CHARACTER OF ANISOTROPY AND ELASTIC PROPERTIES OF HOT-FORGED *ALUMINUM-MATRIX* COMPOSITES PRODUCED BY DIFFERENT PRODUCTION MODES

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The results of investigations of the structure and the elastic characteristics of the aluminum-matrix composites of Al-TiC system, produced by hot forging in accordance with different technological schemes are presented. It is shown that the materials obtained by hot forging differ in appreciable anisotropy, which is characterized by the elongation of the particles of the matrix phase in the direction normal to forging force. Hereupon the resulting values of both normal elasticity modulus and shear modulus in the plane normal to the direction of the deforming force during hot forging, are of 12-15% higher than the corresponding characteristics in the direction of deformation. For all of the above manufacturing processes the elastic characteristics of the investigated aluminum-matrix composites exceed by 40-70% (depending on the direction of sounding) the Young modulus of aluminum, and the respective characteristics of the shear modulus are higher by 8-15%.

Keywords: ALUMINUM-MATRIX COMPOSITE, HOT FORGING, MODULUS OF ELASTICITY, STRUCTURE, ANISOTROPY.

Introduction

Aluminum-matrix composites have a wider application in automotive, aviation and aerospace industries owing to the unique combination of high strength and low specific gravity, high modulus of elasticity, and good friction characteristics [1-3].

SiC, Al_2O_3, TiC and TiB_2 are the most often used strengthening ceramic additions to the aluminum alloys. Torralba J. M. et al. [1] consider that among the above mentioned additions, TiC is the most catching as it possesses high hardness and modulus of elasticity, and low specific gravity. Lattice parameters of particles of transition metal carbides, especially TiC, are the closest to those of aluminum solid solution.

As a rule, strengthening particles are introduced into the aluminum-matrix composites through mechanical mixing with aluminum powder (by powder metallurgy methods) or their direct introduction into aluminum liquid followed by mixing (in case of casting redistribution) [1].

However, such methods do not allow one to realize in full measure possibilities of dispersed strengthening due to unsatisfactory wetting of TiC particles with aluminum because of the oxide layers present on their surface.

At creation of such materials, the method of introducing strengthening phases into the liquid or powdered mixture based on aluminum and using master alloys is considered more acceptable, in particular, from the Al-Ti-C system synthesized by *in-situ* reaction at thermal synthesis of bricks from the mixture of Al, Ti, and C powders followed by hot pressure treatment of sintered bars [3-7]. At the same time, to provide homogeneous distribution of strengthening phase particles through the product volume it is necessary to realize the schemes of intense plastic deformation at the stage of powder mixture preparation or at the following pressure treatment of sintered bars [7-9].

Evidently, when the content of strengthening particles in the matrix alloy is equal, the degree of the particles conglomeration (uniformity of their distribution through the volume), and the character of anisotropy, which as a rule occurs after additional pressure treatment of sintered bars, would have significant effect on the properties of the matrix alloy. One of the effective methods of mediate evaluation of the mentioned material parameters is determination of elastic characteristics using acoustic, in particular, impulse ultrasonic methods [10-11].

In this connection, the object of the research is to investigate the influence of prior treatment of powder mixtures and the scheme of hot forging of compressed powder bars on the degree of anisotropy of forged material and the values of elastic characteristics in two orthogonal planes.

Materials and research methods

To synthesize master alloys of the Al-Ti-C system, aluminum (20 mass %), titanium (64 %) and carbon (16 %) powders were mixed in a drum mixer and porous bricks were compressed from this mixture under pressure of 500 MPa. Thermal synthesis was realized in a sealed chamber filled with commercially pure argon in a furnace of indirect induction heating at 900 ^oC for 1 h.

The bricks from the synthesized master alloy were milled in a planetary mill for 5 min. to obtain the powder with maximum particle size equal to 80-100 µm which was used as a component of the blend to produce aluminum-matrix composites.

