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Primary phase growth and microstructure evolution of rapidly solidifying ternary Ti-12Al-8V alloy

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ABSTRACT

Liquid Ti-12Al-8V alloy was rapidly solidified by electromagnetic levitation and drop tube techniques. The levitation processing avoided the violent heterogeneous nucleation of primary β phase and led to an actual maximum undercooling of 212 K ($0.11T_L$). The primary β dendrites exhibited a high growth velocity up to 14.9 m/s but subsequently transformed into basket weave structures. Drop tube experiments indicated that the final microstructure morphology was determined by the coupled influences of undercooling extent and cooling rate. If the cooling rate exceeded 3.31×10^3 K/s, the primary β phase was retained metastably to ambient temperature.

1. Introduction

Ternary Ti-Al-V system forms the basis of numerous high-performance titanium alloys widely applied in aerospace industry and chemical engineering [1–3]. Although the subsequent plastic deformation and heat treatment are the crucial procedures to produce advanced Ti-based alloys [1,4], it is equally essential to control their initial solidification process for optimizing desirable microstructures [5]. Indeed there are extensive investigations on their directional solidification [6] and rapid solidification [2,7,8] characteristics. But the underlying kinetic mechanisms of phase selection and structure evolution are still far from being completely understood. In particular, much work remains to be done about the high undercooling and dendritic growth of liquid titanium alloys. The technical barrier arises mainly from the very strong chemical reactivity of molten titanium at elevated temperatures. Nowadays, the containerless processing by electromagnetic levitation [2,9] and drop tube [10,11] techniques may provide an effective access to solve such a challenge.

The dendrite growth of primary crystalline phase usually dominates the rapid solidification process of undercooled liquid alloys [12–15]. Both the structural morphology and solute distribution, which determine the applied properties of solidified alloys, depend upon the growth kinetics of primary phases. Therefore, the quantitative measurement of dendritic growth velocity versus liquid alloy undercooling is a vital step to explore the rapid solidification mechanisms of titanium alloys. Another controlling factor is the cooling rate of alloy melt during solidification, which represents the time-dependent feature of crystallization kinetics. The objective of this work is to investigate the liquid state undercoolability and primary dendrite growth of ternary Ti-12 wt%Al-8 wt%V alloy by both electromagnetic levitation and drop tube techniques. A comparative study of bulk undercooled alloy melt with rapidly cooled alloy droplet may shed a bit more light on the microstructural evolution mechanisms of titanium alloys.

2. Materials and methods

Ternary Ti-12 wt%Al-8 wt%V (equivalent to $Ti_{73.5}Al_{19.6}V_{6.9}$ in atomic fraction) master alloy was prepared with ultrahigh vacuum arc melting furnace from 99.99% pure Ti, 99.999% pure Al and 99.8% pure V. Its liquidus temperature was determined as 1905 K by measuring the heating and cooling curves of inductively melted 10 g sample with a W-Re5/26 thermocouple. The electromagnetic levitation apparatus was equipped with a 200 kHz and 30 kW power source and a Raytek Marathon MRIS infrared pyrometer. It was firstly evacuated to 10^{-5} Pa and then backfilled with Ar gas to 1 atm. Each levitated sample with 6–8 mm diameter was superheated to 300–500 K above the liquidus temperature and cooled

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down by a flow of He gas refrigerated in liquid nitrogen. In order to experimentally determine the dendrite growth velocity of primary β phase, the infrared pyrometer device was applied to monitor the specimen temperature; meanwhile a photoelectric detector was used to measure the recalescence time. The 3 m drop tube with 150 mm inner diameter, attained a vacuum of 5×10^{-5} Pa. It provided a free-fall time period of 0.78 s and a reduced gravity level of $10^{-3}-10^{-6}\,g_0$. For each experiment, a sum of 1–3 g master alloy was contained inside a 13 mm ID × 15 mm OD × 160 mm quartz tube with a 0.2 mm diameter orifice at its bottom. The bulk alloy was melted by induction heating, superheated to 100 K above its liquidus temperature and finally atomized by a high-pressure ejecting gas into a great number of freely falling droplets. After experiments, all the samples were analyzed according to standard metallographic procedure with an aqueous etchant of $HF+HNO_3$. An FEI Sirion 200 scanning electron microscope and an INCA 300 energy dispersive spectrometer were applied to investigate their phase constitution and microstructural morphology.

3. Results and discussion

3.1. Bulk undercooling at levitated state

As shown in Fig. 1(a), ternary Ti-12Al-8V alloy is located at the Ti-rich corner of Ti-Al-V phase diagram [3]. Under equilibrium conditions, its solidification process is dominated by the nucleation and growth of primary β-Ti solid solution phase, which has a BCC (body centered cubic) structure and dissolves both Al and V solutes. Because titanium involves a polymorphic transformation at solid state, the primary β-Ti phase usually transfers into HCP (hexagonal close packed) structured α-Ti phase as long as the cooling rate is not extremely high.

