Titanium-Niobium Alloys

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Abstract

Titanium-Niobium is a technically important alloy which is a type II superconducting material. Current research is being carried out to search for the potential of Artificial Pinning Center composite wires. In this write-up I review the structure, some of the properties including superconducting properties, and uses of Titanium-Niobium and current interests.

1 Structure

Structure of Ti-Nb depends largely on the solute percentage and the temperature. (It has some dependence on the way it is formed as well.) Depending on these parameters the Ti-Nb system molds itself into several phases. Figure 1 shows an approximate structural phase diagram of the Ti-Nb system.

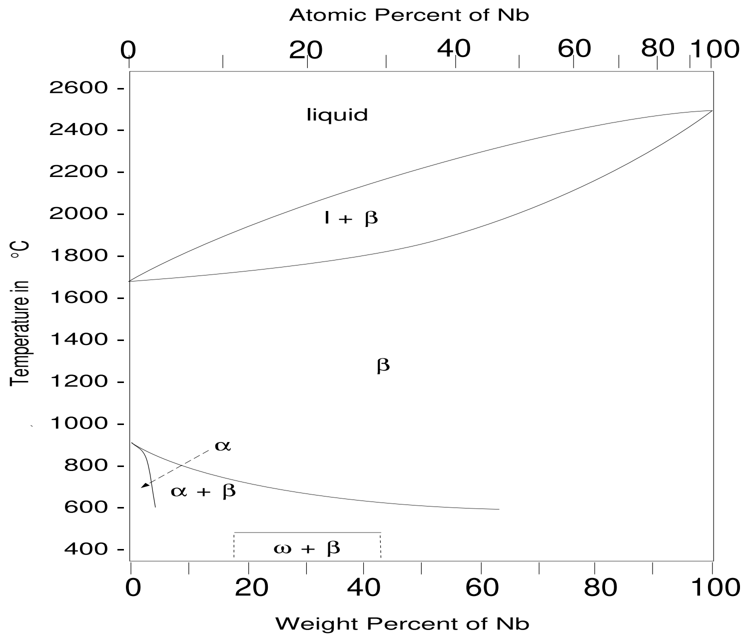

Figure 1: Structural Phase Diagram of Ti-Nb

α phase has hcp structure and β has bcc. ω phase is a regime of structural fluctuations; it has hexagonal structure for low solute concentrations and triagonal structure for high concentrations. It has been concluded from the experimental results that $(56 \pm 1)\%$ of solute in weight (*i.e.* 42 atomic %) is the practical limit for macroscopic α phase precipitation at about $400^0 C$. X-ray studies have shown that Ti-Nb exhibit short range order for atomic ratios 1:3, 1:1 and 3:1 (*i.e.* solute atomic percent 25%, 50% and 75%)

2 Mechanical Properties

2.1 Elastic Moduli

Figure 2 shows a very close variation of Young's Modulus: Y and Shear Modulus: G of Ti-Nb with the solvent percentage (or e/a ratio[1]).

[1] electron/atom (e/a) ratio is defined as the average number of valence electrons. The importance of the e/a ratio lies in the fact that structures of all transition metals change from hcp to bcc as e/a increases from 4 to 6. Similarly, properties of transition metal alloys show more or less a similar variation with e/a ratio.

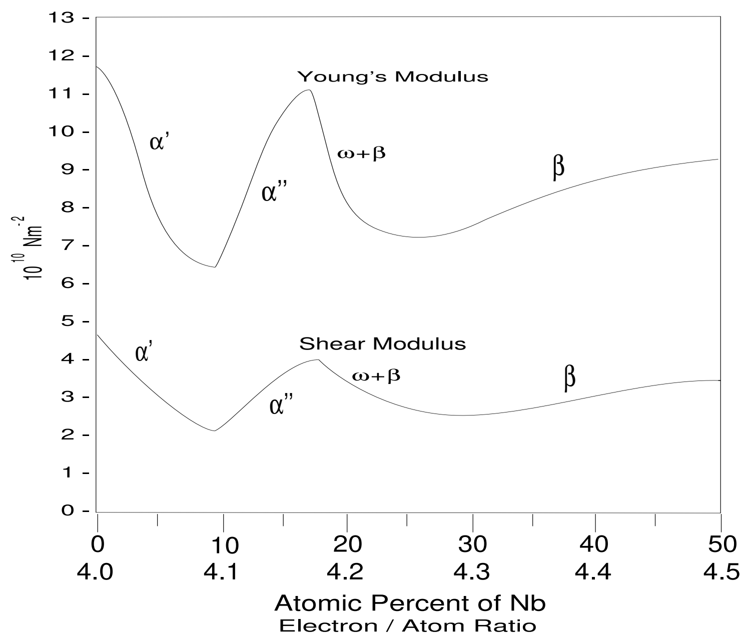

Figure 2: Elastic Moduli of Ti-Nb

The variation of elastic moduli with e/a ratio takes place in response to the variation in structure with later. As e/a ratio increases the structure goes from α' to β phase through α'' and $\omega + \beta$ [2]. The similarity between the variation of Y and G can be attributed to the linear relation;

$$G = \frac{Y}{2(1+\nu)}$$

where ν is the poisson's ratio.

