Study on the Tensile and High-Cycle Fatigue Properties of Cold-Crucible Directionally Solidified Ti-47Al-2Cr-2Nb Alloy*

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Abstract

This study successfully prepared directionally columnar-grained Ti-47Al-2Cr-2Nb alloy ingots using cold crucible directional solidification technology. By varying the withdrawal rate, the obtained ingots exhibited dual-phase fully lamellar microstructures with different lamellar spacings, distributed with a small amount of B2 phase. Through tensile property tests, the ultimate tensile strength at room temperature was measured to reach a maximum of 652 MPa, with a maximum elongation of 1.5%, while the ultimate tensile strength at elevated temperature could reach 490 MPa with an elongation of 5.0%. Through high-cycle fatigue property tests, the fatigue life S-N curves of directionally solidified specimens at withdrawal rates of 1.0 mm/min and 1.2 mm/min were plotted, along with the fatigue limit values at a stress ratio R of 0.1. Comparative fracture surface morphology analysis indicated that: at room temperature, the tensile fracture mode of specimens was brittle fracture, while the fracture mode after high-cycle fatigue testing was brittle cleavage fracture; at elevated temperature, the tensile fracture mode of specimens consisted of mostly brittle fracture coexisting with a small portion of ductile fracture. Analysis of high-cycle fatigue specimen fracture surfaces revealed that fatigue cracks initiated near phase interfaces and B2 phases. Based on this, the crack propagation mechanism was analyzed using plastic blunting theory, and a high-cycle fatigue crack propagation model diagram was constructed.

Full Text

Study on the Tensile and High-Cycle Fatigue Properties of Cold-Crucible Directionally Solidified Ti-47Al-2Cr-2Nb Alloy*

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Abstract Directionally columnar-crystalline Ti-47Al-2Cr-2Nb alloy ingots were prepared using cold-crucible directional solidification technology. At different withdrawal rates, the obtained ingots exhibited fully lamellar structures with different lamellar spacings. Tensile property tests showed that the maximum ultimate tensile strength at room temperature reached 652 MPa, and the maximum elongation reached 1.5%; at high temperature, the maximum ultimate tensile strength reached 490 MPa, and the maximum elongation reached 5.0%. High-cycle fatigue property tests were used to plot the stress-cycle number (S-N) curves of the directionally solidified alloy at withdrawal rates of 1.0 and 1.2 mm/min, as well as the fatigue limit at a stress ratio R of 0.1. Comparative fracture morphology analysis showed that the tensile fracture mode of the specimen at room temperature was brittle fracture, whereas after high-cycle fatigue testing it was brittle cleavage fracture; at high temperature, the tensile fracture mode of the specimen consisted mostly of brittle fracture with a small amount of ductile fracture. Analysis of the fracture surfaces of high-cycle fatigue specimens showed that fatigue cracks initiated at phase interfaces and near the B2 phase. On this basis, the crack propagation mechanism was analyzed using the plastic blunting theory, and a schematic diagram of the high-cycle fatigue crack propagation mode was drawn.

Keywords Ti-47Al-2Cr-2Nb alloy, directional solidification, cold crucible, tensile properties, high-cycle fatigue

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TENSILE AND HIGH CYCLE FATIGUE PROPERTIES OF Ti-47Al-2Cr-2Nb DIRECTIONALLY SOLIDIFIED BY COLD CRUCIBLE METHOD

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ABSTRACT TiAl-based alloys have recently received considerable attention as one of the promising candidates for application in aero engine blades by replacing the Ni-based superalloys because of their unique properties, such as high specific strength, high specific stiffness and good oxidation resistance. However, there are some shortcomings limiting the application of TiAl-based alloys, namely, their brittleness and poor processing properties. Nevertheless, aero engine blades usually suffer a variety of cyclic loadings during the period of services, which finally results in fatigue failure. According to statistics, fatigue failure, mainly high cycle fatigue (HCF), occupies almost 80% failure modes of gas turbine blades in aero engines. Consequently, more and more researches about fatigue behavior of blade materials have been done in the last tens of

years. However, there are less relevant results about TiAl-based alloys, especially HCF properties. Recently, the advancement of directional solidification (DS) of TiAl-based alloys using cold crucible has revealed that the ductility can be enhanced at room and elevated temperature.

