Металлофиз. новейшие технол. / *Metallofiz. Noveishie Tekhnol.*
2018, т. 40, № 1, сс. 37–43 / DOI: 10.15407/mfint.40.01.0037

МЕДИЦИНСКОЕ МЕТАЛЛОВЕДЕНИЕ

PACS numbers: 61.72.S-, 62.20.de, 62.20.dj, 62.30.+d, 62.65.+k, 81.05.Bx, 81.70.Cv

Influence of Boron Adding on the Acoustic Materials Signature Curves for Computing of Surface Acoustic Wave Velocities of Ti64 Alloys

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The effect of Boron admixture with five different concentrations $x = 0.0$, 0.04, 0.09, 0.30 and 0.55% wt. B on elastic properties of Ti–6Al–4V alloy is investigated. The values of velocities of propagating surface acoustic wave as well as bulk wave for additional structures are deduced. As found, with the increasing of Boron content in Ti–6Al–4V alloy, its acoustic material signature (Young's modulus E, shear modulus G, bulk modulus B), longitudinal velocities, and shear velocities increase from 113 to 126 GPa, from 42.5 to 47.4 GPa, from 110.8 to 123.5 GPa, from 6148 to 6492 m/s, from 3097 to 3171 m/s, respectively. Using angular spectrum model, we calculate the reflectance function and the acoustic materials signature of Ti–6Al–4V–xB, which show an oscillatory behaviour. The spectral treatment of these signatures provides the exact definition of Rayleigh wave velocity.

Key words: elasticity of Ti–6Al–4V alloy, acoustic material signature, surface acoustic wave velocities, Boron admixture.

Досліджено вплив домішки Бору за п'ятьох значень концентрації $x = 0{,}0$, 0,04, 0,09, 0,30 та 0,55% мас. B на пружні властивості стопу Ti–6Al–4V. Визначено значення швидкостей поширюваної поверхневої акустичної хвилі, а також об'ємної акустичної хвилі для додаткових структур. Встановлено, що при збільшенні вмісту Бору в стопі Ti–6Al–4V акустичні характеристики матеріялу (модуль Юнґа E, модуль зсуву G, об'ємний модуль B), поздовжні швидкості та швидкості зсуву збільшуються від 113 до

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Citation: Y. Al-Sayad, Z. Hadjoub, and A. Doghmane, Influence of Boron Adding on the Acoustic Materials Signature Curves for Computing of Surface Acoustic Wave Velocities of Ti64 Alloys, *Metallofiz. Noveishie Tekhnol.*, **40**, No. 1: 37–43 (2018), DOI: 10.15407/mfint.40.01.0037.

126 ГПа, від 42,5 до 47,4 ГПа, від 110,8 до 123,5 ГПа, від 6148 до 6492 м/с, від 3097 до 3171 м/с відповідно. З використанням моделю кутового спектру розраховано функцію відбивання й акустичні характеристики матеріялу Ti–6Al–4V–xB, які проявляють осцилівну поведінку. Спектральна обробка цих характеристик забезпечує можливість точного визначення швидкости Релейової хвилі.

Ключові слова: пружність стопу Ti–6Al–4V, акустичні характеристики матеріялу, швидкості поверхневої акустичної хвилі, домішка Бору.

Исследовано влияние примеси бора при пяти значениях концентрации $x = 0{,}0$, 0,04, 0,09, 0,30 и 0,55% масс. B на упругие свойства сплава Ti–6Al–4V. Определены значения скоростей распространяющейся поверхностной акустической волны, а также объёмной акустической волны для дополнительных структур. Установлено, что при увеличении содержания бора в сплаве Ti–6Al–4V акустические характеристики материала (модуль Юнга E, модуль сдвига G, объёмный модуль B), продольные скорости и скорости сдвига увеличиваются от 113 до 126 ГПа, от 42,5 до 47,4 ГПа, от 110,8 до 123,5 ГПа, от 6148 до 6492 м/с, от 3097 до 3171 м/с соответственно. С использованием модели углового спектра вычислены функция отражения и акустические характеристики материала Ti–6Al–4V–xB, которые проявляют осциллирующее поведение. Спектральная обработка этих характеристик позволяет точно определить скорость волны Рэлея.