Initial bars for hot forging of experimental composite samples were obtained by two technological schemes.

According to the first technological scheme, aluminum powders and 15 mass % of master alloy were mixed in a drum tumbler for 1 h. In the second scheme, aluminum powders and master alloy were mixed in ethanol in a planetary mill for 7.5 min. The ratio of powder mass and milling balls was 1:5.

In the sequel for both schemes, the produced powdered blend was compressed under pressure of 550 MPa, the bars were heated in a vertical laboratory furnace in argon to the temperature of 600 ^0C for 10-15min and subjected to hot forging on a crank press in a semi-enclosed die.

As the initial bars for forging were used two types of compressed specimens: cylindrical one (41 mm in diameter) and the one in the form of a hollow cone with the same diameter in a base (fig.1). After forging the forged specimens had the form of a two-dimensional cylinder with diameter 43 mm and ~9.5 mm in height. The part of bars before hot forging was sintered at 600^oC in argon for 1 h.

To evaluate elastic characteristics of composites, the respective templates were cut from the obtained forged specimens. The microstructure of the obtained master alloys and composites was studied using a metallographic microscope XJL-17AT and an electron microscope Jeol Superprob-733. The specimens were etched with 40% NaOH solution.

Hence four types of forged material produced by different technological schemes (Table 1) were used as the specimens for the evaluation of elastic characteristics of the obtained material.

Acoustic methods of nondestructive testing were employed to evaluate the elastic characteristics and the degree of anisotropy in the forged material produced by different technological schemes. The methods are based on measuring elastic wave velocity, namely, the method of radio-frequency pulse with discrete delay [11] combined with measuring elastic wave velocity and attenuation coefficients for longitudinal and transverse waves at frequencies of 5 and 1 MHz, correspondingly. It is taken into consideration that the wave velocity is functionally connected with elasticity and density of the material. Characteristics of the above-mentioned parameters in different planes of a hot-forged specimen can be served as a qualitative criterion of the degree of anisotropy in the produced material.

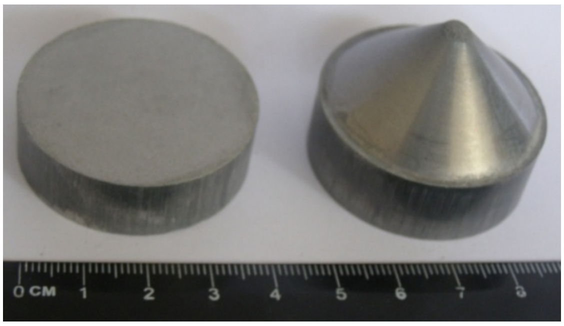


Fig.1. *Appearance of preforms for hot forging at different thechnological schemes*

Table 1

Technological schemes for specimen preparation

No.	Method of mixing	Form of initial bar	Prior sintering of bars
1	Drum tumbler	Cylinder	Without sintering
2	Planetary mill	Cylinder	Without sintering
3	Planetary mill	Hollow cone	Without sintering
4	Planetary mill	Cylinder	Sintering at 600 ^{0}C

Hypotheses for transversal isotropy in the material were taken when choosing the model connecting the experimentally measured parameters and elastic characteristics. Transversely isotropic media are characterized by uniformity of properties in different directions only in the planes oriented in a certain manner (planes of isotropy). In other directions in the medium, in particular, in the direction perpendicular to the plane of isotropy, these properties have different values [12-13]. In the case of transversely isotropic medium, the condition of the material is described by five elastic characteristics and, correspondingly, by five elastic wave velocities. If the X axis is perpendicularly directed to the plane of a plate (in the direction of application of load at forging), and the Y and Z directions are considered equivalent, they would contain the waves related to the direction of forging (X axis) as follows (fig. 2): the longitudinal wave V_{xx} and transverse elastic waves (V_{yx} and V_{zx}) can propagate in the direction of the X axis; the longitudinal wave $V_{yy}=V_{zz}$ and two transverse elastic waves $V_{yz}=V_{zy}$ and $V_{yx}=V_{zx}$ can propagate in any direction perpendicular to the X axis (the first index indicates the direction of impulse wave propagation, the second one – the direction of wave polarization).

