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ω-Assisted nucleation and growth of α precipitates in the Ti–5Al–5Mo–5V–3Cr–0.5Fe β titanium alloy

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Abstract

This paper discusses the structural and compositional changes at the nanometer scale associated with the nucleation and growth of α precipitates in the β titanium alloy Ti-5553 (Ti–5Al–5Mo–5 V–3Cr–0.5Fe) with ω precipitates acting as heterogeneous nucleation sites. The microstructural evolution in this alloy, during β-solutionizing, quenching and aging type heat-treatments, has been investigated by combining results from scanning electron microscopy, orientation imaging microscopy, transmission electron microscopy, high-resolution TEM and three-dimensional atom probe (3DAP) tomography. Athermal ω precipitates form in this alloy on quenching from above the β transus temperature. On isothermal annealing at low temperatures, these ω precipitates coarsen to form chemically ordered ω precipitates, accompanied by the nucleation of the stable α phase. Annealing at higher temperatures leads to dissolution of ω and further growth of α precipitates accompanied by clustering of different α variants in self-accommodating morphologies. 3DAP results indicate that annealing at lower temperatures (∼350 °C) leads to initial nucleation of α precipitates with a non-equilibrium composition, nearly identical to that of the β matrix. Subsequent aging at higher temperatures (∼600 °C) leads to more pronounced partitioning of alloying elements between the two phases. These results indicate that the structural body-centered cubic to hexagonal close-packed transformation and the compositional partitioning of alloying elements occur in sequential steps, resulting in a mixed-mode displacive-diffusional transformation, similar to the bainite transformation in steels.

Keywords: Titanium alloys; Heterogeneous nucleation of phase transformations; Aging; Metastable phases

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1. Introduction

The alloy Ti–5Al–5Mo–5V–3Cr–0.5Fe (all elemental concentrations in wt.%), patented as Ti-5553, is a recently developed modification of the Russian near-β titanium alloy VT-22 that is expected to be applicable for thick section aerospace components due to its high-strength, reported to be as high as 1250 MPa at room temperature for certain microstructures, and its deep-hardenability [1–4] over larger thicknesses (∼150 mm). Depending on the microstructure, this alloy can exhibit room temperature ultimate tensile strengths as high as 1138–1172 MPa while retaining useful ductility and toughness. In addition, this promising alloy can exhibit outstanding strength and high-cycle fatigue properties compared with those of Ti–6Al–4V. However, it is important to note that the properties of Ti-5553 can vary over a wide range and are critically dependent on the microstructure, warranting a detailed investigation of the microstructural evolution.

The balance of mechanical properties in Ti-5553 is expected to be dependent on the volume fraction, size, morphology and distribution of α precipitates within the β matrix [5,6]. By varying the temperatures, times and cooling rates in individual heat-treatments, it is possible to vary the volume fraction and morphology of the α phase nucleated within the β matrix phase in this alloy. The partitioning of the alloying elements, Al, V, Mo, Cr and Fe, also

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depends on the heat-treatments influenced by the alloy. Furthermore, in addition to these primary alloying elements, interstitials such as oxygen and hydrogen can also play a significant influence on the development of the microstructure in these β titanium alloys. The nucleation sites for the α phase within the β phase of β titanium alloys include prior β grain boundaries, β/ω interfaces, β/β′ interfaces and other defects such as dislocations and intermetallic particles within the matrix [7]. Depending on the overall composition of the β titanium alloy and the specific heat-treatment experienced by the alloy, these different sites may or may not play a substantial role in α nucleation. The influence of these various nucleation sites is also closely associated with competing instabilities inherent within the β phase, i.e. $\beta \rightarrow \beta + \beta'$ (phase separation), $\beta \rightarrow \beta + \omega$ and $\beta \rightarrow \beta + \alpha'$, together with the equilibrium $\beta \rightarrow \beta + \alpha$ transformation that occurs at slower cooling rates. [7]. Typically, in β alloys that are solution treated above the β transus temperature and quenched, athermal ω precipitates form, which on subsequent isothermal aging may undergo coarsening and act as uniformly distributed heterogeneous nucleation sites for α precipitates [8,9]. A consequence of such ω-assisted heterogeneous nucleation is that a relatively large number of α precipitates are formed and uniformly distributed within the β matrix. Furthermore, these α precipitates are of a relatively finer scale (usually nanometers to submicron) and often exhibit morphologies that are distinctly different from precipitates nucleated at higher temperatures at prior β grain boundaries. Different mechanisms have been proposed describing the role of ω precipitates in the nucleation of α precipitates, as discussed below.

