Microstructure Evolution and Solute Segregation in Directionally Solidified High-Nb TiAl Alloys (Postprint)

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Date: 2023-03-19T00:00:00+00:00

Abstract

Directional solidification experiments were conducted on Ti-46Al-(8, 9, 10)Nb alloys in a Bridgman directional solidification furnace to investigate the effects of growth rate and Nb content on the microstructure, phase transformation pathway, and solute segregation of TiAl-Nb alloys, yielding a phase transformation process and microstructure selection diagram for directionally solidified TiAl-Nb alloys. The results demonstrate that increasing the growth rate induces a planar-to-cellular-to-dendritic transition at the solid/liquid interface, and promotes the shift from complete β phase solidification to a solidification process involving the L+β→α peritectic reaction, resulting in a final microstructure that transitions from α_2/γ lamellar structure to a multiphase structure comprising both α_2/γ lamellae and B2 phase. The addition of solute Nb exerts a stabilizing effect on the β phase, promoting the occurrence of complete β phase solidification and the formation of a multiphase structure consisting of α_2/γ lamellae and B2 phase. The influence of growth rate and Nb content on the phase transformation process and microstructure is intimately associated with the solute segregation process (S-type segregation, β-type segregation). Specifically, an enhanced degree of S-type segregation facilitates the peritectic reaction, leading to severe solute segregation in the final microstructure and the concentrated distribution of substantial B2 phase within dendrite cores. In β-type segregation, enrichment of solute Nb in the residual β phase constitutes the primary source of B2 phase formation, with the extent of Nb enrichment directly determining the morphology and size of the B2 phase. According to the phase transformation process and microstructure selection diagram for Ti-46Al alloys as a function of growth rate and Nb content, selecting higher Nb content and lower cooling rate can achieve complete β phase solidification, yielding directionally solidified microstructures with uniform distribution and low solute segregation.

Full Text

Preamble

Acta Metallurgica Sinica Vol. 51 No. 8
August 2015, pp. 957-966

Microstructure Evolution and Solute Segregation in Directionally Solidified TiAl Alloys with High Nb Content

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Supported by National Natural Science Foundation of China (Nos. 51071062, 51274077 and 51271068), Fundamental Research Funds for the Central Universities (No. N140703003) and China Postdoctoral Science Foundation (No. 2014M561245)

Manuscript received 2014-12-22, in revised form 2015-05-29

Abstract

Bridgman-type directional solidification experiments were conducted on Ti-46Al-(8, 9, 10)Nb alloys to investigate the effects of growth rate and Nb content on microstructure, phase transformation pathways, and solute segregation. A selection diagram mapping the phase transition processes and microstructural evolution in directionally solidified TiAl-Nb alloys was established. The results demonstrate that increasing the growth rate induces a planar-cellular-dendritic transition at the solid/liquid interface and promotes a shift from fully β-phase solidification to a peritectic solidification process involving the $L+\beta\rightarrow\alpha$ reaction. Consequently, the final microstructure transforms from an α_2/γ lamellar structure to a multiphase microstructure comprising α_2/γ lamellae and B2 phase. Nb addition stabilizes the β phase, facilitating fully β-phase solidification and promoting the formation of this multiphase microstructure. The influence of growth rate and Nb content on phase transitions and microstructure is intimately linked to solute segregation patterns (S-type segregation and β-type segregation). Enhanced S-type segregation promotes the peritectic reaction, leading to severe solute segregation and concentrated distribution of abundant B2 phase in dendrite cores. In β-type segregation, Nb enrichment in the residual β phase serves as the primary source for B2 phase formation, with the degree of Nb enrichment directly determining the morphology and size of B2 phase. Based on the selection diagram for phase transition and microstructure in Ti-46Al alloys as a function of growth rate and Nb content, employing higher Nb content combined with lower cooling rates during fully β-phase solidification is recommended to obtain directionally solidified microstructures with homogeneous distribution and low solute segregation.

