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DEVELOPMENT OF METHODS FOR MICROTEXTURE CHARACTERIZATION AND DWELL FATIGUE LIFE PREDICTION OF DUAL PHASE TITANIUM ALLOYS

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Abstract: Near alpha and alpha plus beta titanium alloy can exhibit large reductions of dwell fatigue life. These reductions result from the formation of commonly oriented microscopic α-phase regions called microtexture (MTR). In this study, electron backscatter diffraction (EBSD), spatially resolved acoustic spectroscopy (SRAS) and ultrasonic testing have been used for characterization of MTR. The results of in-situ dwell fatigue test by digital image correlation (DIC) and the related quantitative fractography have been utilized to establish the role of MTR for dwell fatigue fracture. To develop a physical model to predict dwell fatigue life reduction depending on MTR, crystal plasticity analysis also has been conducted. This recently acquired information aims to be used to create a tool to estimate reduction of dwell fatigue life by non-destructive ultrasonic evaluation of titanium forgings, which will enable classification of materials from a MTR perspective and will support improvement of material quality in actual production. Results for Ti-64 will be presented here as it is a widely used alloy.

Keywords: Ti-6Al-4V, Microexture, Cold Dwell Fatigue

Introduction

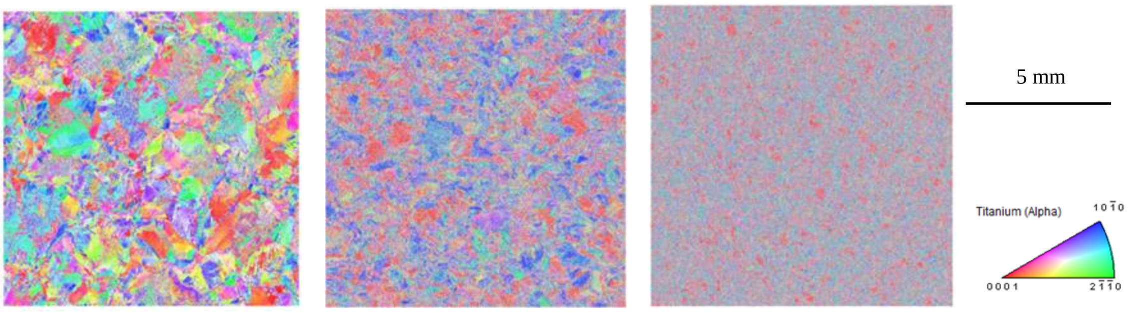
Introduction.

Titanium alloys are widely used in the fan and compressor stages of jet engines due to their lightweight advantages. However near alpha and alpha plus beta titanium alloys can exhibit large reductions of dwell fatigue life [1,2]. These reductions are caused by the presence of commonly oriented microscopic α-phase regions called Micro Texture Regions (MTRs), where the crystallographic orientation is locally aligned in a particular direction. These MTRs occur during the forging process. To support improvement of material quality in production and service from MTR perspective, it is needed to characterize MTR quantitatively and estimate the associated reduction of dwell fatigue life. For such a purpose, advanced works have been recently conducted. Vasisht et al., have suggested destructive MTR quantification method based on EBSD and proposed integrated computational modelling approach [3]. From MTR measurement perspective, Matt et al., have used spatially resolved acoustic spectroscopy (SRAS) which is able to collect EBSD-like data with higher speed than EBSD [4]. Pilchak et al., have reported ultrasonic techniques for non-destructive characterization of MTR in Ti alloys [5]. Crystal plasticity finite element method (CPFEM) has been utilized to predict the effect of MTR on dwell fatigue by considering the slip system of each grain and analyses the stress and strain distributions [6, 7]. In this study, Correlation between destructively measured MTR size, non-destructive ultrasonically measured MTR size and CDF life is investigated. The possibility of establishment of non-destructive ultrasonic MTR size criteria and prediction of CDF life by CPFEM are also discussed.

Experiments

Material

Ti-6Al-4V (Ti-64) forgings having qualitatively different level of MTR were prepared for this study. Ti-64 billets manufactured to the diameter of 10-22 inch were forged at 50-60F below the beta transus to various upset reductions, followed by an alpha plus beta solution treatment and anneal. EBSD images of these forgings are shown in Figure 1.

