



**AFRL-RX-WP-TP-2009-4151**

**LOW  $\Delta K$  FACETED CRACK GROWTH IN TITANIUM  
ALLOYS (POSTPRINT)**

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**DECEMBER 2007**

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YY) December 2007		2. REPORT TYPE Journal Article Postprint		3. DATES COVERED (From - To) 01 December 2007 – 01 December 2007	
4. TITLE AND SUBTITLE LOW $\Delta K$ FACETED CRACK GROWTH IN TITANIUM ALLOYS (POSTPRINT)				5a. CONTRACT NUMBER In-house	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62102F	
6. AUTHOR(S) A.H. Rosenberger (AFRL/RXMLN) A.L. Pilchak, A. Bhattacharjee, and J.C. Williams (The Ohio State University)				5d. PROJECT NUMBER 4347	
				5e. TASK NUMBER RG	
				5f. WORK UNIT NUMBER M02R3000	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Metals Branch (RXMLN) Metals, Ceramics and NDE Division Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH 45433-7750 Air Force Materiel Command, United States Air Force				8. PERFORMING ORGANIZATION REPORT NUMBER  AFRL-RX-WP-TP-2009-4151	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Materials and Manufacturing Directorate Wright-Patterson Air Force Base, OH 45433-7750 Air Force Materiel Command United States Air Force				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL/RXMLN	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RX-WP-TP-2009-4151	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES Published by International Journal of Fatigue 31 (2009) 989-994 PAO Case Number and clearance date: WPAFB 08-0082, 16 January 2008. © 2008 Elsevier Ltd. The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.					
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15. SUBJECT TERMS titanium alloys, short cracks, crack growth, faceted growth, overloads					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			James M. Larsen
					19b. TELEPHONE NUMBER (Include Area Code) N/A



## Technical note

Low  $\Delta K$  faceted crack growth in titanium alloysA.L. Pilchak<sup>a,\*</sup>, A. Bhattacharjee<sup>a</sup>, A.H. Rosenberger<sup>b</sup>, J.C. Williams<sup>a</sup><sup>a</sup> Department of Materials Science and Engineering, The Ohio State University, Columbus, OH 43210, USA<sup>b</sup> Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH 45433, USA

## ARTICLE INFO

## Article history:

Received 11 December 2007

Received in revised form 28 March 2008

Accepted 31 March 2008

Available online 7 April 2008

## Keywords:

Titanium alloys

Crack growth

Faceted growth

Overloads

## ABSTRACT

This communication describes the results of spectrum fatigue loading experiments conducted on cast and hot isostatically pressed Ti–6Al–4V. The purpose of the experiments is to elucidate the nature of faceted crack growth that occurs at low values of  $\Delta K$  in titanium alloys during cyclic loading. The results clearly show that multiple load cycles are required for the crack to traverse one grain and produce a single facet. The confusing terminology related to low  $\Delta K$  fatigue fracture topography is reviewed and the term “low  $\Delta K$  faceted growth” is proposed as a preferred descriptor.

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## 1. Introduction

The propagation of fatigue cracks in structural metals is known to create features on fracture surfaces that can be used in understanding the crack growth history. Fatigue striations are the best known of these features. It also is recognized that crack growth at low stress intensity ranges ( $\Delta K$ ) can create a faceted fracture topography, which is not accompanied by the formation of striations [1–10]. The general form of the stress intensity factor can be defined as  $K = Y\sigma\sqrt{\pi a}$  where  $Y$  is a constant,  $a$  is the crack length and  $\sigma$  is the applied stress.  $\Delta K$  is the difference between the maximum and minimum value of the stress intensity factor during cyclic loading. The value of  $a$  is small near the crack initiation site, thus for a constant cyclic load amplitude, the corresponding value of  $\Delta K$  will be low when compared to longer crack lengths in the same sample. The total amount of crack extension that occurs by faceted growth will be mainly governed by the applied stress level and the load ratio ( $R$ ). When tested at high fractions of the yield strength, a much smaller region of faceted growth is expected compared to samples tested around the fatigue strength at  $10^7$  cycles. On the other hand, faceted growth occurs over longer crack lengths at high  $R$  ratios [11] and in coarser microstructures [12]. The importance of  $\Delta K$  to fracture topography is related to the fact that the cyclic crack tip plastic zone size is proportional to  $\Delta K^2$ . Faceted crack advance is generally observed at low values

of  $\Delta K$  when the cyclic plastic zone size is small compared to the grain size while microvoid coalescence and ductile intergranular failures are typical fracture modes at high  $\Delta K$  with striation growth occurring in between [10].