2.2 Shape Memory Effect

It has been observed that β quenched[3] Ti-Nb(22 at. %) which fully transforms into α'' when quenched through about 175^0C, restores almost it's original shape (about 90%) from 1% permanent strain when heated up to 184^0C. Similar results have been observed for $\omega + \beta$ state as well. In that, it recovered fully (100%) from 1.5% permanent strain. Experiments have indicated that shape memory effect can occur as result of $\beta \rightarrow \alpha''$ transformation.

3 Electrical Resistivity

This is one of the most important properties of Ti-Nb (since it is a superconductor). Resistivity drops drastically at low temperatures[4] and further it uniquely shows a negative

[2] α' and α'' are hcp and orthorhombic respectively

[3] α' and α'' phases are formed when an alloy is β quenched

[4] This phenomenon is discussed later in section 5.1.

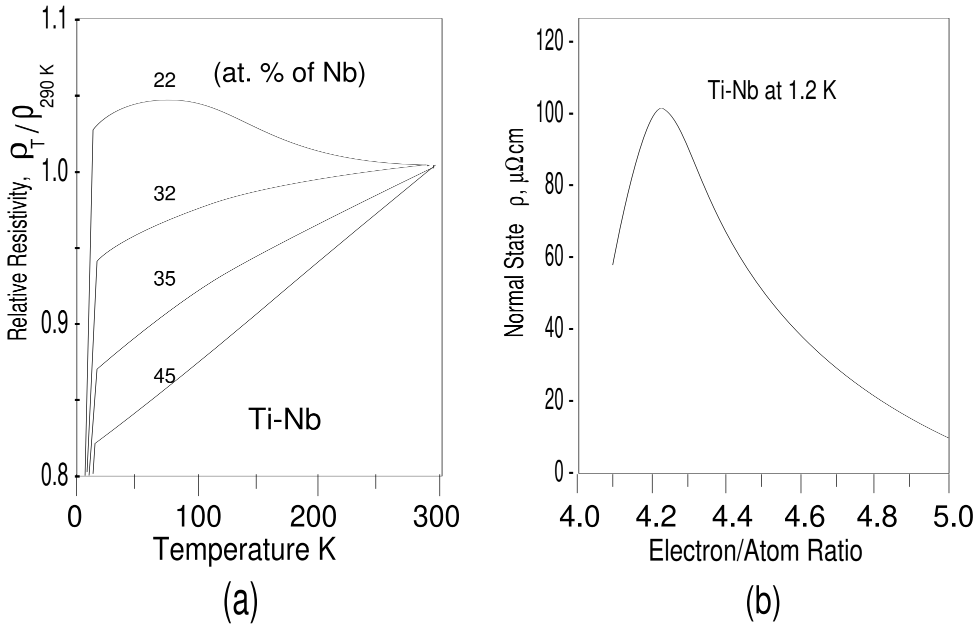

Figure 3: Variation of Resistivity of Ti-Nb: (a) with Temperature (b) with e/a ratio

gradient; $d\rho/dT$ from low temperatures to temperatures as high as 300 K for solvent atom percents of roughly 25%. (see *Figure 3 (a)*; a very close diagram).

Figure 3 (b) shows the variation of resistivity with e/a ratio (hence solvent percent). The parabolic variation at low temperatures and low solvent concentration has been explained with a simple model, which gives the result:

$$\rho(c) \sim c(1-c)$$

where c in the solvent concentration ($0 \leq c \leq 1$).

4 Thermal Properties

4.1 Thermal Conductivity and Diffusivity

It is assumed that in the normal state both the electrons scattered by the static defects and phonon scattered by electrons contribute to the thermal conductivity. So we write;

$$K = fK_{ei} + hK_{pe} \qquad (withf = h = 1, T \geq T_c)$$

which in turn gives

$$K = f(\frac{L}{\rho_s})T + ha_{pe}T^2$$

where L is the Lorentz constant, ρ_s is the solute resistivity and a_{pe} is a constant. Many experiments have shown evidence of the predicted quadratic variation of K with T. [5]

Further, Thermal Diffusivity is given by

$$D_{th} = \frac{K}{\rho_d C}$$

where K is the thermal conductivity, ρ_d is the density and C is the specific heat. Experiments show that, except for, more or less a sudden jump at about 9 K, thermal diffusivity drops with temperature at very low temperatures (of the order of 10 K).

