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# ALUMINA COMPOSITES WITH METAL PARTICLES IN CERAMIC MATRIX

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*Ceramic–metal composites are an important group of materials for many applications due to their unique properties. The combination of the hardness, strength at high temperatures, chemical inertness of ceramics with ductile, electrical or magnetic properties of metal are not achieved in single-phase materials. However, the brittleness of ceramics is the main disadvantage, which is limiting the under stress performance of ceramics and ceramic matrix composites. Theoretical and experimental research is still concentrated on improving the fracture toughness by tailoring the microstructure of composites. The study of metal particles embedded into ceramic particles, their distribution, size, and the interfaces and their influence on mechanical properties of the composites are presented. The important role of production techniques is emphasized. Based on experimental results, the $Al_2O_3$–Ni system is discussed.*

***Keywords***: *fracture toughness, composite, ceramic matrix, ceramics, slip casting, gel casting.*

## INTRODUCTION

Ceramics are attractive engineering materials because they have interesting combinations of properties such as low density, high hardness, high strength, refractoriness, thermal and chemical stability, and wear resistance. However, their low fracture toughness limits their potential applications. The popular concept of improving the fracture strength is to incorporate ductile metallic particles into a ceramic matrix [1]. In many researches, the improvement of mechanical properties by adding metal phase like Mo, Fe, Ni or Cu [2–4] is reported. Also, our own researches proved the increasing of the ceramic–metal composites in fracture toughness [5–8]. There are several toughening mechanisms that may operate, when metal particles are incorporated into the brittle ceramic matrix. The maximum benefit is derived from the plastic deformation of metal particles and bridge of advancing cracks [2]. The above mechanism and others (such as crack deflection of the metal particles), depend on the metal, their size, and distribution. Especially, adding the nanosized metal particles into a ceramic matrix can drastically increase the toughness [2]. The strength of bonding between metal particles and ceramic matrix is crucial. However, the final effect is determined by choosing the production technique.

Powder metallurgy techniques, such as uniaxial, isostatic or hot pressing, are commonly used. Unfortunately, these techniques are not dedicated to obtaining complex-shaped parts. Other techniques, such as wet processing techniques, give a possibility to obtain ready-to-use complex-shaped parts and to avoid the agglomeration of powders.

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This study analyses the microstructure of $Al_2O_3$–Ni composites as viewed from improving the fracture toughness. A review of research results on composites produced by various powder consolidation techniques is presented.

## DISTRIBUTION OF METAL PARTICLES IN CERAMIC MATRIX

For operation of toughening mechanisms, the microstructure should be homogeneous. It means that metal particles should be uniformly distributed in the ceramic matrix. The type of the uniform distribution of metal particles differs depending on the size of powder particles. For sub-micron and nanosized powder particles (both metal and ceramics), the metal particles should be separated by ceramic grains in the composite (Fig 1*a*). Metallic inclusions in the ceramic matrix can be located inside the matrix grains (Fig. 1*b*) or at the grain boundaries only for the size of metal powder particles smaller than ceramics (especially, for nanometer size) (Fig. 1*c*). Consolidation of ceramic and metal powders under high pressure equal to 2.5 GPa and sintering at 700°C allowed obtaining Ni particles at the ceramic grains [9].

A mix distribution of metal particles is also possible [2]. Figure 2 demonstrates various distributions of the metal particles.

Conventional techniques of powder processing are not successful for preparation of such type of microstructures. However, these techniques are easy to use. The main problem is the agglomeration of powder particles from the first stage of consolidation, which is the mixing of powders. This problem occurs for both sub-micron and nanosized particles [2]. Mostly, metal particles make agglomerates consisting of several particles (Fig. 2*d*).

Wet processing, including slip casting and gel-casting techniques, provides a possibility to obtain a homogenous distribution of metal particles. During slip casting, the slurry is poured into a porous mold [2]. During gel-casting, the conventional casting of slip into a mold is linked with *in situ* polymerization reaction [10]. Both of these techniques were used in our research on producing ceramic–metal composites. The results [7, 8, 11] proved that these techniques can be successfully applied for producing alumina–nickel composites with the homogenous distribution of nickel particles (Figs. 2*a* and 2*b*).

Besides the uniform distribution of metal particles in the ceramic matrix, gradient structures are desired. Composites with gradient-distributed metal particles are also important as functionally graded materials (FGM), for example, for air space applications [12, 13]. Also, wet processing techniques can be successfully used for preparing the FGM [14, 15]. These techniques offer new possibilities in producing bulk materials with various types of the metal particle gradient concentration in the ceramic matrix.

