Crack Initiation and Propagation in High-Nb-Content TiAl Alloy under Fatigue-Creep Conditions: Post-Print

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Abstract

In-situ SEM observation was employed to investigate the crack initiation and propagation behavior of a near-lamellar Ti-45Al-8Nb-0.2W-0.2B-0.1Y alloy under fatigue-creep interaction at 750°C. Cyclic experiments utilized a trapezoidal waveform with a hold period at maximum tensile stress. The results revealed that cracks primarily initiated at lamellar colony interfaces, with initiation modes including creep voids and fatigue microcracks. Microcracks at lamellar colony interfaces initially propagated along the interfaces via coalescence of creep voids or under crack tip stress concentration, and subsequently coalesced and grew. When crack propagation was impeded by lamellar colony interfaces with different orientations, the impeded cracks began to propagate along the specimen thickness direction, accompanied by the emergence of microcracks perpendicular to the loading direction in the vicinity. Eventually, the impeded cracks coalesced, leading to final fracture of the alloy. The experimental results were compared with in-situ observation results of fatigue deformation and creep deformation of this alloy under identical conditions. Based on the experimental results, a schematic model for crack initiation and propagation in high-Nb titanium aluminide alloys under fatigue-creep interaction was established.

Full Text

Crack Initiation and Propagation of High Nb-Containing TiAl Alloy Under Fatigue-Creep Interaction

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Abstract

TiAl-based alloys have emerged as potential competitors to steels and superalloys for aerospace and automotive applications due to their low density, high specific strength and stiffness, and good oxidation resistance at elevated temperatures. As a new generation of TiAl-based alloys, high Nb-containing TiAl alloys have become promising high-temperature structural materials with superior high-temperature strength and oxidation resistance compared to conventional TiAl alloys. TiAl-based alloy components such as low-pressure turbine blades and compressor impellers often operate under near-steady conditions for extended durations once peak operating conditions are achieved at high temperature. These components suffer not only from rapidly induced damage during start-up and shutdown cycles, but also from creep damage under sustained loading periods. Moreover, the potential interaction damage between fatigue and creep must be considered. Thus, the study of fatigue-creep interaction in TiAl-based alloys is of great practical importance. While numerous studies have focused on the fatigue or creep properties of TiAl-based alloys, the fatigue-creep interaction behavior has rarely been reported.

Therefore, this work investigated the crack initiation and propagation behavior of a nearly lamellar Ti-45Al-8Nb-0.2W-0.2B-0.1Y alloy under fatigue-creep interaction at 750 °C using in situ SEM observation. Cyclic loading tests were conducted using a trapezoidal waveform with a dwell time at maximum tensile stress. The results indicate that cracks initiated primarily at lamellar colony boundaries through two mechanisms: creep void formation and fatigue microcracking. Microcracks at lamellar colony boundaries first propagated along the colony boundaries by absorbing creep voids or through stress concentration at crack tips, then coalesced and grew larger. When crack propagation was impeded by colony boundaries of different orientations, the blocked cracks began to extend through the specimen thickness direction, accompanied by the emergence of microcracks perpendicular to the loading direction. Eventually, the blocked cracks interconnected, leading to fracture. The experimental results were compared with in situ observations of the alloy under fatigue-only and creep-only deformation at identical conditions. Based on these findings, a schematic model for crack initiation and propagation in high Nb-containing TiAl alloys under fatigue-creep interaction was established.

KEY WORDS TiAl alloy, fatigue-creep interaction, in situ observation, crack initiation, crack propagation

1. Introduction

TiAl-based intermetallic compounds exhibit promising application prospects in aerospace, aviation, and automotive engine industries due to their low density, relatively high elastic modulus, and excellent high-temperature strength, creep resistance, and oxidation resistance [1-4]. Among these materials, high Nb-containing TiAl alloys demonstrate even greater development potential because of their higher service temperatures and superior high-temperature oxidation performance [5-9]. Components made from high Nb-containing TiAl alloys, such as turbine blades and compressor impellers, experience complex loading conditions during service, including start-up/shutdown cycles, external load variations, and dwell periods under constant load at high temperature. These components are subjected not only to dynamic loading but also to static loading, requiring not only good fatigue and creep resistance but also consideration of the interaction between fatigue damage and creep damage. Therefore, analyzing fatigue-creep interaction is critically important for life assessment of high Nb-containing TiAl alloys and their components.

In recent years, numerous studies have reported on the fatigue and creep properties of TiAl-based alloys. Research has shown that the creep properties of TiAl-based alloys are related to microstructure, grain size, lamellar orientation, and lamellar spacing [10-14], with → phase transformation occurring during creep deformation [15-16]. During high-temperature fatigue deformation, small changes in stress amplitude can cause significant differences in fatigue life [17], and the alloys exhibit cyclic stability in stress (strain) amplitude [18-20], with fatigue cracks initiating primarily at lamellar interfaces or colony boundaries [21-23]. However, detailed reports on the combined effect of fatigue-induced and creep-induced damage in high Nb-containing TiAl alloys at high temperature—namely, fatigue-creep interaction—are currently lacking.

