

## Postprint: Tensile and High-Cycle Fatigue Properties of Cold Crucible Directionally Solidified Ti-47Al-2Cr-2Nb Alloy

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### Abstract

Directionally columnar-grained Ti-47Al-2Cr-2Nb alloy ingots were prepared using the cold crucible directional solidification technique. By varying the withdrawal rate, the obtained ingots exhibited fully lamellar microstructures with different lamellar spacings. Through tensile property testing, 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 reached a maximum of 490 MPa, with a maximum elongation of 5.0%. Through high-cycle fatigue property testing, the stress-cycle (S-N) curves of the directionally solidified alloys at withdrawal rates of 1.0 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 the tensile fracture mode of specimens at room temperature was brittle fracture, whereas after high-cycle fatigue testing, the fracture mode 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 the fracture surfaces of high-cycle fatigue specimens revealed that fatigue cracks initiated near phase interfaces and the B2 phase. Based on this, the crack propagation mechanism was analyzed using the plastic blunting theory, and a high-cycle fatigue crack propagation pattern diagram was constructed.

## Full Text

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

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## Abstract

TiAl-based alloys have recently received considerable attention as promising candidates for aero-engine blade applications to replace Ni-based superalloys due to their unique properties, such as high specific strength, high specific stiffness, and good oxidation resistance. However, their brittleness and poor processing properties limit practical application. Aero-engine blades typically experience various cyclic loadings during service, ultimately leading to fatigue failure. According to statistics, fatigue failure—primarily high-cycle fatigue (HCF)—accounts for nearly 80% of gas turbine blade failure modes in aero-engines. Consequently, research on fatigue behavior of blade materials has intensified over recent decades, though relevant results for TiAl-based alloys, particularly HCF properties, remain limited. Recent advancements in directional solidification (DS) of TiAl-based alloys using cold crucibles have revealed enhanced ductility at both room and elevated temperatures. To verify the influence of DS structures on tensile and HCF properties, this work prepared and evaluated a TiAl-based alloy with composition Ti-47Al-2Cr-2Nb (atomic fraction, %). Directionally solidified Ti-47Al-2Cr-2Nb alloy ingots were prepared at withdrawal rates of 1.0, 1.2, and 1.4 mm/min using the cold crucible method under an alternating electromagnetic field in a vacuum furnace. Macro- and microstructures were characterized using digital photography, optical microscopy (OM), scanning electron microscopy (SEM), and X-ray diffraction (XRD). Tensile properties at room temperature and 800 °C, as well as HCF properties at room temperature, were measured to elucidate the relationship between microstructure and mechanical properties, particularly HCF behavior, and to discuss HCF crack propagation mechanisms.

The results demonstrate that comprehensive mechanical properties of Ti-47Al-2Cr-2Nb alloy are significantly improved after directional solidification using a cold crucible. Tensile strength reaches 652 MPa at room temperature with a maximum elongation of 1.5%, while tensile strength at 800 °C attains 490 MPa with 5.0% elongation. Based on HCF test data at room temperature with a stress ratio of 0.1, stress amplitude-number of cycles to failure (S-N) curve equations were calculated for different withdrawal rates. Fatigue limits are 300 MPa and 247 MPa at withdrawal rates of 1.0 and 1.2 mm/min, respectively, indicating that fatigue fracture resistance decreases with increasing withdrawal

rate. The HCF fracture mode of directionally solidified Ti-47Al-2Cr-2Nb alloy exhibits brittle cleavage fracture. Micro-cracks propagate both along and perpendicular to the lamellae, observed between  $\alpha_2/\gamma$  lamellae and around B2 phases.