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For purpose to verify the influence of DS structures on the tensile and HCF properties, TiAl-based alloy in composition with Ti-47Al-2Cr-2Nb (atomic fraction, %) was prepared and evaluated in this work. Directionally solidified Ti-47Al-2Cr-2Nb alloy ingots with different withdrawal rates (1.0, 1.2 and 1.4 mm/min) were prepared by cold crucible method under alter electromagnetic field in a vacuum furnace. Based on these ingots, macro and microstructures have been characterized by methods of digital camera, OM, SEM and XRD. Furthermore, the tensile properties at room and high temperature (800 ℃) as well as HCF properties at room temperature have been measured respectively. So, the relationship between microstructures and mechanical properties of TiAl-based alloy, especially HCF properties, was demonstrated reasonably and mechanism in which HCF cracks propagated was discussed. The results show that the comprehensive mechanical properties of Ti-47Al-2Cr-2Nb alloy can be significantly improved after directionally solidified using cold crucible. The tensile strength reaches 652 MPa at room temperature with the maximum elongation of 1.5%. Meanwhile, the tensile strength at 800 ℃ attains 490 MPa with the elongation of 5.0%. Based on the data of HCF test at room temperature with the stress ratio of 0.1, the equations of stress amplitude-number of cycles to failure (S-N) curve at different withdrawal rates are calculated. The fatigue limits are 300 and 247 MPa with the withdrawal rates of 1.0 and 1.2 mm/min, respectively, namely, with the increase of withdrawal rate, the fatigue fracture resistance decreases. The mode of HCF fracture of directionally solidified Ti-47Al-2Cr-2Nb alloy behaves in brittle cleavage fracture. And micro-cracks which can propagate along and perpendicular to the lamellae at the same time are observed between α_2/γ lamellae and around B_2 phases.

KEY WORDS Ti-47Al-2Cr-2Nb alloy, directional solidification, cold crucible, tensile property, high cycle fatigue

With the rapid development of aerospace technology, the performance requirements for structural materials have also increased; among these, the most stringent requirements are placed on aero-engine blade materials[^1]. Statistics show that, among several failure modes of gas-turbine engine blades, 80% of failures are caused by material fatigue fracture. Studies[^2-^4] have found that blade failure is mostly fatigue failure under low-amplitude, high-cycle loading caused by the superposition of vibrational stress under the action of centrifugal stress, i.e., high-cycle fatigue failure. Because the intrinsic properties of the material, microstructural defects, and processing techniques all affect its fatigue-failure behavior, research on the fatigue behavior of blade materials has long been an active subject area. At the same time, the continuous emergence of new high-temperature structural materials has also provided opportunities for the in-depth development of blade materials; however, their service performance must be improved in order to meet the service requirements of aero-engine blades[^5].

TiAl-based alloys are currently among the most promising new high-temperature structural materials for aerospace applications. They possess excellent properties such as high specific strength, high specific stiffness, heat resistance, high-temperature oxidation resistance, and high-temperature creep resistance, and are expected in the future to replace the currently heavier Ni-based superalloys at operating temperatures of 700–900 ℃[^6], thereby satisfying the requirements of modern high-performance aero-engines for high thrust-to-weight ratio, high reliability, and durability[^7-^10]. However, TiAl-based alloys have relatively low room-temperature plasticity and toughness, and their overall service performance still needs improvement; in particular, studies on the fatigue properties of TiAl-based alloys, especially high-cycle fatigue properties, are lacking. Therefore, research on how to improve the microstructure of TiAl-based alloys and thereby enhance their comprehensive mechanical properties, especially high-cycle fatigue properties, is of great importance.

To improve the comprehensive service performance of TiAl-based alloys, on the one hand, defects introduced during materials processing should be reduced as much as possible; on the other hand, by improving the microstructure of TiAl-based alloys—refining the grain size and reducing the lamellar spacing—an appropriate preparation process should be selected, because it is essential for improving the mechanical properties of TiAl-based alloys. Cold-crucible directional solidification is a new type of directional solidification technology that combines induction heating and melting, continuous casting, and unidirectional solidification. Extensive studies using this technology for directional solidification[^11-^15] show that it can not only prepare TiAl-based alloy ingots with high melting point, high purity, and high activity; because the crucible and melt are in soft contact or noncontact, contamination of the TiAl alloy melt can be avoided, enabling highly purified forming, and, through microstructural improvement, the mechanical properties of TiAl-based alloys are enhanced.

