Journal of Alloys and Compounds 691 (2017) 60–66

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Phase transformation mechanisms in a quenched Ti-45Al-8.5Nb-0.2W-0.2B-0.02Y alloy after subsequent annealing at 800 °C

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A R T I C L E I N F O

Article history:
Received 13 June 2016
Received in revised form
16 August 2016
Accepted 23 August 2016
Available online 24 August 2016

Keywords:
Metals and alloys
Phase transformation
Microstructure
TEM

A B S T R A C T

During the processing of high Nb-containing TiAl (Nb-TiAl) alloys, the cooling rate at certain parts of the components can be very high, especially at thin parts. Moreover, annealing treatment must be applied to TiAl alloys to improve their mechanical properties. In this study, the phase transformation mechanisms in a quenched Ti-45Al-8.5Nb-0.2W-0.2B-0.02Y alloy during subsequent annealing were characterized using a scanning electron microscope (SEM) and a transmission electron microscope (TEM). The results show that β_o, α_2, and massively transformed γ phases co-exist in the as-quenched microstructure. Some fine γ laths nucleated in the primary α_2 phase in the quenched samples. After annealing at 800 °C for 1 h, numerous extremely fine γ laths precipitated in the bulk α_2 phase and could only be recognized using TEM imaging. The ω_o particles at sizes of 0.5–1 μm precipitated in the retained β_o phase and nearly consumed all of the β_o areas. More interestingly, some coarsened γ grains in true-twin relationship were observed at the boundaries of the lamellar colony and $\beta_o(\omega)$ regions. The orientation relationship between $\beta_o(\omega)$ and coarsened γ was confirmed to be the following: $[110]\beta//[11\bar{2}0]\omega//[111]\gamma$, $(11\bar{1})\beta//(0001)\omega//(1\bar{1}0)\gamma$. After annealing at 800 °C for 100 h, the β_o phase region transformed into small ω_o particles and equiaxed γ grains and still followed the above-mentioned orientation relationship. The α_2 phase only existed as thin laths in the lamellar structures in a small volume fraction. These results indicate that the ω_o phase is stable at 800 °C. Possible mechanisms of these phase transformations are discussed.

1. Introduction

High Nb-TiAl alloys have been considered to be possible candidates for superalloys because of their good high temperature performance, oxidation resistance and creep properties [1–3]. There is a consensus regarding the importance of high Nb element addition in the development of TiAl alloys together with some trace addition of other elements for adjusting their properties. The high amount of Nb addition expands the β phase field to higher temperatures but also shrinks the single α phase field to a narrower region [4]. During the processing of high Nb-TiAl alloy components, a significant variation of the cooling rates of different parts is possible, especially in thin parts (for which the cooling rate can be extremely high), leaving a heterogeneous microstructure in the components. Furthermore, the annealing process at intermediate temperatures is also necessary for the components to stabilize the microstructure and release internal stress [5,6]. Thus, the phase transformation behavior of the rapid-cooled microstructure during subsequent annealing should be revealed in detail. It is commonly reported that the as-cast and forged microstructures of Nb-containing TiAl alloys, although slowly-cooled to room temperature, are non-equilibrium structures, i.e., several types of phase transformations may occur during annealing at 700 °C–900 °C. Schloffer et al. [7] have shown that a large amount of ω_o phase (ordered ω phase in $B8_2$ structure) existed in Ti-43.5Al-4Nb-1Mo-0.1B alloy after annealing at 750 °C–800 °C for a long time. They also observed the co-existence of the ω_o and γ phase in the β_o area. Huang et al. [8] reported the $\alpha+\gamma\rightarrow\beta_o(\omega)$ transformation in Ti-44Al-8Nb-1B alloy, suggesting the presence of an ordered ω phase field at 700 °C. Similar transformations were observed by different authors in other TiAl alloys with different compositions [9–11]. These results indicate that the ω_o phase, which is in equilibrium at intermediate temperatures, can be transformed from the $\alpha_2+\gamma$ lamella or simply α_2 laths with a sufficient annealing time.

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http://dx.doi.org/10.1016/j.jallcom.2016.08.238

The common formation of the ω_o phase in high Nb-TiAl alloys is considered to be due to the concentration of Nb, which is actually an ω_o phase stabilizer [10]. Meanwhile, the β_o phase stabilizer elements, such as W and Mo, hinder the growth of the ω_o phase; thus, in alloys containing these elements, the co-existence of the ω_o and β_o phases is frequently reported [7,12,13]. However, these studies were mostly conducted on nearly fully lamellar microstructures, which were in the near-equilibrium state or slowly-cooled from high temperatures. For rapidly-cooled microstructures, the phase transformation behavior can be considerably different from the reported ones because of the difference in initial microstructures and composition distribution.

In recent years, some researchers have proposed that annealing in the $\alpha+\gamma$ phase field of massively transformed samples could refine the microstructure of high Nb-TiAl alloys [14–16]. The initial massive transformed microstructure was far from equilibrium to ensure that the precipitation of γ or α_2 laths during subsequent annealing can be established in a short time. The transformation mechanisms of this processing route were mainly developed from the phenomena observed at high annealing temperatures. Although the refining effect is not obvious during annealing at lower temperatures, the related phase transformation behavior should be revealed to deepen the understanding of the phase transformation mechanisms of high Nb-TiAl alloys.