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

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## Introduction

With the rapid development of aerospace technology, performance requirements for structural materials have become increasingly demanding, particularly for aero-engine blade materials. Statistics indicate that 80% of gas turbine engine blade failures result from material fatigue. Research has shown that blade failures predominantly occur under low-amplitude, high-cycle loading conditions induced by centrifugal stresses superimposed with vibratory stresses—namely, high-cycle fatigue failure. Since material characteristics, microstructural defects, and processing techniques influence fatigue behavior, investigating blade material fatigue remains an active research area. Meanwhile, emerging high-temperature structural materials provide opportunities for advanced blade development, though performance improvements are essential to meet service requirements.

TiAl-based alloys represent one of the most promising new high-temperature structural materials in aerospace applications, offering high specific strength, high specific stiffness, heat resistance, high-temperature oxidation resistance, and creep resistance. These alloys are expected to replace heavier Ni-based superalloys at operating temperatures of 700–900 °C to satisfy modern high-performance aero-engine demands for high thrust-to-weight ratio, reliability, and durability. However, TiAl-based alloys suffer from low room-temperature ductility and toughness, requiring comprehensive performance improvements, particularly regarding fatigue behavior—especially high-cycle fatigue properties. Therefore, investigating microstructural modifications to enhance comprehensive mechanical properties, particularly HCF performance, is crucial.

To improve TiAl alloy performance, processing defects must be minimized while refining grain size and reducing lamellar spacing through microstructural optimization. Thus, selecting appropriate processing techniques is critical for enhancing mechanical properties. Cold crucible directional solidification technology represents a novel DS technique combining induction melting, continuous casting, and unidirectional solidification. Extensive research has demonstrated that this technology can produce high-melting-point, high-purity, highly reactive TiAl alloy ingots with soft or non-contact between crucible and melt, avoiding contamination and achieving high-purity forming while improving mechanical properties through microstructural enhancement.

Researchers have long recognized the importance of fatigue property studies in TiAl alloys. Sastry and Lipsitt and Henaff and Gloanec tested fatigue life curves of lamellar Ti-36.5%Al alloys at various temperatures, finding that small stress amplitude changes significantly affect fatigue life. Fatigue properties did not degrade substantially above 800 °C. Since ultimate tensile strength ( $\sigma\{UTS\}$ ) varies with temperature, fatigue amplitude ( $\sigma\{max\}$ ) is typically normalized as  $\sigma\{max\}/\sigma\{UTS\}$ . Due to fatigue hysteresis,  $\sigma\{max\}/\sigma\{UTS\}$  is 0.8 at room temperature and remains above 0.7 at 700 °C, indicating temperature-dependent hysteresis—though this applies to specific microstructures. Literature indicates that lamellar TiAl alloys develop pre-primary-yield cracks during fatigue, causing premature failure, whereas duplex microstructures do not exhibit this behavior. Comparative studies of titanium alloys, Ni-based alloys, and  $\gamma$ -TiAl alloys show that  $\gamma$ -TiAl alloys demonstrate superior fatigue performance when normalized as  $\sigma\{max\}/\sigma\{UTS\}$ .

This work prepared directionally solidified Ti-47Al-2Cr-2Nb alloy using cold crucible DS technology, analyzed microstructural refinement effects of varying withdrawal rates, tested tensile and HCF properties, and investigated the relationship between microstructure and mechanical properties.

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## Experimental Materials and Methods

Ti-47Al-2Cr-2Nb alloy (atomic fraction, %) was selected from the Ti-Al-Cr-Nb system for its good room-temperature ductility, with Al content fixed at 47% to ensure  $\beta$ -type solidification. Master alloy ingots were melted using a 6TP water-cooled Cu crucible vacuum induction melting furnace (ISM). Cylindrical rods of 20 mm diameter and 98 mm length were cut from the master ingot as feedstock for DS experiments.

Directional solidification was performed using a multifunctional cold crucible electromagnetic constraint shaping DS apparatus developed by the Electromagnetic Casting Research Group at Harbin Institute of Technology. Ti-47Al-2Cr-2Nb alloy ingots of 100–110 mm length with 25 mm  $\times$  25 mm cross-section were prepared; process parameters are listed in .