Key Words TiAl-Nb alloy, directional solidification, microstructure, solute segregation

1. Introduction

TiAl-based alloys are promising next-generation high-temperature lightweight structural materials due to their low density, excellent oxidation resistance, high specific strength at elevated temperatures, and good creep properties. However, practical applications of conventional TiAl alloys require further improvements in high-temperature performance and oxidation resistance. Alloying with Nb effectively enhances the high-temperature strength and oxidation resistance of TiAl alloys, and Nb exhibits substantial solubility in TiAl, making it an effective approach for developing high-performance high-temperature TiAl alloys. High-Nb-content TiAl alloys can operate at temperatures 60–100°C higher than conventional TiAl alloys, representing an advanced direction for developing TiAl alloys with higher service temperatures for applications in aircraft engine turbines and gas-fired power generation components. Nevertheless, Nb addition alters the TiAl alloy phase diagram, resulting in significant differences in solidification behavior and correspondingly complex microstructural variations compared to conventional TiAl alloys. Available phase diagrams for TiAl-Nb alloys reveal that Nb addition substantially increases the melting point and promotes expansion of the β-phase region toward higher Al contents, ultimately leading to the formation of complex multiphase microstructures. Furthermore, complex solute segregation induced by varying solidification conditions limits understanding of microstructural evolution in TiAl-Nb alloys and may cause microstructural heterogeneity that degrades mechanical properties. Chen et al. analyzed solute element segregation behavior in TiAl-Nb alloy ingots and identified three primary segregation patterns: S-type, β-type, and α-type segregation, with different solute enrichment processes leading to variations in phase distribution between grains. Therefore, investigating phase transformation behavior, microstructural evolution, and solute segregation patterns in high-Nb-content TiAl alloys under different solidification conditions is essential for deepening understanding and promoting engineering applications of these alloys.

Additionally, enrichment of the β-phase stabilizing element Nb promotes retention of the high-temperature β phase at room temperature, forming the B2 phase. The hard and brittle B2 phase is often considered a crack initiation site during room-temperature deformation and can reduce high-temperature strength. However, controlled B2 phase introduction can improve hot workability. Consequently, the origin and distribution of B2 phase in TiAl-Nb alloys have been extensively investigated. Two primary mechanisms for B2 phase formation have been proposed: (1) ordering transformation promoted by Nb enrichment in residual β phase during the $\beta \rightarrow \alpha$ transformation; and (2) precipitation via the $\alpha+\gamma \rightarrow \alpha_2+\gamma+$B2 transformation during lamellar structure formation. The morphology, size, and distribution of B2 phase strongly depend on solidification conditions and solute segregation levels, yet the underlying mechanisms remain incompletely understood. Therefore, further investigation of B2 phase formation and distribution characteristics in high-Nb-content TiAl alloys is crucial for achieving precise microstructural control and improved mechanical properties.

In this work, directional solidification experiments were performed on Ti-46Al-(8, 9, 10)Nb (at.%) alloys at various growth rates. The study aimed to: (1) investigate the influence of growth rate and Nb content on phase transformation processes, microstructure, and phase composition in high-Nb-content TiAl alloys; (2) examine solute segregation behavior during phase transformation and its effect on microstructure formation and distribution, particularly regarding the B2 phase; and (3) establish a selection diagram for phase transformation processes and microstructure as functions of growth rate and Nb content in Ti-46Al-Nb alloys.

2. Experimental Methods

High-purity titanium (99.95%), aluminum (99.99%), and Al-50%Nb (mass fraction) master alloy were used as raw materials. After weighing according to the target composition, the materials were melted in a water-cooled copper crucible vacuum induction melting furnace to produce master alloy ingots. Using wire electrical discharge machining, cylindrical specimens with a diameter of 3 mm and length of 100 mm were extracted from locations near the outer edge of the ingot at equal intervals.