Ключевые слова: упругость сплава Ti–6Al–4V, акустические характеристики материала, скорости поверхностной акустической волны, примесь бора.

(Received November 11, 2017)

1. INTRODUCTION

Stainless steel and Co type alloys' elasticity are around 206 and 240 GPa, respectively. They are much greater than that of the moduli of bone, which are mostly between 17 and 28 GPa [1]. The moduli of elasticity of titanium alloys are much smaller than that of other metals used as biomaterials. They are much smaller than that of α- and β-type titanium alloys. They are, however, greater than that of bone. The moduli of recently developed β-type alloys are between 55 to 85 GPa [2, 3]. The Ti–6Al–4V alloys are mainly used for replacing materials for more application. Cracks in the alloys are, therefore, one of the big problems for their unfailing use in the body. The cracks' appearance in the alloys is affected by changes in microstructure. The effect of addition of Boron on the mechanical properties of Ti–6Al–4V alloys is also very important to understand the effects of changing elastic modules calculated using the acoustic materials signature curves, which simulate the influence of body environment on the materials' mechanical properties, particularly, the moduli of elasticity of biomedical titanium alloys [1]. Elastic properties of objects are very important, since their measurement gives evidence about the fundamental forces, which are performing between the atoms of materials. This is unlimited importance in understanding of bonding properties in the materials. Therefore, the choice of solid material (Ti64 alloys) for actual application can be resolving based on information about its surface acoustic wave velocities. Hence, the effect of Boron admixture on Ti–6Al–4V alloys' elastic properties can be described using the surface acoustic wave (SAW) velocities [4]. In this work, we investigate the effects of Boron addition on Ti–6Al–4V alloys' acoustic material signature, *i.e.*, on elastic properties such as the B and G modules and on variations of longitudinal, V_L, and shear (or transverse), V_T, SAW velocities of Ti–6Al–4V–xB.

2. MATERIAL DETAILS

The alloys of Ti are widely used in aerospace, chemical and biomedical industries because of their unique combination of physical and mechanical properties as well as their ability to stand elevated temperatures. Amongst these, Ti–6Al–4V (referred to hereafter as Ti64) is one of the most commonly used alloys. It has been found that minor addition of Boron (up to 0.1% wt.) to Ti64 reduces the grain size dramatically (by more than an order of magnitude) and increases the tensile properties such as yield and ultimate tensile strengths [5]. The effect of minor amount of B addition (within the hypoeutectic range) on elastic modulus (E) of Ti64 has not yet been examined in detail, which is the objective of this work. Five different alloys of Ti–6Al–4V–xB (with $x = 0.0$, 0.04, 0.09, 0.30 and 0.55% wt. B) were examined in this work. The alloys were first induction-skull-melted and then hot-isostatic pressed at 900°C for 2 h with an applied pressure of 100 MPa to eliminate cast porosity. Rectangular billets of length 400 mm and cross-section of 52×60 mm^2, thus produced, were obtained [6].

Four specimens of each composition were tested, and average values are reported here. Additionally, we have employed instrumented indentation and dynamic mechanical analysis testing methods to measure E and its variation with Boron content [7]. Scanning acoustic microscopy (SAM) simulation was conducted to estimate the different (B, G) module and SAW velocity values of change in elastic of Ti–6Al–4V alloy. The resulting cargo to V_L, V_T, and V_R curves were analysed with the aid to the B, G and shear wave velocity (SWV) principles [8].

3. COMPUTATIONAL METHOD

Calculating process is created on the SAM technique under standard operative situations [4, 9–12]. It is contains of some ladders calculating.

a) Calculating of elastic moduli (B, G):

$$G = E/[2(\nu + 1)], \tag{1}$$

$$B = EG/[3(3G - E)]. \tag{2}$$

Elastic properties of materials of density ρ = 4500 kg/m^3, and Poisson's ratio $\nu = 0.33$ [6] and coupling liquid as Freon can be expressed in term of independent parameters, shear modulus (G) from Eq. (1), and bulk modulus (B) from Eq. (2).

b) Calculating period Δz:

$$V_R = V_{\text{liq}}/\{1 - [1 - V_{\text{liq}}/(2f\Delta z)]^2\}^{1/2}. \tag{3}$$