The present study focuses on the phase transformation behavior in Ti-45Al-8.5Nb-0.2W-0.2B-0.02Y alloy quenched from the $\alpha+\beta$ phase field and subsequently annealed at 800 °C. The results were mainly obtained via electron microscopy observation to reveal the phase transformation mechanisms in detail.

2. Experimental

An ingot of a Ti-45Al-8.5Nb-0.2W-0.2B-0.02Y alloy, measuring approximately Φ85 × 55-mm, was prepared using a vacuum induction melting furnace. The ingot was remelted three times to ensure compositional homogeneity. Samples with a gauge of 10 × 10 × 15-mm were cut from the ingot for heat treatments. According to the phase diagram reported by Chen et al. [4] and Witusiewicz et al. [17], the Ti-45Al-8Nb alloy is in the $\alpha+\beta_o$ phase field at 1400 °C. As the composition of the present alloy is close to Ti-45Al-8Nb, all of the samples were first heat treated at 1400 °C in a resistance furnace for 4 h, followed by water quenching. Some quenched samples were further annealed at 800 °C for 1 h and 100 h respectively, followed by water quenching. The as-quenched and annealed microstructures were observed using the back-scattered electron (BSE) mode on a Zeiss SUPRA 55 field emission SEM operated at 15 kV. Before preparing the metallographic specimens for SEM observation, a 2 mm surface layer of the samples was removed by the electrospark wire cutting machine to avoid the influence of oxidation and dealumination. X-ray diffraction (XRD) analyses were conducted on the polished SEM samples on a DX2700 X-ray diffractometer using Cu-K_α radiation. TEM analysis was conducted using a Tecnai G2 F30 field emission transmission electron microscope operated at 300 kV. The TEM specimens were cut from the center of the heat treated samples and then mechanically ground to 0.06 mm. The thin foils were prepared by electropolishing in a solution of 30 ml of perchloric acid, 175 ml of butan-l-ol, and 300 ml of methanol at 30 V and −30 °C.

3. Results and discussion

3.1. The as-quenched microstructure

The as-cast microstructure of the Ti-45Al-8.5Nb-0.2W-0.2B-0.02Y alloy is shown in Fig. 1(a). Similar to those reported by our previous studies [18,19], the as-cast ingot has a nearly fully lamellar microstructure that mainly consists of lamellar colonies at sizes of approximately 120 μm and retained $\beta_o(\omega)$ phases in the colony boundaries. Some equiaxed γ grains are also observed next to the β_o phases, which could be formed by direct nucleation of the γ phase within the β_o phase as reported in Refs. [19,20]. After being quenched from 1400 °C (within the $\alpha+\beta_o$ phase region), the

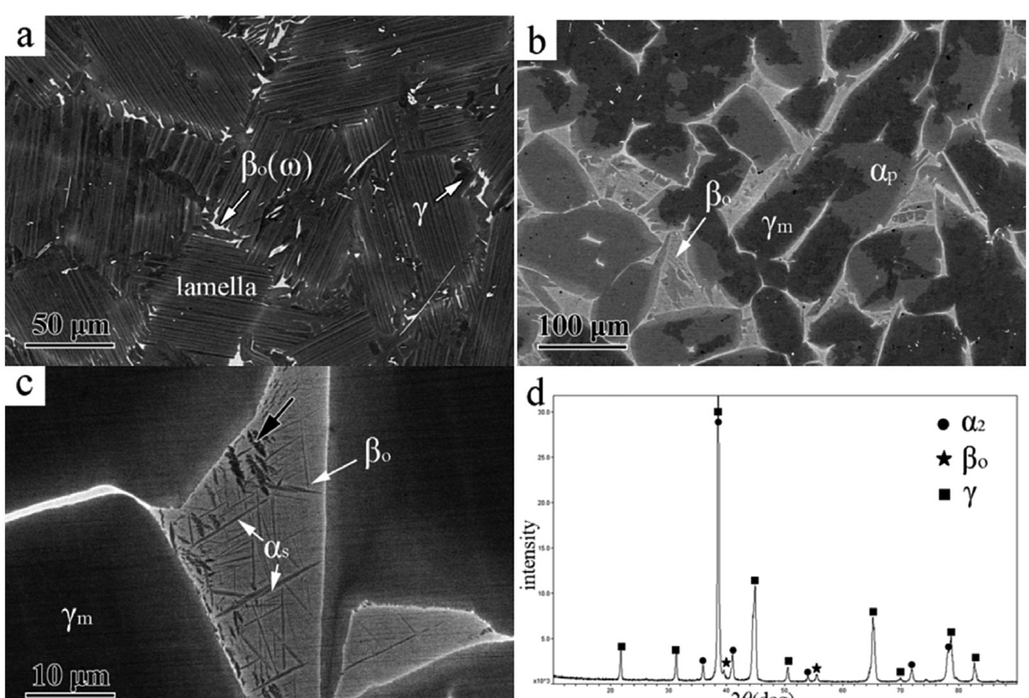

Fig. 1. SEM-BSE images of the as-cast (a) and as-quenched (b)–(c) microstructures; (d) XRD pattern of the as-quenched microstructure.