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# Dependence of the Strength Properties of Aluminum Materials on the Concentration of $ZrO_2$ Nanoparticles

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**Abstract**—New data were obtained concerning the effect of small additions of zirconia nanoparticles on the strength properties of powder matrices produced by cold pressing of powders with subsequent sintering in a forevacuum. The matrices were either a pure aluminum powder or an aluminum—1.5 vol % copper powder mixture. It was shown that the introduction of nanoadditives to even an insignificant concentration causes a tangible increase in the mechanical properties of the materials, such as tensile, flexural, compressive, and offset yield strengths.

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Using high-melting nanoparticles for modification of powder or cast metals and alloys opens up new possibilities of significantly increasing their strength and functional characteristics [1, 2].

Nanoparticles influence differently on the characteristics of sintered composites, depending on their location (at grain boundaries or within grains).

According to interphase layer theory [3], around a nanoparticle in the material of the matrix, a strengthening zone forms, which, in the ideal case, should be spherical. With increasing concentration of nanoadditives, the probability of their aggregation due to high surface energy increases, which can impair the properties of the material because of the formation of additional porosity and the decrease in the adhesion between grains of the matrix. These phenomena lead to the degeneration of the shape of the interphase strengthening zone and prevent from reaching the maximum gain in the strength properties [4]. Therefore, the concentrations of nanoparticles of high-melting compounds for modification of metals should be ultralow (less than 0.15 vol %) for the nanoparticles to be distributed more uniformly and for strengthening zones to have more regular shape and to form throughout the matrix. The fact that the values of the properties are maximum at low concentrations of nanoadditives and decrease with increasing their concentration is due to the increase in the adhesion damage and the development of interphase boundaries with increasing concentration of nanoadditives. Moreover, there is an optimum between the concentrations of nanoparticles, their shape and sizes, and the shapes of the strengthening zones formed around these particles. The process in composite is saturated when the strengthening zones overlap. Previously, we demonstrated the effect on alumina nanoparticles on the mechanical properties of pure aluminum and aluminum supplemented with 1.5 vol % [5].

In this work, we studied the effect of small additions of zirconia nanoparticles on the strength properties of aluminum materials.

We revealed features of the effect of low concentrations of $ZrO_2$ nanoparticles on the strength characteristics of aluminum materials. In particular, we detected a 13–84% increase in the mechanical properties of sintered aluminum, both pure and containing 1.5 vol % copper, after adding a small amount (0.01–0.15 vol %) of zirconia nanoparticles.

## EXPERIMENTAL

As a method for producing aluminum composites, powder metallurgy was chosen because it ensures low sizes of grains of the matrix, low segregation of impurities, and high material utilization ratio in comparison with casting.

The basic component of the test samples was selected to be an ASD-4-grade aluminum powder (Specifications TU 48-5-226-87, average grain size ~4 μm, 99.7% pure) obtained by melt spraying; the alloying component was PMU-grade copper. A nano-

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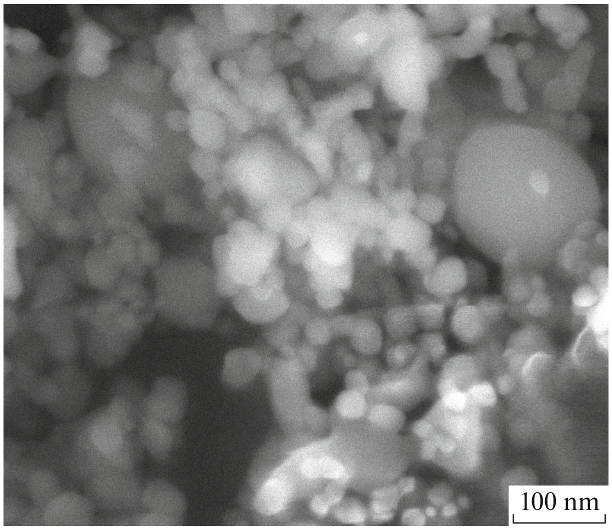