Researchers recognized very early the importance of studying the fatigue properties of TiAl-based alloys. Sastry and Lipsitt[^16], and Henaff and Gloanec[^17], tested the fatigue-life curves of Ti-36.5%Al alloys with lamellar microstructures at different temperatures, and found that small changes in stress amplitude can lead to very significant changes in fatigue life. When the temperature rises above 800 ℃, the fatigue properties do not decrease significantly. Because the ultimate tensile strength (σ_{UTS}) is also a function of temperature, the ratio of the general fatigue amplitude value (σ_{max}) to σ_{UTS}, $\sigma_{\mathrm{max}}/\sigma_{\mathrm{UTS}}$, is used to represent the ordinate of the fatigue-life curve. Owing to the sluggishness of fatigue properties, the $\sigma_{\mathrm{max}}/\sigma_{\mathrm{UTS}}$ of Ti-36.5%Al alloy at room temperature is 0.8; when the temperature increases to 700 ℃, $\sigma_{\mathrm{max}}/\sigma_{\mathrm{UTS}}$ remains above 0.7, indicating that fatigue properties exhibit hysteresis with temperature variation. However, this is only for a specific TiAl-based alloy microstructure. The study in Ref. [18] showed that, during fatigue of TiAl-based alloys with lamellar microstructures, initial cracks produced before yielding occur, leading to premature fatigue-failure behavior, whereas duplex-microstructure TiAl-based alloys do not exhibit this phenomenon. Other studies[^19-^22] compared the fatigue properties of titanium alloys, Ni-based alloys, and γ-TiAl alloys, and found that when the ratio $\sigma_{\mathrm{max}}/\sigma_{\mathrm{UTS}}$ is used⋯

when expressed in terms of the fatigue limit, the fatigue performance of the γ-TiAl alloy is markedly higher than that of titanium alloys and nickel-based alloys.

In this work, a Ti-47Al-2Cr-2Nb alloy with a directionally solidified microstructure was prepared by cold-crucible directional solidification. The refinement effect of varying the withdrawal rate on the microstructure was analyzed, the tensile properties and high-cycle fatigue properties of the alloy were tested, and the relationship between the microstructure and mechanical properties was investigated.

1 Experimental Methods

The experimental material selected was the TiAl alloy system Ti-Al-Cr-Nb, which has good room-temperature plasticity. To make the solidification path β-type solidification, the Al content was selected as 47%; the nominal composition was Ti-47Al-2Cr-2Nb (atomic fraction, %). A 6TP water-cooled Cu-crucible vacuum induction melting furnace (ISM) was used to melt the master-alloy ingot. A cylindrical bar with a diameter of 20 mm and a length of 98 mm was cut from the master-alloy ingot and used as the master material for the directional solidification experiment. The directional solidification experiment used multifunctional cold-crucible electromagnetic-confinement precision-forming directional-solidification equipment developed by the Electromagnetic Casting Research Group of Harbin Institute of Technology. Ti-47Al-2Cr-2Nb alloy square ingots with a length of 100–110 mm and a cross section of 25 mm × 25 mm were prepared; the process parameters are shown in Table 1. The prepared directionally solidified Ti-47Al-2Cr-2Nb alloy ingots were sectioned by wire cutting, and then ground, polished, and etched (etchant: 10% HNO_3 + 5% HF + 85% H_2O, by volume fraction) to observe the macroscopic microstructure. A Quanta 200 FEG field-emission scanning electron microscope

(SEM) and its attached backscattered-electron (BSE) and secondary-electron (SE) imaging systems were used to observe the microstructure. Meanwhile, to determine the phase composition of the Ti-47Al-2Cr-2Nb alloy, a D/MAX-RB rotating-anode X-ray diffractometer (XRD) was used to conduct phase analysis on different regions of the solidified microstructure obtained by directional solidification.

Room-temperature and 800 °C tensile tests were carried out on an Instron 5500R electronic universal testing machine. The specimens were first ground and electrolytically polished (polishing solution: a solution with volume fractions of 35% n-butanol, 60% methanol, and 5% perchloric acid) to remove residual stresses. High-cycle fatigue tests were performed on a PLC-100C high-frequency tension-compression testing machine. For room-temperature tensile tests, the gauge length was 10 mm and the strain rate was 1×10^{-4} s^{-1}; high-temperature tensile tests were conducted in a vacuum environment at 800 °C, with a gauge length of 20 mm, a holding time of 5 min, and a strain rate of 0.5×10^{-4} s^{-1}. The parameters for the high-cycle fatigue tests were as follows: the stress ratio was 0.1; the testing environment was room temperature and atmospheric pressure; the loading waveform was sinusoidal; and the frequency was the resonant frequency of the system. The stress for fatigue testing was selected according to the room-temperature tensile strength of the directionally solidified Ti-47Al-2Cr-2Nb alloy, and the stress was applied using the staircase method. Fatigue grips were designed and machined in-house; the test blocks and shim materials were both No. 45 manganese steel. A 0.5 mm anti-slip groove was cut by electrical discharge machining on the surface in contact with the fatigue specimen. After tensile and fatigue fracture, fracture-surface microstructural morphology analysis was performed on the specimens; the fracture surfaces were observed by SEM and the fracture mechanisms were analyzed.