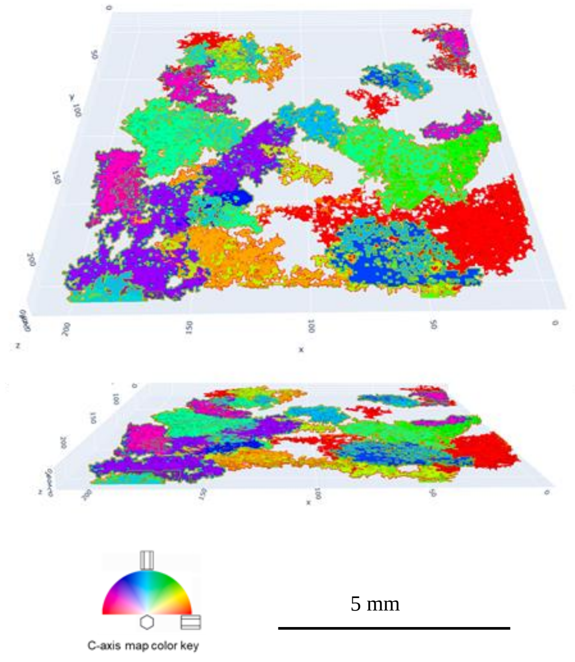


(a) Big size of MTR (BC) (b) Middle size of MTR (MC) (c) Small size of MTR (SC)

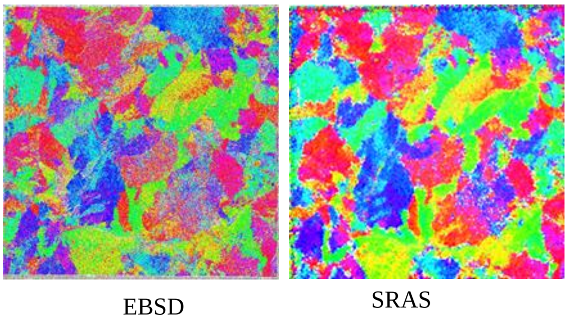
Figure 1. EBSD Images for forging samples having different levels of MTR.

Destructive 3D MTR measurement

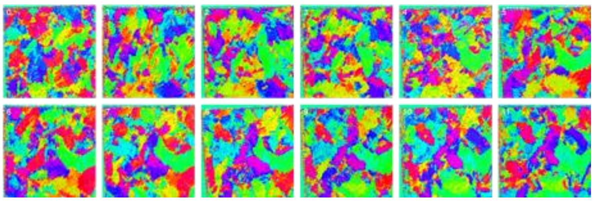
For the purpose to correlate destructive MTR data with non-destructive ultrasonic data, 3D MTR features should be obtained by destructive method because ultrasonic technique only captures 3D information. Destructive data acquisition was conducted using EBSD and Robo-Met. 3D automated serial sectioning system equipped with SRAS by Coherent Photon Imaging, LLC (CPI). Open-source software, Dream 3D was utilized to determine MTR size [5]. Representative scan is shown in Figure 2



(a) 3D MTR image of big MTR (BC)



(b) Comparison of EBSD and SRAS for 1st Slice



(c) Slices of SRAS

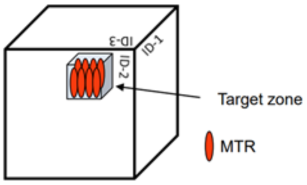
Figure 2. Representative destructive 3D MTR Images