Then the relation between the experimentally measured elastic wave velocities, V_{ij}, density, ρ,and corresponding elastic characteristics, C_{ij}, has the form [12-13]:

$$C_{xx}=\rho(V_{xx})^2;\ C_{xy}=C_{xz}=\rho(V_{xy})^2;\ C_{yy}=C_{zz}=\rho(V_{yy})^2;\ C_{yz}=\rho(V_{yz})^2;\ C_{yx}=\rho(V_{yx})^2 \qquad (1)$$

To evaluate the elastic characteristics from (1), rectangular parallelepipeds ~6 mm high and ~28,0 mm of transverse dimensions were cut from the forged materials produced by the respective technological schemes, and subjected to sounding in two perpendicular directions (fig.3).

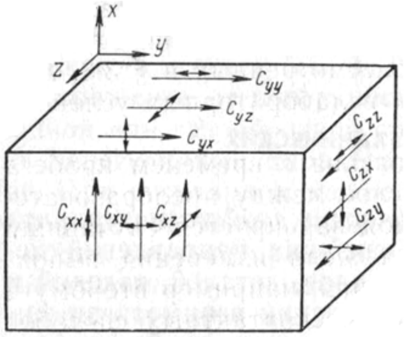
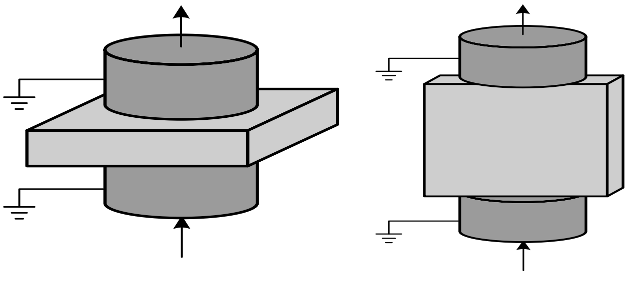


Fig.2. *Geometry of elastic wave propagation in transversal isotropic medium*



a *b*

Fig.3. *Schemes of sounding the specimens in different directions: a – parallel to the forging stress; b – perpendicular to the forging stress*