2 Experimental Results and Analysis

2.1 Microstructural Analysis

Figure 1 shows the macroscopic microstructures of the directionally solidified Ti-47Al-2Cr-2Nb alloy at different withdrawal rates. It can be seen from the figure that each cast ingot exhibits a good directional effect, and the length of the directionally solidified zone reaches more than 60% of the total specimen length. The greater the withdrawal rate, the larger the depression of the solid/liquid interface, Δh. This is because, as the withdrawal rate increases, the energy q_{in} obtained by the melt per unit time decreases relatively, thereby causing the lateral heat flow q_x to increase, and Δh also increases accordingly. At the same time, the growth direction of columnar crystals is perpendicular to the solid/liquid interface; as the withdrawal rate increases, the included angle between the columnar-crystal growth direction and the interface normal also increases. This is due to the increase in lateral heat flow, so that the columnar crystals grow toward the side facing the incoming flow.

The microstructure of the directionally solidified Ti-47Al-2Cr-2Nb alloy is a fully lamellar structure, and its lamellar spacing and grain size have a great influence on the mechanical properties of TiAl-based alloys. According to the Hall–Petch relationship, the smaller the lamellar spacing and the smaller the grain size, the higher the strength of the TiAl-based alloy. Figure 2 shows BSE images of the lamellar structure in the stable-growth region of the Ti-47Al-2Cr-2Nb alloy. The average lamellar spacing of the alloy was measured and calculated using the intercept method. Figure 3 shows the transverse-section macrostructure of the alloy in the stable-growth region; Image-Pro Plus 6.0 software was used to assist in calculating the average grain diameter. Table 2 gives the average values for the alloy at different withdrawal rates—

Table 1 Process parameters of directionally solidified (DS) Ti-47Al-2Cr-2Nb alloy

Withdrawal rate v / mm/min	Power / kW	Ingot length / mm	Dummy height (initiation/end) / mm	Primer height (initiation/end) / mm	Feeding length / mm
1.0	49	110.3	56/51	84/80	228.5
1.2	49	114.0	56/60	84/88	234.1
1.2	49	109.8	56/57	84/87	224.8
1.2	49	110.1	56/64	84/86	231.5
1.2	49	110.0	56/52	84/82	228.1
1.4	49	99.6	56/50	84/82	202.8

Fig. 1 Macrostructures of directionally solidified Ti-47Al-2Cr-2Nb alloy ingots at withdrawal rates of 1.0 mm/min (a), 1.2 mm/min (b), and 1.4 mm/min (c) (S/L—solid/liquid)

The calculated results for lamellar spacing, lamellar orientation, and average grain size show that, with increasing withdrawal rate, the lamellar spacing of the alloy gradually decreases, the angle between the lamellar orientation and the growth direction increases, and the grain size also gradually decreases.

Figure 4 shows the XRD patterns of Ti-47Al-2Cr-2Nb alloy in different solidification regions at a withdrawal rate of 1.2 mm/min. It can be seen that, near the solid/liquid interface, in the quenched region and in the steady-state growth region, the phase constituents are all the γ phase, the α_2 phase, and a small amount of the B_2 phase. Among them, the peak intensity of the α_2 phase in the liquid-phase region is lower than that near the solid/liquid interface and in the steady-state growth region, indicating that the liquid-phase region contains less α_2 phase and relatively more equiaxed γ phase.

Fig. 3

Figure 1: Fig. 3

2.2 Room-temperature tensile properties

Figure 5 shows the room-temperature tensile stress–strain curves of Ti-47Al-2Cr-2Nb alloys at different withdrawal rates. It can be seen that the tensile strength of the alloy can reach as high as 652 MPa, and the elongation can reach as high as 1.5%. Compared with the as-cast microstructure, the room-temperature tensile strength and plasticity of Ti-47Al-2Cr-2Nb alloy with a directionally solidified microstructure are both improved to some extent. Moreover, as the withdrawal rate increases, the room-temperature tensile strength continuously increases, while the variation in elongation is not large.

For directionally solidified Ti-47Al-2Cr-2Nb alloy, the smaller the lamellar spacing, the higher the tensile strength. According to the study by Meyers et al.[23], the lamellar spacing and tensile strength satisfy the Hall–Petch relationship:

Fig. 2 BSE images of lamellar microstructures of DS growth parts in directionally solidified Ti-47Al-2Cr-2Nb ingots at withdrawal rates of 1.0 mm/min (a), 1.2 mm/min (b), and 1.4 mm/min (c)

$$\sigma_{\mathrm{b}} = \sigma_0 + k_1 \lambda^{-0.5} \tag{1}$$

where σ_{b} is the tensile strength, σ_0 is the intrinsic strength, k_1 is the Hall–Petch constant, and λ is the lamellar spacing.