Facets are commonly observed on the fracture surfaces of Ti alloys subjected to both continuous cyclic and dwell fatigue loading. In the case of continuous cyclic loading, in the absence of surface residual compressive stresses, cracks tend to initiate at the surface of the sample and propagate along planar slip bands [5,13]. This should tend to favor initiation on a plane of high resolved shear stress that is oriented at  $45^\circ$  to the loading axis, and indeed this is observed experimentally. In an investment cast and hot isostatically pressed (HIP'd) Ti–6–4 alloy, Eylon and Strope [14,15] observed that the facets were inclined to the loading axis when tested at maximum stress levels less than half the yield strength ( $R = 0.1$ ). Several facets initiated along residual casting pores, and in one instance a crack initiated along grain boundary  $\alpha$  that was oriented at  $45^\circ$  to the load axis. Jin and Mall [12] observed that cracks initiated at  $45^\circ$  to the load axis in Ti–6242(+0.1Si) in both basket-weave and fully lamellar conditions with reported colony sizes in the range of 10–95  $\mu\text{m}$  and 70–250  $\mu\text{m}$ , respectively. These tests were conducted at stress levels below the yield strength,  $R = 0.1$  and the cracks initiated from semi-circular notches. Davidson and Eylon [16] investigated a large number of facets on the fracture surfaces of Ti–11 and IMI685 samples subjected to both cyclic and dwell loading. The crack initiation sites were generally surface and subsurface for continuously cycled and dwell samples, respectively. The samples were tilted up to  $40^\circ$  in order to get the plane of the facet perpendicular to the electron optic axis to make

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selected area electron channeling measurements, implying that the facets were inclined to the load axis, though the required tilt angles were not reported for specific facets. Many facets were identified as being on or near the basal plane, although deviations as high as  $35^\circ$  were also measured.

Facets found in subsurface initiation sites are different than those found in near free surfaces and stress concentrations caused by pores and notches. The most obvious difference is that the facets are oriented approximately perpendicular to the loading axis when tested at maximum stress levels below the yield strength [11,17–22]. When tested at values exceeding the yield strength, the facet angle becomes inclined at  $45^\circ$  to the load. This is typically considered to be a characteristic of dwell fatigue, though the facets in continuously cycled samples follow the same trend when the initiation site is subsurface [11,17,21]. This behavior is apparently independent of microstructure having been observed in coarse lamellar [20], fine basket-weave [11] and bi-modal microstructures [20,21]. Since a critical combination of shear and normal stresses are required to initiate a crack [5], the Stroh-like model proposed by Evans and Bache [11] is often invoked to explain how a shear stress is developed on the basal plane even when it is perpendicular to the applied load. Dislocation pileups in an adjacent grain impose additional normal and shear stresses onto the basal plane, which can assist in the formation of a crack. Stress-strain redistribution is certainly an important factor in dwell fatigue crack initiation.

