Available online at www.sciencedirect.com
ScienceDirect
Journal of the European Ceramic Society 27 (2007) 1287–1292
www.elsevier.com/locate/jeurceramsoc

Residual stresses in particulate composites with alumina and zirconia matrices

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Available online 6 June 2006

Abstract

The paper summarized a calculation of typical stresses caused by the coefficients of thermal expansion (CTE) mismatch in particulate composites with alumina and zirconia matrices containing tungsten carbide and metallic tungsten. The differences in local stress distribution due to the type of matrix and inclusion were established. The FEM simulations were compared with the results of mechanical tests on mentioned composites. The conclusions were assisted by SEM analyses of true composite microstructures, especially focused on a crack path near the interphase boundaries.

Keywords: Composites; Residual stresses

1. Introduction

The possibility of some improvement of mechanical properties of oxide ceramics by manufacturing of particulate composites has been very well recognized recently. Among the oxide ceramics, zirconia and alumina are the most important materials, widely used in structural applications, due to their properties. Fabrication of two-phase particulate composites could be the simplest way to the improvement of mechanical properties. Despite a wide range of alumina–zirconia composites, non-oxide particles were also often utilized as strengthening agents. Many phases were introduced into zirconia and alumina matrices—TiC,[1] SiC,[2,3] TiB_2,[4] TiN[5] and metals—nickel,[6] molybdenum[7] and tungsten.[8] In this way, the materials with improved properties, when compared with "pure" matrix materials, were obtained. Depending on the type of inclusions, their size and amount as well as sintering conditions, one can achieve a significant improvement of hardness, stiffness, fracture toughness and/or strength of the material. It was also reported that the decrease of inclusion size to the nanometric scale allowed extremely high values of flexural strength and fracture toughness to be achieved.[9]

The manufacturing of composites with ceramic matrix almost always leads to residual stresses caused by the mismatch of thermal properties of constituent phases. A large difference in thermal expansion coefficients (CTE's) could introduce stresses reaching even hundreds of megaPascals to the composite system. Such a phenomenon has to influence fracture toughness of the material.

This paper presents the investigation results of fracture toughness improvement of composites based on tetragonal zirconia or alumina—containing tungsten carbide (WC) and metallic tungsten (W). The level of fracture toughness changes is different in both types of composites. The authors tried to connect this fact with the differences in the stress level in materials.

2. Experimental

Composite powders investigated in this work were prepared from the commercial powders of alumina (Nabaltec), yttria stabilized zirconia (Tosoh), tungsten carbide (Baildonit) and metallic tungsten (Baldonit). The content of additives (WC or W) was 10 vol% in each case. The mean grain size of WC and W powders was about 1 μm (by supplier). The composite constituents were homogenised in an atrittor mill in ethyl alcohol. The grains of constituent phases were intensively mixed for 4 h.

Sintering of samples was conducted using the hot-pressing technique. The powders were placed in a carbon die, under argon atmosphere. Samples with zirconia matrix (and pure zirconia material) were sintered at 1500 °C with 1 h soaking time. Sintering of alumina-based materials was conducted at 1500 °C, also with 1 h soaking time. The pressure applied during sintering process was always 25 MPa. Discs, 25 mm in diameter and ∼3 mm

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0955-2219/$ – see front matter
doi:10.1016/j.jeurceramsoc.2006.04.096

thick, were formed. These discs were polished and cut to obtain the samples for tests. Six types of materials were prepared: pure alumina, Al_2O_3/WC and Al_2O_3/W composites, pure zirconia, ZrO_2/WC and ZrO_2/W composites (described relatively as A, A/WC, A/W, Z, Z/WC and Z/W).

The densities of the sintered bodies (ρ) were measured by the Archimedian method. Hardness was measured by the Vickers pyramid indentation (HV) on the polished surface of samples. The values of critical stress intensity factor (K_{Ic}) were determined by the Vickers pyramid indentation. Calculations of the K_{Ic} value were made according to the Niihara equation,[10] applying the Palmqvist crack model.

The composite microstructures were examined using the SEM technique.