Based on the average lamellar spacing and room-temperature tensile data, linear regression gives the following relationships:

$$\sigma_{\mathrm{b}} = 573.7 + 0.364\lambda^{-0.5} \tag{2}$$

$$R^2 = 0.99 \tag{3}$$

Fig. 3 Macrostructures of cross-sections at DS growth parts of directionally solidified Ti-47Al-2Cr-2Nb ingots at withdrawal rates of 1.0 mm/min (a), 1.2 mm/min (b) and 1.4 mm/min (c)

where R is the correlation coefficient.

Figure 6 shows the fracture morphology of the Ti-47Al-2Cr-2Nb alloy after tensile fracture at a withdrawal rate of 1.2 mm/min. As can be seen from Fig. 6a, the fracture mode is mainly cracking through lamellae and tearing along lamellae. Fracture through lamellae forms fracture steps, as shown in Fig. 6c. The reason for the formation of fracture steps is that, when the lamellar orientation

Fig. 4

Figure 2: Fig. 4

is parallel to the tensile-stress direction, cracks pass through each lamellar plane, thereby forming the fracture steps shown in the figure. As can be seen from Fig. 6d, the torn lamellar microstructure forms because the lamellar direction is perpendicular to the tensile-stress direction; cracks propagate parallel to the lamellar planes and finally form a torn lamellar morphology. In the fully lamellar TiAl alloy, the macroscopic fracture mode is brittle fracture, but river patterns can also be observed in some regions (Fig. 6b), which are precisely characteristic features of cleavage-fracture morphology. Meanwhile, a small amount of cleavage planes and cleavage steps can also be observed in some microscopic regions; therefore, the room-temperature tensile fracture mode is brittle cleavage fracture.

2.3 High-temperature tensile properties

Figure 7 shows the high-temperature (800 °C) tensile stress–strain curves of Ti-47Al-2Cr-2Nb alloys at withdrawal rates of 1.0, 1.2 and 1.4 mm/min, respectively. It can be seen from the figure that, when the withdrawal rate is 1.0 mm/min, the alloy has the highest tensile strength, 490 MPa, and the elongation can reach 5.0%. With increasing withdrawal rate, both the high-temperature tensile strength and elongation of the directionally solidified Ti-47Al-2Cr-2Nb alloy increase continuously. This is caused by the gradual decrease in interlamellar spacing with increasing withdrawal rate. At high temperature, the interlamellar spacing and tensile strength still satisfy the Hall–Petch relationship. According to the average interlamellar spacing at different withdrawal rates,

Table 2 Grain size, lamellar orientation and interlamellar spacing of directionally solidified Ti-47Al-2Cr-2Nb alloy at different withdrawal rates

v / $(\mathrm{mm \cdot min^{-1}})$	D / μm	θ / (°)	λ / μm
1.0	251	36.4	1.81
1.2	198	49.3	1.42
1.4	135	67.2	1.16

Note: D—average diameter of grains, θ—angle between lamellar orientation and the direction of grain growth, λ—average interlamellar spacing

Fig. 4 XRD spectra of different parts of directionally solidified Ti-47Al-2Cr-2Nb alloy at withdrawal rate of 1.2 mm/min

Fig. 5 Tensile stress-strain curves of directionally solidified Ti-47Al-2Cr-2Nb alloy with different withdrawal rates at room temperature

Fig. 5

Figure 3: Fig. 5

Fig. 6 Fracture morphologies of directionally solidified Ti-47Al-2Cr-2Nb alloy with a withdrawal rate of 1.2 mm/min after tensile fracture at room temperature: fracture morphologies showing fracture along and through lamellae (a), river pattern (b), fracture step of lamellae (c), and lamellar tearing (d)

Fig. 7 Tensile stress–strain curves of directionally solidified Ti-47Al-2Cr-2Nb alloy at different withdrawal rates at 800 °C

