Acta Materialia 106 (2016) 374–387

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

On variant distribution and coarsening behavior of the α phase in a metastable β titanium alloy

Shanoob Balachandran [a], Ankush Kashiwar [a, 1], Abhik Choudhury [a], Dipankar Banerjee [a, *], Rongpei Shi [b], Yunzhi Wang [b]

[a] Department of Materials Engineering, Indian Institute of Science, Bangalore, India
[b] Department of Materials Science and Engineering, The Ohio State University, Columbus, USA

ARTICLE INFO

Article history:
Received 18 June 2015
Received in revised form
8 January 2016
Accepted 9 January 2016
Available online xxx

Keywords:
Titanium alloys
Variant selection
Self-accommodation
Coarsening

ABSTRACT

The stereology, variant distribution and coarsening behavior of semicoherent α(hcp) precipitates in a β(bcc) matrix of a Ti5553 alloy has been analyzed, and a dominant 3-variant cluster has been observed in which the variants are related to each other by an axis-angle pair $<11\bar{2}\,0>/\,60^{\circ}$. Shape and spatial distribution independent elastic self and interaction energies for all pairwise and triplet combinations of α have been calculated and it is found that the 3-cluster combination that is experimentally observed most frequently has the lowest energy for the semicoherent state. The coarsening behavior of the delta distribution follows LSW kinetics after an initial transient, and has been modeled by phase field methods.

1. Introduction

The aging of metastable β titanium alloys below a certain critical temperature in a two-phase $\alpha+\beta$ region has been shown to result in a distribution of fine, intragranular α precipitates with a characteristic triangular arrangement of α plates, shown in Fig. 1a. We call this distribution a delta distribution. The thermal paths that lead to these distributions have been discussed in earlier work [1,2]. The morphology and crystallography of the delta distribution has been examined in the past [3]. These distributions have also been shown to be associated with superior mechanical properties [4]. The α plates precipitate in a Burgers relationship (0001)//(110): $<11\bar{2}0>//<111>$ to the parent β with 12 crystallographic variants of which 4 sets of 3 variants taken together share a common $<111>//<11\bar{2}\,0>$ zone axis, as shown in Fig. 1b. The misorientations between all possible pairs of these 12 variants of α laths in terms of reduced axis-angle pairs reduces to 6 different types as described in Ref. [5] and is reproduced in Table 1. Any deviations from random distribution of these 12 variants can be described in the terms of the frequency of occurrence of these pairs. Fig. 1a suggests that a preferred, non-random distribution does indeed exist with local, spatial correlations between certain types of variants.

The mechanical behavior of alloys with these α distributions will be affected by elastic interactions and slip transfer processes between α and β that are strongly determined by the relative orientations of slip planes and directions in the two phases determined by the Burgers relationship [6]. The presence of multiple variants of the α phase within a single β grain will therefore restrict slip as discussed in Ref. [7]. The α phase variant distribution and its coarsening with heat treatment are therefore important parameters that will determine mechanical response. It is against this background that we have examined the stereology and coarsening of α plates in delta distributions in a variant of the Ti5553 alloy widely used in undercarriage applications in aircraft.

2. Experimental

The alloy used in this study was melted by non-consumable vacuum arc melting into a pancake that is typically 15 cm in diameter and 1 cm in thickness to the nominal composition of the Ti5553 alloy (without Fe). Samples from the alloy were heat treated from the as-cast condition for 0.2 h, 0.83 h, 2 h, 4.5 h, 16 h and 144 h at 765 °C. Fig. 2 shows the starting microstructure preceding heat treatment in the as cast condition that indicates that the delta

* Corresponding author.
E-mail address: banerjee52@gmail.com (D. Banerjee).
[1] Current address: Institute of Nanotechnology, Karlsruhe Institute of Technology, Germany.