Directional solidification experiments were conducted using a high-vacuum Bridgman furnace. The specimens were placed in high-purity Al_2O_3 crucibles, with the bottom 10 mm of each specimen immersed in Ga-In-Sn cooling liquid circulated through cooling water to preserve the original microstructure. The specimens were slowly heated to 1980°C to establish a stable temperature gradient, then directionally solidified over a broad range of growth rates (1–100 m/s). After pulling for 40 mm at the predetermined rate, the specimens were rapidly quenched to retain the directionally solidified microstructure. The prepared specimens were sectioned, mounted in dental acrylic resin for grinding convenience, and polished. Etching was performed using a solution of HNO_3:HF:H_2O = 1:1:18 (volume ratio). Microstructural observation and analysis were carried out using an Olympus-GX-71 optical microscope (OM) and a Quantan-200 scanning electron microscope (SEM) equipped with energy-dispersive spectroscopy (EDS). Phase identification was performed using a Bruker D8 Discover X-ray diffractometer (XRD).

2.1.1 Solid/Liquid Interface Morphology

[Figure 1: see original paper] presents the solid/liquid interface morphologies of directionally solidified Ti-46Al alloys under various growth rates and Nb contents. The results show a clear transition from planar to cellular to dendritic interface morphology as the growth rate increases. At growth rates of 2 and 3 m/s, the quenched interfaces exhibit shallow cellular and cellular-dendritic mixed growth, respectively (Figures 1a1–a3 and b1–b3). At higher growth rates ($ $5 m/s), the solid/liquid interface is characterized by well-developed dendritic growth, with the dendrite arm spacing gradually decreasing as the growth rate increases (Figures 1c1–c3, d1–d3, and e1–e3). During the dendritic growth stage, the secondary dendrite arms grow strictly perpendicular to the primary arms. Based on the symmetry of the primary phase dendrites in TiAl alloys, the primary phase for all three alloy compositions can be identified as the β phase with bcc structure.

Additionally, at higher growth rates ($ $3\mu m/s), aperitecticreactionofL+$

$$\rightarrow$$

 $ occurs at the solid/liquid interface in the directionally solidified Ti-46Al-8Nb alloy. As the growth rate increases, the peritectic reaction interface gradually moves away from the quench interface, as indicated by arrows in Figures 1b1–d1. In the three-phase mixing zone, the peritectic α phase nucleates on and envelops the primary β phase, causing the primary β phase to dissolve gradually while the peritectic α phase grows. The peritectic reaction occurs primarily because the growth of primary β phase enriches Al in the interdendritic liquid; when the Al content satisfies the nucleation condition for the peritectic α phase, it nucleates on the primary β phase, initiating the peritectic reaction. These results demonstrate that increasing the growth rate alters the degree of solute enrichment, causing the phase transformation to shift from fully β-phase solidification to a solidification process involving peritectic reaction. Notably, in the alloy containing 9% Nb, the peritectic reaction occurs at growth rates above 10 m/s (Figures 1c2–e2), indicating that increased Nb content stabilizes β-phase solidification and delays the onset of peritectic reaction. When the Nb content reaches 10%, no peritectic reaction is observed at the quench interface, and the alloy exhibits fully β-phase solidification across the entire growth rate range (Figures 1a3–e3). These findings confirm that Nb addition expands the β-phase region in the TiAl alloy phase diagram, shifting it toward higher Al content and thereby promoting fully β-phase solidification, consistent with previously reported TiAl-Nb phase diagrams.

2.1.2 Phase Composition

[Figure 2: see original paper] illustrates the typical microstructure and phase composition of directionally solidified Ti-46Al-Nb alloys. The lamellar structures are oriented at 45° or parallel to the growth direction, which is determined by the leading β-phase solidification process. A specific orientation relationship exists between the final lamellar structure and the leading β phase in TiAl alloys: $\{110\}\beta//(0001)\alpha//\{111\}\gamma$ and $<111>\beta//<11\text{-}20>\alpha//<110>\gamma$. The XRD spectrum reveals the presence of α_2 (Ti_3Al), γ (TiAl), β (B2), and Y_2O_3 phases in the final microstructure (Figure 2b). The α_2/γ lamellar structure forms through the $\alpha \rightarrow \alpha_2 + \gamma$ transformation, while the Y_2O_3 phase originates primarily from the protective coating applied to prevent oxidation reactions between the TiAl melt and the crucible. Notably, the B2 phase is present in the final microstructure, with its corresponding electron diffraction pattern shown in the inset of Figure 2c. The hard and brittle B2 phase in TiAl alloys is often considered detrimental to mechanical properties. As shown in Figures 2c and d, the bright B2 phase is concentrated in Nb-rich regions, distributed as elongated strips on the lamellar structure and along lamellar colony boundaries, indicating that B2 phase formation is closely related to Nb enrichment and occurs at elevated temperatures prior to lamellar structure formation. According to existing literature, massive blocky B2 phase in TiAl-Nb alloys primarily originates from the $\beta \rightarrow \alpha$ transformation process.

