrence of powerful stress concentrations of different physical nature near the interfaces in heterogeneous materials is one of the key factors determining a non-uniform deformation [1-3]. This effect is the most clearly pronounced in composite materials: metal matrix composites, materials with coatings, surface–hardened materials, alloys with inclusions, etc. That is why fundamental investigations in this area could be further applied in computer-aided design of new constructional materials.

2 MATHEMATICAL FORMULATION

In this work mesoscale deformation of aluminum-alumina metal-matrix composite is investigated within the plane-strain formulation [4,5]. Numerical solutions were performed in terms of Lagrangian variables, using the finite-difference method. Hierarchical simulation presumes the use of different models for describing mechanical behaviour of the plastic metal matrix and brittle ceramic inclusions: elasto-plastic formulation with the strain hardening and a cracking model using a fracture criterion of Huber's type, respectively. The criterion takes into account the difference in critical values (strength in Table.1) for different local stress-strain states: tension and compression.

$$\sigma_{eq} = \begin{cases} C_1, \text{ if } P > 0 \Rightarrow S_{ij} = 0 \text{ and } P = 0 \\ C_2, \text{ if } P < 0 \Rightarrow S_{ij} = 0 \end{cases} \quad (1)$$

Here C_1, C_2 are the constants that characterize yield strength of Al_2O_3 under tension and compression, respectively. The fracture criterion (1) means that the following conditions are associated with any local region of Al_2O_3 : if bulk deformation ε_{kk} takes on a positive value and σ_{eq} reaches its critical value of C_1 then pressure and all components of stress deviator tensor in this region tend to zero. In the case of $\varepsilon_{kk} < 0$ and $\sigma_{eq} \geq C_2$ the pressure does not tend to zero. In so doing, if the fracture criterion fulfills, inclusions behave themselves as an uncompressed liquid. The material density maintains to be constant and corresponds to the density of Al_2O_3 .

Strain hardening function for the aluminum matrix is chosen to fit experimental data [7,8] and is described by the relation $\phi(\varepsilon_{eq}) = 170 - 65\exp(-\varepsilon_{eq} / 0.048)$ [MPa], where in a general case

$$\sigma_{eq} = \frac{1}{\sqrt{2}}\left\{(S_{11}-S_{22})^2 + (S_{22}-S_{33})^2 + (S_{33}-S_{11})^2 + 6\left(S_{12}^2 + S_{23}^2 + S_{31}^2\right)\right\}^{\frac{1}{2}},$$

$$\varepsilon_{eq} = \frac{\sqrt{2}}{3}\left\{\left(\varepsilon_{11}^p - \varepsilon_{22}^p\right)^2 + \left(\varepsilon_{22}^p - \varepsilon_{33}^p\right)^2 + \left(\varepsilon_{33}^p - \varepsilon_{11}^p\right)^2 + 6\left({\varepsilon_{12}^p}^2 + {\varepsilon_{23}^p}^2 + {\varepsilon_{31}^p}^2\right)\right\}^{\frac{1}{2}}.$$

Table 1: Experimental mechanical properties of Al_2O_3 [6, 7].

K, GPa	G, GPa	Density, ρ, kg/m^3	Strength, MPa	
			Tension C_1	Compression C_2
318	147	3990	260	4000

3 CALCULATION RESULTS

It has been shown that the composite mesovolume exhibits complex mechanical behaviour controlled by both shear band formation in the matrix and cracking of inclusions (Fig.1). Fig. 1A shows map of the test cut-out. The image corresponds to the real structure of the mesovolumes, which were experimentally investigated in [7,8].

Boundary conditions on the right and left boundaries of the area under calculation determine grip displacement velocity, while on the top and bottom surfaces they correspond to the free surface conditions (Figure 1**A**):

BC1: $U_X = -U =$ constant; BC3: $U_X = U$; BC2: $\sigma_{ij}n_j = 0$; BC4: $U_y = 0$.

The integral stress-strain diagram of the mesovolume under study is presented in fig. 1B. The stress was calculated as an average value of equivalent stress over the mesovolume:

Stress = $\sum_{k=1,N}\sigma_{eq}^k v^k \Big/ \sum_{k=1,N} v^k$, where N is the amount of the grid nodes, v^k is the local volume.

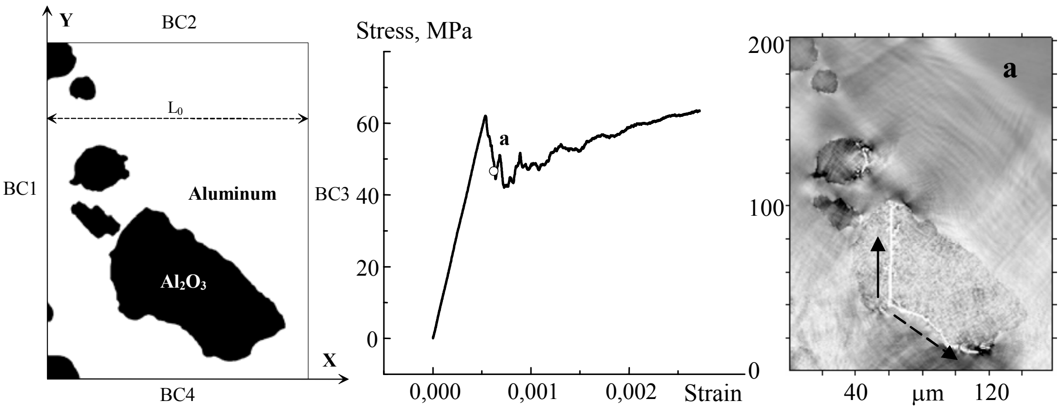
Deformation represents relative mesovolume elongation towards X direction. $\text{Strain} = L - L_0/L_0$, L_0 is the initial length in X direction, L is the current length.

Fig.1C shows equivalent stress pattern. Initially the local fracture area is formed in the vicinity of the most powerful stress concentrator at the “aluminum-alumina” interface (solid arrow in Fig.1C). This gives rise to significant increasing in strain intensity in the neighboring regions. A new stress concentrator nucleates in the Al_2O_3 inclusion and crack propagates transversely to the loading direction. As the crack reaches an opposite boundary of the inclusion it stops and then begins to propagate along the interface, starting from the place of crack origination (dashed arrow in Fig.1C). This process is accompanied by stress relaxation throughout the mesovolume that results in descending portion in the stress-strain curve (fig. 1B).

To sum up the computational results obtained under different types of external loading (tension and compression) the following conclusions remarks could be made.

1. Due to strain incompatibility near the “aluminum-alumina” interfaces, there are formed local tension regions under macroscopic compression. And vise versa, under macroscopic tension in the same direction these local regions are under action of compression stresses.
2. Local fracture areas firstly appear near the most powerful concentration of tension stresses, under action of which cracks propagate under both tension and compression, i.e. all the cracks are so-called “tensile cracks”.

3. Cracking of inclusions is accompanied by the intensive plastic flow in the matrix under compression, whereas under tension cracks originate and begin to grow at the elastic stage of deformation.
4. Cracks propagate perpendicular to the loading direction under tension and in parallel under compression.



A B C

Figure 1: Initial structure **A**, stress-strain curve **B** and equivalent stress pattern **C** for the mesovolume.

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