In the Ti alloy fatigue literature, the facets have been called variously: cleavage facets [8,23–25], quasi-cleavage facets [11,17,20,26], cleavage-like facets [5,6,14] and cyclic cleavage facets [1,3,9]. The difficulty is that the term “cleavage” implies to some extent, among other things, that each facet is created in a single load cycle and that crack extension is a normal stress controlled process. There is limited evidence in the literature that this is not the case [1,4], but there is still some uncertainty [9]. McBagonluri et al. [9] varied  $R$ , and, therefore,  $\Delta K$ , during fatigue testing to alter fracture topography in order to examine crack front profiles in Ti-6242. The authors pointed out that, at low values of  $\Delta K$ , faceted fracture topography was observed but the overload cycles in the command pattern had insufficient resolution to determine if the facets were formed in a single cycle or multiple cycles. In contrast, in a study of coarse grained, high oxygen, unalloyed Ti by Paton et al. [1] there were multiple overload markers on a single facet providing clear evidence of cyclic crack propagation across the facet. The facets were approximately  $100\ \mu\text{m}$  in diameter and there were 200 cycles in between overloads. Paton et al. [1] have also observed that fatigue fracture topography varies as a function of  $\Delta K$ . A notable result from the study was that no sharp transition between faceted growth and striation growth existed. Rather, there was a gradual change from faceted growth to striation growth in Ti-6-4 and Ti-6246 in several microstructural conditions. Facets were observed at values of  $\Delta K$  up to  $22\ \text{MPa}\sqrt{\text{m}}$ , although striations were observed at values of  $\Delta K$  as low as  $7.7\ \text{MPa}\sqrt{\text{m}}$ . Wanhill et al. [3] observed a similar trend in forged Ti-6-4 with a bi-modal microstructure. At locations corresponding to  $\Delta K = 10\text{--}14\ \text{MPa}\sqrt{\text{m}}$  the fracture surface was faceted through both the primary  $\alpha$  and transformed  $\beta$  regions. At slightly higher  $\Delta K$  ( $16\text{--}18\ \text{MPa}\sqrt{\text{m}}$ ) both facets and fatigue striations were visible on some locations of the fracture surface. The observations that both striations and facets are present over a range of  $\Delta K$  can be accounted for on the basis of crystallographic orientation. From the work of Bowen on the effect of crystallographic orientation on fatigue crack growth in strongly textured Ti-6-4 [27], it can be inferred that a crack advancing through a grain suitably oriented for easy slip on two prismatic slip systems can extend by striation growth at lower values of  $\Delta K$  than a grain loaded parallel to the  $c$ -axis where only  $\langle c+a \rangle$  slip, which has higher CRSS [28], is active. This is important

because it means that striation spacing measurements cannot be correlated to  $\Delta K$  as is often done in cubic materials, especially Al alloys [10].

In an attempt to clarify the nature of faceted crack growth during continuous cyclic loading, we have performed several specially designed fatigue tests that include periodic overloads to mark the fracture surface. The results of these tests are summarized in this communication and reveal that many cycles are required for the crack to traverse a single facet. The exact number would depend on  $\Delta K$ , the materials microstructure, especially length scale, and on the local crystallographic orientation. Quantifying these dependencies, however, is not the focus of the present study. The practical significance of this issue relates to the degree of accuracy associated with striation counting, which is often done during failure analysis to estimate cyclic loading history after crack initiation. The central point we make here is that counting striations while either completely neglecting or counting each facet as one cycle leads to incorrect cycle counts that can significantly underestimate the number of cycles during crack propagation. We recommend this practice be discontinued by failure analysts who may be using it.

## 2. Experimental procedure

Investment cast and HIP'd Ti-6Al-4V (Ti-6-4) was chosen for this study because of the large prior  $\beta$  grain and  $\alpha$  colony sizes. Fatigue fractures in this microstructural condition contain faceted initiation sites that compare well with  $\alpha$  colony size. The microstructure consisted of prior  $\beta$  grains of the order of  $1\ \text{mm}$  in diameter with an approximate  $\alpha$  colony size of  $500\ \mu\text{m}$  (Fig. 1). The  $\alpha$  colonies consisted of packets of aligned  $\alpha$  lamellae that obey the Burgers orientation relationship (BOR) with the parent  $\beta$  phase and the remaining  $\beta$  ‘ribs’ that separate them. The BOR states that  $(0001)\alpha \parallel \{110\}\beta$  and  $\langle 2\bar{1}\bar{1}0 \rangle\alpha \parallel \langle 1\bar{1}\bar{1} \rangle\beta$ .

Four-point bending fatigue tests were performed using a servo-hydraulic test frame fitted with a self-aligning fixture that was similar to the one fabricated by Zhai et al. [29]. Samples with dimensions of  $25\ \text{mm} \times 7\ \text{mm} \times 3\ \text{mm}$  were excised from the as-cast and HIP'd plate using a wire electrical discharge machine (EDM). The samples were tested with the as-machined surface finish (unnotched). Several preliminary tests were performed in order to establish the correct combination of stress amplitude,  $R$ , peak overload and the number of cycles in between overloads to permit multiple overload markers to be placed on a single facet. The resul-

