Assessment of short fatigue crack closure behavior in Ti-6Al-4V alloy via 3D image-based analyses using high-resolution X-ray microtomography

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論 文 名　：Assessment of short fatigue crack closure behavior in Ti-6Al-4V alloy via 3D image-based analyses using high-resolution X-ray microtomography
(高分解能 X 線マイクロトモグラフィーを用いた 3D イメージベース解析による Ti-6Al-4V 合金の微小疲労亀裂閉口挙動の評価)

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論 文 内 容 の 要 旨

The main objective of this thesis is to understand the local closure behavior of a short fatigue crack in Ti-6Al-4V titanium alloy and how this contributes to the scatter of short fatigue crack growth rates. To achieve this objective, a series of image-based analyses of short fatigue crack growth and closure behavior were performed. The thesis consists of five chapters as outlined below.

Chapter 1 provides the general introduction and the background of this research. Titanium alloys are utilized in critical parts such as the landing gear of aircrafts which are subjected to severe fluctuating loads during landing and takeoff. Therefore, the understanding of fatigue behavior of titanium alloys is crucial for the development of materials that are difficult to fracture to guarantee safety. However, fatigue behavior in titanium alloys is extremely complicated resulting in difficulty to predict fatigue life. This is mainly due to scatter of short fatigue crack growth rates which is associated with the microstructure and crack closure variations. Significant efforts have been dedicated towards understanding the role of microstructure, but few studies have analyzed the effects of crack closure and in mainly 2D. However, crack closure is a local phenomenon which is associated with the local degree of plasticity and fracture surface roughness which is influenced by the underlying local microstructural features. This is particularly pronounced in titanium alloy due to the highly crystallographic nature of short fatigue crack growth. To address this issue, this thesis focuses on 3D observation of local short fatigue crack closure behavior to understand their mechanisms and the effects on crack growth rate. Such understanding provides insights on how material microstructure can be designed to realize fatigue resistant titanium alloys.

Chapter 2 reveals the general 3D closure behavior of a short fatigue crack in Ti-6Al-4V titanium alloy and its development with crack extension. This was achieved via in-situ fatigue testing and imaging using high-resolution X-ray microtomography at a resolution of 1 μm. The crack geometry in this material is extremely complicated and consists of facets, deflections, overlapping and branched crack segments caused by the interaction of the crack front with inhomogeneous microstructural features. It was revealed that the complex crack closure behavior in 3D with highly inhomogeneous distribution of closed patches is caused by the variation of crack path morphologies along the crack front. Crack closure was observed to be higher in crack segments with deflections and overlap which mainly occur in α+β lamellar compared to a crack segment consisting of facet paths which occur in α phase. In addition, scatter of crack growth rates was observed in the crack segments with deflections and overlap compared to facet paths which is associated with variations of roughness induced crack closure.

Chapter 3 reports the local short fatigue crack closure behavior in Ti-6Al-4V titanium alloy. The separation and analysis of roughness-induced and plasticity-induced crack closure in the near-front region was performed using ultra-high-resolution X-ray microtomography. This is owing to the development of apodization Fresnel Zone Plate in 2018 at SPring-8, Japan which significantly increased the X-ray energy available for nano-tomography to 30 keV making it possible to achieve spatial resolution levels of up to 0.1 μm. In this study, a spatial resolution of 0.15 μm was achieved that enabled the accurate observation of the actual crack front and crack morphology including ridges on the fracture surface that are known to influence roughness induced crack closure. From analysis of microstructural features around the crack path using electron backscatter (EBSD) technique coupled with serial sectioning, crack growth in α+β lamellar and high misorientation angle between grains was found to lead to low crack growth rates. For the studied bimodal Ti-6Al-4V alloy, the fatigue crack length at which scatter of crack growth rate converges was found to be larger than about 5 α grains. Plasticity induced crack closure was found to be controlled by the degree of local plasticity while roughness induced crack closure was dependent on the extent of crack path tilt and twist. This was attributed to the varying deformation behavior of α and α+β lamellar due to the varying crystallographic orientations. In addition, the microstructural details obtained using EBSD were combined with the large and diverse sets of information on crack morphology and crack closure obtained via ultra-high-resolution imaging to perform surrogate-based statistical analysis to assess the dependency of crack growth rate on a range of factors. A general trend of decrease in Schmid factor with decrease in equivalent diameter was found to enhance crack growth resistance. These microstructural factors significantly influence the crack geometry and the generation of ridges which in turn influence roughness induced crack closure. It was revealed that roughness induced crack closure is the main factor leading to scatter of short fatigue crack growth rates.

Chapter 4 describes the mechanism that controls the local generation of roughness induced crack closure. For this analysis, 3D image-based FEM simulation of short fatigue crack closure was performed using the actual 3D crack geometry in Ti-6Al-4V titanium alloy obtained via ultra-high-resolution X-ray tomography. From the simulation result, modes II and III displacements were observed to be highly fluctuated on the fracture surface. These variations of modes II and mode III displacements was found to originate from the variation of the degree of crack tip tilt and twist with respect to the overall crack growth direction which is caused by crack front interaction with the grains with inhomogeneous crystallographic orientations. It was revealed that the orientation of the ridge with respect to the overall crack growth direction and the local modes II and III displacements are critical factors controlling roughness induced crack closure.

Chapter 5 provides a summary of the results and discussions of chapter 2, 3, and 4. In addition, the possible future directions that can be extended from this research are discussed. This thesis investigated the actual short fatigue crack behavior in 3D in Ti-6Al-4V titanium alloy with an in-depth analysis of crack closure and the microstructural features around the crack path and how these influence the crack growth rate. In titanium alloys, scatter of short fatigue crack growth rates can be reduced via texture control to achieve certain preferred crystallographic orientations through thermomechanical processing such that crack deflection is enhanced which in turn leads to high roughness induced crack closure but with less variations due to reduced orientation heterogeneity. In addition, this study demonstrated the unique capabilities of ultra-high-resolution X-ray tomography for the accurate analysis of crack growth and closure behavior. This technique can therefore be applied to understand the true fatigue behavior especially in materials with high yield strength where the expected crack tip opening is low i.e., < 1 μm.