Non-Destructively 3D MTR measurement

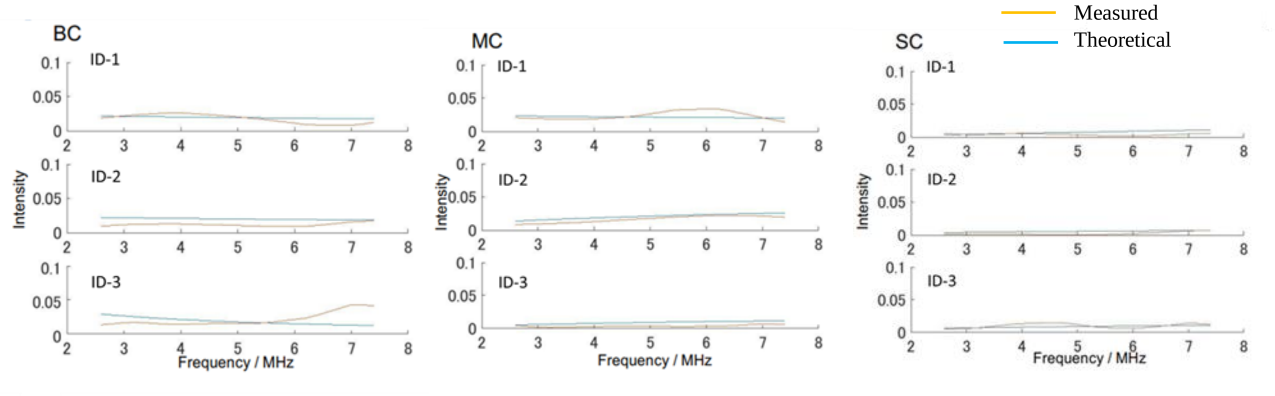
The volume range of 10 x 10 x 10 mm in 50 mm cube sample cut up from each forging was ultrasonically investigated as shown in Figure 3. Experimental backscattering was fitted with theoretical equation (1) to estimate average MTR size [5].

$$\sqrt{\frac{\alpha}{\eta}} = 8\pi k_L \frac{(l_\mathrm{r}/2)^2\sqrt{a^\mathrm{r}_\mathrm{MTR}}}{\sqrt{V}} \qquad (1)$$

α: : attenuation coefficient
$\eta^{1/2}$: backscattering coefficient
k_L: wavenumber
l_r: interaction length
α_{MTR}: radius of average MTR
V: effective volume of average MTR



(a) Image of MTRs in the cubic sumple

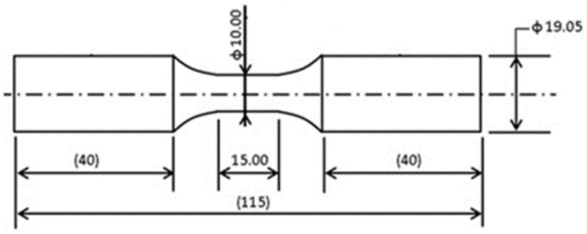


(b) Measured and fitted theoretical curves of backscatterng

Figure 3. Measured and theoretical backscattering coefficient

Cold Dwell Fatigue Testing

Fatigue samples applied in this work had an average gage diameter of 10 mm and a gage length of 15 mm shown in Figure 4. All gage sections were ground and polished with a low stress method to minimize the effect of residual stress. CDF tests were carried out using a hydraulic uniaxial fatigue testing machine and subjected to loading waveforms shown in Figure 5. The maximum stress was set at 0.9 x 0.2% yield stress, with stress ratio of 0.01. The dwell time at maximum load was 120 s.



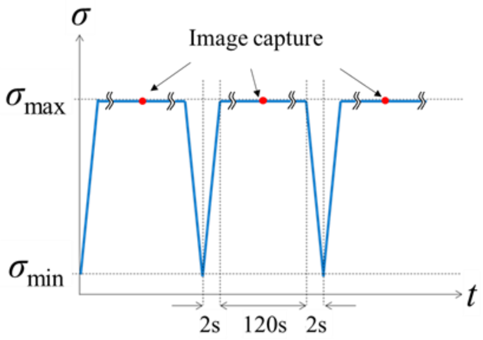


Figure 4. Dimensions of the dwell fatigue specimen (Unit: mm)

Figure **5**. Loading wave form

Calibration for Crystal Plasticity Model

Ti-64 consists of α-phase with HCP structure and β-phase with BCC structure. Since the volume fraction of the β-phase is small in this study, only the α- phase was modelled in this study. As a model expressing the relationship between the slip velocity $\dot{\gamma}^i$ and the resolved shear stress τ^i of the slip system i, the following viscoelastic constitutive equation proposed by Cuddihy [8] was used and was calibrated by stress vs strain curves of tensile tests with various strain rates.

