# Quantitative Characterization of Fracture Features in Titanium Alloys

## Introduction

Fatigue is an important consideration in life management of aircraft engine components made from Ti-alloys. Understanding and *quantifying* the fatigue fracture mechanisms are critical for design and sustainment of components. Traditional fractography in a scanning electron microscope (SEM) provides important, but *qualitative* information on fracture mechanisms.

## Challenge

The main challenge is to *non-destructively* quantify the fracture mechanisms. Transmission electron microscopy (TEM) can provide quantitative crystallographic information associated with fatigue crack-initiation. However, specimen preparation with focused ion beam (FIB) is time-consuming and destructive. Electron BackScatter Diffraction (EBSD) in an SEM can also be a destructive approach, if cross-sectional polishing of fractured specimens is required. Moreover, with this approach, spatial orientation of fracture features in 3D needs to be determined.

## Objectives

(1) Characterize quantitatively the spatial orientation of fracture features in 3D, including serrations that were observed for the first time within an *α grain* in this work, and

(2) Obtain EBSD data directly (non-destructively) from fracture surface and combine with spatial orientation to determine crystallography of fracture features

## Material and Experimental Details

The methodology is demonstrated with characterization of a fatigue-tested specimen of near-α titanium alloy (Ti-6Al-2Sn-4Zr-2Mo), which had a duplex microstructure consisting of globular primary α grains and lamellar transformed β regions. The diameter of specimen in gage section was 4.27 mm, and it had been tested under uniaxial loading at room temperature, a stress ratio (= $\sigma_{min}/\sigma_{max}$) of 0.1, frequency of 20 Hz and $\sigma_{max}$ = 713 MPa. The specimen failed at 61,477 cycles.

The failed specimen was cleaned ultrasonically in acetone and then in alcohol. To preserve the pristine fracture surface representing the underlying fatigue micromechanisms, no additional preparations (e.g., etching) were carried out. The characterization in SEM was conducted at 20 kV (Fig. 1 and 2), and stage was tilted to 70° for collection of EBSD data (Fig. 3). At stage tilt of 0°, the longitudinal direction of specimen (i.e., the loading axis during fatigue test) is aligned with the electron beam direction.

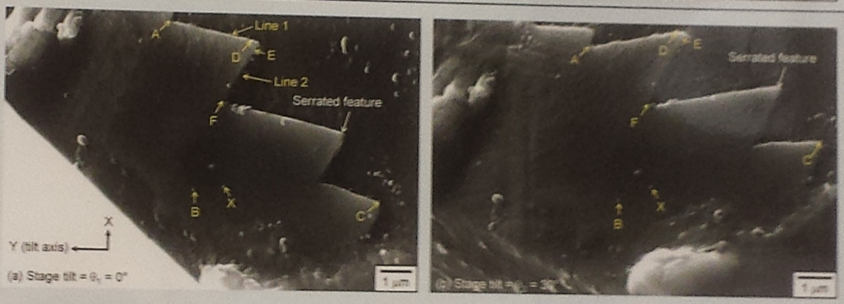
**Fig. 1:** SEM images of the fatigue fracture surface in Ti-6Al-2Sn-4Zr-2Mo. (a) Two fatigue crack-initiation sites (I and II), (b) faceted fracture at the initiation site I, and (c) crack initiation in a surface-connected primary *α* grain.