The slip casting technique allows producing composites with a gradient of the metal particle concentration. The gradient of the metal particles can be achieved either by gravity-induced sedimentation or under magnetic field. The magnetic field is the driving force of the motion of the ferromagnetic metal particles (Fe, Ni) and it controls the spatial arrangement of metal particles in the FGM (Fig. 2*e*) [15].

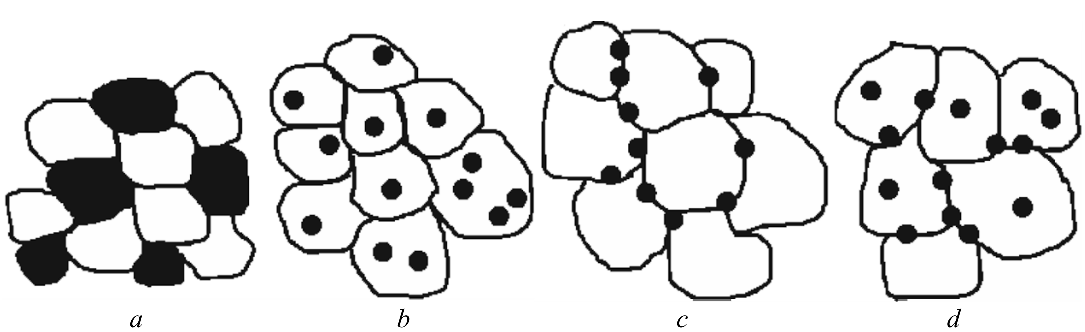
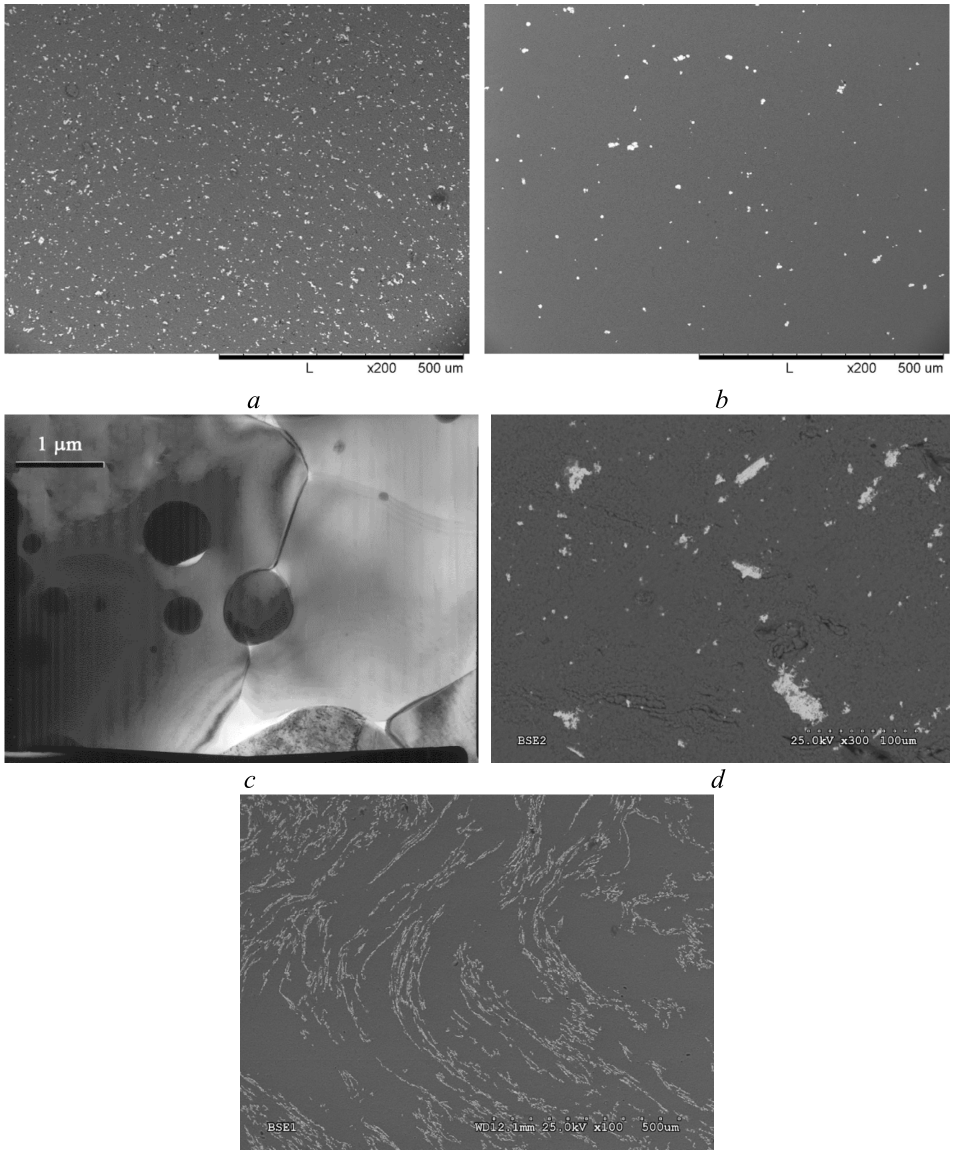