$$\dot{\gamma}^i = \begin{cases} 0, & |\tau^i| < \tau_c^i \\ \rho_{\mathrm{SSD}}^{\mathrm{m}} b^{i^2} v \exp\left(-\frac{\Delta F}{kT}\right) \sinh\left(\frac{(|\tau^i|-\tau_c^i)\Delta V^i}{kT}\right), & |\tau^i| \ge \tau_c^i \end{cases} \qquad (2)$$

$\dot{\gamma}^i$: slip velocity
τ^i : resolved shear stress
$\rho_{\mathrm{SSD}}^{\mathrm{m}}$: density of mobile dislocations
b^i : magnitude of the Burgers vector,
v: dislocation jump frequency,
ΔF : activation energy
k: Boltzmann constant
T : absolute temperature
ΔV^i : activation volume
τ_c^i : critical resolved shear stress,

DIC Measurement

For the purpose to verify determine stress criteria for dwell fatigue life, in situ DIC dwell fatigue testing was performed. Rectangular fatigue sample was used with random patterns consisting of fine dots to the specimen. Figure 6 illustrates DIC dwell fatigue specimen shape and Figure 5 shows loading wave form and timing of image capture. Strain distribution of fracture initiation MTR is shown in Figure 7. In order to identify crack initiation MTR, quantitative EBSD fractography is applied as shown in Figure 7(c).

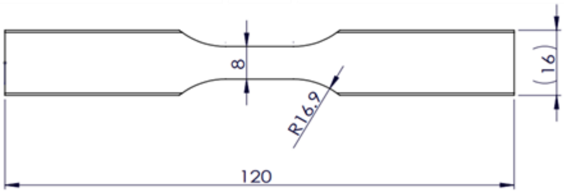
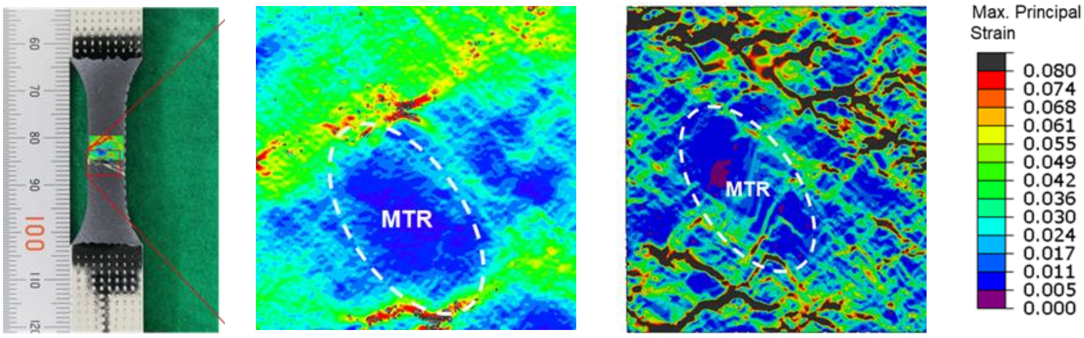
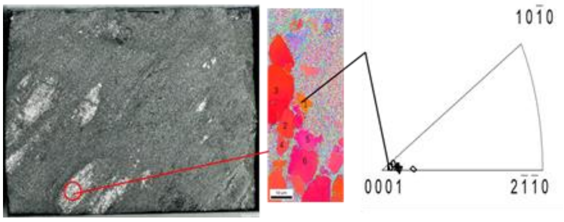


Figure 6. Dimensions of DIC dwell fatigue specimen (Unit: mm)