Consequently, this study utilized a high-temperature fatigue testing machine equipped with a scanning electron microscope (SEM) to analyze the fatigue-creep interaction of a nearly lamellar high Nb-containing TiAl alloy by applying dwell time at maximum tensile stress during cyclic deformation. In situ SEM observation was employed to investigate the crack initiation and propagation processes under fatigue-creep interaction conditions, thereby revealing the mechanisms of crack initiation and growth in this alloy.

2. Experimental Procedures

The material used in this study was a high Nb-containing TiAl alloy with a nominal composition of Ti-45Al-8Nb-0.2W-0.2B-0.1Y (at.%). The alloy ingot was prepared by the consumable-shell-consumable electrode process, with uniform composition distribution; the composition deviation was 0.16 at.% for Al and 0.07 at.% for Nb. Fatigue-creep interaction tests were conducted on a Shimadzu SEM-SERVO high-temperature tensile fatigue testing machine, which uses a hydraulic servo system to acquire strain-cycle curves and an integrated SEM for real-time microstructural observation and imaging. This testing method has been widely applied to investigate crack initiation and propagation behavior [24-26]. The temperature and displacement accuracies of the instrument are ±1 °C and 10 ^{3} mm, respectively. All tests were performed in vacuum to avoid the influence of high-temperature oxidation on mechanical properties.

Test specimens were directly cut from the alloy ingot by wire electrical discharge machining. The specimen geometry and dimensions are shown in [Figure 1: see original paper] (prepared according to instrument specifications). The top/bottom surfaces and side surfaces were carefully ground and polished. This study employed load-controlled tension-tension cyclic tests with dwell time, and the loading waveform schematic is shown in [Figure 2: see original paper]. The test temperature was T = 750 °C, maximum stress _max = 0.8 . = 468.8 MPa, stress ratio R = 0.1, loading rate = 50 N/s, and dwell time Δt = 10 s. The dwell time at maximum tensile stress introduced significant creep damage during cyclic testing, enabling investigation of fatigue-creep interaction behavior. In situ observation technology was used to capture the crack initiation and propagation processes in the high Nb-containing TiAl alloy under fatigue-creep interaction conditions.

3. Experimental Results

[Figure 3: see original paper] shows an SEM image of the as-cast Ti-45Al-8Nb-0.2W-0.2B-0.1Y alloy microstructure. The alloy exhibits a nearly lamellar (NL) structure consisting of / lamellar colonies with a small amount of equiaxed phase distributed between colonies. The average colony size is approximately 70 m, and colony boundaries appear serrated. The high-temperature tensile properties of this alloy at 750 °C are: yield strength . = 586 MPa, tensile strength _b = 795 MPa, and elongation = 1.1%.

[Figure 4: see original paper] presents the mean strain versus cycle number curve for the Ti-45Al-8Nb-0.2W-0.2B-0.1Y alloy under cyclic deformation. Differentiating the mean strain curve with respect to time yields the creep rate versus time curve, shown in [Figure 5: see original paper]. Both figures reveal that the mean strain curve under these cyclic conditions exhibits typical creep curve characteristics, including a primary decelerated stage (Stage I), a steady-state stage (Stage II), and a tertiary accelerated stage (Stage III). The dwell time at maximum tensile stress induces static creep damage, giving the mean strain its characteristic creep behavior. Additionally, the mean stress during cyclic deformation is _m = 258.5 MPa, and the cyclic creep damage caused by this positive mean stress also influences the mean strain behavior [27-28]. Under these conditions, the damage process includes not only fatigue damage but also creep damage and the resulting fatigue-creep interaction.

[Figure 6: see original paper] shows in situ SEM images of the alloy during cyclic deformation. Figures 6a-f correspond to the positions marked in [Figure 4: see original paper] and [Figure 5: see original paper]. After the mean strain enters the accelerated growth stage (Stage III), [Figure 6: see original paper]a and b reveal that numerous creep voids nucleate at lamellar colony boundaries, particularly where the boundary orientation forms a large angle with the applied stress direction. With increasing cycle number, these creep voids grow and coalesce along colony boundaries to form microcracks. Additionally, a small number of fatigue microcracks form directly at colony boundaries. [Figure 6: see original paper]a and b also show that microcracks at colony boundaries propagate by absorbing creep voids (e.g., cracks C1 and C3 in [Figure 6: see original paper]b) or through stress concentration at crack tips (e.g., crack C2 in [Figure 6: see original paper]b), extending along colony boundaries on the specimen surface.

At N = 1093 cycles ([Figure 6: see original paper]c), crack C2 connects with cracks C1 and C3 to form a larger crack C4. Meanwhile, the propagation of this large crack is impeded by other colony boundaries of different orientations. [Figure 6: see original paper]c also reveals that new microcracks nucleate near the blocked crack, oriented perpendicular to the loading direction. At N = 1269 cycles ([Figure 6: see original paper]d), crack C4 primarily propagates through the specimen thickness direction. Prior to fracture ([Figure 6: see original paper]e and f), the number and size of microcracks perpendicular to the loading direction increase, and under their influence, the blocked cracks C4 and C5 interconnect to form crack C6, ultimately causing unstable fracture. Significant necking occurs before fracture, and the fracture mode is intergranular. The cyclic life is N_f = 1395 cycles (fracture time t_r = 19.38 h).