The DS ingots were sectioned by wire electrical discharge machining, then ground, polished, and etched (etchant: 10% HNO<sub>3</sub> + 5% HF + 85% H<sub>2</sub>O by volume) for macrostructural observation. Microstructures were examined using a Quanta 200 FEG field-emission SEM with backscattered electron (BSE) and secondary electron (SE) imaging systems. Phase identification was conducted using a D/MAX-RB rotating anode X-ray diffractometer (XRD) on different regions of the DS microstructure.

Tensile tests at room temperature and 800 °C were performed on an Instron 5500R universal testing machine. Specimens were ground and electropolished (electrolyte: 35% n-butanol, 60% methanol, 5% perchloric acid by volume) to

eliminate residual stresses. High-cycle fatigue testing was conducted on a PLC-100C high-frequency tension-compression fatigue machine. Room-temperature tensile tests used a 10 mm gauge length at  $1 \times 10^{-4} \text{ s}^{-1}$  strain rate. High-temperature tensile tests at 800 °C were performed in vacuum with a 20 mm gauge length, 5 min holding time, and  $0.5 \times 10^{-4} \text{ s}^{-1}$  strain rate. HCF test parameters were: stress ratio  $R = 0.1$ , room temperature and atmospheric pressure, sinusoidal waveform at system resonance frequency.

HCF stress levels were selected based on the room-temperature tensile strength of DS Ti-47Al-2Cr-2Nb alloy using the staircase method. Custom fatigue fixtures were fabricated from 45# manganese steel, with 0.5 mm anti-slip patterns cut by wire EDM on contact surfaces. Fracture surfaces of tensile and fatigue specimens were analyzed by SEM to investigate fracture mechanisms.

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## 2.1 Microstructural Analysis

[Figure 1: see original paper] shows the macrostructures of DS Ti-47Al-2Cr-2Nb alloy at different withdrawal rates. All ingots exhibit good directional solidification with DS zones exceeding 60% of total length. Higher withdrawal rates produce greater solid-liquid interface concavity ( $\Delta h$ ) because increased withdrawal rate reduces relative energy input ( $q_{\text{in}}$ ) per unit time, increasing lateral heat flux ( $q_{\text{x}}$ ) and consequently  $\Delta h$ . Columnar grains grow perpendicular to the solid/liquid interface; with increasing withdrawal rate, the angle between grain growth direction and interface normal increases due to enhanced lateral heat flux, causing grains to grow toward the upstream side.

The DS Ti-47Al-2Cr-2Nb alloy microstructure consists of fully lamellar  $\alpha_2 + \gamma$  phases. Lamellar spacing and grain size significantly influence mechanical properties. According to the Hall-Petch relationship, smaller lamellar spacing and grain size yield higher strength. [Figure 2: see original paper] presents BSE images of lamellar microstructures in the stable growth zone. Lamellar spacing was measured using the line intercept method. [Figure 3: see original paper] shows cross-sectional macrostructures of the stable growth zone, with average grain diameter calculated using Image-Pro Plus 6.0 software. summarizes average lamellar spacing, lamellar orientation, and grain size at different withdrawal rates. Increasing withdrawal rate decreases lamellar spacing, increases the angle between lamellar orientation and growth direction, and reduces grain size.

[Figure 4: see original paper] shows XRD spectra of different solidification zones at 1.2 mm/min withdrawal rate. All regions—near the solid-liquid interface, chill zone, and stable growth zone—contain  $\gamma$  phase,  $\alpha_2$  phase, and minor B2 phase. The  $\alpha_2$  peak intensity in the liquid zone is lower than near the solid-liquid interface and stable growth zone, indicating less  $\alpha_2$  phase and more equiaxed  $\gamma$  phase in the liquid zone.

## 2.2 Room-Temperature Tensile Properties

[Figure 5: see original paper] shows room-temperature tensile stress-strain curves at different withdrawal rates. Maximum ultimate tensile strength reaches 652 MPa with 1.5% elongation. Compared with as-cast structures, DS Ti-47Al-2Cr-2Nb alloy exhibits improved tensile strength and ductility. Tensile strength increases with withdrawal rate, while elongation variation is minimal.

