Intermetallics 90 (2017) 113–118

Contents lists available at ScienceDirect

Intermetallics

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

# Effects of solidification parameters on the growth direction of α phase in directionally solidified Ti-49Al alloy

Jianglei Fan[a,b,*], Chi Zhang[a], Shen Wu[a], Hongxia Gao[a], Xiao Wang[c], Jingjie Guo[d], Hengzhi Fu[d]

[a] Institute of Mechanical and Electrical Engineering, Zhengzhou University of Light Industry, Zhengzhou, 450002, PR China
[b] Henan Key Laboratory of Mechanical Equipment Intelligent Manufacturing, Zhengzhou University of Light Industry, Zhengzhou, 450002, PR China
[c] School of Energy and Power Engineering, Zhengzhou University of Light Industry, Zhengzhou, 450002, PR China
[d] School of Material Science and Engineering, Harbin Institute of Technology, Harbin, 150001, PR China

ARTICLE INFO

*Keywords:*
A. Intermetallics
A. Titanium aluminides
C. Crystal growth
C. Casting
D. Microstructure

ABSTRACT

Growth directions (GD) variation of α phase in Ti-49Al (at.%) alloy with solidification parameters were studied by using directional solidification technology. GD of the primary phase (α phase) changed with growth rate ($V$) and temperature gradient ($G$). Evolutions of $\Theta$ (the angle between the preferred growth direction (PG) and heat flow direction (HD) and $\Psi$ (the angle between GD and HD) with $V$ and $G$ are presented. By controlling the solidification parameters accurately, the grains of α solidified TiAl alloy can grow with <11$\bar{2}$0> direction or close to this direction during directional solidification, which is beneficial to the lamellar orientation control of TiAl alloys. For present experimental conditions, the feasible solidification condition for the lamellar orientation control of TiAl alloy by the seeding technology is: $V$ = 10 μm/s ~ 20 μm/s and $G$ = 10 K/mm ~ 12.1 K/mm.

## 1. Introduction

TiAl based alloys offer numerous attractive properties as lower density (~3.9–4.2 g/cm$^3$), excellent resistance to oxidation and high temperature strength, which meet the demands of the newer generation aircrafts and automotive engines [1–7]. The main obstacles that restricted the mass commercial applications of TiAl alloys are the inherently brittle nature, low fluidity, complex processing and high processing cost [4,5,8–11]. Extrusion, forging and power metallurgy/additive manufacturing have been used to produce components of TiAl alloys [4,12]. Nevertheless, the casting process provides a method with greater advantages (such as lower cost and more complex shape) for the manufacture components of TiAl alloys, comparing with the above methods [4,13,14]. Especially, TiAl based alloys with aligned lamellar orientation that prepared by directional solidification technology have a good combination of strength and ductility in a wide range of temperature [15–20]. Previously, Johnson et al. [15–17] have studied the TiAl alloy with PST (polysynthetically twinned crystals) structure and found that the full-lamellar TiAl-based alloys with aligned lamellar structures have a good ductility at room temperature and high strength in a wide range of temperature. Chen et al. [18] have reported that the directionally solidified Ti-45Al-8Nb (at.%) alloy with aligned lamellar structures exhibited the average ductility of 6.9% and tensile strength of 978 MPa at room temperature. Therefore, it is an effective method to improve the mechanical property of TiAl alloys by controlling the lamellar orientation.

Due to the lamellar structure is not formed from the liquid but the solid-state transformation, the orientation of high temperature α phase must be controlled initially to obtain the preferred lamellar orientation [15,16,21,22]. Furthermore, the aligned lamellar structure can be obtained by directional solidification technology [16,21,23–28]. Thus, to achieve columnar grain materials of TiAl alloys with the lamellar orientation aligned parallel to the growth direction, appropriate processing technologies have been developed [15–17]. One way is using directional solidification technology with a seed material having specific orientation of α phase, and the other is controlling the solidification path by directional solidification without a seed material. Recently, extensive works have been carried out to achieve columnar grain materials of TiAl alloys with the lamellar orientation aligned parallel to the growth direction by directional solidification with [15–17,29–32] or without seeding technology [18,25,33,34]. These studies have focused on the control of lamellar orientation by optimizing solidification parameters during directional solidification. However, the effect of solidification parameters on the variation of growth direction is not well understood.