The calculation of stresses in materials was made using the finite elements model based on following predictions:

- The grain in the matrix with a crack in neighborhood in two-dimensional geometry (see Fig. 1).
- The model was constrained to enable a free deformation in *xy* plane to be carried out and, additionally, in one corner.
- The geometric model was discretized with the AutoGEM modulus.[11,12] The mesh was condensed near the crack tip and in the area between the grain and the crack (see Fig. 2). For calculations the elements neighboring the point of support were excluded. This eliminated the stress accumulation at the model edge.
- Grain boundaries inside constituent phases were omitted.
- Calculations were made using the mechanical property values (Young's moduli, Poisson ratio's and CTE's) described in Table 1. Isotropy of these constants was taken as a principle.
- Modeling was performed for the plain stress state.
- Two methods of load were used:

(1) Cooling from temperature of 1200 °C to room temperature.

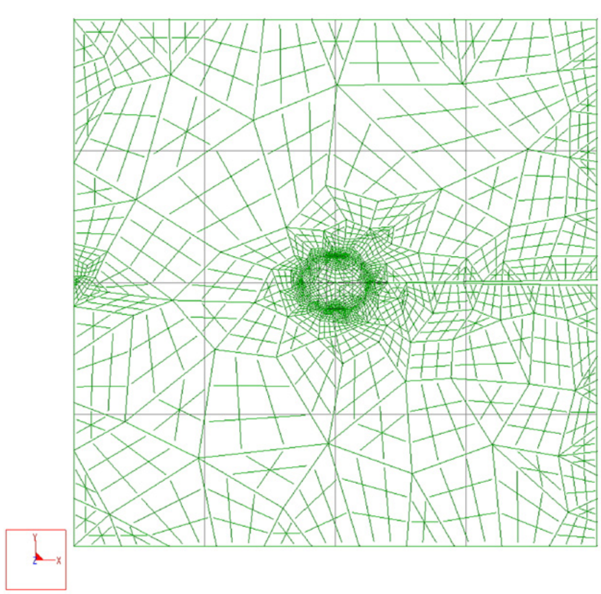

Fig. 1. The model for FEM calculations-grain in the matrix with crack in neighborhood in two-dimensional geometry.

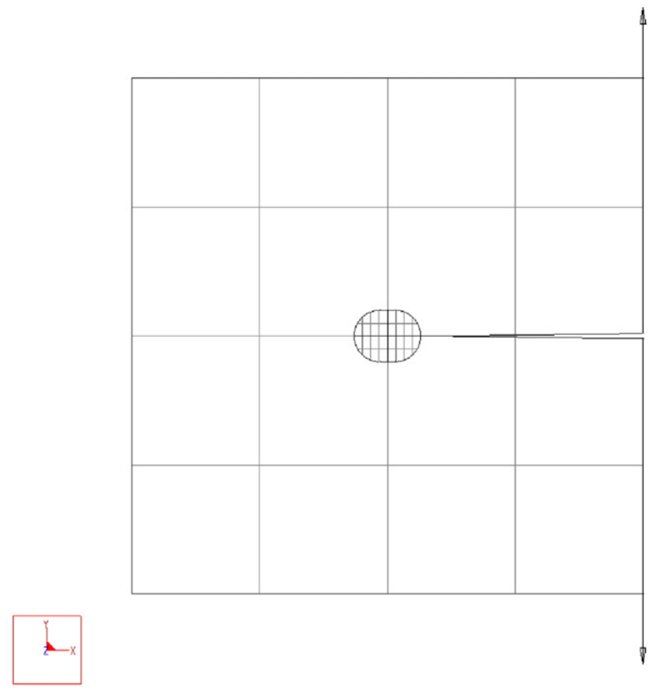

Fig. 2. The mesh used for FEM calculations-condensed near crack tip and in the area between the grain and the crack.

Table 1
Data utilized for FEM calculations

Material	CTE, α [$\times10^{-6}$ C^{-1}]	Young modulus, *E* [GPa]	Poisson ratio, ν
Al_2O_3	7.9	385	0.250
TZP	11.0	210	0.210
WC	5.2	700	0.300
W	4.4	400	0.280

(2) External load causing crack extension was applied at corners.

