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研究課題名（和文）Elucidation of dwell-fatigue behavior in Ti-6Al-4V alloys by AE monitoring and Crystal plasticity simulations

研究課題名（英文）Elucidation of dwell-fatigue behavior in Ti-6Al-4V alloys by AE monitoring and Crystal plasticity simulations

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研究成果の概要（和文）：この研究では、チタン合金Ti-6Al-4Vにおける冷間滞留疲労の挙動を、微細構造に敏感な観点から解明し、予測することが達成されました。光学顕微鏡（OM）、音響放射（AE）などのイン・シチュ非破壊評価手法、SEM、EBSDなどの微細構造特性評価、結晶塑性理論（CPFEM）に基づく多尺度シミュレーションの統合により、Ti-6Al-4V合金における滞留疲労のリアルタイム評価と予測のためのフレームワークが開発されました。具体的には、以下のタスクが取り組まれました：1. 滞留疲労下の微細メカニカル損傷メカニズムの統計的特性評価。2. 物理的に基づく、微細構造に敏感な滞留疲労損傷モデルの開発。

研究成果の学術的意義や社会的意義
Dwell-fatigue is a critical issue in titanium Ti-6Al-4V alloy and was clarified by means of a high-resolution strain mapping approach and numerical simulations. The developed tools could be used to predict the dwell-fatigue behavior and improve the reliability of Ti alloys under dwell condition.

研究成果の概要（英文）：The research successfully achieved the elucidation and prediction of cold dwell fatigue behavior in Ti-6Al-4V alloys from a microstructure-sensitive perspective. Through the integration of in-situ non-destructive evaluation methods (OM, AE), microstructural characterizations (SEM, EBSD), and multi-scale simulations based on crystal plasticity theory (CPFEM), a framework for real-time assessment and prediction of dwell-fatigue in Ti-6Al-4V alloy was developed. Specifically, the following tasks were addressed:
1. Statistical characterization of micro-mechanical damage mechanisms under dwell-fatigue.
2. Development of a physically based microstructure-sensitive dwell-fatigue damage model.

研究分野：Micromechanics

キーワード：DIC　Dwell-fatigue　Crystal plasticity　Finite Element Method　Titanium alloy

１．研究開始当初の背景

Cold dwell fatigue stands as a formidable challenge within the domain of structural materials, particularly in titanium alloys like Ti-6Al-4V (Ti-64). This phenomenon, a confluence of fatigue and creep behaviors, poses significant risks to component service life. The gravity of its effects became starkly apparent in September 2017, when an Airbus A388 encountered an uncontained engine failure due to cold dwell fatigue in its titanium fan blades. Subsequent investigations illuminated the susceptibility of Ti-64 alloys to cold dwell fatigue, contradicting earlier assumptions of their resilience. This revelation underscored critical knowledge gaps, including the presence of macro-zones in forged pieces and the lack of non-destructive flaw detection methods for cold creep-induced flaws. Additionally, while techniques such as Acoustic Emission (AE) showed promise in monitoring structural integrity under fatigue conditions, their application to cold dwell fatigue remained relatively unexplored.

２．研究の目的

In response to these pressing challenges, this research embarked on a comprehensive quest to unravel the intricacies of cold dwell fatigue mechanisms in Ti-6Al-4V alloys vis-à-vis pure fatigue. The overarching objectives were twofold: to elucidate these mechanisms and to develop predictive capabilities regarding cold dwell fatigue behavior. Embracing a microstructure-sensitive perspective, the research integrated in-situ non-destructive evaluation methods such as OM and AE, alongside microstructural characterizations like SEM and EBSD. Leveraging multi-scale simulations rooted in crystal plasticity theory (CPFEM), it aimed to construct a robust framework for real-time assessment and prediction of dwell-fatigue in Ti-6Al-4V alloy. Specifically, it sought to tackle three key tasks:

1. In-situ monitoring of dwell fatigue damage evolution.
2. Statistical characterization of micro-mechanical damage mechanisms under dwell-fatigue.
3. Development of a physically based microstructure-sensitive dwell-fatigue damage model.

３．研究の方法

To achieve its objectives, the research embraced a multifaceted approach, blending experimental and computational techniques across four main components:

Preparation and Characterization of Ti-64 Microstructures: Through varied thermo-mechanical treatments, an assortment of Ti-64 microstructures was crafted, each exhibiting distinct mechanical properties. These microstructures underwent meticulous characterization via optical microscopy (OM), scanning electron microscopy (SEM), and electron backscattered diffraction (EBSD), yielding comprehensive insights into their grain morphology, crystallographic texture, and other pertinent features.

Fatigue and dwell fatigue experiments under in-situ AE and OM monitoring: An experimental setup was developed for in-situ observation of the entire specimen surface by an OM mounted on a motorized stage. Fatigue and dwell-fatigue tests were interrupted at regular cyclic intervals, and the specimen surfaces were recorded automatically. The setup allowed for direct observation of naturally occurring cracks without the need for introducing defects such as notches or holes. Recorded pictures were also used to estimate accumulated plastic strain at the grain scale by the digital image correlation (DIC) method. Additionally, two AE sensors were fixed, one on both sides of the specimen, and AE waveforms generated during the tests were recorded in real-time by the Continuous Wave Memory (CWM) system developed in our group. The different characteristics of the AE data (amplitude, count rate, frequency) were analyzed by Bayesian inference methods such as the Markov Chain Monte Carlo (MCMC) to objectively connect the different stages of strain accumulation or crack propagation observed by OM as they generally related to local mechanisms near crack tips. The aim was to propose AE-derived strain accumulation or crack propagation models allowing the real-time monitoring of damage formation under fatigue or dwell-fatigue.