presents the compositional analysis of constituent phases in the directionally solidified Ti-46Al-8Nb alloy. The results show that the γ phase is enriched in both Al and Nb, while the α_2 phase is depleted in both elements, which is determined by the different solute partition coefficients of Al and Nb in the lamellar structure. Additionally, the B2 phase exhibits relatively high Nb content and low Al content, demonstrating that B2 phase formation requires significant Nb enrichment in directionally solidified TiAl-Nb alloys. Therefore, detailed investigation of solute element segregation during phase transformation is essential for understanding B2 phase formation.

2.1.3 Phase Transition Path

[Figure 3: see original paper] displays the macrostructures and corresponding microstructures of directionally solidified Ti-46Al-Nb alloys under various growth rates and Nb contents. Figure 3a shows the macrostructure of the directionally solidified Ti-46Al-8Nb alloy at a growth rate of 2 m/s, revealing uniform solute distribution without obvious segregation in the directional solidification zone. The microstructure (Figure 3b) shows deep cellular growth of the primary β phase at the solid/liquid interface. As the phase transformation proceeds, a precipitation interface for lamellar structure appears (Figure 3c, arrow). The final microstructure consists of lamellae oriented at 45° to the growth direction, while the microstructure also confirms that the primary phase is β under these conditions (Figure 3d). Based on this analysis, the phase transformation path for Ti-46Al-8Nb alloy at the lower growth rate of 2 m/s can be described as: L$\rightarrow\beta\rightarrow\alpha\rightarrow\alpha_2+\gamma$.

When the growth rate increases to 3 m/s (Figure 3e), columnar crystals grow parallel to each other along the growth direction with good alignment. In the directional solidification zone, bright Nb-rich segregation zones are observed in dendrite cores, while gray Al-rich segregation zones exist in interdendritic regions. The corresponding microstructure reveals mixed cellular-dendritic growth of primary β phase and the occurrence of the L+$\beta\rightarrow\alpha$ peritectic reaction (Figure 3f, arrow). The peritectic reaction induces severe solute segregation, increasing the enrichment of Al in interdendritic regions and Nb in dendrite cores. Nb enrichment promotes retention of residual β phase at room temperature, leading to B2 phase formation (Figure 3h). The final microstructure consists of a multiphase structure containing α_2/γ lamellae and B2 phase. The α_2/γ lamellar structure forms through the $\alpha\rightarrow\alpha_2+\gamma$ transformation, and under the influence of the primary β phase, the lamellae are oriented at 45° to the growth direction (Figures 3g and h). From these observations, the phase transformation path for directionally solidified Ti-46Al-8Nb alloy at a growth rate of 3 m/s can be summarized as: L$\rightarrow\beta\rightarrow$L+$\beta\rightarrow\alpha\rightarrow\alpha_2+\gamma$+B2.

These results indicate that increasing the growth rate transforms the solidification from fully β-phase to peritectic reaction, with the corresponding microstructure changing from α_2/γ lamellae to a multiphase structure of α_2/γ and B2 phase. The increased growth rate, corresponding to faster cooling, promotes a shift of the solidus and liquidus lines in the TiAl phase diagram toward lower Al content and facilitates B2 phase precipitation. Notably, when the Nb content is 10% at a growth rate of 30 m/s, no peritectic reaction occurs at the solid/liquid interface, resulting in fully β-phase solidification (Figures 3i–l). As the phase transformation proceeds, the α phase precipitates preferentially from interdendritic Al-rich regions and grows further (Figure 3k). The final microstructure consists of a mixture of abundant basket-weave B2 phase and α_2/γ lamellae oriented at 45° to the growth direction (Figure 3l and inset). Thus, the phase transformation path for directionally solidified Ti-46Al-10Nb alloy at a growth rate of 30 m/s can be described as: L$\rightarrow\beta\rightarrow\alpha$+B2$\rightarrow\alpha_2+\gamma$+B2.