Theoretically, the final lamellar orientations of TiAl alloys depend on the type of the primary phase during solidification, due to the crystallographic relationships among β phase, α phase and γ phase,

* Corresponding author. Institute of Mechanical and Electrical Engineering, Zhengzhou University of Light Industry, Zhengzhou, 450002, PR China.
*E-mail addresses:* JLFan2011@163.com, fanjianglei@zzuli.edu.cn (J. Fan).

http://dx.doi.org/10.1016/j.intermet.2017.07.008
Received 4 January 2017; Received in revised form 9 July 2017; Accepted 12 July 2017

namely $\{110\}_\beta//\{0001\}_\alpha//\{111\}_\gamma$ and $<11\bar{2}0>_\alpha//<111>_\gamma$. If β phase is the primary phase, the PG of β phase is < 001 > direction, and the final lamellar orientation is 0° or 45° (the ratio is 1: 2) inclined to growth direction. If α phase is the primary phase, the PG of α phase is < 0001 > direction, and the final lamellar orientation is perpendicular to growth direction. However, the PG of primary phase is not always the theoretical direction, namely < 001 > direction for β phase and < 0001 > direction for α phase, and the lamellar orientations departure from the theoretical values. For β solidification TiAl alloys, the lamellar orientations are not only just 0° or 45° inclined to growth direction, but also other orientations have been found [35–38]. For Ti-47.5Al-2W-0.5Si (at. %) and Ti-46Al-2Mo-2Nb (at.%) alloys [37], the lamellar orientations were angled or normal to the growth direction near the top of the directionally solidified specimens. Jung et al. [36] also have found that the lamellar orientation inclined with angles of 60°-90° to growth direction at a growth rate of 90 mm/h in the directional solidification of Ti-47Al-2W (at.%) alloy. Xiao et al. [38] have indicated that the lamellar orientation with angles of 74°, 80° and 84° to the growth direction in directionally solidified Ti-47Al-2Cr-2Nb (at.%) alloy, which was β solidified. These results disagreed with the theoretical predictive results. Jung [36] and Xiao [38] considered that the variation of lamellar orientation resulted from the changed growth direction of β phase. For the α solidified TiAl alloy (Ti-46Al-0.5W-0.5Si at.%), Fan et al. [39] have found that the lamellar orientation is not always perpendicular to the growth direction under different directional solidification conditions. Hence, the understanding of dendritic growth and crystallographic orientation is very important for the lamellar orientation control of TiAl alloys. To eliminate the influence alloying elements, we have studied the GD of α phase and the lamellar orientation of directionally solidified TiAl binary alloy (Ti-49Al at. %) under different solidification parameters, and found that the lamellar orientation was not perpendicular to the growth direction at some solidification conditions. However, there is lack of information about the mechanism of the growth directions vary with solidification parameters of TiAl alloys.

The purpose of this paper is to study the effect of solidification parameters on the α phase growth direction in Ti-49Al (at.%) alloys. These results will contribute to understanding the dendrite growth behavior, and help to optimize the solidification parameters for the lamellar orientation control of α solidified TiAl alloys.

