Metal Matrix Composites Reinforced With Nanoparticles for the Needs of Space Exploration

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ABSTRACT. Aluminum (Al) matrix composite materials reinforced with small amounts (0.01 – 0.15 % vol.) of aluminum or zirconium oxides nanoparticles were fabricated by tradition powder metallurgy (PM) techniques with cold pressing and vacuum sintering. Nanoparticles and their clusters were located on grain boundaries of a matrix. The microhardness of the produced composites was dramatically increased than bulk pure Al, by increasing the amount of nanoparticles. The tensile strength of the produced composites was dramatically increased (more than 2 times) than bulk pure Al, by increasing the amount of nanoparticles. This powder metallurgical approach could also be applied to other nanoreinforced composites, such as ceramics or complex matrix materials.

Introduction. For the development of space techniques we need lung and durable materials. As you know, reduction of weight payload per 1 kg reduces the cost of flying to 100 thousand rubles [1]. From this standpoint, aluminum based composites reinforced with nanoparticles of different refractory materials are promising materials. However, aware of the high activity of nanoparticles associated with an increased number of atoms on the surface and thus uncompensated surface energy, it is advisable to create aluminum composites with small concentrations of nano-additives (order of tenths and hundredths of a mass). In addition, according to the works of the school of Academician I.F.Obraztsov and results of empirical research under the supervision of a member-correspondent of RAS V.I.Kostikov, small additions of nanoparticles can contribute a substantial modification of the properties of interfacial layer [2, 3]. These factors can increase the mechanical properties of the composite with a metal matrix two or more times. Use of nanoparticles to reinforce metallic materials lead to the development of novel composites with unique mechanical and physical properties. In order to achieve desired mechanical properties of composites, reinforcing nanoparticles must be distributed uniformly within metal matrix of the composites. Various impact on characteristics of the baked composites is made by nanoparticles depending on the arrangement (on borders of grains or in grains) [4, 5]. Results of such influence are given in table 1, without specifying concentration. Composites on basis "aluminum – ceramic particles" have lower density, than bronze, possess an optimum ratio of durability and plasticity and sufficient corrosion resistance in combination with high operational mechanical characteristics.

Table 1. Influence of an arrangement of nanoparticles on properties of composites

<table>
<thead>
<tr>
<th>Nanoparticles in grain.</th>
<th>Nanoparticles on grain border</th>
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<tr>
<td>Reduce subgrains in grain</td>
<td>Reduce grain, without allowing to grow borders, increasing durability</td>
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<tr>
<td>Brake diffusive creep through grain volume</td>
<td>Brake creep on borders of grains, being pressed into a matrix and on turning at the movement</td>
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<tr>
<td>Interfere with distribution of cracks</td>
<td>Interfere with origin and promote annihilation of vacancies, increasing creep resistance on borders of grains</td>
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<tr>
<td>Increase crack resistance at the expense of a hitch of the dispersing crack passing through a nanoparticle</td>
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1. Experimental procedure. At least five measurements were made per sample. The microstructure of the composites was observed by optical microscopy (Zeiss Axiovert 40 MAT light microscope), high resolution cold-field emission scanning electron microscopy (FEI Quanta...
The micro-Vickers hardnesses of the composites were measured according to EN ISO 6507-1 with a load of 20 and 0.02 kg for 15 s (Micromet 5114 microhardness tester). Determination of the compressive strength, bending and stretching performed on a universal servo-hydraulic machine for mechanical testing «LF-100KN» production «Walter + Bai» (Switzerland) with maximum force in static 100kN with an external digital controller (EDC) and a universal machine for mechanical tests VakEto-TestSystems.

Nanopowders of Al₂O₃ and ZrO₂ (Keldysh Research Center, purity 99.5%, d = 50-60 nm) and aluminum powder ASD-4 (SUAL, TU (Technical Specifications) 48_5_226–87, S = 0.34–0.38 m²/g, d = 2–10 μm) as a matrix were used as starting materials. The Al₂O₃ and ZrO₂ nanoparticles were produced in an electro arc plasma reactor (the process is described in detail elsewhere [6, 7]), producing an average particle size between 50 and 60 nm.

**Mixing.** To achieve a homogeneous material structure and mechanical properties necessary that the distribution of the components in the powder batch was uniform. As to achieve this nanosized additives is very difficult, a method of mixing the charge in several steps:

1. Deagglomeration of the matrix powder ASD-4 in the ultrasonic treatment in ethanol.
2. Preparation of nanoparticle suspension in ethanol with their deagglomeration simultaneously exposed to ultrasound.
3. Mixing ethanol aluminum nanoparticles under the action of ultrasound.
4. Drying of the slurry.
5. Averaging dried charge in the mill with cylinders of ZrO₂ in the mode of transition from slide to roll.
6. Request repeated charge and its mixing in a tumbling mixer.

**Pressing.** Compression was performed in a batch cylindrical steel molds in a press 50T "Mekamak" at pressures of 100, 200, 300, 400, 500 MPa.

**Sintering.** Sintering is carried out in an automatic vacuum furnace VMS-22-10,5. The sintering temperature was varied from 550 to 670°C in forevacuum (5 • 10⁻² mm Hg. V.), The sintering time is from 60 to 150 minutes. The resulting samples had a 15 mm diameter and a thickness of approximately 18 mm.

2. **Results and discussions.** Fig. 1 shows the microstructure of the samples with additives nanoparticles of zirconium oxide. Visible small bit elongated grains. The size of grains of pure aluminum was 7 microns. The average diameter of the grains of material with nanoparticles was 4-5 microns.

In fig. 2 the composite microstructure removed from the transmission electronic microscope is shown. The cluster of nanoparticles of oxide of aluminum located on borders of grains of a matrix is visible. Besides, on borders of grains the set of nanodimensional films of oxide of aluminum is located.
The introduction of small amounts of nanoparticles of aluminum oxide prevents the recrystallization of aluminum grains during sintering and stores grain size in the sintered material at the particle size of the starting powder. In fig. 3, the mechanical properties of the Al-Al$_2$O$_3$/ZrO$_2$ composites resulted from microhardness test of specimens, is graphically represented.

![Microstructure of aluminum composites with Al$_2$O$_3$ nanoparticles, TEM](image)

**Figure 2. Microstructure of aluminum composites with Al$_2$O$_3$ nanoparticles, TEM**

In fig. 4 the mechanical properties of the Al-Al$_2$O$_3$/ZrO$_2$ composites resulted from tensile test of specimens, is graphically represented in compare with the mechanical properties of the Al AVPP (Russian analogue of 6xxx (Mg+ Si)-alloys) which is a precipitation hardening aluminum alloy, containing magnesium and silicon as its major alloying elements. This alloy is widely used for construction of aerospace structures [8].

![Vickers microhardness of aluminum composites](image)

**Figure 3. Vickers microhardness of aluminum composites**

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Summary. A homogeneous distribution of the Al$_2$O$_3$/ZrO$_2$ nanoparticles and clusters reinforcement phase in the Al matrix was obtained by combination of wet and dry mixing. Characterization of the mechanically milled powders confirmed uniform distribution of the reinforcement phase. Low concentration additions of nanoparticles in Al powder leads the composite towards steady-state condition in which, all microstructure properties such as powder size, powder shape and distribution of Al$_2$O$_3$ within Al matrix remain fixed. An optimum concentration of nanopowders (0.1 %vol.), is established for the processing of the Al-Al$_2$O$_3$/ZrO$_2$ composites, that assures mechanical strength close to those of the Al AVPP alloy.

References