From the data for high-temperature tensile properties, the following relationship can be obtained by linear regression:

$$\sigma_{\mathrm{b}} = 413.9 + 0.332\lambda^{-0.5} \tag{4}$$

$$R^2 = 0.99 \tag{5}$$

Figure 8 shows the high-temperature tensile fracture morphologies of directionally solidified Ti-47Al-2Cr-2Nb alloy at a withdrawal rate of 1.2 mm/min. As shown in Fig. 8a–c, the microstructure consists of densely arranged transverse fracture surfaces of lamellae and torn lamellar colonies with river-like patterns, indicating that the principal fracture modes during high-temperature tensile deformation of the directionally solidified Ti-47Al-2Cr-2Nb alloy are still translamellar fracture and tearing along the lamellae. Cracks extend along the lamellar planes or pass through the lamellar interfaces. In the fracture microstructure after high-temperature tensile testing, densely distributed dimples between lamellae can also be observed (Fig. 8d), indicating that the Ti-47Al-2Cr-2Nb alloy exhibits a certain degree of plasticity at 800 °C. As in the room-temperature tensile fracture surface, a small number of cleavage planes and river-pattern features can also be observed at high magnification, indicating that cleavage fracture also occurs during high-temperature tensile deformation. In summary, the high-temperature tensile fracture mode of the directionally solidified Ti-47Al-2Cr-2Nb alloy is a mixed fracture mode consisting of brittle cleavage fracture accompanied by a small amount of ductile fracture.

2.4 High-cycle fatigue properties

Figure 9 shows the morphology of directionally solidified Ti-47Al-2Cr-2Nb alloy after fracture in the high-cycle fatigue test. It can be seen that the fracture location of the fatigue specimen is concentrated at the circular-arc transition region near one end of the specimen. This is because high-cycle fatigue behavior is highly sensitive to stress concentration, and the specimen···

Figure 8

Figure 4: Figure 8

Figure 9

Figure 5: Figure 9

Fig. 8 Fracture morphologies of directionally solidified Ti-47Al-2Cr-2Nb under withdrawal rate of 1.2 mm/min at 800 °C, showing fracture behaviors of lamellar cracking (a), lamellar tearing (b), fracture step of lamellae (c), and dimple (d).

Fig. 9 Morphologies of directionally solidified Ti-47Al-2Cr-2Nb alloy after high-cycle fatigue (HCF) fracture

The arc-shaped transition region is the location where stress concentration is most likely to occur; therefore, fatigue cracks preferentially initiate there, and consequently the fatigue-fracture positions are also mostly concentrated at the arc-shaped transition region of the specimens.

Under two withdrawal rates, 1.0 and 1.2 mm/min, high-cycle fatigue tests were carried out on the Ti-47Al-2Cr-2Nb alloy. Scatter plots of stress versus number of cycles (S-N) were drawn, and, according to the S-N curve equation, the expression for the S-N curve was fitted and the curve was plotted, with the results shown in Fig. 10. Because the fatigue amplitude $\sigma_{\max}$ is related to the ultimate tensile strength σ_{UTS}, σ_{UTS} can be taken as the intrinsic value of the fatigue stress. The ordinate of the S-N curve is expressed by the ratio of $\sigma_{\max}$ to σ_{UTS}; in this way, the shape of the plotted S-N curve does not change, but it can more truly characterize the fatigue performance of the material. This curve, plotted using $\sigma_{\max}/\sigma_{\mathrm{UTS}}$ versus the number of cycles N, is generally also called the S-N curve. However, to distinguish it from the preceding stress–number of cycles curve, this curve is referred to as the derived S-N curve, as shown in Fig. 11. When the withdrawal rate is 1.0 mm/min, the fatigue limit is 300 MPa and $\sigma_{\max}/\sigma_{\mathrm{UTS}}$ is 0.60; when the withdrawal rate is 1.2 mm/min, the fatigue limit is 247 MPa and $\sigma_{\max}/\sigma_{\mathrm{UTS}}$ is 0.45, indicating that the smaller the withdrawal rate, the better the fatigue performance.

According to the three-parameter power-function expression, the S-N curve equation was calculated as follows[24–26]:

$$(\sigma_{\max} - \sigma_t)^m \cdot N = C \tag{6}$$

where m and c are constants to be determined, and σ_t is the fatigue limit. The calculated S-N curve equations are as follows:

$$\begin{cases} (\sigma_{\max} - 300)^{0.563} N = 3.28 \times 10^6 \quad (v = 1.0 \text{ mm/min}) \\ (\sigma_{\max} - 247)^{1.782} N = 3.27 \times 10^7 \quad (v = 1.2 \text{ mm/min}) \end{cases} \tag{7}$$