## 2. Experimental procedure

A master ingot with a nominal composition of Ti-49Al (at. %) was prepared using a water-cooled copper crucible induction furnace in an argon atmosphere; Ti (99.96%) and Al (99.99%) were used as the raw materials. The ingot solidified in a metal mould. The samples used for directional solidification experiments were rods (⌀3 mm × 100 mm) cut from the ingot using electrical discharge machine. The experiments were performed in a Bridgman-type system as previously described in Ref. [40]. The samples are placed into 99.99 pct pure alumina crucibles with a 4/5.5mm diameter (insider/outside diameter) $Y_2O_3$ skull and a length of 150mm. The directional solidification process was carried out in a vacuum chamber in an argon atmosphere. Before heating, the chamber of the directional solidification furnace was evacuated to $10^{-4}$Pa and filled back with argon to avoid oxidation. The specimen was heated to 1773 K over 2 h and thermally stabilized for 1800 s. The sample was then directionally solidified with different growth rates ranged from 5 μm/s to 30 μm/s and different temperature gradient ranged from 2.8 K/mm to 12.1 K/mm. The growth length of the samples was about 30mm. At the end of the experiment, the sample was quenched with a liquid Ga-In-Sn alloy to capture the morphology of the solid/liquid interface. The temperature gradient was measured by W/Re thermocouples and details were described in Ref. [41]. Optical microscopy was used to characterize the microstructure of the samples after polishing and etching with a solution of 10ml HF-10ml $HNO_3$-180ml $H_2O$.

**Table 1**
The growth directions of α phase and lamellar orientation in directionally solidified Ti-49Al (at.%) alloy under different solidification parameters.

| Growth rate *V* (μm/s) | Temperature gradient *G* (K/mm) | Lamellae orientation *θ* (°) | Estimated GD of α dendrite < *HKTL* > α |
|---|---|---|---|
| 5 | 12.1 | 86.2 | < 0001 > |
| 8 | | 85.4 | < 0001 > |
| 10 | | 84.8 | < 0001 > |
| 15 | | 30.8 | $<10\bar{1}0>$ |
| 20 | | 25.2 | $<10\bar{1}0>$ |
| 30 | | 48.6 | $<\bar{2}\bar{2}43>$ |
| 10 | 2.8 | 87.2 | < 0001 > |
| | 4.2 | 86.8 | < 0001 > |
| | 6.2 | 42.6 | $<10\bar{1}1>$ |
| | 8.5 | 47.8 | $<10\bar{1}1>$ |
| | 9.6 | 28.4 | $<11\bar{2}1>$ |
| | 12.1 | 84.8 | < 0001 > |

The HD is approximatively identified as the drawing direction of the furnace. The PG is confirmed according to the lamellar orientation of the specimens. Values of *Θ* and *Ψ* are measured by using Olycia-3 image processing software.

The measured lamellar orientation is not always the real value, because the observed lamellar orientation depends on the sectional plane [42]. To measure the real orientation of the lamellar structure, the specimen was cut longitudinally again normal to the lamellar boundaries on transverse section [35,39]. Details to calculate the PD of α phase are illustrated in Ref. [39]. Growth directions of α phase and lamellar orientations of directionally solidified Ti-49Al alloy under different solidification parameters are shown in Table 1.

## 3. Results and discussion

### 3.1. Macrostructure of directionally solidified Ti-49Al alloys

The macrostructures of directionally solidified (DS) specimens at different growth rates are shown in Fig. 1. There are four distinguished sections in the DS specimens, i.e. unmelted region, directional solidification region, mushy zone and quenched zone, respectively. The lengths of each region are different from each other relate to the solidification conditions for specimens. In unmelted-region which was at the bottom of the specimen in the Ga-In-Sn alloy, the temperature was not high enough to melt the original alloy. The equiaxed grains were coarsened by heat treatments during the temperature stabilization process. Above this region, the original alloy was completely melted. Solid-liquid interfaces of DS Ti-49Al (at.%) alloy are shown in Fig. 2. The morphologies of solid-liquid interface are dendritic structures under present solidification conditions.

### 3.2. Lamellar structures of directionally solidified Ti-49Al alloys

The lamellar structure consists of γ and $\alpha_2$ phases. The orientation of γ phase dependents on α phase according to the relationship of $\{111\}_\gamma//\{0001\}_\alpha$. When the α phase is the primary phase, the orientation of the lamellar structure should be perpendicular to the growth direction. However, orientations of lamellar structures of DS Ti-49Al (at.%) alloy are changed with solidification parameters, as shown in Fig. 3. This phenomenon is related to the changed growth direction of α phase.

### 3.3. Variation of the α phase growth direction with solidification parameters

Under ideal conditions, the lamella orientation of the directionally solidified specimen would have the same orientation with the seed.