Second-Order and Third-Order Elastic Constants of B95 Aluminum Alloy and B95/Nanodiamond Composite

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Abstract—All independent second-order and third-order elastic constants in B95 aluminum alloy and B95/nanodiamond composite have been determined. To determine the second-order elastic constants, the densities and velocities of longitudinal and shear bulk acoustic waves in the materials under study have been measured. To quantitatively characterize the nonlinear elastic properties, the third-order elastic constants (TOECs) of B95 alloy and B95/nanodiamond composite have been determined. The Thurston–Brugger method has been used to experimentally determine the TOECs. For this purpose, the relative changes in the bulk wave velocity have been experimentally measured depending on the uniaxial compression applied to the samples under study and all independent TOECs have been calculated. The elastic wave velocities have been measured by the ultrasonic pulse method at a frequency of 10 MHz. The results obtained have been discussed.

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1. INTRODUCTION

To describe the nonlinear elastic properties of solids, the third-order elastic constants (TOECs) are used. The TOECs describe the deviation from the Hooke’s law and control the anharmonic properties of the crystal lattice, such as thermal expansion and high-frequency ultrasound attenuation. They are also used to analyze the interaction of acoustic waves in solids [1]. A number of experimental methods were developed to measure TOECs [2, 3]. Simultaneously with the experimental methods, the TOECs are estimated by theoretical calculations [4]. To determine the TOECs, we used the Thurston–Brugger quasi-static method [3]. Recently, a large number of structural materials appeared, including composites whose nonlinear elastic properties have not yet been completely studied. Heightened interest in the study of nonlinear properties of structural materials is caused by the appreciable correlation between the nonlinearity and the strength of such materials, which was revealed in [5]. Therefore, the study of nonlinear elastic properties of materials is of not only fundamental, but also of practical importance [6, 7].

This paper is devoted to the study of linear and nonlinear elastic properties of structural materials: four-component (Al–Zn–Mg–Cu) B95 aluminum alloy and B95/nanodiamond composite with diamond nanoparticles of detonation synthesis as a reinforcing additive.

2. EXPERIMENTAL TECHNIQUE AND MATERIALS

The velocities of small-amplitude bulk acoustic waves (BAWs) in solids of any symmetry are determined in terms of the second-order elastic constants (SOECs) [8],

\[ V^2 = \frac{1}{\rho_0} C_{jrk} U_j U_k N_r N_s, \]  

where \( \rho_0 \) is the density of an undeformed material, \( C_{jrk} \) are SOECs, \( U_j \) and \( N_r \) are the components of the unit displacement vector \( U \) and the wave vector \( N \) of BAWs. Expression (1) allows calculation of SOECs in solids by the results of experimentally measured acoustic wave velocities. In the isotropic solid, 12 SOECs are nonzero, among which only two, i.e., \( C_{11} \) and \( C_{44} \), are linearly independent. The others are linear combinations of these two SOECs [8]. For an isotropic solid, it follows from expression (1) that \( \rho_0 V_L^2 = C_{11} \) and \( \rho_0 V_T^2 = C_{44} \).

To determine the TOEC, as noted above, we used the Thurston–Brugger quasi-static method [3] consisting in measuring the dependence of the BAW velocity in a solid on the applied uniaxial compression \( P \),

\[ \left( \frac{\partial (\rho_0 W^2)}{\partial P} \right)_{P=0} = 2 \rho_0 W^2 F + G, \]