When a bulk sample of Ti-12Al-8V alloy was melted and solidified at levitated state, the elimination of crucible and mould walls minimized the chances to induce the heterogeneous nucleation of β phase. Furthermore, the ultrahigh vacuum plus Ar filling ensured an efficient protecting atmosphere for the alloy melt to avoid oxidation. Thus a maximum undercooling of $\Delta T=212$ K ($0.11T_L$) has been achieved experimentally by this alloy, as shown in Fig. 1. The levitation experiments also revealed that a superheating of at least 300 K above its liquidus temperature was necessary to obtain a significant undercooling. A higher degree of superheating favors the enhancement of alloy melt undercooling in two respects. At first, the potential heterogeneous nuclei formed by the inherent impurities of master alloy may be either melted or passivated at sufficiently high temperatures. Secondly, the atomic cluster size inside the liquid alloy is reduced so that the evolution of homogenous nuclei is hindered to a certain extent.

Once a crystalline nucleus of β phase forms in the undercooled liquid Ti-12Al-8V alloy, the negative temperature gradient in front of solid-liquid interface drives it to grow rapidly in dendritic mode. Fig. 1(b) presents the measured dendrite growth velocity V of primary β phase versus alloy melt undercooling ΔT. Evidently, β phase dendrites attained a maximum growth velocity of 14.9 m/s at 212 K undercooling. The statistical fitting analysis of experimental data revealed a power function relation as below:

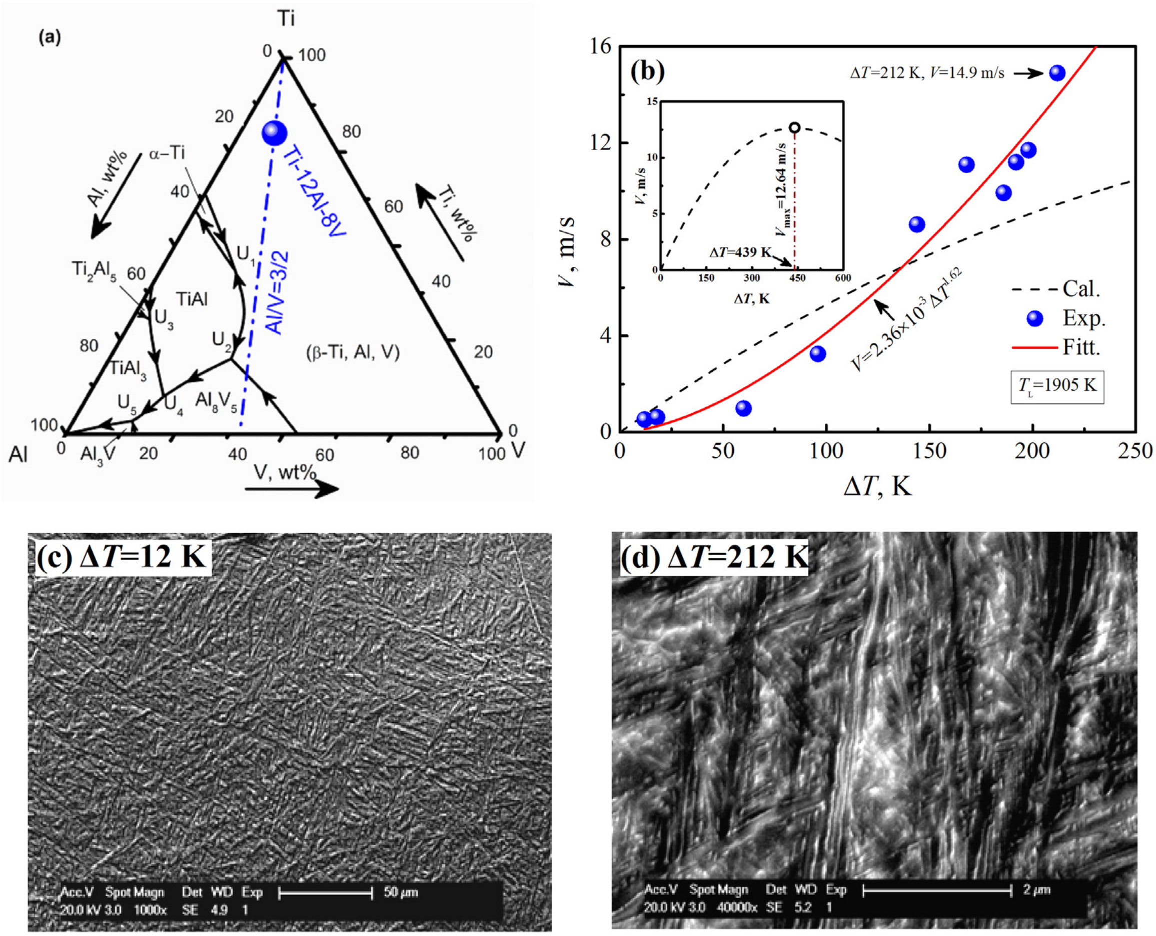

Fig. 1. Dendritic growth of primary β phase in undercooled Ti-12Al-8V alloy at levitated state: (a) alloy composition selection in ternary Ti-Al-V phase diagram, (b) measured and calculated dendritic growth velocity, (c) microstructure at 12 K undercooling and (d) microstructure at 212 K undercooling.