*Fig. 1*. Distribution of metal particles in the ceramic matrix: metal particles (black area) are separated by ceramic grains (*a*); metal particles are located inside matrix grains (*b*); metal particles are located at grain boundaries (*c*); and mixed distribution of metal particles (*d*)




*a* *b* *c* *d* *e*

*Fig. 2*. Various distribution of Ni particles in the $Al_2O_3$ matrix: homogenous distribution of Ni particles (light-grey areas correspond to the Ni particles) in the composite made by slip casting technique, SEM image (*a*); homogeneous distribution of Ni particles (light-grey areas) in the composite made by gel-casting technique, SEM image (*b*); Ni particles (black dots) located inside ceramic grains and at the grain boundaries, TEM image (*c*); agglomeration of Ni particles (light-grey areas) in the ceramic matrix, SEM image (*d*); graded $Al_2O_3$–Ni composite, produced by slip casting, magnetic-field induced sedimentation, SEM image showing the Ni particles arranged along the magnetic lines (*e*)

## SPINEL PHASE IN CERAMIC–METAL COMPOSITES

The interfaces are responsible for operating of particular toughening mechanism and its effectiveness. A ceramic/metal interface is the contact between two classes of materials having different properties due to their different atomic structure and bonding. This induces stress at the interfaces, which, together with thermal residual stress, can degrade the strength of ceramic/metal bonding and, as a consequence, the cracks appear in microstructures.

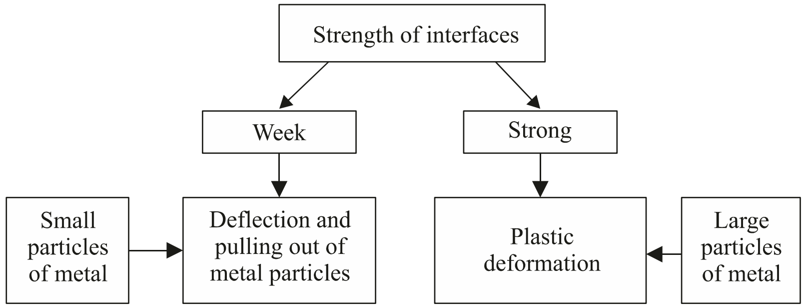


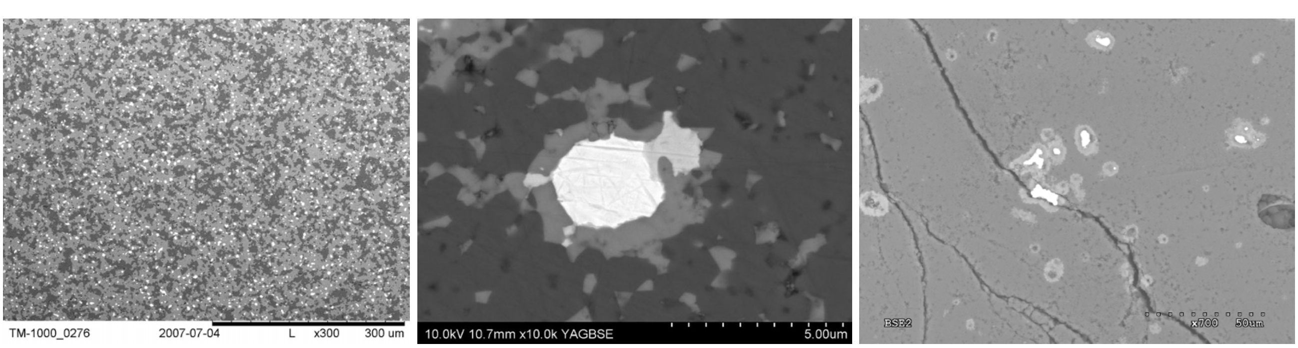

*Fig. 3*. Schematic of correlation between the strength of interfaces and crack propagation mechanisms in the composites