Smaller lamellar spacing correlates with higher tensile strength. According to Meyers et al., lamellar spacing and tensile strength follow the Hall-Petch relationship:

$$\sigma_b = \sigma_0 + k_1 \lambda^{-0.5}$$

where  $\sigma_b$  is tensile strength,  $\sigma_0$  is intrinsic strength,  $k_1$  is the Hall-Petch constant, and  $\lambda$  is lamellar spacing.

Linear regression using average lamellar spacing and room-temperature tensile data yields:

$$\sigma_b = 573.7 + 0.364\lambda^{-0.5} \quad (R = 0.99)$$

where  $R$  is the correlation coefficient.

[Figure 6: see original paper] shows fracture morphology at 1.2 mm/min withdrawal rate. The fracture mode primarily involves translamellar cracking and interlamellar tearing. Translamellar fracture creates fracture steps ([Figure 6: see original paper]c) when lamellae are parallel to tensile stress, causing cracks to propagate across lamellar planes. Interlamellar tearing ([Figure 6: see original paper]d) occurs when lamellae are perpendicular to stress, with cracks extending parallel to lamellar planes. Although macroscopically brittle, river patterns characteristic of cleavage fracture are observed ([Figure 6: see original paper]b), along with occasional cleavage facets and steps, confirming a brittle cleavage fracture mode at room temperature.

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## 2.3 High-Temperature Tensile Properties

[Figure 7: see original paper] shows tensile stress-strain curves at 800 °C for withdrawal rates of 1.0, 1.2, and 1.4 mm/min. At 1.0 mm/min, maximum tensile strength is 490 MPa with 5.0% elongation. With increasing withdrawal rate, both high-temperature tensile strength and elongation increase as lamellar spacing decreases. The Hall-Petch relationship remains valid at high temperature, yielding:

$$\sigma_b = 413.9 + 0.332\lambda^{-0.5} \quad (R = 0.99)$$

[Figure 8: see original paper] shows fracture morphology at 1.2 mm/min and 800 °C. The fracture surface exhibits densely packed lamellar cross-sections and torn lamellar structures with river patterns, indicating predominant translamellar cracking and interlamellar tearing. Dimple structures between lamellae ([Figure 8: see original paper]d) demonstrate some plasticity at 800 °C. Occasional cleavage facets and river patterns confirm that high-temperature fracture occurs through mixed brittle cleavage and minor ductile fracture modes.

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## 2.4 High-Cycle Fatigue Properties

[Figure 9: see original paper] shows HCF-fractured specimen morphology. Fracture locations concentrate near the arc transition at one end, as HCF behavior is highly sensitive to stress concentration, which is most severe at these transitions.

HCF tests at withdrawal rates of 1.0 and 1.2 mm/min produced stress-number of cycles (S-N) scatter plots. Using the S-N curve equation, fitted curves were generated ([Figure 10: see original paper]). Since fatigue amplitude ( $\sigma_{max}$ ) relates to ultimate tensile strength ( $\sigma_{UTS}$ ),  $\sigma_{UTS}$  serves as an intrinsic fatigue stress value. Plotting  $\sigma_{max}/\sigma_{UTS}$  versus cycles yields a derived S-N curve ([Figure 11: see original paper]) that better characterizes fatigue performance. At 1.0 mm/min, the fatigue limit is 300 MPa ( $\sigma_{max}/\sigma_{UTS} = 0.60$ ); at 1.2 mm/min, it is 247 MPa ( $\sigma_{max}/\sigma_{UTS} = 0.45$ ), indicating better fatigue resistance at lower withdrawal rates.