4.2 Low Temperature Electronic Specific Heat and Debye Temperature

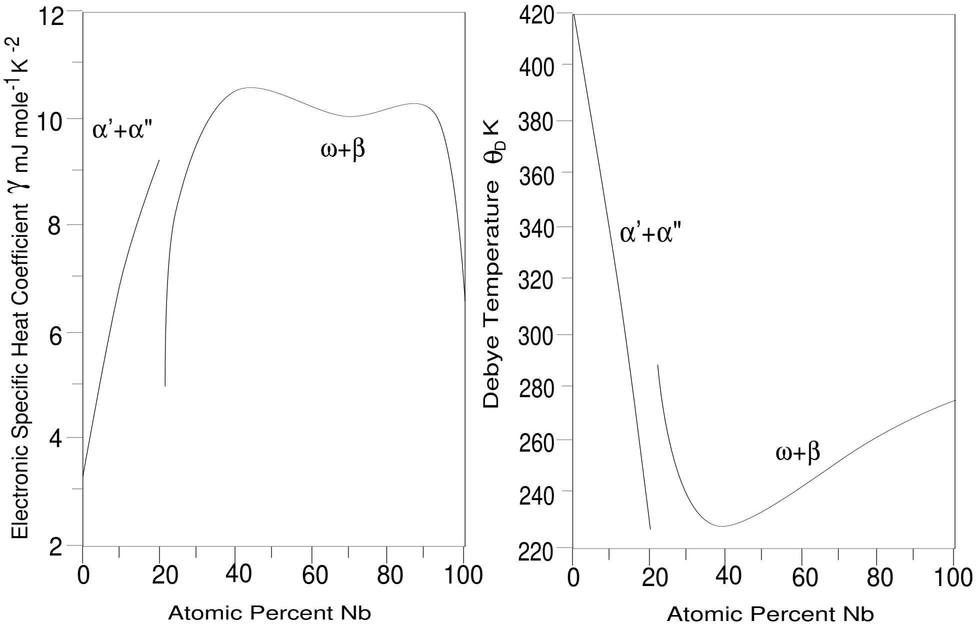

Figure 4: Low Temperature Specific Heat and Debye Temperature of Ti-Nb

The total molar low temperature specific heat of a metal can be written in the form;

$$C = \gamma T + \beta T^3$$

where γ is the Electronic Specific Heat Coefficient at low temperature. γ and β are usually obtained as the intercepts and slope of the plots; $C/T \; vs \; T^2$. The importance of these two quantities more or less lies in the fact that the Debye temperature; $\theta_D \sim \beta^{-1/3}$ and the Density of states; $n(E_F) \sim \gamma$.

[5] plots are not shown in this section since the variation is trivially quadratic and experimental results well agree with theory and due to space limitations too.

Figure 4 shows a very close variation of Low Temperature Specific Heat Coefficient; γ and Debye Temperature; θ_D of Ti-Nb with atomic percent of Nb. Variation of both is very rapid at the transition from $\alpha' + \alpha''$ to $\omega + \beta$. According to the plots, the variation of θ_D and γ is more or less inverse of each other.