3. Results and discussion

The results of FEM simulations are visualized in Figs. 3–6. They present the distribution of von Mises stresses around the inclusion for Al_2O_3/W, Al_2O_3/WC, TZP/W and TZP/WC composites, respectively. Generally, the maximum value of von Mises stresses in the zirconia matrix is about 15% higher than in the alumina one. The tensile stress level near the interphase boundary in the zirconia matrix materials exceeds 1500 MPa all around the inclusion grain (Figs. 3 and 4). In the alumina-based materials maximum stress values in this area are much lower (Figs. 1 and 2). This fact influences the path of crack in the investigated materials. In zirconia-based composites crack goes along the interphase boundary (Figs. 7 and 8). The crack course in composites with alumina matrix is different. It usually goes near the inclusion grains, but it is deflected before it reaches the interphase boundary (Figs. 9 and 10). This means that the crack goes through alumina grains.

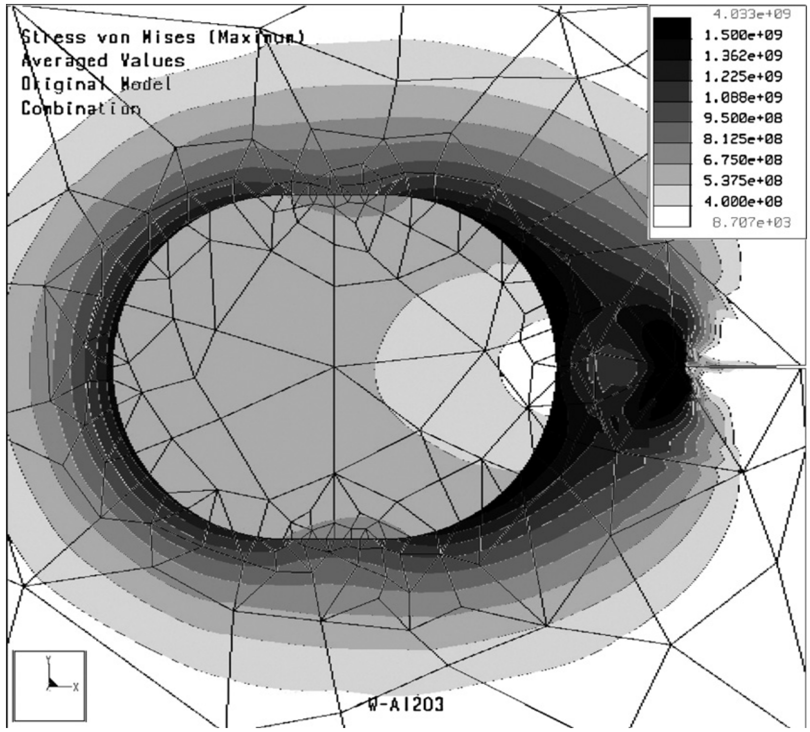

Fig. 3. The von Mises stresses calculated for Al_2O_3/W composite.

The final effect of behaviour of such crack for material toughening is summarized in Table 2. As it is clearly visible, the relative fracture toughness increase observed for the alumina-based composites is higher than for the zirconia ones.

This phenomenon should be attributed to the lower stress level in the alumina-based composites. As it can be seen in Figs. 3–6, the maximum stress values are present in some distance before the inclusion grain. Probably the strength of alumina grain is comparable with the strength of interphase boundaries (Al_2O_3–W and Al_2O_3–WC) in composites. Such a situation promotes transgranular cracking of alumina, but in a specific way, the crack still wanders around inclusions and