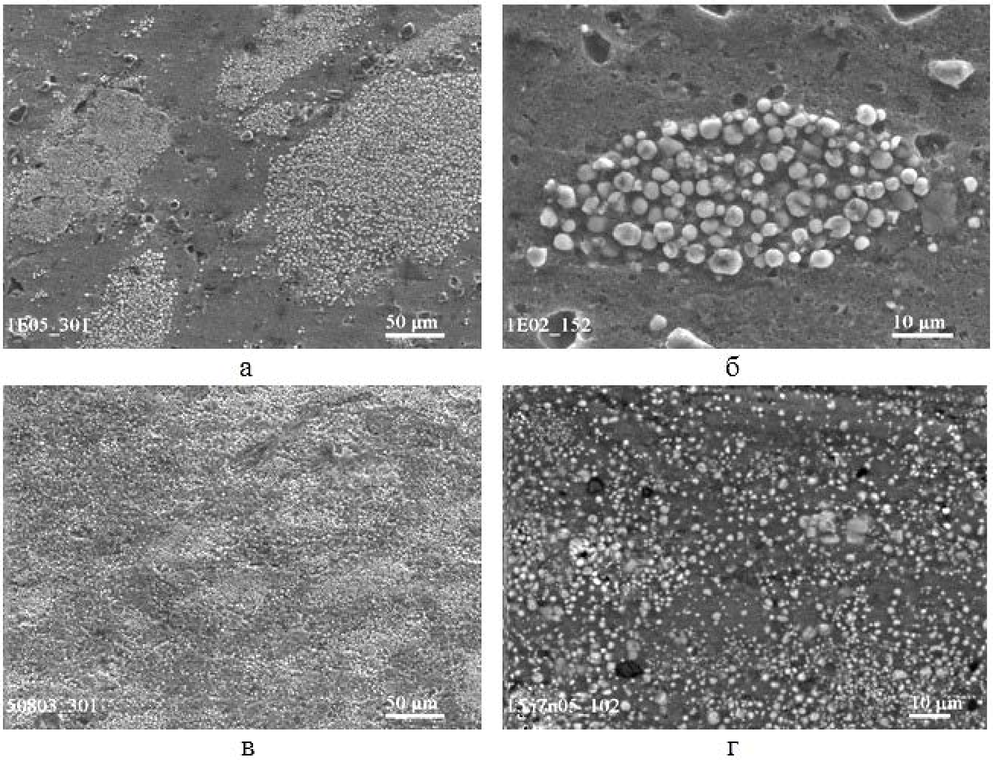
Results and discussion

Microstructure of the specimens produced from the mixture of aluminum powder and master alloy by hot forging the porous bars are characterized by the presence of two distinct phases: the base is an aluminum matrix in which the strengthening phase is distributed. This phase constitutes agglomerates of TiC dispersed particles of size 1.0-2.5 µm (fig.4).

Comparative analysis of microstructures of the hot forged specimens produced by mixing the blend components in a mixer of drum tumbler type and by milling in a planetary mill has revealed that significant agglomeration of master alloy component particles is observed (fig.4, a,b) in the structure of the materials from the first group, whereas in the case of milling the mixture in a planetary mill (fig. 4, c,d) the carbide phase particles are distributed through the volume considerably more uniformly.

The materials produced by hot forging from the green bars possess more distinct texture with characteristic matrix phase particles elongated in the direction perpendicular to the application of forging stress (fig. 5,a), whereas the degree of anisotropy in the materials produced from sintered bars is considerably lower (fig. 5, b). Considerable difference in the character of carbide component distribution in the composites produced from sintered and green bars is noteworthy. For the material produced from green bars, carbide conglomerates are mainly arranged in the form of thin interlayers along the boundaries of matrix phase particles elongated in the transverse direction. In the case of initial sintered bars, the carbide phase particles are distributed on the section surface more uniformly.

At forging the cone bars, the scheme of the stressedly-deformed state of which is characterized by higher values of gradients of tensors of strain rates, the influence of sintering on the character of the intergrain parts of the composite structure (fig. 5, c,d) is substantially graded. In this case, the orientation of the material yield trajectory reveals considerable gradients of shear strains at forging (area of whirl yield) (fig. 5, c, d) compared to forging the cylindrical specimens (fig. 5, a, b).



а б

в г

Fig. 4. *SEM images of hot forged composites produced from powder mixtures by mixing in a drum tumbler (a, b) and in a planetary mill (c, d)*

The results of sounding the specimens of the produced composites with the use of impulse ultrasonic methods have allowed one to evaluate the values of longitudinal and transverse elastic wave velocity in two orthogonal planes (parallel and normal to the forging direction) and calculate respective elastic characteristics from relations (1) (fig. 6).

As seen in fig.6, appreciable structural anisotropy (fig. 5) in hot forged specimens also appears in their elastic characteristics in different directions: the values of both normal coefficient of elasticity (fig. 6, a), and modulus of shearing (fig. 6, b) in the plane perpendicular to the direction of deforming force application at forging (C_{yy} and C_{yx}) exceed the respective characteristics in the direction of deformation (C_{xx} and C_{xy}) by 12-15 %.