Evidently, compared with the directionally solidified Ti-46Al-8Nb alloy, increased Nb content expands the β-phase region in the TiAl phase diagram, thereby delaying the peritectic reaction and maintaining fully β-phase solidification across the growth rate range. Simultaneously, Nb enrichment promotes extensive B2 phase precipitation, resulting in a multiphase structure of α_2/γ lamellae and B2 phase during fully β-phase solidification.

2.2 Solute Segregation Behavior and Its Effect on Microstructure

The above results demonstrate that increased Nb content and growth rate alter the phase transformation process and create complex multiphase microstructures in TiAl-Nb alloys, processes intimately related to solute segregation behavior. [Figure 4: see original paper] illustrates the segregation characteristics of solute elements and corresponding EDS line scans during different phase transformation processes in directionally solidified Ti-46Al-8Nb alloy. As shown in Figures 4a1 and a2, during primary β-phase growth with bcc structure, the dendrite core is enriched in Nb and depleted in Al, while the interdendritic region is enriched in Al and depleted in Nb. The Nb content in the primary β phase is 9.51%, while the Al content in the interdendritic region reaches 52.25%. Since this segregation occurs during solidification, it is termed S-type (solidification) segregation. This segregation pattern is determined by the partition coefficients of solute elements Nb and Al in the β phase. The primary β phase is Al-depleted and rejects Al into the interdendritic region during growth while enriching Nb in the dendrite core. Similarly, S-type segregation also occurs during primary α-phase solidification. Segregation during solidification is significantly influenced by solidification conditions. Trivedi noted that the solute concentration at dendrite tips is governed by constitutional undercooling and interfacial energy; increasing the growth rate inevitably intensifies constitutional undercooling and reduces solute diffusion capacity, thereby increasing solute enrichment. Therefore, in directionally solidified TiAl-Nb alloys, increasing the growth rate gradually increases Al enrichment in interdendritic regions. During primary β-phase solidification, when the Al content in the liquid reaches the composition required for peritectic reaction, the solidification transforms to a process involving the $L+\beta\rightarrow\alpha$ peritectic reaction.

Figures 4b1 and b2 show the microstructure and corresponding solute distribution during the peritectic reaction in directionally solidified Ti-46Al-8Nb alloy. The peritectic α phase nucleates on the primary β phase and grows as the peritectic reaction proceeds, while the primary β phase gradually dissolves. During this process, after the peritectic α phase isolates the primary β phase from the liquid, further growth of the Al-rich peritectic α phase requires solute diffusion between the liquid and primary phases, with the phase transformation driving force depending on the concentration gradient within the peritectic α phase. While Al diffuses into the peritectic α phase, the Nb content in the residual β phase in the dendrite core gradually increases. The composition profile reveals Nb enrichment and Al depletion in the residual β phase in the dendrite core, with Nb enrichment further increasing to 11.21%. Similarly, high segregation levels of Al and Nb are observed in the interdendritic liquid, and the concentration differences between phases promote the peritectic reaction. However, solute diffusion in the solid phase is relatively limited, making complete peritectic reaction difficult to achieve under typical solidification conditions, especially at higher growth rates corresponding to faster cooling rates, where only a thin peritectic reaction zone exists on the primary β-phase surface. Subsequently, as the phase transformation proceeds, the residual β phase in the dendrite core undergoes the $\beta\rightarrow\alpha$ transformation.