Typically in case of systems where there is a large misfit between the ω and β phases, α precipitates nucleate on ledges and misfit dislocations at ω/β interfaces [8–11]. For such systems, the morphology of the ω precipitates in the β matrix has been observed to be more cuboidal, and, as ω loses coherency with the β matrix on coarsening, these ω precipitates are believed to act as potent nucleation sites for α. An example of such a system is the binary Ti–V system [8,9]. In contrast, in systems exhibiting a lower mismatch between the ω and β phases, such as the Ti–Mo system, the ω precipitates exhibit a more spherical or ellipsoidal morphology and these precipitates do not often act as nucleation sites for α on further aging of the alloy [8]. In more recent studies on the Ti–10V–2Fe–3Al (Ti-10-2-3) alloy, Ohmori et al. [10] have discussed the role of ω precipitation on α nucleation and growth, clearly presenting evidence of ω precipitates acting as heterogeneous nucleation sites for α precipitates.

In systems exhibiting a lower ω/β misfit, the role of ω precipitates on the nucleation of α precipitates is not clearly understood. Although ω precipitates typically exhibit an ellipsoidal morphology in binary Ti–Mo alloys, studies on Ti–15 wt.% Mo by Pennock et al. [12] report that a two-step aging process after quenching from the β-solutionizing temperature possibly results in ω-assisted nucleation of α precipitates. Their results also suggested an influence of heating rate on the role of ω precipitates in nucleating α. Similar results were reported more recently for a two-step aging treatment applied to the Ti–15V–3Cr–3Sn–3Al (all wt.%) alloy, with a low ω/β misfit, wherein a homogeneous distribution of intragranular α precipitates was obtained [13]. Currently, there are two different schools of thought regarding the mechanism of ω-assisted nucleation of α in low ω/β misfit systems.

1. Detailed studies on the alloy, Ti–6.8Mo–4.5Fe–1.5Al (all wt.%), also referred to as low-cost β (LCB) alloy, by Azimzadeh and Rack [14] indicate that the α precipitates nucleate near, but at a certain distance from, the ω/β interface. The local rejection of certain alloying elements such as Al in the LCB alloy, which are ω-destabilizers but α stabilizers, during the isothermal aging of ω precipitates aids the nucleation of α precipitates in the vicinity of the ω precipitates. Such local enrichment of Al in the vicinity of isothermally growing ω precipitates has been reported, based on atom probe tomography results, in a different paper [15]. This is a possible mechanism leading to the nucleation of α precipitates in association with ω precipitates in low ω/β misfit systems [14].

2. There is a displacive transformation within the core of the ω precipitates, leading to the formation of α platelets, as suggested by some recent high-resolution transmission electron microscopy (HRTEM) studies on the LCB alloy [16]. Previous studies had assumed the possibility of a direct ω to α structural transformation in Ti alloys [17,18], but without any direct microscopic imaging evidence. The recent paper on LCB alloys by Prima et al. [16], shows dark-field TEM and HRTEM results indicating that α platelets nucleate within the core of the ω precipitates. While these results are promising, if such a displacive mechanism was indeed the only mechanism operative, there should not be any influence of ω/β misfit on the propensity of ω precipitates to act as potential nucleation sites for α precipitates, which is obviously not the case based on many previous reports [8,9,19,20].

Despite these previous studies, the role of ω precipitates on the nucleation of α in the β phase of Ti alloys, especially in case of low ω/β misfit systems, is still not well understood. Furthermore, subsequent to ω-assisted nucleation, the growth of α precipitates, partitioning of alloying elements between the equilibrium α and β phases, and the overall microstructural evolution have not yet been addressed in detail. Therefore the specific aims of the present paper are as follows:

1. To investigate the role of ω precipitates on the intragranular nucleation of α precipitates in the Ti-5553 alloy containing the β stabilizers Mo and V as well as the α stabilizer Al as alloying additions.
2. To investigate the subsequent growth of multiple variants of these intragranular nucleated α precipitates, and its role in the overall microstructural evolution.