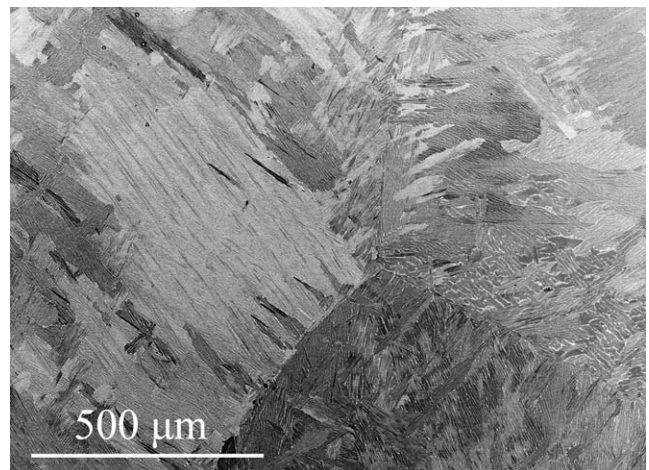
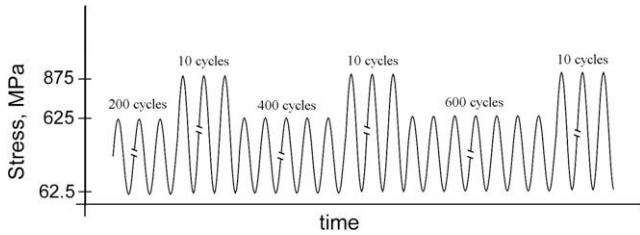


Fig. 1. A typical backscatter electron image of cast and HIP'd Ti-6Al-4V used in this study. A triple point between three prior  $\beta$  grains is shown.

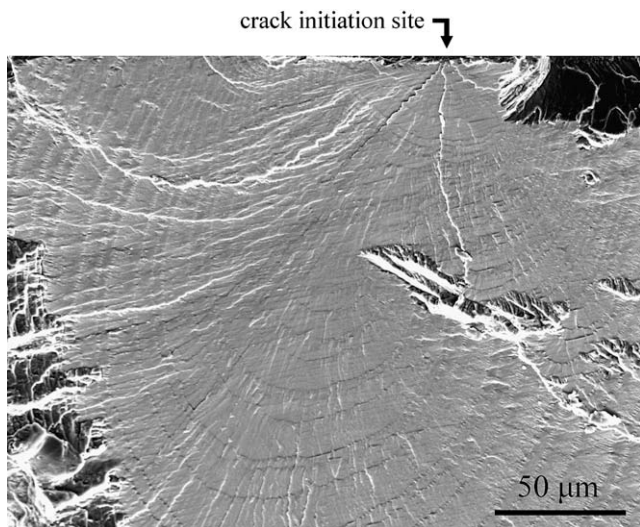


**Fig. 2.** A schematic representation of the loading sequence used to mark the faceted initiation sites in the cast alloy.

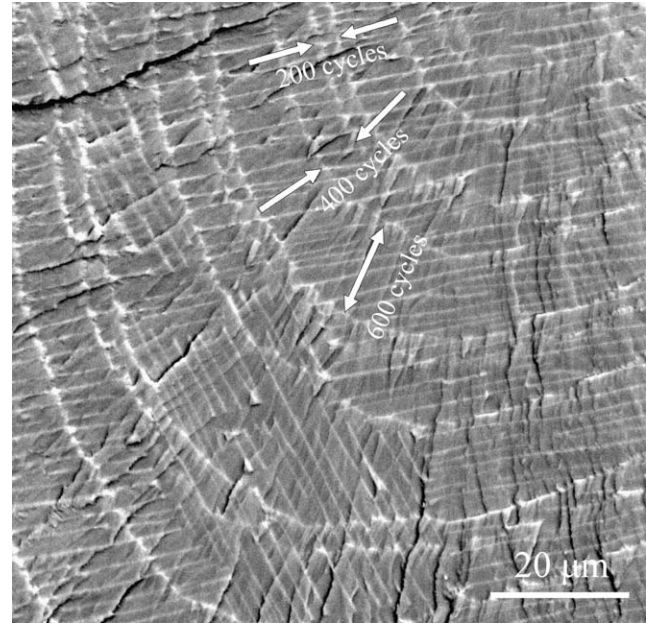
tant loading pattern is shown schematically in Fig. 2. Continuous cycling was performed at a maximum surface tensile stress of 625 MPa,  $R = 0.1$  at a frequency of 60 Hz in ‘blocks’ of 200, 400 and 600 cycles. Ten overload cycles at a peak stress of 875 MPa, approximately 1.05 times the macroscopic yield strength, separated each block of continuous cycling. Tests without overload spikes were performed at a variety of maximum stress levels to observe naturally occurring facets. Qualitatively, the facets were quite comparable for both loading schemes in terms of size and orientation with respect to the loading axis. Microscopically, the surfaces of the facets produced with the overload peaks were generally rougher than those in the continuously cycled samples. The overload peaks introduced additional ‘tongues’ on the facet, often at  $\alpha/\beta$  interfaces, that are similar to those described by Beachem and Pelloux [30].