[Figure 7: see original paper] shows an in situ SEM image of the alloy immediately before fracture under cyclic deformation with Δt = 60 s. The cyclic life is N_f = 251 cycles (t_r = 6.97 h). Compared to Δt = 10 s, the surface crack types include creep voids, microcracks along colony boundaries, and microcracks perpendicular to the loading direction, with crack propagation directions both along surface colony boundaries and through the specimen thickness. This indicates similar crack initiation and propagation mechanisms. However, increasing Δt leads to more microcracks perpendicular to the loading direction and reduces cyclic life.

4. Analysis and Discussion

The essence of fatigue-creep interaction lies in the relationship between fatigue damage and creep damage. The primary form of fatigue damage is transgranular crack propagation, while creep damage mainly manifests as void nucleation and growth at grain boundaries. When both damage mechanisms occur simultaneously, each influences the development of the other, thereby accelerating or decelerating the total damage and affecting cyclic life [29]. [Figure 8: see original paper] shows the surface morphology of the alloy before and after fracture during fatigue testing without dwell time. The main crack propagates perpendicular to the loading direction, and fracture occurs when the main crack reaches 719 m. No significant necking is observed before fracture, and the fracture mode is transgranular, with N_f = 4192 cycles (t_r = 46.58 h). Microcracks perpendicular to the loading direction are also observed near the main crack ([Figure 8: see original paper]c). Compared with in situ observations at $\Delta t =$ 10 s under identical conditions, the addition of dwell time significantly increases the probability of crack initiation at colony boundaries, markedly changes the crack propagation path, transforms the fracture mode from transgranular to intergranular, and substantially reduces cyclic life.

Previous research [30] has shown that during creep deformation of high Nb-containing TiAl alloys at 750 °C and 470 MPa, numerous creep voids appear at colony boundaries after entering the steady-state creep stage. These voids grow and coalesce to form microcracks, with their number and size increasing during creep deformation. Upon entering the accelerated creep stage, microcracks at colony boundaries interconnect until fracture occurs. Under fatigue-creep interaction at the same temperature and stress, creep voids and microcracks nucleated at colony boundaries grow and coalesce along colony boundaries during the early crack propagation stage. In the later stage, surface microcracks include both those along colony boundaries and those perpendicular to the loading direction. Under the influence of microcracks perpendicular to the loading direction, cracks at adjacent colony boundaries on the specimen surface reconnect, leading to final fracture. Comparative analysis with in situ observations under fatigue-only and creep-only conditions reveals that the coexistence of these two microcrack types and the reconnection of cracks at colony boundaries are characteristic features of crack initiation and propagation in high Nb-containing TiAl alloys under fatigue-creep interaction.

[Figure 9: see original paper] presents a schematic model of the crack initiation and propagation process in high Nb-containing TiAl alloys under fatigue-creep interaction. When dwell time is introduced during cyclic deformation, cracks primarily nucleate at colony boundaries forming large angles with the tensile stress direction through two mechanisms: (1) predominantly creep voids, and (2) fatigue microcracks ([Figure 9: see original paper]a and b). At high temperatures, colony boundaries have relatively low strength, and dislocation motion during deformation is impeded by these boundaries, causing pile-up and localized high stress concentration that facilitates creep void formation or direct fatigue microcracking.

With increasing cycle number, microcracks at colony boundaries first grow by absorbing creep voids or through stress concentration at crack tips, propagating along colony boundaries ([Figure 9: see original paper]b). These cracks then interconnect and continue extending until blocked by colony boundaries of other orientations. Meanwhile, microcracks perpendicular to the loading direction emerge near the blocked cracks ([Figure 9: see original paper]c). As the alloy enters the unstable stage, the blocked cracks begin to propagate through the specimen thickness direction ([Figure 9: see original paper]d). Finally, under the influence of microcracks perpendicular to the loading direction, the blocked cracks interconnect, causing fracture ([Figure 9: see original paper]e).

5. Conclusions

1. During fatigue-creep interaction of Ti-45Al-8Nb-0.2W-0.2B-0.1Y alloy, cracks initiate primarily at lamellar colony boundaries through creep void formation and fatigue microcracking. Microcracks at colony boundaries first propagate by absorbing creep voids or through crack-tip stress concentration, then coalesce and grow. When propagation is impeded by colony boundaries of different orientations, the blocked cracks extend through the specimen thickness direction, accompanied by microcracks perpendicular to the loading direction. Ultimately, the blocked cracks reconnect, leading to fracture.
2. Compared with fatigue deformation without dwell time, the addition of dwell time significantly increases the probability of crack initiation at colony boundaries, markedly changes the crack propagation mode, transforms the fracture mechanism from transgranular to intergranular, and substantially reduces cyclic life.
3. The coexistence of microcracks along colony boundaries and perpendicular to the loading direction, along with reconnection of cracks at colony boundaries, represents the characteristic features of crack initiation and propagation in high Nb-containing TiAl alloys under fatigue-creep interaction.

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