http://dx.doi.org/10.1016/j.actamat.2016.01.023
1359-6454/

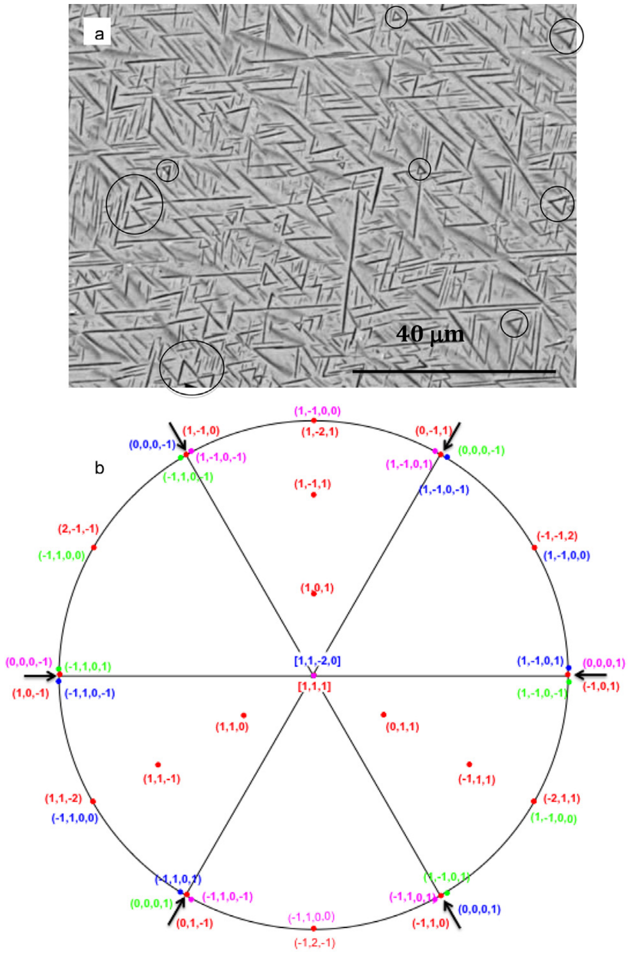

Fig. 1. (a) The typical triangular appearance of α plates in metastable β alloys aged at low temperatures (b) The crystallography of α plates in the Burgers orientation relationship. Only one set of 3 variants (in purple, green and blue) out of the possible 12 is shown for clarity. These share a common [111] β direction parallel to <11$\overline{2}$ 0>. The 12 variants are constituted by 3 other similar clusters parallel to the 3 other <111> β directions. The β poles are red in color.

distribution had already formed during cooling after melting. The microstructure was characterized by back-scattered electron (BSE) imaging, and by electron back-scattered diffraction (EBSD) to identify the crystallographic orientations of the α variants. The EBSD data was used to derive 'non-correlated' misorientation information between pairs of α variants using the proprietary TSL

Table 1
The 6 types of pair-wise misorientation between α plates in the Burgers orientation relationship and their probability of occurrence in the random case. There are 78 possible pair-wise combinations (allowing repetition) of the 12 variants that are distributed as shown in these 6 types of pairs.

Type	Axis/angle pair	Number of possible combinations	Probability of occurrence
Type A	0	12	15.38%
Type B	[11−20]/60°	12	15.38%
Type C	[−1.377,−1, 2.377, 0.359]/60.83°	24	30.77%
Type D	[−10 5 5 3]/63.26°	12	15.38%
Type E	[1, −2.38, 1.38, 0]/90°	12	15.38%
Type F	[0001]/10.53°	6	7.69%

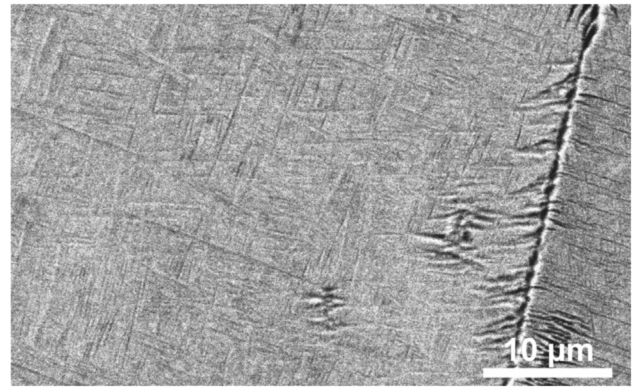

Fig. 2. The starting structure for the aging treatments.

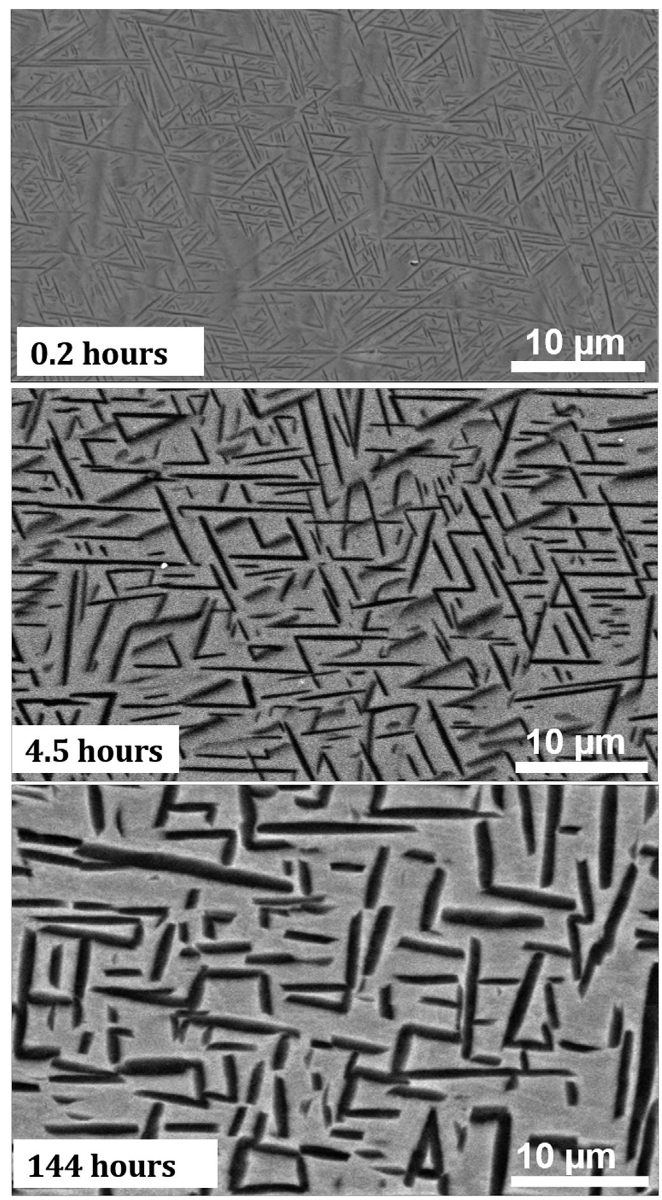

Fig. 3. The effect of aging time at 765 °C on α size and distribution, BSE images.