(a) DIC strain distribution

(b) CPFEM strain distribution

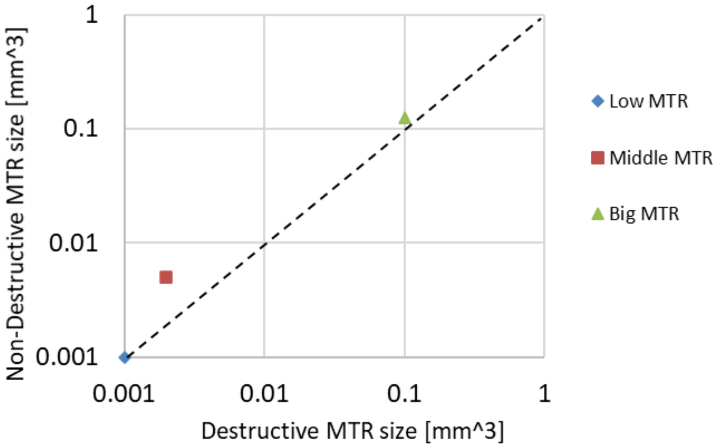


(c) Quantitative EBSD fractography

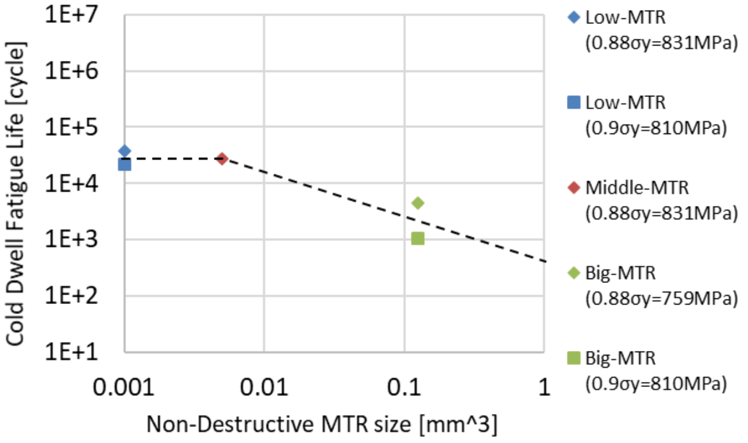
Figure 7. Strain distribution around MTR during dwell fatigue

Result and Discussion

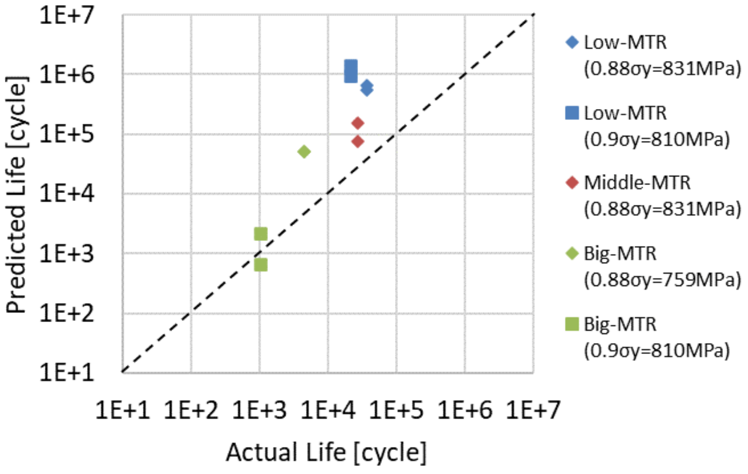
Comparison of non-destructive and destructive MTR size is summarized in Figure 8(a). Although the amount of data is small, a good correlation between both is shown. Figure.8(b) shows a comparison of non-destructive ultrasonic MTR size and CDF life. As the MTR size decreases, the CDF life increase, but remains constant. It implies the existence of a threshold criteria for non-destructive MTR size to significantly decrease in CDF life. Figure 8(c) illustrates a comparison of measured CDF fatigue life and predicted life by CPFEM model. It shows relatively good agreement, but the difference between prediction and actual life is larger in the part of with small MTR.



(a) Destructive vs Non-Destructive average MTR size



(b) Non-Destructive average MTR size vs CDF life



(c) Actual vs Predicted CDF life

Figure 8. Correlation between destructive MTR size, non-destructive ultrasonic MTR size and CDF life

Result and Discussion

Correlation between destructively measured MTR volumetric size, non-destructive ultrasonically measured MTR size and CDF life was investigated by using 3D methodology, and good agreement was shown. It suggests that there is the possibility that non-destructive method to detect MTRs that reduce CDF life is established. It was confirmed that CPFEM prediction for CDF life using input parameter as MTR size, MTR orientations and stress level is relatively fitted to actual life but further investigation is needed to understand the difference in the part with small MTR.

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