学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Initiation and propagation processes of internal fatigue cracks in beta titanium alloys
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Beta titanium alloys have received considerable attention as promising structural materials owing to their excellent mechanical properties and corrosion resistance. As they are increasingly used in the aerospace industry, research on their fatigue behavior has become important in recent years. Recently, internal fatigue fracture has been reported as a novel fatigue fracture mode. When the applied stress is lower than the conventional fatigue limit, a fatigue crack is initiated inside the material. In most high-strength materials, internal fatigue fractures are commonly reported in very high cycle fatigue (VHCF) where the number of cycles exceeds 10^7 cycles. The "invisible" feature of internal fatigue crack leads to significant challenges in investigating its growth behaviors, leading to the phenomenon of VHCF that is yet to be fully clarified. Moreover, specifically in beta titanium alloys, internal fatigue fractures have been reported one and two orders earlier than in the VHCF regime. The abnormal early internal fatigue fracture brings a significant risk for industrial utilization.

The purpose of the present study is to investigate the characteristics of internal fatigue fractures and the internal crack growth behaviors in beta titanium alloys. The author integrally studied internal fatigue fracture through fractography, direct observation via synchrotron radiation computed tomography (SR-CT), and replicating internal fatigue crack behaviors by surface crack growth tests in a vacuum. The contents of this dissertation are as follows:

Chapter 1: The concept of VHCF associated with internal fatigue fracture, the background of beta titanium alloy with its research status in the VHCF field, and the objective of the present study are introduced.

Chapter 2: Fatigue properties and fractographic features of beta titanium alloys are exhibited. Under a positive stress ratio of 0.1, internal fatigue fracture occurs from 10^5 cycles in beta titanium alloys, 100 times earlier than (alpha + beta) titanium alloys and high-strength steels. By fractography, multiple facets were observed at the crack initiation site, surrounded by a smooth area feature corresponding to the crack propagation process. Three facet initiation models were proposed based on the surface appearances and the 3D facet bonding patterns of the multiple facets.

Chapter 3: To non-destructively observe the inside of beta titanium alloys, SR-CT experiments were conducted at beamline code "BL20XU" at a synchrotron radiation facility "SPring-8" located in Hyogo, Japan. The details of the SR-CT system at BL20XU including micro-tomography (micro-CT) and nano-tomography (nano-CT), called multiscale SR-CT, are introduced. The optimization results for micro-/nano-CT regarding specimen configuration and imaging conditions are illustrated individually.

Chapter 4: An in situ piezoelectric fatigue testing system was developed for efficiently observing fatigue crack growth. A small surface crack growth test was conducted to establish the measurement technique of crack growth by in situ multiscale SR-CT and evaluate the accuracy. The crack status, propagation process, and initiation process were successfully obtained. Microstructural visualization and three-dimensional rendering were achieved on a crack in grain size. It showed that the early crack growth was heterogeneous and significantly affected by the microstructure, such as the grain boundary blocking.

Chapter 5: A full-life growth behavior of a naturally initiated internal fatigue crack was observed by multiscale SR-CT. Crack initiation and propagation contributed to 57% and 43% of the fatigue life, respectively. After specimen fracture, the crack fronts at various cycles were superimposed on the fracture surface. The crack propagation process consisted of multiple facets formations and subsequent growth in the matrix corresponding to the smooth area. The multiple facets formations represented 95% of the crack propagation life, which was dominant in the internal crack propagation in the beta titanium alloy. Moreover, the factor that triggered crack growth associated with facets to the surrounding matrix was examined based on the crack opening and blunting behavior. In addition, the internal crack propagation rate in beta titanium alloy was found to be slower than its surface crack but was 20˜100 times faster than the internal crack in the most widely used (alpha+beta) titanium alloys.

Chapter 6: In the case of crack propagation, to explain the significant difference in the internal crack propagation rate between beta and (alpha+beta) titanium alloys, the present study focused on the environment surrounding the internal crack. It was reported that in (alpha+beta) titanium alloys, the crack propagation rate decreased with the increase of vacuum level, and the internal crack has similarities with the crack in a high vacuum. To investigate the appropriate environment surrounding an internal crack in beta titanium alloy, crack propagation tests in a high vacuum were conducted. As a result, the crack propagation rate in a high vacuum is slightly slower than that in the air and agrees with that of the internal crack in beta titanium alloy. It can be concluded that between beta and (alpha+beta) titanium alloys, the environment surrounding the internal cracks is similar but leads to a significant difference in crack propagation behaviors. In other words, various crack mechanisms have different sensitivities against vacuum regarding crack propagation.

Chapter 7: The main findings obtained in the present study were summarized.