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Properties and structural characteristics of Ti–Nb–Al alloys

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Abstract

The use of Al as an α stabilizer in different Ti–Nb alloys has been investigated for its effect on some properties and changes in structural characteristics. Quenched alloys with 10–40% Nb and 2–15% Al were analyzed in terms of their phase transformations, as well as elastic modulus, density and internal friction. It was found that the rhombic distortion introduced in the α′-HCP phase transforms into another martensitic α″ structure. Above 5% Al, metastable β-BCC is formed and eventually predominates. The appearance of another metastable phase, ω, was verified in alloys between 2 and 5% Al with less than 35% Nb. These structure transformations are a consequence of the obstructing effect of Al on the redistribution of Ti and Nb. The elastic modulus increases with Al and decreases with Nb percentage due to different developed structures, especially at lower Al content. Small fluctuations in the generally increasing variation of the density with Nb, for Al percentages, were attributed to the phase transformations. The internal friction was relatively large for the martensitic, α′ or α″, structure but decreases significantly with the appearance of β phase.

Keywords: Ti–Nb–Al alloys; Metastable phases; Elastic modulus; Internal friction

1. Introduction

The Ti–Nb system has been extensively investigated for scientific and applied reasons [1–12]. Special properties such as superconductivity and shape memory effect (SME) together with a considerable dumping phenomenon due to peaks in the internal friction, justify the interest for Ti–Nb alloys [1,2]. The multiplicity of phase transformations in this system is associated with complex structures and a broad range of mechanical and thermal properties [3–8]. Binary alloys with β phase, body centered cubic (BCC) structure, obtained after quenching, have been widely studied for most Nb concentrations of useful interest [3–6].

Ternary alloys were also object of investigations. For some industrial applications it is common practice to add Al as an α, hexagonal closed-packed (HCP) Ti structure stabilizer. The Al addition increases both the mechanical and thermal resistance of the alloy [10,11]. This advantageous effect of Al addition has been reported in other Ti alloys. Previous works on Ti–Cr, Ti–Mo and Ti–V systems [12–14] have shown the additional influence of Al as an α stabilizer in the presence of a strong β stabilizer, such as Cr, Mo or V.

Since Nb is also a strong β stabilizer, the objective of the present paper was to expand the knowledge on the combined α and β phases effects using Al as an addition to Ti–Nb. These effects were investigated in properties directly related to the SME, such as the elastic modulus, E, and the internal friction, Q^{-1}. Alloys with 10–40% in weight of Nb and 2–15% in weight of Al were chosen for the investigation. These ranges of composition investigated correspond to the relevant struc-

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tural transformations and property modifications, which occurs in the Ti–Nb–Al system.

It has been known that quenched alloys in the binary Ti–Nb system present a metastable α' martensitic structure for Nb contents up to 12% in weight [3–5]. This martensite has the same HCP structure of α-Ti. With increasing Nb content, the value of the elastic modulus, $E = 110$ GPa, for pure Ti, decreases sharply and reaches 60 GPa for the 12% Nb alloy.

Above 12% Nb the α'-HCP martensite undergoes a rhombic distortion, giving rise to a typical α''-orthorhombic martensite [2–5]. At the same time, β-BCC and its precursor ω phase, both metastable, are also formed. The ω phase has a highly distorted transitional hexagonal lattice between α and β. In particular, the corresponding increase that occurs in the value of E, which reaches 90 GPa for 32% Nb, was attributed to the participation of the ω phase [3]. An increase in hardness, from 12 to 32% Nb, was also associated with the occurrence of ω [2–4,10,11].

Between 32 and 42% Nb the amount of ω decreases while increasing the relative proportion of β. As a consequence, E decreases once again to its lowest value of 60 GPa [3,4]. In this range of percentages, the α'' martensitic structure is still the main structure. However, for Nb contents above 42%, the structure tends to transform into single β and the value of E goes up again. For instance, at 50% Nb, it reaches $E = 70$ GPa.