Figures 4c1 and c2 present the microstructure and solute distribution during the $\beta\rightarrow\alpha$ transformation in directionally solidified Ti-46Al-8Nb alloy. The α phase nucleates and grows in the high-temperature β phase and eventually transforms into α_2/γ lamellar structure. The lamellae within each colony exhibit different orientations, indicating that α-phase grains with various orientations formed during the $\beta\rightarrow\alpha$ transformation. Bright Nb-rich segregation zones exist between lamellar colonies (Figure 4c1). The composition profile shows that the lamellar colonies are Al-rich and Nb-poor with relatively uniform solute distribution, while the colony boundaries are Nb-rich and Al-poor, with Nb content reaching 15.23%. This segregation occurs during the $\beta\rightarrow\alpha$ solid-state transformation and is primarily influenced by solute atom diffusivity, interphase concentration gradients near interfaces, and saturation levels. During the $\beta\rightarrow\alpha$ transformation, Nb enrichment arises from α-phase growth, and this segregation pattern is termed β-type segregation.

Multiple segregation modes exist for solute elements in directionally solidified TiAl-Nb alloys, significantly affecting phase transformation processes and microstructural evolution. [Figure 5: see original paper] illustrates solute segregation and microstructural evolution during different phase transformation processes (fully β-phase solidification and peritectic solidification). Figures 5a1–c1 show solute segregation and microstructural evolution at different stages of the L+$\beta\rightarrow\alpha$ peritectic reaction process in directionally solidified Ti-46Al-8Nb alloy at a growth rate of 5 m/s. As shown in Figure 5a1, the initial stage involves primary β-phase growth (L+β region), where S-type segregation occurs, enriching Al in interdendritic regions and Nb in dendrite cores. As primary β-phase growth continues, the degree of Al enrichment in interdendritic regions gradually increases, and when the conditions for peritectic reaction are met, the L+$\beta\rightarrow\alpha$ peritectic reaction occurs. As shown in Figure 5b1, the gray peritectic α phase grows on the bright primary β phase, with residual β phase in the dendrite core and Al-rich liquid in interdendritic regions. As the peritectic reaction proceeds, the volume fractions of primary β phase and interdendritic liquid gradually decrease, while Nb enrichment and Al depletion in the residual β phase in dendrite cores increase. With further temperature reduction, the residual β phase in dendrite cores undergoes the $\beta\rightarrow\alpha$ transformation, during which β-type segregation occurs, creating dispersed network-like Nb-rich zones in dendrite cores and promoting B2 phase precipitation. Interdendritic regions are occupied by peritectic α phase, where no Nb segregation is observed (Figure 5c1). The final microstructure consists of α_2/γ lamellae and B2 phase concentrated in dendrite cores. These results demonstrate that the peritectic reaction causes severe solute segregation, leading to concentrated distribution of abundant B2 phase in dendrite cores. The hard and brittle B2 phase is often considered a crack source during room-temperature fracture and reduces high-temperature strength; therefore, peritectic reaction and concentrated B2 phase distribution may cause microstructural and mechanical property heterogeneity and should be avoided during alloy design and solidification condition selection.

Figures 5a2–c2 show solute segregation and microstructural evolution at different stages of fully β-phase solidification in directionally solidified Ti-46Al-9Nb alloy at a growth rate of 5 m/s. During primary β-phase solidification, S-type segregation causes Al enrichment in interdendritic regions that is insufficient to promote peritectic reaction. As the phase transformation proceeds, the interdendritic liquid disappears, and the primary β phase directly undergoes the $\beta \rightarrow \alpha$ transformation. β-type segregation distributes Nb-rich zones primarily in dendrite cores (Figures 5a2 and b2). As the phase transformation continues, solute diffusion gradually reduces the enrichment of Al in interdendritic regions and Nb in dendrite cores, resulting in a final lamellar structure with relatively low segregation, consisting of α_2/γ lamellae and uniformly distributed B2 phase (Figure 5c2). Compared with the peritectic reaction process, fully β-phase solidification produces a more uniform microstructure with lower solute segregation. Therefore, in directionally solidified TiAl-Nb alloys, low growth rates and appropriate Nb content should be selected to avoid severe solute segregation and obtain homogeneous microstructures.