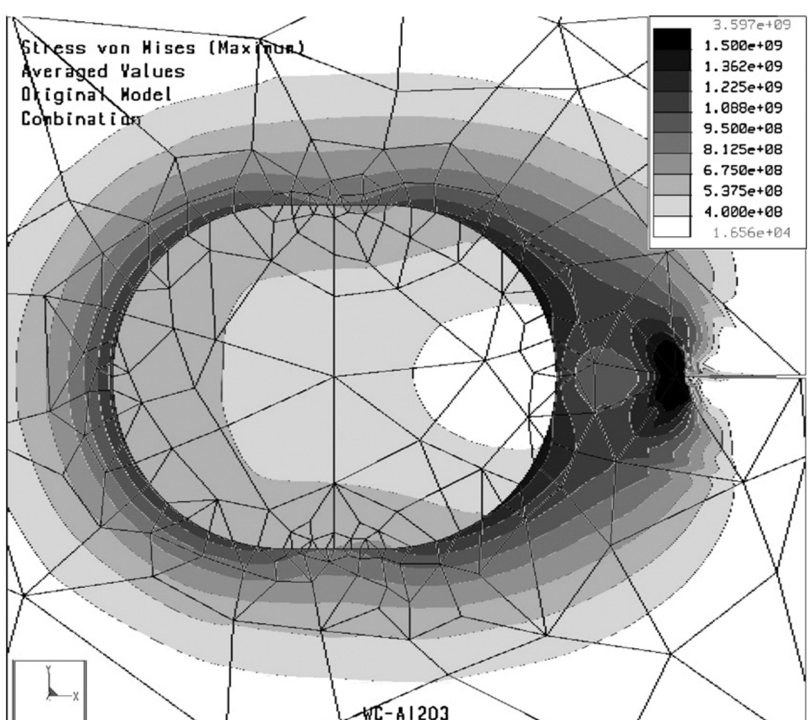

Fig. 4. The von Mises stresses calculated for Al_2O_3/WC composite.

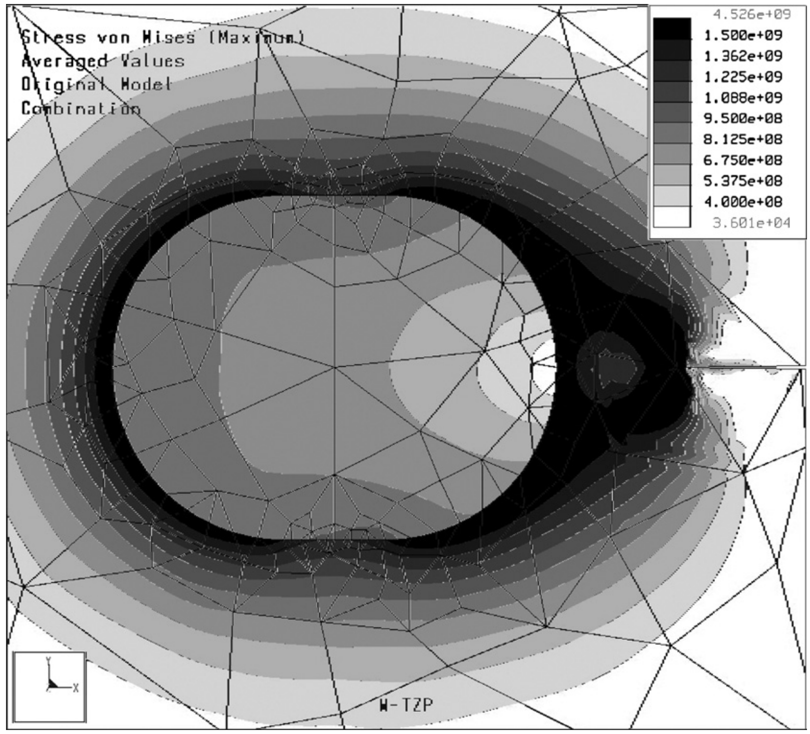

Fig. 5. The von Mises stresses calculated for ZrO_2/W composite.

crack deflection mechanism is still active and it consumes energy effectively.