where \( \rho_0 \) is the medium density at \( P = 0 \), \( W \) is the “natural velocity” of the acoustic wave, \( G = S_{ipab} C_{jrksp} U_j U_k N_r N_s M_a M_b, S_{ipab} \) are the components of
the elastic compliance tensor, \( C_{ijklpr} \) is the TOEC, 
\[
\rho_0 W^2 = C_{ijklpr} U_i U_j N_k N_r, \quad F = S_{ijklpr} M_i M_j U_k U_r, \quad C_{ijklpr} \text{ are the components of the adiabatic SOEC tensor, } U_i \text{ and } N_r \text{ are the components of the unit displacement vector } U \text{ and wave vector } N \text{ of the BAW, } M_i \text{ are the components of the unit vector } M \text{ in the uniaxial compression direction. In the isotropic solid, } 18 \text{ TOECs are non-zero. In this case, three coefficients } C_{111}, C_{112}, \text{ and } C_{123} \text{ are considered as independent; the others are their linear combinations } [9] 
\]
\[
\begin{align*}
C_{111} &= C_{222} = C_{333}, \\
C_{112} &= C_{113} = C_{123} = C_{223} = C_{333}, \\
C_{144} &= C_{235} = C_{366} = (C_{122} - C_{112})/2, \\
C_{155} &= C_{166} = C_{244} = C_{266} = C_{344} = C_{355} = (C_{111} - C_{112})/4.
\end{align*}
\]
To determine three independent coefficients \( C_{111}, C_{112}, \text{ and } C_{123} \) in the isotropic solid, three independent measurements of the dependence of the BAW velocity on the uniaxial compression \( P \) at the following relative positions of the unit vectors \( \mathbf{M}, \mathbf{N}, \mathbf{U} \), 
\[
\begin{align*}
\mathbf{N} &\parallel \mathbf{U} \parallel \mathbf{M}, \quad \mathbf{N} \perp \mathbf{U} \parallel \mathbf{M}, \quad \mathbf{N} \perp \mathbf{U} \perp \mathbf{M}.
\end{align*}
\]
The convolutions \( \rho_0 W^2, F, \text{ and } G(2) \) for these cases are given in Table 1.

As materials to be studied, we used four-component (Al–Zn–Mg–Cu) B95 aluminum alloy and B95/nanodiamond composite. The latter is the B95 alloy with diamond nanoparticles of bulk detonation synthesis with a content of 0.1 wt % . The B95/nanodiamond composite samples were prepared by direct melting of B95 commercial alloy at \( T_m \approx 1000 \text{ K} \), diamond nanopowder introduction into the melt, melt mixing by Ar bubbling followed by melt cooling under conditions of turned off furnace.

The nanodiamond powder was obtained detonation synthesis; its characteristics are given in [10].

Preliminarily prepared B95/nanodiamond composite samples were studied using Raman spectroscopy (RS). The diamond line at 1332 cm\(^{-1}\) and the lines in the region of 1350 cm\(^{-1}\) (graphite \( D \)-line) and 1580 cm\(^{-1}\) (graphite \( G \)-line) were observed in the spectrum. The \( D \) and \( G \) lines are comparatively narrow, and their intensities are identical, which suggests indicates the presence of carbon (diamond) nanoclusters in the sample (Fig. 1). In [11], the nanodiamond–graphite phase transformation upon annealing in the temperature range from 720 to 1400 K was studied in detail. It was shown that the diamond structure in diamond nanoparticles of detonation synthesis is retained in this annealing temperature range. The graphite phase is nucleated only at an annealing temperature above 1200 K. The RS studies of the composite, in which nanodiamond was introduced at a temperature of ~1000 K, confirm the diamond phase retention in composite nanoparticles.

3. EXPERIMENTAL RESULTS
AND DISCUSSION

To perform ultrasonic measurements, samples shaped as rectangular parallelepipeds with edge sizes of 10 \( \times \) 12 \( \times \) 50 mm\(^3\) were cut from source B95 alloy and B95/nanodiamond composite. Opposite sample faces strictly parallel to each other were polished. Preliminarily, we measured the density \( \rho_0 \) and velocities of longitudinal \( V_L \) and shear \( V_T \) BAWs in these materials. The numerical velocities of BAWs in the samples, measured in three directions parallel to their edges were identical within the error of measurements. This allowed us to consider the samples as isotropic. All measurements were performed using a Ritec RAM-5000 automated experimental ultrasonic system (United States) based on the pulse measurement method [12]. The BAW velocities in the samples and their changes under a uniaxial compression pressure were measurement at a frequency of 10 MHz. The error of measurements of BAW velocity magnitudes did not exceed 1–2%. The determined velocities of

![Fig. 1. Spectrum of resonant Raman spectroscopy in the B95/nanodiamond nanocomposite sample.](image-url)