Fig.10 Stress-number of cycle to failure (S-N) curves

Figure 6: Fig.10 Stress-number of cycle to failure (S-N) curves

Fig.11 Derived S-N curves

Figure 7: Fig.11 Derived S-N curves

where v is the withdrawal rate. The expression for the derived S-N curve equation is as follows:

$$\left(\frac{\sigma_{\max}}{\sigma_{\mathrm{UTS}}}-\frac{\sigma_{\mathrm{t}}}{\sigma_{\mathrm{UTS}}}\right)^{m'}\cdot N=c' \tag{8}$$

where m' and c' are undetermined coefficients. The calculated derived S-N curve equations are as follows:

$$\begin{cases}\left(\dfrac{\sigma_{\max}}{\sigma_{\mathrm{UTS}}}-0.60\right)^{2.467}N=764.78 \quad (v=1.0\ \mathrm{mm/min})\\ \left(\dfrac{\sigma_{\max}}{\sigma_{\mathrm{UTS}}}-0.45\right)^{1.782}N=428.13 \quad (v=1.2\ \mathrm{mm/min})\end{cases} \tag{9}$$

Analysis of the fracture-surface microstructure of the high-cycle fatigue fracture specimens shows that the fracture surface is bright and crystalline, which is a typical cleavage-fracture morphology. Moreover, most fracture surfaces are very flat, indicating that the high-cycle fatigue fracture mode of the Ti-47Al-2Cr-2Nb alloy is macroscopically a brittle cleavage-fracture mode. From the SE images of the high-cycle fatigue fracture surfaces, a large number of fatigue striations (fatigue 辉纹) can be found on every valid fatigue-fracture specimen. Fatigue striations are an important morphological feature of the crack-propagation region and are also the main path of crack-source propagation. As shown in Fig. 12a, the fatigue striations are a set of mutually parallel and slightly curved striations; in general, the concave direction of the fatigue-striation arc is the direction of local propagation of the fatigue crack [27, 28]. From Fig. 12b and c, it can be observed that river patterns in the sample microstructure specifically have both fan-shaped and fishbone-shaped morphologies. River patterns generally originate at grain boundaries and phase interfaces, and continuously propagate forward through stepped planes of different lamellae,

Fig. 10 Stress-number of cycle to failure (S-N) curves of directionally solidified Ti-47Al-2Cr-2Nb alloy at withdrawal rates of 1.0 and 1.2 mm/min, respectively ($\sigma_{\max}$—the max of stress, σ_{UTS}—ultimate tensile strength)

Fig. 11 Derived S-N curves of directionally solidified Ti-47Al-2Cr-2Nb alloy at withdrawal rates of 1.0 and 1.2 mm/min, respectively

Fig.12 Fracture morphologies

Figure 8: Fig.12 Fracture morphologies

Fig. 12 Fracture morphologies of directionally solidified Ti-47Al-2Cr-2Nb alloy at withdrawal rate of 1.2 mm/min after high cycle fatigue (HCF)
(a) fatigue striation (b) river pattern (c) herringbone pattern (d) cleavage plane and step (e) tearing ridge

···the direction in which the river pattern extends outward is the crack-propagation direction, and the source of the river pattern is the site where the microcrack initiated[1]. Fig. 12d shows the morphology of the cleavage plane and cleavage-step structure. Cleavage cracks mostly initiate at the phase interface, that is, between two lamellae, or at certain small-angle tilted grain boundaries. This is because, in the Ti-47Al-2Cr-2Nb alloy, precipitation of the B2 phase at phase interfaces and grain boundaries provides heterogeneous nucleation sites for crack initiation. A small number of tearing ridges can be observed in Fig. 12e. It can be inferred that the fatigue-fracture mode of the Ti-47Al-2Cr-2Nb alloy is brittle cleavage fracture.

Fig. 13 shows the macroscopic morphology of the unfractured high-cycle-fatigue specimen of directionally solidified Ti-47Al-2Cr-2Nb alloy at a withdrawal rate of 1.0 mm/min, as well as BSE images of different regions. From Fig. 13b, it can be seen that many microcracks are distributed between the α_2/γ lamellae in the unfractured fatigue specimen, and the directions of the microcracks are parallel to the lamellar direction. From Fig. 13c, it can be found that herringbone-like B2 phase precipitates are present at the lamellar-colony boundaries, and the microcracks surround the vicinity of the B2 phase. Therefore, it can be inferred that fatigue cracks tend to nucleate near the B2 phase precipitated at lamellar interfaces and grain boundaries.

2.5 High-Cycle Fatigue Crack-Propagation Mechanism

Macroscopically, fatigue cracks propagate along the lamellar and translamellar directions, while microscopically they propagate along the normal direction of the fatigue striations or along the extension direction of the river pattern. Fatigue-crack propagation in the directionally solidified Ti-47Al-2Cr-2Nb alloy is realized through asymmetric propagation of brittle fatigue striations (also called cleavage striations). At present, there are various explanations for the propagation mechanism of fatigue cracks, among which the plastic-blunting model proposed by Laird[2] is the most widely applied.