(a) Secondary electron image

(b) Secondary electron image

(c) Backscattered electron image

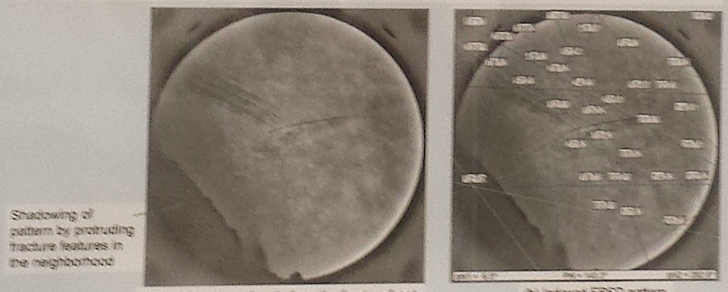
**Fig. 2:** Higher magnification SEM (secondary electron) images of the crack-initiating facet at stage tilts of (a) 0 and (b) 30°. The orientation of SEM stage axes system relative to images is also shown in (a). The tilt axis is along the horizontal direction of SEM images. The (x, y) coordinates of three features ('A', 'B' and 'C') with respect to an arbitrarily selected origin (feature 'X') were analyzed using equations (1) – (3) to determine the facet normal vector $\vec{n}$ (= i – 7.38 j – 10.50 k). The (x, y) coordinates of two features on a line (e.g., 'A' and 'D' on line 1) were analyzed using equations (1) and (2) to determine vectors $\overline{AD}$ (= i + 4.51 j – 3.35 k) and $\overline{EF}$ (= i – 0.55 j + 0.62 k), which represent lines 1 and 2, respectively. The angle between these two lines was calculated from equation (4) and equals 61°. Fracture lines parallel to $\overline{AD}$ and $\overline{EF}$ form the serrated feature.



(a) Stage tilt = $\theta_1$ = 0°

(b) Stage tilt = $\theta_2$ = 30°

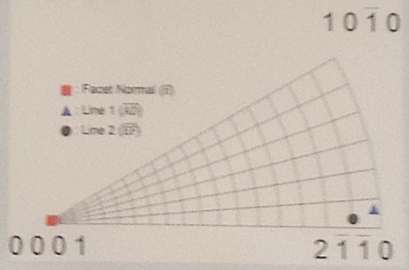
**Fig. 3:** By rotating stage in small increments (~15°) and checking the image of phosphor screen at each rotation, it was possible to obtain EBSD pattern directly from the fracture facet (a). Indexing of the pattern (b) gives the crystallographic orientation of grain, which corresponds to crack-initiating facet.



(a) EBSD pattern directly from the fracture facet

(b) Indexed EBSD pattern

**Fig. 4:** Inverse pole figure showing the crystallographic orientation of facet normal ($\vec{n}$), and lines 1 ($\overline{AD}$) and 2 ($\overline{EF}$). The methodology including determination of spatial orientation and EBSD, is accurate to within ~3°.



$(x_A^o, y_A^o)$ ar [illegible] feature 'A' (Fig. 2) [illegible] $\theta_1$ and $\theta_2$, respectiv[illegible] ates of feature 'A' [illegible] (X, Y and Z). $\overline{AB}$ [illegible] 'A' to 'B' in 3D [illegible] feature 'B' to 'C'. [illegible] X, Y and Z, res[illegible] and $\overline{BC}$ is $\vec{n}$ [illegible] feature (facet) pl[illegible] and 'C'. α is the [illegible]

On the [illegible] is observe[illegible] lines (F[illegible]

The fac[illegible] basal, wherea[illegible] the serrate[illegible] (<$2\bar{1}\bar{1}$[illegible] orienta[illegible] betwe[illegible] ~60° [illegible] with [illegible] two < [illegible] crysta[illegible] ns in a packe[illegible]

## [illegible]sion[illegible] Sign[illegible]

Obs[illegible] feature cra[illegible] an α grai[illegible] ha[illegible] in literatur[illegible]

From [illegible] image pa[illegible] stage tilts, the spatial orientations of planar and linear features were determined in 3D.

A non-destructive approach was demonstrated to collect EBSD data from the grain associated with faceted crack-initiation, without recourse to cross-sectional polishing.

Combining the spatial orientation and EBSD data established that the facet plane was basal and the lines forming the serrated feature were along <a>-type slip directions.

Although this methodology is demonstrated with fatigue fracture surface in a Ti-alloy, the approach is applicable to characterization of crystallography for other planar (e.g., growth facets) and linear (e.g., whiskers) features in crystalline materials.

**Class 2: Electron Microscopy**

BEST IN SHOW 2016

JACQUET-LUCAS AWARD