This effect results from anisotropic features of hot forged specimens. The anisotropy makes itself evident in the fact that conglomerates of TiC, which has considerably higher coefficient of elasticity (~494 GPa [14]) compared to that of the aluminum matrix phase (66-70 GPa [15]), are mainly elongated in the transverse direction and thus form peculiar “sound tracks” in the direction normal to that of active stress application at forging. Such a structure is the most characteristic of the specimens produced from cylindrical bars (fig. 5, a, b) and provides higher values of coefficient of elasticity for these specimens (No 2) compared to those of the specimens produced from conical bars (No 3). For the structure of the bars forged from the conical ones (fig. 5, c), anisotropy manifests itself to a smaller extent, and carbide phase particles are distributed on the section surface more uniformly. This fact is responsible for somewhat lower values of the coefficient of elasticity for the specimens from this series (No 3).

Prior sintering the bars for forging (specimen No 4) has an insignificant effect on the elastic characteristics of hot forged materials.

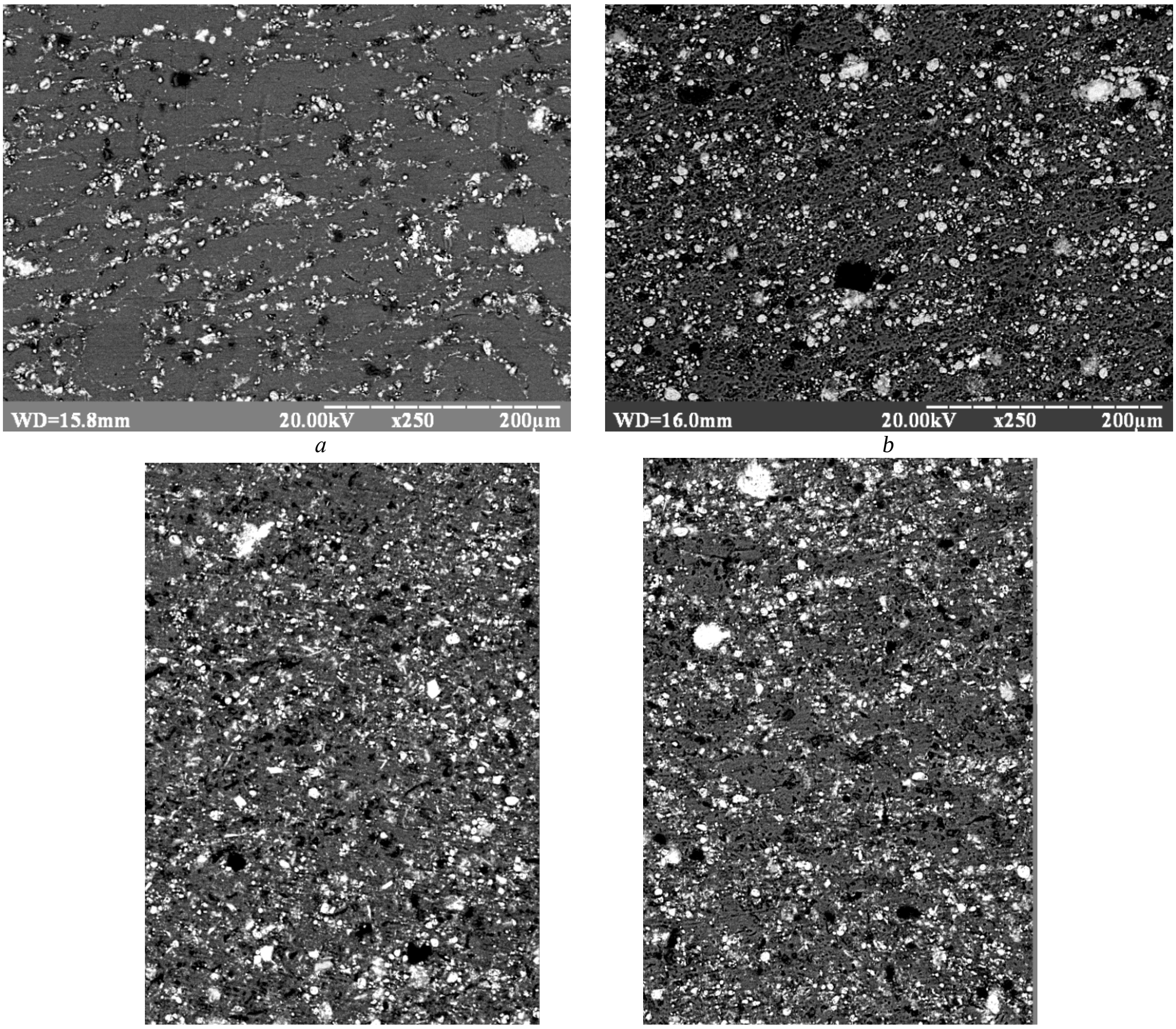
Comparison of the values of the coefficients of elasticity for the specimens produced from the initial mixtures (No 1) and from the mixtures after mechanical activation in a planetary mill (No 2-4) has revealed that the values for the latter are appreciably higher both in the longitudinal and in the transverse directions (fig. 6, a). This fact is associated with the considerable distinction in the structure between the composite produced from untreated blend with significant agglomeration of master alloy component particles (fig. 4, a, b) and the materials which were produced from the blend milled in a planetary mill, and in which the carbide phase particles are distributed through the volume much more uniformly (fig. 4, c, d).