2.3 Selection Diagram of Phase Transition and Microstructure in Directionally Solidified TiAl-Nb Alloys

Based on the above analysis, the phase transformation processes and microstructures in directionally solidified TiAl-Nb alloys vary with growth rate and Nb content and are closely related to solute segregation patterns. [Figure 6: see original paper] presents the selection diagram for phase transformation processes and microstructure in directionally solidified Ti-46Al-Nb alloys. At lower growth rates (<3 m/s) and across a wide Nb content range, fully β-phase solidification and α_2/γ lamellar microstructure can be obtained (Zone I in Figure 6). At higher Nb content (>9%Nb) corresponding to fully β-phase solidification, the microstructure consists of α_2/γ lamellae and B2 phase (Zone II). At lower Nb content combined with high growth rate, the L+$\beta \rightarrow \alpha$ peritectic reaction occurs, yielding a multiphase microstructure of α_2/γ lamellae and B2 phase (Zone III).

Growth rate and Nb content exert opposing effects on the solidification process in TiAl-Nb alloys while both promoting the formation of multiphase microstructures (α_2/γ lamellae and B2 phase). Increasing the growth rate promotes the L+β transformation line in the TiAl phase diagram to shift toward lower Al content, transforming fully β-phase solidification to peritectic solidification. This effect primarily results from reduced solute diffusion capacity at higher growth rates, leading to severe S-type segregation that promotes the L+$\beta \rightarrow \alpha$ peritectic reaction, while higher cooling rates enhance β-type segregation and Nb enrichment, facilitating B2 phase precipitation. These results are consistent with Kim et al.'s findings on the effect of growth rate on the binary TiAl phase diagram. As a β-phase stabilizing element, Nb expands the β-phase region in the TiAl phase diagram, shifting the liquidus and solidus lines toward higher Al content and promoting fully β-phase solidification. Additionally, increased Nb content enhances Nb enrichment and promotes B2 phase precipitation. These experimental results agree with the TiAl-(8,10)Nb phase diagrams reported by Chen et al. The results indicate that increasing both Nb content and growth rate has opposing effects on the solidification process while simultaneously promoting multiphase microstructure formation (α_2/γ lamellae and B2 phase), leading to complex solidification processes and microstructures in directionally solidified TiAl-Nb alloys. Therefore, when preparing high-service-temperature TiAl-Nb alloys, appropriate Nb content and low cooling rates should be selected to avoid peritectic reaction and concentrated distribution of hard and brittle B2 phase, thereby obtaining homogeneous microstructures with low segregation levels.

Conclusions

1. In directionally solidified TiAl-Nb alloys, increasing the growth rate induces a planar-cellular-dendritic transition at the solid/liquid interface and promotes transformation from fully β-phase solidification to peritectic solidification involving the $L+\beta\rightarrow\alpha$ reaction, resulting in a final microstructure that changes from α_2/γ lamellae to a multiphase structure containing α_2/γ lamellae and B2 phase. Solute Nb stabilizes the β phase, promoting fully β-phase solidification and the formation of multiphase microstructures comprising α_2/γ lamellae and B2 phase.
2. Both S-type and β-type segregation significantly influence phase transformation processes and microstructural evolution in directionally solidified TiAl-Nb alloys. Enhanced S-type segregation promotes the peritectic reaction, leading to severe solute segregation and concentrated distribution of abundant B2 phase in dendrite cores. In β-type segregation, Nb enrichment in residual β phase serves as the primary source for B2 phase formation, with the degree of Nb enrichment directly determining the morphology and size of B2 phase.
3. Increasing growth rate and Nb content exert opposing effects on the solidification process in TiAl-Nb alloys while both promoting the formation of multiphase microstructures (α_2/γ lamellae and B2 phase). During processing of high-Nb-content TiAl alloys, appropriate Nb content and low cooling rates should be selected to avoid peritectic reaction and concentrated distribution of hard and brittle B2 phase, thereby obtaining homogeneous microstructures with low segregation levels.

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Note: Figure translations are in progress. See original paper for figures.