ISSN 1063-7834, Physics of the Solid State, 2016, Vol. 58, No. 12, pp. 2472–2480. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © A.I. Korobov, A.I. Kokshaiskii, V.M. Prokhorov, I.A. Evdokimov, S.A. Perfilov, A.D. Volkov, 2016, published in Fizika Tverdogo Tela, 2016, Vol. 58, No. 12, pp. 2384–2392.

MECHANICAL PROPERTIES, PHYSICS OF STRENGTH, AND PLASTICITY

Mechanical and Nonlinear Elastic Characteristics of Polycrystalline AMg6 Aluminum Alloy and *n*-AMg6/C_{60} Nanocomposite

A. I. Korobov[a], **A. I. Kokshaiskii**[a, *], **V. M. Prokhorov**[b], **I. A. Evdokimov**[b], **S. A. Perfilov**[b], **and A. D. Volkov**[a]
[a] *Moscow State University, Moscow, Russia*
[b] *Technological Institute for Superhard and Novel Carbon Materials, Moscow oblast, Troitsk, Russia*
**e-mail: aikor42@mail.ru*

Received April 26, 2016

Abstract—The influence of nanostructuring on the mechanical and nonlinear elastic characteristics of polycrystalline AMg6 aluminum alloy and *n*-AMg6/C_{60} nanocomposite has been experimentally studied. The independent second- and third-order elastic coefficients are measured via the ultrasonic method. The third-order elastic coefficients have been evaluated via the Tearstone–Bragger approach from the experimentally established velocities of shear and longitudinal bulk acoustic waves as the functions of the uniaxial compression in the studied samples. The nonlinear elastic properties are examined via the spectral acoustic technique in AMg6 aluminum alloy and *n*-AMg6/C_{60} nanocomposite, and the nonlinear acoustic parameters are determined.

DOI: 10.1134/S106378341612012X

1. INTRODUCTION

More than 150 aluminum alloys are used in the fabrication of industrial products. AMg6 alloy belongs to the Al–Mg–Mn system, containing 93.68% aluminum, 5.8–6.8% magnesium, and 0.5–0.8% manganese, and other impurities [1, 2]. Being well-welded at room and higher temperatures, it combines good strength and plastic characteristics. This set of properties favored the wide application of this alloy in the aerospace industry, building, and automobile engineering, while the corrosion resistance in various media, including seawater, explains its successful use in shipbuilding. In order to improve the mechanical properties of aluminum alloys, they are preliminarily exposed to mechanical deformation and heat treatment. It is, however, difficult to increase the strength characteristics of magnesium-containing AMg6 via quenching, as this alloy is not thermally hardenable.

One of the modern progressive methods to improve the mechanical properties of metals and alloys is nanostructuring, or the nanostructure formation in the bulk of material. In recent years, there has been advanced progress in the development of nanostructuring techniques allowing for novel unusual combination of properties, such as high strength and plasticity with increased hardness, as well as the peak fatigue life, superplasticity, and other [3]. So, equal channel angular pressing of AMg6 cast alloy allowed one in [4] to obtain the material with the average grain size of 400 nm with the significantly improved mechanical properties (the breaking point σ_B increased from 210 MPa of cast alloy to 440 MPa, and the elongation at break δ is twice augmented to 25% at room temperature). The higher values of mechanical characteristics in nanocomposite carbon-hardened AMg6 alloy prepared via the milling in a ball mill with the subsequent extruding were acquired in [5]. The elongation at break in nanocomposite AMg6 was increased to ~500–700 MPa, and failure strain to 10.5–14.1% at higher hardness of 1.5–1.7 GPa.

A pronouncedly risen strength and hardness of metals and alloys upon their nanostructuring is well described by the Hall–Patch empirical relationship for the dependence between the yield strength σ_y and hardness H and the average grain size d [6–8]:

$$\sigma_y = \sigma_0 + K_y d^{-0.5}, \quad H = H_0 + K_H d^{-0.5}, \tag{1}$$

where d is the grain size in polycrystalline material, σ_0, H_0, K_y, and K_H are the constants typical of this material.

Obviously, the mechanical characteristics, as well as the elastic parameter, are interrelated. There is, however, no simple relationships between the mechanical properties (hardness, yield strength, breaking point, and relative elongation) and the elastic characteristics (share modulus, Young's modulus, Poisson coefficient, and bulk elastic modulus) which could be generalized for polycrystalline materials. The establishment of these relationships needs the combined experimental studies of the mechanical and elastic properties on certain materials. At the same time, there are some trends and defined empirical correlations [9] that are valid for high-modulus, fragile, and solid materials satisfying the Pague ratio between the share modulus G and the bulk modulus B as $G/B > 0.571$ [10, 11].