According to the plastic-blunting theory proposed by Laird, a simplified model of the fatigue-crack propagation mechanism is summarized as shown in Fig. 14.

[1] Reference number visible on the page.
[2] Reference number visible on the page.

Fig. 13

Figure 9: Fig. 13

Fig. 14 Schematics of interlamellar (a) and translamellar (b) fatigue crack propagation modes of directionally solidified Ti-47Al-2Cr-2Nb alloy (σ—stress; the little black arrows show the directions of crack propagation)

Figure 10: Fig. 14 Schematics of interlamellar (a) and translamellar (b) fatigue crack propagation modes of directionally solidified Ti-47Al-2Cr-2Nb alloy (σ—stress; the little black arrows show the directions of crack propagation)

Under tensile stress, the crack branches in the most favorable direction for cleavage fracture and the cleavage plane, and opens radially over a certain distance; this is crack-tip blunting. Under compressive stress, the crack gradually closes, causing it to become sharpened. When tensile stress is applied again, the crack reopens and blunts. However, relative to the position subjected to the previous tensile stress, the crack has by then propagated forward by a certain distance. Under the alternating action of tensile and compressive stresses, the crack continuously propagates forward until the crack tip is completely blunted. After the crack closes, it can no longer reopen, and the crack stops propagating; alternatively, some cracks can continue to propagate and reach a critical length, at which point instantaneous fracture occurs. From this crack-propagation mechanism, it can be seen that the spacing between mutually parallel fatigue striations reflects the length by which the fatigue crack advances during each cycle of tensile–compressive stress.

Fig. 13 Macromorphology of directionally solidified Ti-47Al-2Cr-2Nb alloy at withdrawal rate of 1.0 mm/min after HCF without fracture (a) and BSE images of area A at longitudinal direction (b) and area B at transverse direction (c) in Fig.13a

Fig. 14 Schematics of interlamellar (a) and translamellar (b) fatigue crack propagation modes of directionally solidified Ti-47Al-2Cr-2Nb alloy (σ—stress; the little black arrows show the directions of crack propagation)

3 Conclusions

(1) A Ti-47Al-2Cr-2Nb alloy with a directionally solidified structure was prepared by cold-crucible directional solidification. Its microstructure is a fully lamellar $\alpha_2 + \gamma$ structure, and the interlamellar spacing gradually decreases with increasing withdrawal rate.

(2) The room-temperature tensile properties of the directionally solidified Ti-47Al-2Cr-2Nb alloy are markedly improved: the tensile strength reaches 652 MPa and the elongation reaches 1.5%. With increasing withdrawal rate, the room-temperature tensile strength gradually increases, while the

variation in elongation is not large.

(3) At 800 °C, the high-temperature tensile strength and elongation of the Ti-47Al-2Cr-2Nb alloy both increase as the interlamellar spacing of the fully lamellar structure decreases. The high-temperature tensile strength of the directionally solidified Ti-47Al-2Cr-2Nb alloy reaches a maximum of 490 MPa, and the elongation reaches 5.0%.

(4) When the withdrawal rate is 1.0 mm/min, the high-cycle fatigue limit of the Ti-47Al-2Cr-2Nb alloy is 300 MPa, and the ratio of the maximum stress to the ultimate tensile strength ($\sigma_{\mathrm{max}}/\sigma_{\mathrm{UTS}}$) is 0.60. When the withdrawal rate is 1.2 mm/min, the high-cycle fatigue limit is 247 MPa, and the ratio of the maximum stress to the ultimate tensile strength is 0.45. This indicates that at lower withdrawal rates, the fatigue resistance of the material is higher. The stress–number of cycles (S–N) curve equation of the directionally solidified Ti-47Al-2Cr-2Nb alloy under different withdrawal rates was calculated.

(5) The high-cycle fatigue fracture mode of the directionally solidified Ti-47Al-2Cr-2Nb alloy is brittle cleavage fracture. Macroscopically, fatigue cracks propagate either along lamellar interfaces or in directions perpendicular to the lamellar interfaces; microscopically, they propagate along river-pattern extension directions or along directions normal to fatigue striations. Fatigue microcracks mainly initiate at the α_2/γ lamellar interfaces and around the B_2 phase near grain boundaries.

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Figure 8

Figure 11: Figure 8

Figure 9

Figure 12: Figure 9

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Figures

Figure 11

Figure 13: Figure 11

Figure 13

Figure 14: Figure 13

Figure 15

Figure 15: Figure 15

Figure 16

Figure 16: Figure 16

Figure 17

Figure 17: Figure 17

Figure 21

Figure 18: Figure 21