In TZP matrix composites, the tensile stress acting on the interphase boundary is much higher than in these with alumina matrix. It decreases the amount of energy dissipated during cracking. Additionally, high toughness of the zirconia material causes that the crack does not deflect as in the case of alumina. The crack rather goes to the interphase boundary and deflects directly on it. These observations are only qualitative but they could help to understand the effect of a relatively high level

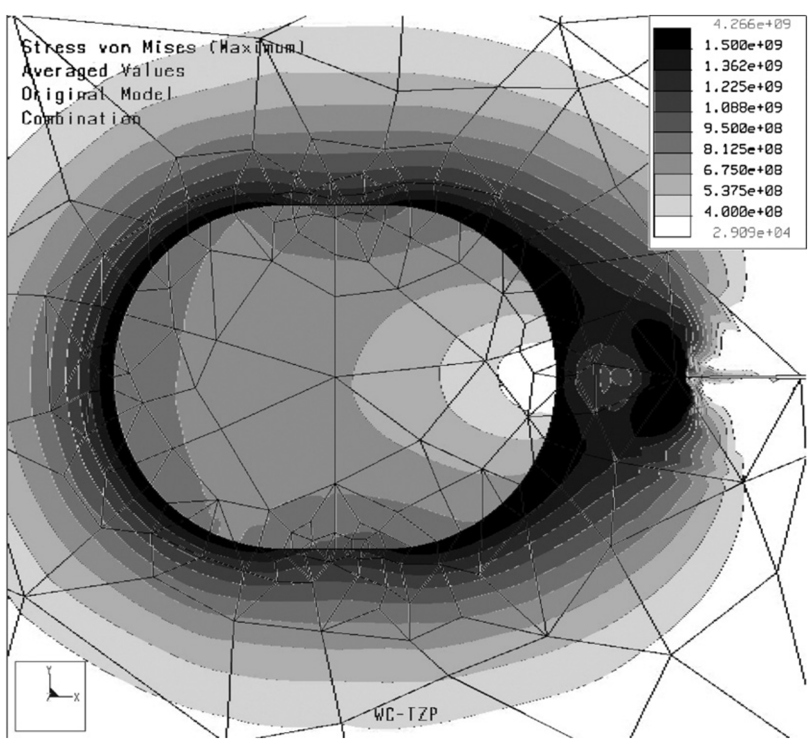

Fig. 6. The von Mises stresses calculated for ZrO_2/WC composite.

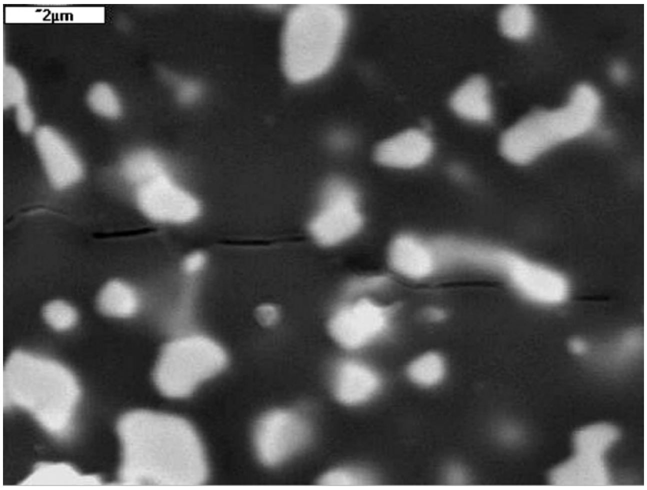

Fig. 7. The SEM image of crack path in ZrO_2/W composite.

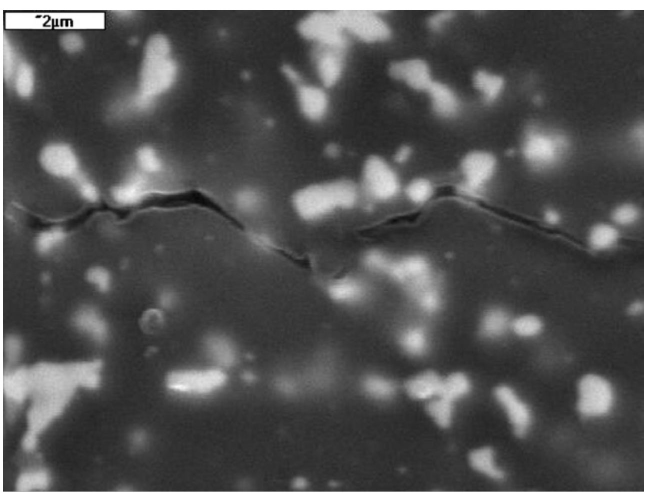

Fig. 8. The SEM image of crack path in ZrO_2/WC composite.