It should be noted that despite the above-considered technological schemes, the elastic characteristics of the investigated aluminum-matrix composites exceed Young modulus of aluminum by 40-70 % (depending on the direction of sounding), and the respective values of modulus of shearing are higher by 8-15 %.

Along with elastic characteristics, inelastic ones of the material also characterize indirectly the quality of interparticle contacts and the structural homogeneity. For impulse methods, the measure of inelasticity is coefficient of attenuation of a plane elastic wave in material at a certain frequency. When passing through the medium, the wave attenuates and its amplitude lowers with the distance from exponential law:

$$A = A_0 exp(-ax) \tag{2}$$

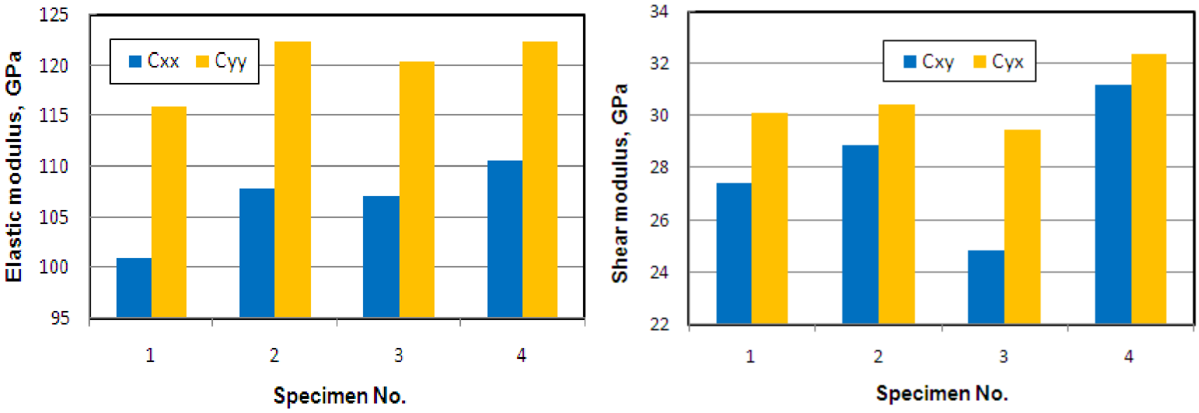
where a is coefficient of attenuation. Ultrasound attenuation is determined by the decrease in the ultrasonic wave amplitude which requires for passing the length of the specimen. Coefficient of attenuation is calculated by a formula (2). Fig. 7 illustrates oscillograms of signals of an elastic wave passing through specimen 1 and 3 times.