5 Superconducting Properties

5.1 Transition Temperature and Upper Critical Field

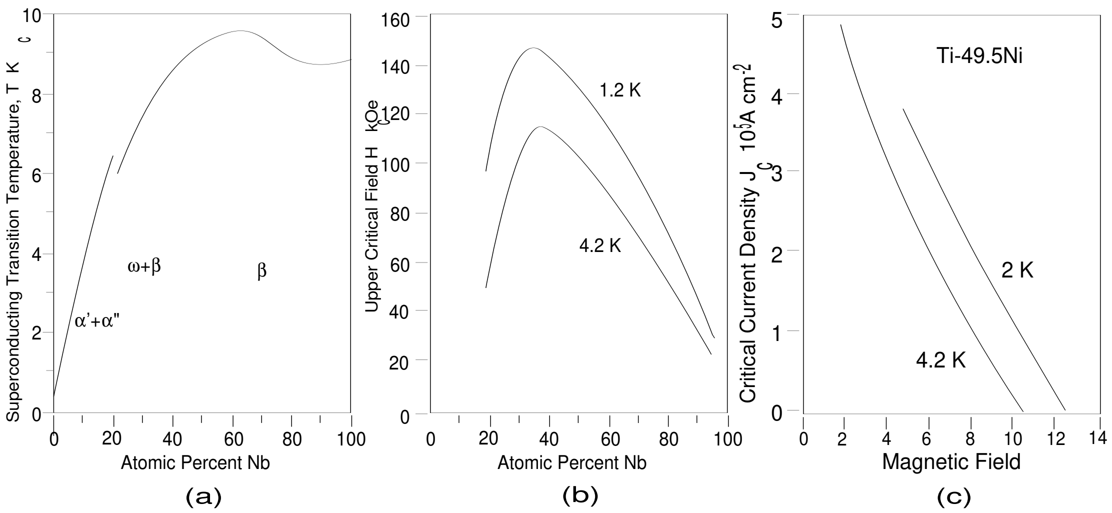

Figure 5: Superconducting Transition Temperature (a) and Upper Critical Field (b) as a function of composition and Critical Current Density (c) as a function of Magnetic Field, of Ti-Nb

Ti-Nb is a technically important type II Superconductor. Figure 5 (a) and (b) show the variations of Superconducting Transition Temperature; T_c and the Upper Critical Field; H_c of Ti-Nb respectively, with composition. The relation between T_c and H_c is given -to a good approximation- by;

$$H_{c2} = \sqrt{2}\kappa_1(T/T_c)H_c(T/T_c)$$

where H_c is the thermodynamic critical field which is given by $H_c(T/T_c) = H_0[1 - (T/T_c)^2]$ and $\kappa_1(T/T_c)$ is what is known as Maki's first "Ginzburg-Landau" parameter. $\kappa_1(T/T_c)$ is more or less a complicated function of (T/T_c). In most of the cases the dominant temperature dependence of H_{c2} comes from H_c through $[1 - (T/T_c)^2]$.

The variations of T_c and H_c with it's composition are interpreted in terms of microstructural conditions as estimated from the equilibrium phase diagram shown in Figure 1. The curious minimum of T_c parallels that of γ (see Figure 4) just about at the same composition, showing their dependence on it.

5.2 Critical Current Density and Flux-Pinning Precipitates

Figure 5 (c) shows the variation of Critical Current Density[6]; J_c with Magnetic Field. Current densities as high as few 100A (or few 1000A with low magnetic fields) can be achieved with a Ti-49.5Nb wire of 1mm thickness. Optimization of J_c is normally done by manipulating Flux-Pinning[7] Precipitates through appropriate processing. It has been positively identified that -although dislocation centers also contribute- dominant centers of Flux-Pinning Precipitates are α-phase. This area is somehow still under investigation.

6 Uses and Current Research

Ti-Nb is a technically important alloy. The uses of Ti-Nb lies mainly in the fact that it is a superconductor; especially to construct solenoids with high B fields. Research is being carried out to search for the potential of Artificial Pinning Center (APC) composite wires. The properties of the best APC wire at a reduced temperature have been measured so that it's H_{c2} was the same as $H_{c2}(4.2K)$ for Ti-47Nb(wt %) [3]. The dependence of J_c anisotropy and Bulk Pinning Force on H have been computed recently [6]. Experimental conditions under which the hysteretic magnetization of a superconductor with anisotropic pinning center arrays can be measured and longitudinal J_c can be extracted, have also been established [6]. In investigations of electrical characteristics of Ti-Nb. anomalous variations in those of bulk have been observed and attributed to structural instabilities [5].

References

[1] Collins, E. W., *Applied Superconductivity, Metallurgy and Physics of Titanium Alloys (Vol. 1), International Cryogenics Monograph Series, Plenum Press (1986).*

[2] Collins, E. W., *Applied Superconductivity, Metallurgy and Physics of Titanium Alloys (Vol. 2), International Cryogenics Monograph Series, Plenum Press (1986).*

[3] Heussner, R. W., Nunes, C. B. and Lee, P. J., *Journal of Applied Physics, vol. 80 (Aug. 1996) p1640-6.*

[4] Hook, J. R. and Hall, H. E., *Solid State Physics (2nd ed.), The Manchester Physics Series, Ch10(1991).*

[5] Mani, A., Vaidhyanathan, L. S. and Hariharan, Y., *Cryogenics, vol. 36 (Nov. 1996) p937-41.*

[6] Nunes, C. B., Heussner, R. W. and Larbalestier, D. C., *Journal of Applied Physics, vol. 80 (Aug. 1996) p1647-51.*

[6]This is the current above which the superconducting state is destroyed. This phenomenon is known as Silbee Effect.

[7]This is a mechanism (material inhomogeneities) that prevents free migration of quantized flux lines in type II superconductors.