The three-parameter power function expression calculates S-N curves:

$$\sigma_{max} - \sigma_{\infty} = mN^c$$

where m and c are coefficients and  $\sigma_{\infty}$  is the fatigue limit. The calculated S-N equations are:

For v = 1.0 mm/min:

$$(\sigma_{max} - 300) = 3.28 \times 10^{10} N^{-1.782}$$

For v = 1.2 mm/min:

$$(\sigma_{max} - 247) = 3.27 \times 10^{10} N^{-1.782}$$

Derived S-N curve equations are:

For v = 1.0 mm/min:

$$(\sigma_{max}/\sigma_{UTS} - 0.60) = 764.78 N^{-1.782}$$

For v = 1.2 mm/min:

$$(\sigma_{max}/\sigma_{UTS} - 0.45) = 428.13 N^{-1.782}$$

Fracture surface analysis reveals bright crystalline facets typical of cleavage fracture, with most fractures being very flat, indicating macroscopic brittle cleavage. Numerous fatigue striations appear on all valid fracture surfaces ([Figure 12: see original paper]a)—parallel, slightly curved bands whose convex direction indicates local crack propagation. River patterns ([Figure 12: see original paper]b,c) include fan-shaped and herringbone morphologies originating at grain or phase boundaries and extending across lamellar steps. Cleavage facets and steps ([Figure 12: see original paper]d) show cracks nucleating at phase interfaces between lamellae or at small-angle tilt boundaries where B2 phase precipitation provides nucleation sites. Minor tearing ridges ([Figure 12: see original paper]e) confirm brittle cleavage fracture.

[Figure 13: see original paper] shows an unfractured HCF specimen at 1.0 mm/min. Microcracks parallel to lamellae are distributed within  $\alpha_2/\gamma$  lamellae ([Figure 13: see original paper]b), while ridge-like B2 phase precipitates at lamellar colony boundaries with microcracks surrounding them ([Figure 13: see original paper]c). Thus, fatigue cracks readily nucleate at  $\alpha_2/\gamma$  interfaces and near B2 phases at grain boundaries.

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## 2.5 High-Cycle Fatigue Crack Propagation Mechanism

Macroscopically, fatigue cracks propagate interlamellarly or translamellarly; microscopically, they extend along river pattern directions or perpendicular to fatigue striations. Crack propagation in DS Ti-47Al-2Cr-2Nb alloy occurs through asymmetric extension of brittle fatigue striations (cleavage striations).

Multiple theories explain fatigue crack propagation, with Laird's plastic blunting model being most widely applied. Based on this theory, a simplified crack propagation model is summarized in [Figure 14: see original paper]. Under tensile stress, cracks bifurcate along preferred cleavage directions and open radially (tip sharpening). Under compressive stress, cracks close and blunt. Subsequent tensile stress reopens and sharpens the crack, which has now advanced relative to its previous position. Alternating tensile-compressive stresses drive continuous crack extension until complete blunting prevents further opening, arresting the crack; other cracks may reach critical length and cause instantaneous fracture. Parallel fatigue striation spacing reflects crack extension per stress cycle.

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## Conclusions

1. Directionally solidified Ti-47Al-2Cr-2Nb alloy with directional microstructure was prepared by cold crucible DS technology. The microstructure consists of fully lamellar  $\alpha_2 + \gamma$  phases, with lamellar spacing decreasing as withdrawal rate increases.

2. Room-temperature tensile properties of DS Ti-47Al-2Cr-2Nb alloy are significantly improved, achieving 652 MPa tensile strength and 1.5% elongation. Tensile strength increases with withdrawal rate, while elongation variation is minimal.
3. At 800 °C, both tensile strength and elongation increase with decreasing lamellar spacing. Maximum high-temperature tensile strength reaches 490 MPa with 5.0% elongation.
4. At 1.0 mm/min withdrawal rate, the HCF limit is 300 MPa ( $\sigma_{max}/\sigma_{UTS} = 0.60$ ); at 1.2 mm/min, it is 247 MPa ( $\sigma_{max}/\sigma_{UTS} = 0.45$ ), demonstrating greater fatigue resistance at lower withdrawal rates. S-N curve equations for DS Ti-47Al-2Cr-2Nb alloy were calculated for different withdrawal rates.
5. HCF fracture of DS Ti-47Al-2Cr-2Nb alloy occurs through brittle cleavage. Macroscopic crack propagation follows interlamellar or translamellar directions; microscopically, cracks extend along river pattern directions or perpendicular to fatigue striations. Microcracks primarily nucleate at  $\alpha_2/\gamma$  interfaces and near B2 phases at grain boundaries.