a *b*

c *d*

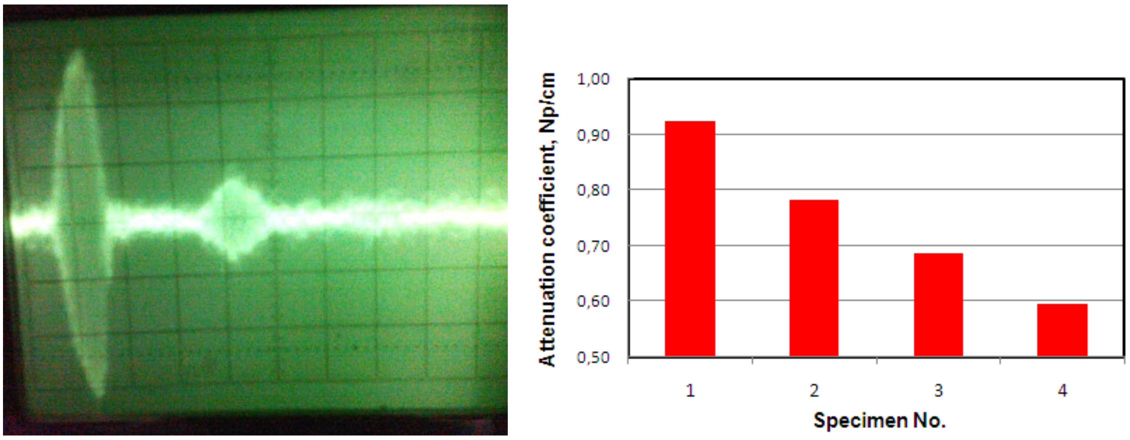
Fig. 5. *Microstructure of forged materials produced by hot forging cylindrical (a, b) and cone (c, d), green (a, c) and sintered (b, d) bars*



a *b*

Fig. 6. *Elastic characteristics of the specimens produced by different technological modes*

As seen in fig.7, b, composite No. 1 produced from the blend without milling demonstrates the highest coefficient of attenuation. Milling the initial blend in a planetary mill (specimen No 2) and the scheme with high gradients of shear strains (area of whirl yield) (initial bars have the form of a hollow cone, specimen No 3), in comparison with forging of cylindrical specimens, brings about the considerable decrease in the degree of agglomeration of the strengthening phase particles and, thus, not only the increase in coefficient of elasticity, but also the appreciable reduction in coefficient of attenuation. Prior sintering the bars before hot forging (specimen No 4) also contributes to the decrease in coefficient of attenuation owing to the improved conditions for interparticle binding at sintering [16].



a *b*

Fig. 7. *Oscillograms of two successive echo pulses (a) and coefficients of attenuation for the specimens produced by different technological schemes (b)*

Conclusions

1. The materials produced by hot forging possess appreciable anisotropy characterized by elongation of matrix phase particles in the direction perpendicular to the application of forging force. In this case, the degree of anisotropy in the materials produced from green bars is notably higher than that of hot forged sintered composites.

2. Structural anisotropy in hot forged specimens manifests itself in their elastic characteristics in different directions: the values of both normal coefficient of elasticity and modulus of shearing in the plane perpendicular to the direction of deforming force application at forging exceed the respective characteristics in the direction of deformation by 12-15 %.

3. Comparison of the values of the coefficients of elasticity for the specimens produced from the initial (untreated) powder mixtures and from the mixtures after mechanical activation in a planetary mill has revealed that the values for the latter are appreciably higher both in the longitudinal and in the transverse directions. This fact is associated with the considerable distinction in the structure between the composite produced from untreated blend with significant agglomeration of master alloy component particles and the materials which were produced from the blend milled in a planetary mill, and in which the carbide phase particles are distributed through the volume considerably more uniformly.

4. For the considered technological schemes, the elastic characteristics of the investigated aluminum-matrix composites exceed Young modulus of aluminum by 40-70 % (depending on the direction of sounding), and the respective values of modulus of shearing are higher by 8-15 %.

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