Initially, the difference between the recorded curve $V(z)$ and the lens response curve $V1(z)$ is obtained. Then, $V(z)$ curve is transformed into oscillatory form with a constant period via fast Fourier treating. Fast Fourier transform (FFT) is used to determine such a period from which the velocity of any propagating mode can be associated with Rayleigh wave excitation. The Rayleigh wave velocity V_R can then be calculated for an operating frequency f = 142 MHz from the relationship (3).

c) Calculating acoustic material signature $V(z)$:

$$V(z) = \int R(\theta)P_2(\theta)e^{-i2kz\cos\theta}\sin\theta\cos\theta d\theta, \tag{4}$$

where $V(z)$ is output signal voltage, when the sample is displaced by a distance z from the focal plane toward the acoustic lens computing the $V(z)$ curves of the whole specimen–lens system from the angular spectrum model (4) with pupil function $P_2(\theta)$.

4. RESULTS AND DISCUSSIONS

4.1. Effects of Boron Adding on Elastic Moduli of Ti–6Al–4V Alloys

In this work, we first determine the whole set of acoustic parameters (ν, σ, E, B, and G) for different additions of Boron in Ti–6Al–4V–xB alloys (with x = 0.0, 0.04, 0.09, 0.30 and 0.55% wt. B) using some results and relations (1) and (2). The calculated values of Poisson's ratio and acoustic parameters are briefly shown in the Table 1. The effect of varying the Boron concentration is clearly noticeable due to changes of distance between atoms in the material as well as to molecules springing. In fact, the microstructure of Ti–6Al–4V alloy sample is composed of meaningful grains with size leads to change density.

TABLE 1. Elastic moduli of Ti–6Al–4V alloys for different Boron admixture.

Boron concentration in Ti–6Al–4V alloy	Experimental	Calculated	
	E, GPa	B, GPa	G, GPa
0.0	113	110.8	42.5
0.04	121	118.6	45.5
0.09	114	111.8	42.8
0.3	120	117.7	45.1
0.55	126	123.5	47.4

We evaluate, plan and fit the results of Young's modulus E, shear modulus G, bulk modulus B due to different Boron admixture. Figure 1 shows us that the diagram is separated on two modifications. One of them corresponds to linear increasing of E, G, and B with increase of Boron concentration (x = 0.09, 0.30, and 0.55% wt. B) in Ti–6Al–4V alloy.

4.2. Effects of Boron Addition on Periods Δz of Acoustic Materials Signatures to Recognize Velocities V_L, V_T, and V_R for Ti–6Al–4V Alloys

A series of periodic maxima and minima occurs at acoustic materials signatures, characterized by a period Δz. This region is an important characteristic of the sample's acoustic properties. Distances between following maxima and minima are known as the spatial period Δz, which related to the Raleigh velocity of the propagating mode by means of Eq. (3).

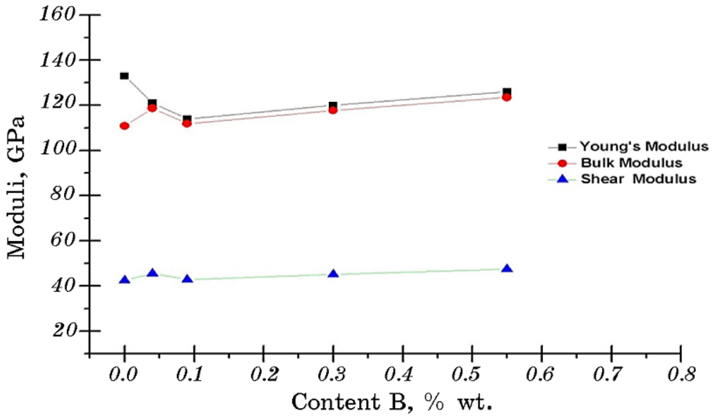

Fig. 1. Calculated elastic moduli of Ti–6Al–4V–xB alloys.

To improving our investigation, it should be cleared an influence of Boron addition on periods Δz because of every changes of velocities V_L, V_T, and V_R at surface and interface of Ti–6Al–4V alloys. From obtained curves, we deduced the acoustic signatures, which are illustrated in Fig. 2, *a*. One can see that an increasing of Boron concentration leads to a few change in amplitudes of $V(z)$ as well as in periods.