The most frequently observed correlation between the Young modulus E, the share modulus G of polycrystalline materials and the theoretical tensile strength is $\sigma_{\text{th}} \cong E/10$, and $\sigma_{\text{sh}} \cong G/2\pi - G/10$ in share [11].

The second-order elastic coefficients (SOECs) for nanomaterials are almost equal to those of the appropriate initial microcrystalline objects. This conclusion is, however, valid for materials with the low interface fraction (the atom content at the interface to the amount of atoms in the bulk). At the crystallite size of ≤10 nm, when this fraction is dozens of percent, the elastic characteristic values are expected to additively reduce owing to the inner porosity in the nanomaterial. Obviously, the pronounced decrease in the elastic characteristics can be avoid by filling the voids of nanoparticle joints with a material possessing high elastic and strength properties (i.e., by forming a nanocomposite), whereas the formation of the chemical bounds between this material and the nanoparticle surface can also favor the increase in the elastic moduli [12].

The elastic properties of the solid bodies can be evaluated with the SOECs C_{ijkl} and the third-order elastic coefficients (TOECs) C_{ijkqr}. The TOECs characterize the linear dependence of the stress on the strain of the solid body in Hooke's law. The deviation from the linear behavior of Hooke's law is determined by TOECs, which quantitatively describe the anharmonic properties of the crystal lattice, such as the heat expansion, phonon interaction, and high-frequency ultrasonic absorption. These coefficients also allow calculating the Grüneisen anisotropy parameter and analyzing the interplay between the finite-amplitude acoustic waves in solids [13–16]. However, it is still unclear how the TOECs change in nanostructuring, as well as their interrelation with other mechanical characteristics of polycrystalline materials.

In structurally inhomogeneous media, including the polycrystalline metal alloys, the elastic nonlinearity caused by the anharmonism of the crystal lattice (the classic nonlinearity) is accompanied with the elastic structural nonlinearity (nonclassic nonlinearity), which is due to the macroscopic defects in solids, whether being the microcracks, intergrain boundaries, remaint stress, discontinuity, and so on. The structural nonlinearity is local, being defined by the presence of the above defects at the specific area of the solid and can significantly exceed the elastic nonlinearity caused by the anharmonism of the crystal lattice [16]. The main physical mechanisms of the structural nonlinearity are considered in [17].

The correlation between the elastic nonlinearity and strength of the material has been experimentally established in [18, 19]. Herewith, it was observed in both structurally inhomogeneous composites and in crystals. The study of nonlinear elastic properties of materials has not only the fundamental, but also the practical importance.

To characterize the nonlinear elastic properties, a series of experimental methods was developed in [14, 20–22], among them the widely used techniques are the Thurston–Bragger [20] and spectral [14, 21] methods.

The second- and third-order elastic coefficients in polycrystalline AMg6 alloy were experimentally determined in our previous work [23].

In the present work these studies are continued and completed with the measurements of mechanical (the breaking point and the plasticity) and nonlinear elastic characteristics (including the nonlinear acoustic parameter N) in the polycrystalline AMg6 aluminum alloy and the n-AMg6/C_{60} nanocomposite on its base.

2. MATERIAL AND METHODS

The polycrystalline industrial AMg6 aluminum alloy corresponding to GOST 4784-74 was applied as the precursor for the synthesis of nanocomposite. The n-AMg6/C_{60} nanocomposites were obtained via grinding the initial alloy in a planetary ball mill with adding 0.3 wt % C_{60} fullerite. To avoid the oxidation and other unwanted reactions, the manipulations with the precursors and the acquired powders were implemented in the MBraun Unilab glawbox filled with argon. The obtained powders were composed of 50–200-micron agglomerates, being the ensemble of nanocrystallites. The study of powder samples with X-ray coherent scattering (CSL) revealed that the average crystalline size was 40–60 nm [24]. After the milling, the powders were pressed in the cylindrical brickets with a diameter of 180 mm at a temperature of 250°C and a pressure of 200–300 MPa. The obtained blank was exposed to a direct hot extrusion at 300°C with a 4-time decrease in the cross section (the section of the extruded blank was 70 × 70 mm). Figure 1 displays the metallography images of the microstructures of the initial AMg6 alloy and nanostructured n-AMg6/C_{60} after extrusion, obtained on a BX51 Olympus microscope.

As is seen, the aluminum grains after extrusion are oriented along the extrusion axis and there are no pores between the grains. The study of the density via the hydrostatic weighing revealed that the density of the extruded samples is 2.63 ± 0.02 g/cm^3, which corresponds to 99% of the specific density of the AMg6