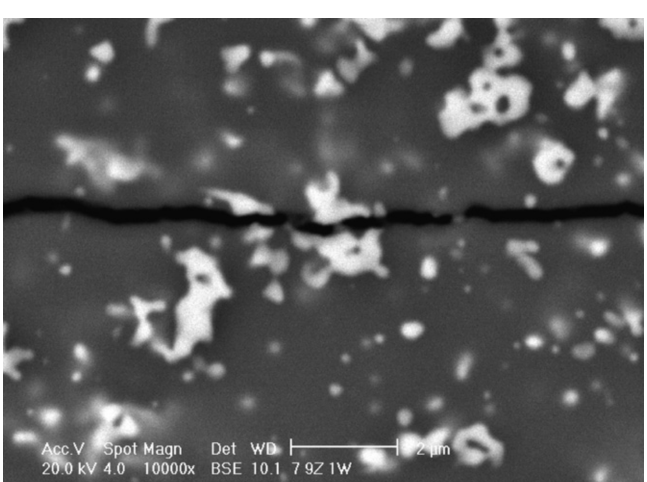

Fig. 9. The SEM image of crack path in Al_2O_3/W composite.

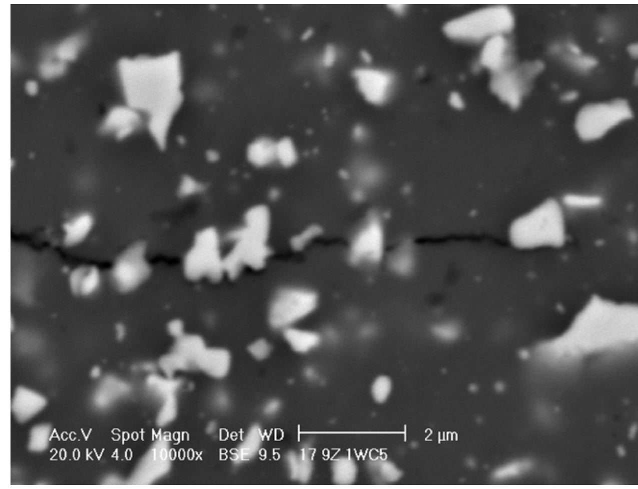

Fig. 10. The SEM image of crack path in Al_2O_3/WC composite.

Table 2
Properties of the matrices and composites

Material	Density [% theo.] ±0.1	Young modulus, E [GPa]	Hardness, $HV_{0.5}$ [GPa]	Fracture toughness, K_{Ic} [$MPam^{0.5}$]
Al_2O_3	99.3	378 ± 6	15.0 ± 0.8	4.0 ± 0.5
Al_2O_3/WC	99.1	432 ± 5	18.0 ± 1.0	6.0 ± 0.6
Al_2O_3/W	99.0	421 ± 8	16.0 ± 1.1	8.0 ± 0.8
TZP	99.7	209 ± 5	14.0 ± 0.5	5.0 ± 0.5
TZP/WC	99.9	228 ± 6	16.0 ± 0.8	6.5 ± 0.8
TZP/W	99.8	217 ± 6	14.0 ± 0.8	7.5 ± 1.2

Symbol (±) denotes of the confidence interval on confidence level of 0.95.

of toughening in the alumina-based composites. Information given in this paper demands confirmation by stress measurements performed by means of an using independent method (e.g. fluorescence or Raman spectroscopy).[13]

4. Conclusions

The effective improvement of fracture toughness in the alumina-based composites is larger than in the zirconia-based ones. This fact could be connected with the stress state in the materials, which influenced the type of cracking. In zirconia-based materials, crack is deflected directly on inclusion grains, probably due to the extremely high tensile stress value in the interphase boundary area). In the materials with the alumina matrix the crack is deflected before it reaches the interphase boundary. Such a type of cracking assures a more effective improvement of fracture toughness.

Acknowledgements

The Polish State Committee for Scientific Research under grants 7T08D 015 23 financially supported this work. The authors are greatly indebt to Prof. Marek Faryna for help in microscopic observations.

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