

## Accepted Manuscript

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PII: S0925-8388(14)02458-X  
DOI: <http://dx.doi.org/10.1016/j.jallcom.2014.10.038>  
Reference: JALCOM 32384

To appear in: *Journal of Alloys and Compounds*



Please cite this article as: J. Coakley, V.A. Vorontsov, K.C. Littrell, R.K. Heenan, M. Ohnuma, N.G. Jones, D. Dye, Nanoprecipitation in a Beta-Titanium Alloy, *Journal of Alloys and Compounds* (2014), doi: <http://dx.doi.org/10.1016/j.jallcom.2014.10.038>

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## Nanoprecipitation in a Beta-Titanium Alloy

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## Abstract

This paper represents the first application of small angle neutron scattering (SANS) to the study of precipitate nucleation and growth in  $\beta$ -Ti alloys in an attempt to observe both the precipitation process *in-situ* and to quantify the evolving microstructure that affects mechanical behaviour. TEM suggests that athermal  $\omega$  can be induced by cold-rolling Gum metal, a  $\beta$ -Ti alloy. During thermal exposure at 400°C, isothermal  $\omega$  particles precipitate at a greater rate in cold-rolled material than in the recovered, hot deformed state. SANS modelling is consistent with disc shaped nanoparticles, with length and radius under 6nm after thermal exposures up to 16 h. Modelling suggests that the nanoprecipitate volume fraction and extent of Nb partitioning to the  $\beta$  matrix is greater in the cold-rolled material than the extruded. The results show that nucleation and growth of the nanoprecipitates impart strengthening to the alloy.

*Key words:* Metals and Alloys, Precipitation, Transmission Electron Microscopy, TEM, Neutron Scattering, Titanium Alloys

## 1. Introduction

The use of  $\beta$ -titanium alloys in industry is steadily increasing due to their attractive properties. The low elastic modulus is of significance for orthopaedic applications, and the high yield strength is a requirement for aero applications such as landing gear. Ultimate tensile strengths far in excess of 1GPa have been reported [1, 2]. However, the mechanisms producing this level of strength are still not fully understood. Raghunathan *et al.* [3] attribute the high strength of Ti-10V-2Fe-3Al  $\beta$ -Ti alloy to fine scale  $\alpha$  precipitates, which create a high number of  $\beta/\alpha$  interfaces that hinder dislocation motion through the matrix. Nag *et al.* attribute high strength in a TNZT (Ti-Nb-Zr-Ta)  $\beta$ -Ti alloy to metastable B2 ordering in the matrix and found that precipitation of fine scale  $\alpha$  particles destroyed this ordering, thereby softening the material [4].

The attribution of strengthening mechanisms in  $\beta$ -Ti alloys is further complicated by the metastable athermal  $\omega$  ( $\omega_{\text{ath}}$ ) and isothermal  $\omega$  ( $\omega_{\text{iso}}$ ) phases that can nucleate on quenching and appropriate ageing respectively.  $\omega_{\text{ath}}$  forms from the *bcc*  $\beta$  lattice by displacement of two  $\{111\}_{\beta}$  planes [5, 6]. It appears that the  $\omega_{\text{iso}}$  phase is a continuation of the  $\omega_{\text{ath}}$  transformation, such that after the  $\omega_{\text{ath}}$  structure is formed,  $\beta$  stabilising elements are continuously rejected from the  $\omega$  interface during isothermal

ageing [7]. The precipitation mechanism from quenching to a stable precipitate on appropriate heat-treatment in a binary  $\beta$ -Ti alloy (Ti-18Mo wt.%) is believed to be  $\beta \rightarrow \beta + \beta' \rightarrow \beta' + \omega \rightarrow \beta' + \omega + \alpha \rightarrow \beta' + \alpha$  [8], where  $\beta$  and  $\beta'$  are solute lean and solute rich *bcc* phases respectively. It is unknown if this precipitation path holds true for more highly alloyed  $\beta$ -Ti alloys.

Nag concluded that the dissolution of  $\omega$  on ageing causes a reduction in hardness in Ti-15Mo [4], while Jones *et al.* concluded that the  $\omega$  does not impart strengthening, and attributes an increase in strength to precipitation of nanoscale  $\alpha$  laths in Ti-5Al-5Mo-5V-3Cr (Ti-5553) [9]. This brief literature review shows that there is much confusion over the strengthening phases in high strength  $\beta$ -Ti alloys. In this work, pinhole small angle neutron scattering (SANS) is used in conjunction with X-ray diffraction (XRD) and extensive complementary transmission electron microscopy (TEM) to study the precipitation process *in-situ* of Gum metal, a  $\beta$ -Ti alloy. The aim has been to implement an additional scientific technique to aid the un-

The term ‘Gum metal’ refers to an alloy composition range defined by Saito *et al.* that exhibit “super properties”: ultralow elastic modulus, ultrahigh strength, superelasticity and superplasticity, at room temperature, as well as invar and elinvar properties [1, 10]. The fundamental composition of Gum metals are Ti-24(Nb+Ta+V)-(Zr,Hf)-O (at.%), and must satisfy specific values of average electron valence number, bond order and d-electron orbital energy, to ensure  $\beta$  phase stability. Thus a range of alloys may be referred to as Gum metal.

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