Local strain analysis by High-resolution digital image correlation: An automated framework for identifying slip systems and assessing strain localization of slip bands, termed ASSISL (automated Slip System Identification and Strain Localization analysis of slip bands), was introduced, using the results from high-resolution digital image correlation (HR-DIC), and was demonstrated in 1591 primary alpha grains of a bimodal Ti-6Al-4V alloy under tensile loading. The framework included: (1) alignment of electron backscattered diffraction (EBSD) maps with strain field maps from HR-DIC through treatment of EBSD distortion, (2) identification of slip band orientations from the strain field map of each grain through a Radon-transform-based algorithm, (3) assignment of slip systems with combined Schmid factor and critical resolved shear stress analysis, (4) quantification of plasticity by slip activities, which provided information on the numbers, positions, and mean strain of slip bands in each grain. This framework provided a method for analyzing slip activities in a large number of grains of polycrystalline metals in a time-saving and automated fashion. A quantitative examination of operating slip systems and strain localization on large-field HR-DIC data was then conducted using an automated analysis framework developed in a previous study. The findings revealed higher slip activities under dwell-fatigue conditions, evidenced by parameters such as slip band density, area fraction of grains activated with slips, and mean equivalent plastic strain intensities along slip bands through statistically sound analysis. A notable shift in dominant slip activity from basal slips to prismatic slips was observed under pure fatigue conditions, while dominant prismatic slip activity persisted throughout dwell-fatigue processes. Furthermore, slip bands with early-developed high strain localization, referred to as slip markings, were identified as prerequisites for surface crack initiation, and three types of slip markings were discovered. Finally, possible reasons for dwell-life debits, and potential anisotropy in the two major slip systems, basal and prismatic slips, were discussed.

Numerical simulations of fatigue and dwell-fatigue life using the CPFE method: Crystal Plasticity simulations were conducted on Ti-6Al-4V EBSD-based microstructures to elucidate the role of various hypotheses, including strain rate sensitivity and hardening rate, on the local response. The model was subjected to either fatigue or dwell-fatigue conditions (R=0.1, σmax=870 MPa) with a dwell period of 120s for 100 cycles. The local mechanical response was modeled by a rate-dependent phenomenological CP model considering dislocation slip on basal, prismatic, and pyramidal slip systems. The results were compared with experimental data from a previous study using DIC analysis. The developed model could reliably predict the local strain activity of the different availble slip system as well as the effect of the dwell-period on the strain accumulation. A model was finally proposed to predict the number of cycle for final failure based on the evolution of the strain accumulation.

４．研究成果

The culmination of these exhaustive efforts yielded profound insights into the micromechanical features influencing dwell life in Ti-64 alloy. Moreover, the successful application of AE for monitoring cold dwell fatigue underscored its potential as a potent tool for structural health monitoring. The research not only advanced our understanding of cold dwell fatigue mechanisms but also furnished a practical framework for real-time assessment and prediction of dwell-fatigue behavior in Ti-6Al-4V alloy. By synthesizing experimental observations with numerical simulations, the study not only elucidated the underlying physics but also proffered pragmatic guidelines for mitigating dwell fatigue effects in structural components.

5．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　2件／うちオープンアクセス　0件）

1．著者名 Hu Haoyu、Briffod Fabien、Shiraiwa Takayuki、Enoki Manabu	4．巻 103618
2．論文標題 Automated slip system identification and strain analysis framework using high-resolution digital image correlation data: Application to a bimodal Ti-6Al-4V alloy	5．発行年 2023年
3．雑誌名 International Journal of Plasticity	6．最初と最後の頁 1-43
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ijplas.2023.103618	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Hu Haoyu、Briffod Fabien、Yin Wujun、Shiraiwa Takayuki、Enoki Manabu	4．巻 182
2．論文標題 Quantitative investigation of slip band activities in a bimodal titanium alloy under pure fatigue and dwell-fatigue loadings	5．発行年 2024年
3．雑誌名 International Journal of Fatigue	6．最初と最後の頁 108203～108203
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ijfatigue.2024.108203	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　0件）

1．発表者名 Hu Haoyu, Briffod Fabien, Shiraiwa Takayuki and Enoki Manabu
2．発表標題 Pure fatigue and dwell-fatigue study on forged Ti-6Al-4V alloys through slip analysis by high resolution digital image correlation
3．学会等名 Japan Institute of Metals Lecture Meeting
4．発表年 2022年

1．発表者名 Amino Kyosei, Briffod Fabien, Shiraiwa Takayuki and Enoki Manabu
2．発表標題 Evaluation of scattering of fatigue propagation in Ti-6Al-4V alloys using Acoustic emission method
3．学会等名 Japan Institute of Metals Lecture Meeting
4．発表年 2022年

１．発表者名 Hu Haoyu, Briffod Fabien, Shiraiwa Takayuki and Enoki Manabu
２．発表標題 An automated slip system identification and strain analysis framework using high-resolution digital image correlation in of bimodal Ti-6Al-4V alloys
３．学会等名 Japan Institute of Metals Lecture Meeting
４．発表年 2023年

１．発表者名 Amino Kyosei, Briffod Fabien, Shiraiwa Takayuki and Enoki Manabu
２．発表標題 Comparison of fatigue crack prediction model in rolled Ti-6Al-4V alloys by acoustic emission parameters
３．学会等名 Japan Institute of Metals Lecture Meeting
４．発表年 2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関