**Fig. 1.** Zirconia nanoparticles.

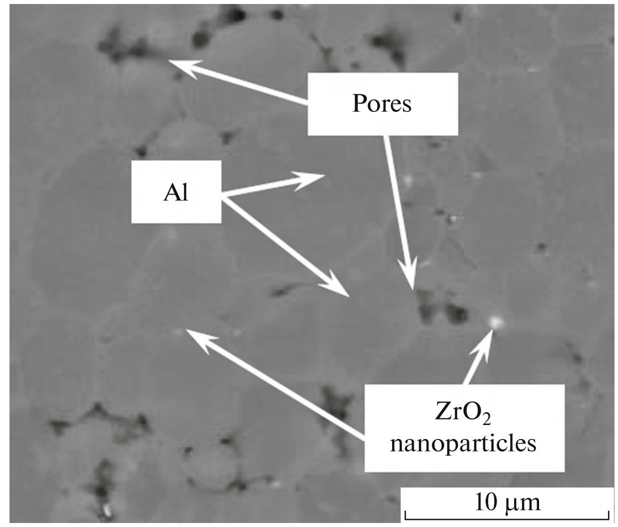


**Fig. 2.** Microstructure of aluminum composite sample containing 0.15 vol % $ZrO_2$.

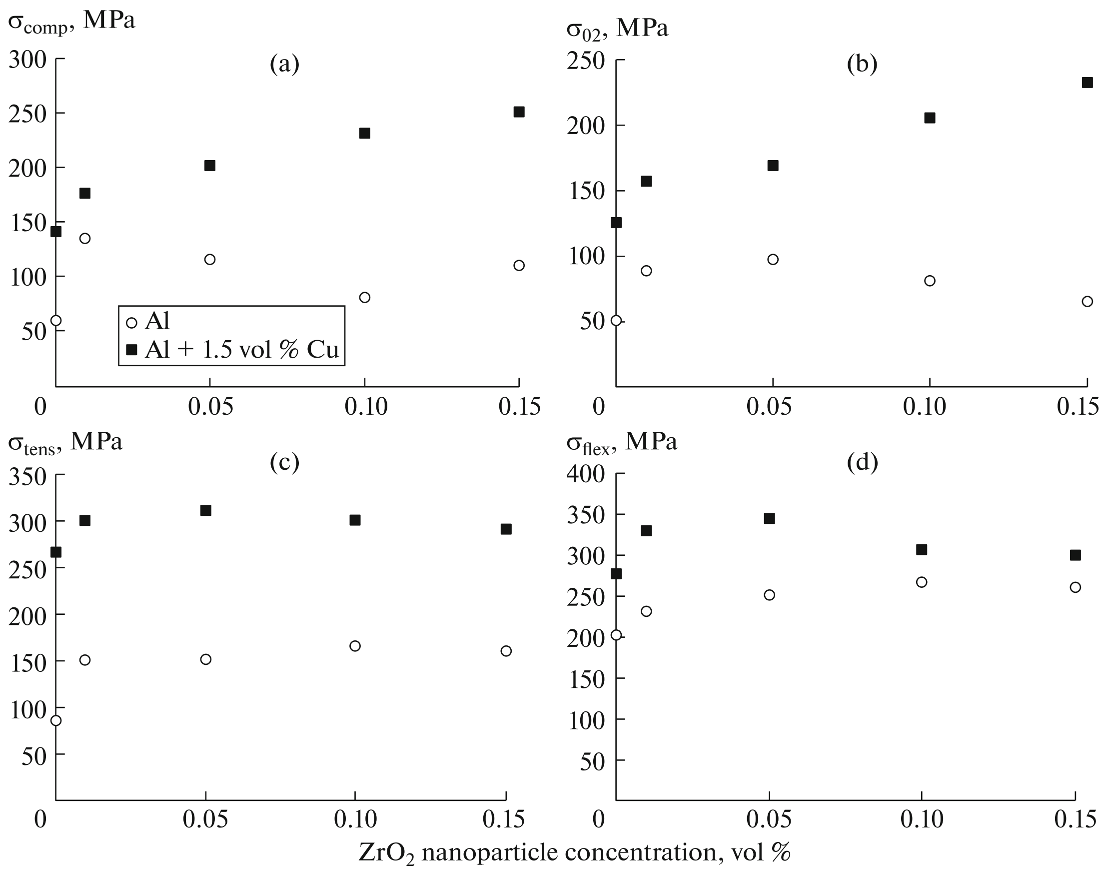


**Fig. 3.** Mechanical characteristics of aluminum composites strengthened with zirconia nanoparticles: (a) compressive strength, (b) offset yield strength, (c) tensile strength, and (d) flexural strength.

dispersed zirconia powder (Fig. 1) was produced on a PU 2-16/10.03-004 plasma-chemical synthesis setup at the GNTs FGUP Keldysh Research Center, Moscow, Russia.

## RESULTS AND DISCUSSION

Figure 2 shows the microstructure of the Al–0.15 vol % $ZrO_2$ composite as visualized with a FEI Quanta 600 FEG scanning electron microscope.

Clusters of zirconia nanoparticles are seen; these clusters are uniformly distributed over grain boundaries.

Figure 3 illustrates the dependences of the mechanical properties of the obtained composites on the concentrations of $ZrO_2$ in comparison with the properties of the materials of the matrix.

For the matrix containing no copper, the dependences of the mechanical properties on the nanoparticle concentration are extremal for the offset yield strength and the compressive strength (at 0.01 vol % $ZrO_2$ in both cases). The dependences of the tensile and flexural strengths are not extremal. The dependence of the flexural strength is extremal for the material containing 1.5 vol % copper with 0.05 vol % zirconia nanoparticles.

Analysis of the dependences in Fig. 3 showed that, within the studied nanoparticle concentration range, the maximum values of the mechanical properties of the composites with the pure aluminum matrix were the following: compressive strength, 130 MPa (0.01 vol % $ZrO_2$); offset yield strength, 75 MPa (0.01 vol % $ZrO_2$); tensile strength, 165 MPa (0.1 vol % $ZrO_2$); and flexural strength, 265 MPa (0.1 vol % $ZrO_2$). For the composites doped with 1.5 vol % copper, compressive strength, 250 MPa (0.15 vol % $ZrO_2$); offset yield strength, 232 MPa (0.15 vol % $ZrO_2$); tensile strength, 310 MPa (0.05 vol % $ZrO_2$); and flexural strength, 343 MPa (0.05 vol % $ZrO_2$).

## CONCLUSIONS

It was determined that the modification of aluminum powder with a small amount of $ZrO_2$ nanoadditives causes a noticeable increase in the mechanical characteristics both for pure aluminum and for aluminum containing 1.5 vol % copper. The average percentage increases in these characteristics in the pure aluminum matrix/copper-doped aluminum matrix pairs are the following: offset yield strength, 55%/55%; compressive strength, 83%/53%; tensile strength, 84%/13%; and flexural strength, 26%/16%.

The results of this work confirmed the hypothesis of the existence of interphase strengthening zones in materials based on sintered aluminum (including copper-doped aluminum), which form around insoluble zirconia nanoparticles added to a concentration of 0.01–0.15 vol %. Therefore, we could conclude that this approach is promising for increasing the mechanical properties of aluminum and other metals by adding small amounts of oxide nanoparticles. The composites obtained in this work will be used for manufacturing various rocket turbopump assembly parts operating at moderate mechanical and thermal loads, e.g., impellers, liners, lugs, and others.

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