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## References

- [1] Lin J P, Zhang L Q, Song X P, Ye F, Chen G L. Mater China, 2010; 29(2): 1
- [2] Suresh S. *Fatigue of Materials*. Cambridge: Cambridge University Press, 1998; 2: 345
- [3] He Y H, Su B. Aeroengine, 2005; 31(2): 51
- [4] Li Q H, Wang Y R, Wang J J. Aeroengine, 2003; 29(4): 16
- [5] Li J S, Zhang T B, Chang H, Kou H C, Zhou L. Mater China, 2010; 29(3): 1
- [6] Chen G L, Lin J P. *Physical Metallurgy for the Structural Ordered Intermetallics*. Beijing: Metallurgical Industry Press, 1999: 285
- [7] Kim Y W. Trans Nonferrous Met Soc China, 1999; 9: 298
- [8] Yamaguchi M, Inui H. Acta Mater, 2000; 48: 307
- [9] Kim S W, Wang P, Oh M H, Wee D M, Kumarb K S. Intermetallics, 2004; 12: 499
- [10] Chan K S, Kim Y W. Acta Metall, 1995; 43: 439
- [11] Qian J H, Qi X Z. Chin J Rare Met, 2002; 26: 477
- [12] Fu H Z, Ding H S, Chen R R, Bi W S. Rare Met Mater Eng, 2008; 37: 565

- [13] Wang Y L, Ding H S, Bi W S, Guo J J, Fu H Z. Rare Met Mater Eng, 2006; 35: 1597
- [14] Fu H Z, Shen J, Hao Q T, Li S M, Li J S. Chin J Nonferrous Met, 2002; 12: 1081
- [15] Pericleous K, Bojarevics V, Djambazov G. Appl Math Model, 2006; 30: 1262
- [16] Sastry S M L, Lipsitt H A. Metall Trans, 1977; 8A: 299
- [17] Henaff G, Gloanec A L. Intermetallics, 2005; 13: 543
- [18] Zhang W J, Deevi S C, Chen G L. Intermetallics, 2002; 10: 403
- [19] Jones P E, Eylon D. Mater Sci Eng, 1999; A263: 296
- [20] Jha S K, Larsen J M, Rosenberger A H. Acta Mater, 2005; 53: 2006
- [21] Zhang Y G, Han Y F, Chen G L, Guo J T, Wan X J, Feng D. *Structural Intermetallics*. Beijing: National Defense Industry Press, 2001: 705
- [22] Gloanec A L, Milani T, Henaff G. Int J Fatigue, 2010; 32: 1015
- [23] Meyers M A, Mishra A, Benson D J. Prog Mater Sci, 2006; 51: 427
- [24] Xu R P, Fu H M, Gao Z T. J Mech Strength, 1994; 16(1): 58
- [25] Mine Y J, Fujisaki H, Matsuda M, Takeyama M, Takashima K. Scr Mater, 2011; 65: 707
- [26] Kumpfer J, Kim Y W, Dimiduk D M. Mater Sci Eng, 1995; A192-193: 465
- [27] Tsutsumi M, Takano S. Intermetallics, 1996; 4: 77
- [28] Cao R, Lin Y Z, Hu D. Eng Fract Mech, 2008; 75: 4343
- [29] Jones P E, Eylon D. Mater Sci Eng, 1999; A263: 296
- [30] Laird C. Fracture, 1984; 84: 261

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