Structure and properties of sintered Al-Cr-Zr alloy

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Abstract. Aluminum alloy Al-Cr-Zr was obtained by mechanical alloying and spark plasma sintering. The structure, tensile strength, and elastic properties at different chromium contents in the alloy were studied. The best properties both at room and at elevated temperature were shown by Al-0.5% Cr-0.3% Zr alloy samples (Young's modulus ~65 GPa, tensile strength ~358 MPa). An increase in the Cr content in the composite to 1% leads to the formation of large chromium-containing inclusions (possibly coarse intermetallic compounds) along the grain boundaries of the alloy, which impairs the mechanical properties of the material.

1. Introduction
Powdered aluminum composites are promising structural materials due to their low weight, low capital cost of production and, most importantly, high specific strength. Nevertheless, to increase the operating life of jet engines, as well as various pumps used in mechanical engineering, it is necessary to find ways to improve the properties of traditional and new aluminum materials development. Composite materials with an aluminum matrix are great prospective in this field. The functional properties of aluminum matrix powder composites can be improved by metals alloying modification (Zr, Cr, Co, Ti, Cu), nanoparticles of refractory substances additions, and surface coating formation [1–7]. For example, the addition of 0.1% Zr increases the resistance to high temperature creep of aluminum. The addition of zirconium to aluminum leads to substantial hardening due to the formation of dispersed secondary precipitates of the metastable Al₃Zr phase [1, 8]. These materials will find application in increasing the resource and work efficiency of units of various machine-building units (engine impellers, gear wheels, bushings, spacers, etc.), including under the influence of aggressive oxidizing gaseous or liquid media.

In this work, aluminum alloy Al-Cr-Zr was obtained using mechanical alloying and spark plasma sintering. The structure, tensile strength, and elastic properties were studied at various chromium contents in the alloy.

2. Experimental setup and characterization techniques
An aluminum mechanical alloying was carried out in an Activator-2SL ball planetary mill. The hardened steel balls with a diameter of 5 mm were taken in the ratio powder to balls 1:10 for grinding. The powders of Aluminum «ASD-4», Chromium «PH-1C», Zirconium «PCRK-1» were used. Hexamethyldisilazane (0.1%) was added as a lubricant. Mixing were provided for 30 min in argon medium in the Activator-2SL planetary mill. The samples were obtained by spark plasma sintering in vacuum. Alloys of the systems Al-0.25%Cr-0.3% Zr, Al-0.5%Cr-0.3% Zr, and Al-1%Cr-0.3%Zr were obtained.
Studies of alloys elastic properties were carried out using the ultrasonic diagnostics setup "MUZA". Young's modulus (normal elastic modulus) were studied in the temperature range from 25 to 400 °C in high vacuum (10⁻⁵ Torr). The thermomechanical properties of alloy samples were studied using high-temperature test setup at temperatures up to 300 °C. The setup was designed on the basis of UTS 110M electromechanical universal machine with a rated load of 100 kN and VE-3-24-RM furnace. The structure of the sintered alloy samples was studied using a Quanta 600 scanning electron microscope. The density of the samples was measured by hydrostatic weighing.

3. Results and discussion
Figure 1 shows the results of Young's modulus analysis of the samples at room temperature and 400 °C. The error of Young's modulus measuring is ± 3%. The best result was obtained for the Al -0.5%Cr-0.3%Zr alloy both at room and at elevated temperatures.

A temperature change leads to atoms bonding forces changes in the crystal lattice that leads to alloys Young's modulus decrease with temperature increasing to 400 °C. A sample temperature change can cause the appearance of internal (thermoelastic) stresses in it (due to different coefficients of thermal expansion in different crystallographic directions). This leads to elastic properties changes due to the anharmonicity of atomic vibrations in the crystal lattice. If thermoelastic stresses relax (for example, due to microplastic shifts), a change of the elastic properties is also possible.

The thermomechanical properties of alloys were studied by three-point bending at room temperature and at a temperature of 300 °C in vacuum (10⁻² Torr). Figure 2 shows the results of thermomechanical tests of the various composition samples after three-point bending at room and elevated temperatures. As in the study of elastic properties, the best result (tensile strength of more than 350 MPa) was obtained for a sample Al-0.5%Cr-0.3%Zr both at room and at elevated temperature.

According to the results of hydrostatic weighing, the smallest total porosity (~5 %) was obtained for alloy Al-0.5%Cr-0.3%Zr, which confirms that it has a higher tensile strength and Young's modulus. For Al-0.25%Cr-0.3%Zr and Al-1%Cr-0.3%Zr alloys, the total porosity is ~7 and 13 %, respectively.

The average grain size of the alloy samples is ~5 μm. The structure consists the grains groups separated by elongated pores. With an increase in the Cr content, changes in the grain sizes of the samples were not observed. The images of the alloys surface structure obtained using a scanning electron microscope are shown in figure 3.
Figure 2. Tensile strength of alloys depending on the chromium content and test temperature.

Figure 3. The structure of sintered Al-Cr-Zr alloys.

The structure of the Al-Cr-Zr system alloys is a partially supersaturated solid solution of Zr and Cr in Al. Chromium inclusions are apparently intermetallic compounds of chromium aluminide Al₇Cr presented in the form of plate crystals up to 5 μm in size. Primary Al₃Zr crystals in form of needles in an aluminum matrix were not noticed, which indicates a rather fast solidification of the composites and dissolution of zirconium in aluminum.

Figure 4. The structure of Al-Cr-Zr alloys in cross-sections after bending tests.
Figure 4 shows structural images of Al-Cr-Zr alloys in cross-sections after bending tests. The structure of the samples doped with 0.25 and 0.5% Cr is almost identical. The structure of the Al-1%-Cr-0.3%Zr sample is less dense, pores are visible along the boundaries of the particles, and cohesion between them is worse. An increase in the Cr content in alloys to 1% leads to the formation of large chromium-containing inclusions (possibly coarse intermetallic compounds) along the grain boundaries and a deterioration in the mechanical properties of the material.

The Young’s modulus calculations of aluminum sintered alloys with microadditions of nanoparticles (SiC, MgAl₂O₄, W-Cu) and alloying metals using the micromechanical model based on the gradient theory of elasticity [9] showed that a further increase in strength can be achieved with the addition of nanoparticles: MgAl₂O₄ in concentration 0.01-0.02%, SiC - 0.15-0.22%, W-Cu - 0.12-0.18%.

4. Conclusions
The lowest total porosity (~5%) was obtained for alloy Al-0.5%-Cr-0.3%Zr. Al-0.25%-Cr-0.3%Zr and Al-1%-Cr-0.3%Zr alloys have total porosity ~7 and 13%, respectively. The best properties were shown by sintered alloy sample Al-0.5%-Cr-0.3%Zr both at room and at elevated temperature (Young’s modulus ~ 65 GPa, tensile strength ~ 358 MPa). An increase in the Cr content in alloys to 1% leads to the formation of large chromium-containing inclusions (possibly coarse intermetallic compounds) along the grain boundaries, which impairs the mechanical properties of the material.

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