High strength of ceramic/metal interface is a necessary condition for enhancement of the fracture toughness by crack bridging mechanism. Plastic deformation of metal particles results from the fracture energy exceeding adhesion [16]. Contrary, the deflection and pulling out of metal particles dominate, if week interfaces. Also, these toughening mechanisms are sensitive to the size of the metal particles (Fig. 3). It is noticed that, opposite to the smallest particles, where the deflection and pulling out of particles are dominating, the plastic deformation is more expected for larger particles [2, 16]. This fact should be considered in tailoring the ceramic–metal composite microstructure.

New phases, such as spinel, can appear in some ceramic–metal systems, leading to the formation of new interfaces. During sintering in argon or in the air, the spinels $FeAl_2O_4$ and $NiAl_2O_4$ appeared in the $Al_2O_3$–Fe and $Al_2O_3$–Ni systems. Spinel makes separated areas located in ceramic matrix or surrounds metal particles (Figs. 4*a* and 4*b*). The thickness of the spherical spinel layer changed. In comparison with the volume of metal particles, the volume of spinel areas is larger by a factor of 8 [17]. Moreover, the spinel grains linked to each other were observed (Fig. 4*b*).

The spinel and its distribution affect the fracture behavior of the composites. The distribution and thickness of the spinel layer around metal particles give various contributions to the change of the fracture toughness.

The crack propagation along the interface metal/spinel is dominating for the weak bonding. Here are some research results on the various values of the thermal expansion coefficient ($\alpha$). Thermal linear expansions of $Al_2O_3$ and $NiAl_2O_4$ are similar: $\alpha = 9.0 \cdot 10^{-6}$ K$^{-1}$ for $Al_2O_3$ and $\alpha = 9.1 \cdot 10^{-6}$ K$^{-1}$ for $NiAl_2O_4$ [18]. Therefore, there is an expansion mismatch between Ni ($\alpha = 17.3 \cdot 10^{-6}$ K$^{-1}$ for Ni) and $NiAl_2O_4$ [18]. Most likely, the cracks will occur in the interface Ni/$NiAl_2O_4$ (Fig. 4*c*). Also, the crack branching of the spinel layer is seen in the thick area of the spinel [8, 15, 17]. Consequently, the fracture toughness increases in composites with spinel. An increase in the fracture toughness of the tested composites $Al_2O_3$–Fe and $Al_2O_3$–Ni was reported [5–8, 15, 17].




*a* *b* *c*

*Fig. 4*. SEM images of $Al_2O_3$–Ni composites: spinel makes separated areas located in ceramic matrix or surrounds the metal particles (*a*); spinel phase around Ni particles, spinel grains linked to each other (*b*); and propagation of cracks along interface Ni/$NiAl_2O_4$ (*c*)

In gradient composites, the fracture toughness changed together with the gradient concentration and distribution of metal particles [14, 15].

## CONCLUSIONS

Ceramic–metal composites have attracted much attention due to an interesting combination of properties: mechanical, electrical, optical, and magnetic properties. Such composites as $Al_2O_3$–Fe and $Al_2O_3$–Ni with a fracture toughness improved are considered for engineering applications. However, the dependence of the microstructure and properties is not well known yet. The technological parameters of production techniques are the crucial factors of tailoring the microstructure of composites.

Conventional PM techniques are not good enough to produce a homogenous distribution of the metal particles. The wet processing techniques (slip casting and gel-casting) are more efficient. Such techniques lead to higher densification, good quality, and homogenous distribution of metal particles. During gel casting, the control of the time (the gelation starts upon) is an important advantage in the distribution of metal particles.

To produce composites with a gradient concentration of metal particles during wet techniques, the gravity sedimentation or the effect of magnetic field on the metal particles can be used. The fracture toughness and properties changed according to the gradient concentration of metal particles.

Spinel phase existed in the microstructure of the composite, influenced the crack propagation, and enhanced the fracture toughness.

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