With all these changes taking place in the binary Ti–Nb system, an important question to be addressed refers to the effect of adding an α stabilizer. Therefore the present work analyzes the effect of Al as a third element added up to a maximum of 15% into Ti–Nb alloys with a limit of 40% Nb.

2. Experimental procedure

Ti–Nb–Al alloys were fabricated by direct combination of the pure metallic constituents:

- 99.99% iodide titanium;
- 99.9% zone refined niobium;
- 99.999% electrolytically refined aluminum.

Each alloy was prepared using a five melting technique in an electric-arc furnace. After tapping, ingots with approximately 100 g were vacuum encapsulated in individual quartz containers and homogenized at 1200 °C for 5 h. Each ingot was then taken out of the container and reheated at 1200 °C in a controlled argon atmosphere before being forged as bars with 8 mm in diameter. The bars were then machined down to 6 mm in diameter and cut for samples with distinct length:

- 80 mm to measure E, G and Q^{-1};
- 20 mm to characterize the crystalline structure by X-ray diffraction.

For the final annealing treatment, the samples were, once again, vacuum encapsulated. The annealing condition for the 2–5% Al alloys was 5 h at 1000 °C and for the 10 and 15% Al alloys was 2 h at 1150 °C, following previous experience [3,4]. The annealing treatment was immediately accompanied by water quenching.

The measurement of, both the elastic, E, and the shear, G, modulus was performed by the dynamic resonance method. In this method the longitudinal, f_l, and the transversal, f_t, oscillation resonance frequencies are measured. The values of E and G are then calculated through the relationships:

$$E = 4.0775 \rho l^2 f_l^2 \tag{1}$$

$$G = 4.0775 \rho l^2 f_t^2 \tag{2}$$

where l is the length and ρ the density of the samples.

The Poisson coefficient, ν, which varies significantly with the alloy content, can also be obtained by the relationship:

$$\nu = \left(\frac{f_l^2}{2 f_t^2} \right) - 1 \tag{3}$$

Both the longitudinal and transversal frequencies were measured at room temperature in an Elastomat equipment using oscillations of up to 26 kHz with a maximum tension of 0.1 MPa and strains less than 10^{-3}%. The sample density, ρ, was measured by the hydrostatic weighting technique, inside distilled water, using an analytic scale with 10^{-4} g of precision. A confidence interval smaller than 1% was then estimated in the values of E and G, as given in Eqs. (1) and (2).

The structural characterization to determine the stable and metastable phases was done by X-ray diffraction, XRD, using a Dron-2 diffractometer operating with Cu Kα radiation. The a parameter of the α'-HCP martensite was calculated by the $(1\,1\,0)_{\alpha'}$ plane diffraction. The a and b parameters of the α'' orthorhombic martensite were obtained, respectively, by the $(2\,0\,0)_{\alpha''}$ and $(1\,3\,0)_{\alpha''}$ phase diffractions. The c parameter of both, α' and α'' phases, was obtained by the $(0\,0\,4)_{\alpha}$ phase diffraction. The estimated precision of the parameter measurements was $\pm 10^{-2}$ nm.

The damping of the crystalline lattice was evaluated by the internal friction, Q^{-1}, measured through tests of oscillation frequency attenuation of the proper lattice. A confident interval of the order of 10% was estimated in the values of Q^{-1}.

3. Results

Fig. 1 depicts four examples of diffractograms obtained for: (a) Ti–15% Nb–3% Al, (b) Ti–24% Nb–3% Al, (c) Ti–32% Nb–3% Al and (d) Ti–34% Nb–3% Al alloys. Fig. 2 presents the lattice parameters for the α'-HCP martensitic and α''-orthorhombic structures calculated from diffractograms in the quenched Ti–Nb–Al alloys, with 2–5% Al, as a function of the Nb content. For higher values of Al content, 10 and 15%, it was difficult to evaluate the parameters due to the superposition of the metastable β X-ray peaks. A rough