The evolution of the FFT spectra displayed in Fig. 2, *b* confirms that the velocity of longitudinal and Rayleigh modes increase with x, in

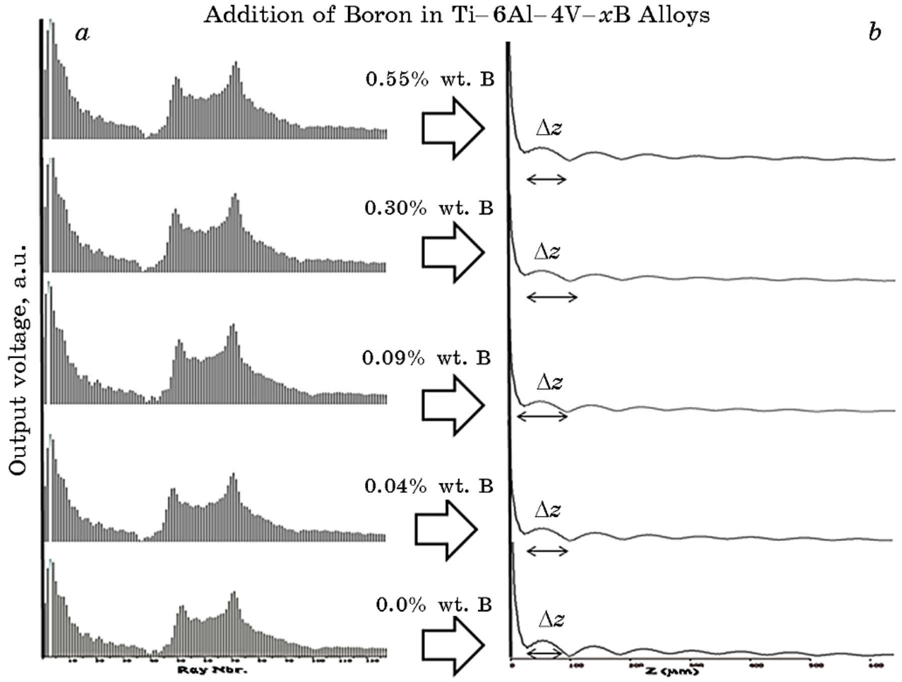

Fig. 2. FFT spectra (*a*) and acoustic material signatures Δz (*b*) at several values of x for Ti–6Al–4V–xB alloys ($0.0 < x \leq 0.5\%$ wt. B).

TABLE 2. Acoustic characteristics V_L, V_T, V_R, and Δz.

Boron concentration in Ti–6Al–4V alloy	Acoustic signatures	Acoustic wave velocities		
B, % wt.	Δz, µm	V_L, m/s	V_T, m/s	V_R, m/s
0.0	79.4	6148	3097	2864
0.04	84.3	6361	3205	2951
0.09	80.5	6174	3108	2884
0.3	84	6336	3191	2944
0.55	83	6492	3171	2927

concordance with the results of Fig. 2, *a*. In fact, it was found that as x change from 0.0 to 0.55% wt. B, V_L increases from 6148 to 6492 m/s, V_T—from 3097 to 3171 m/s and V_R—from 2864 to 2927 m/s. As well as with x changing from 0.0% wt. B, Δz of V_L increases from 79.4 to 83 μm. All these observations are regrouped in Table 2.

5. SUMMARY

Elastic properties of Titanium−6Aluminum−4Vanadium composite with Boron admixture and different constriction due to several concentration $x = 0.0$, 0.04, 0.09, 0.30 and 0.55% wt. B were investigated by means of the simulation of scanning acoustic microscopy $V(z)$ curves as well as corresponding periods Δz. Remarkable variations were deduced.

The values of shear modulus B, bulk modulus and G at different Boron admixture vary from 110.8 to 123 GPa and from 42.5 to 47 GPa, respectively.

Changes were put into data via the calculation of SAW velocities depended on forces between matrix atoms and Boron impurities in Ti−6Al−4V alloys.

As found, the velocities V_L, V_T, and V_R changed in Ti−6Al−4V alloys from 6148 to 6492 m/s, from 3097 to 3171 m/s, and from 2864 to 2927 m/s with Boron concentration increasing in range of $0 < x \leq 0.55$.

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