### 3. Results and discussion

Examination of the facets in samples subjected to the periodic overload command pattern revealed a set of markings whose spacing qualitatively matched the spacing between the periodic overloads in Fig. 2. A typical one of these facets is shown in Fig. 3. Quantitative tilt fractography [22,31] was used to determine the angle between the facet normal vector ( $F$ ) and the loading axis, which was  $40.1^\circ$ . The semi-elliptical markings on the facet bear no obvious relation to the microstructural features, but are consistent with the expected crack front profile (Fig. 4). Therefore, it is concluded that the markings are a result of the periodic overloads that were applied to the sample. Similar markings have been



**Fig. 3.** Secondary electron image of the crack initiation facet with overload markings present. The crack initiation site directly bordered the surface of maximum tension during cyclic loading.



**Fig. 4.** A higher magnification of Fig. 3 generated by collecting backscattered electrons. Atomic number contrast between the  $\alpha$  and  $\beta$  phases clearly shows that two variants of the BOR are present on a single facet.

attributed to periodic overloads in aluminum alloys [32], titanium alloys [8,9] and also nickel based alloys [33].

The significance of the markings is that they show that multiple cycles are involved in the formation of a single facet. Consequently, use of the word ‘‘cleavage’’ to describe such facets is at the very least misleading and should be avoided. Cleavage fracture is generally associated with a monotonic loading failure mechanism where crack extension is rapid and driven by a critical normal stress while fatigue crack growth in metals is related to cyclic slip induced damage accumulation. To be explicit, true cleavage fracture occurs when the concentrated normal stresses at the crack tip are able to break atomic bonds, i.e. there is no local plastic flow [34]. Thompson [35] has noted that the terms ‘‘cleavage’’ and ‘‘quasi-cleavage’’ are often used inappropriately and the fact that a fatigue facet resembles a cleavage facet is not sufficient evidence to term it as such. Evans and Bache [11,36] have stated that the term ‘‘quasi-cleavage’’ does not mean that the failure was as a result of a brittle fracture mechanism, but instead due to the gradual separation of slip damage concentrated within a persistent planar slip band. We agree with this point but argue that use of the term ‘‘quasi-cleavage’’ should be discontinued. The term was originally introduced by Beachem and Pelloux [30] to describe the mechanism associated with the formation of the transgranular, brittle appearing fracture facets in quenched and tempered steels. Due to the fine scale of the microstructure, the techniques necessary to fully characterize the crystallography of the fracture facets were unavailable at the time. The modifier ‘‘quasi-’’ was adopted primarily because it remained unproven that the fracture had occurred along a crystallographic plane. The facets were much larger than the fine scale martensite and also did not appear as flat as cleavage facets in iron indicating that some amount of plasticity was associated with the fracture. Closer examination of the facets revealed that the river markings that were present were not steps like in conventional cleavage, but rather a series of ridges. Comparing mating sides of the fracture surfaces revealed that steps were opposite and complementary for cleavage fracture, but there was non-complementary ridge-to-ridge matching in quasi-cleavage [30,35].

According to Beachem and Pelloux [30], quasi-cleavage fractures generally initiate internally within a grain and propagate in a step-wise fashion by linking submerged microcracks with the main crack front. Ridges on the facet were thought to be formed when the last ligament between the microcrack and the primary crack failed. In a later work, Beachem [37] used single surface trace analysis to establish that the facet plane was parallel to the  $\{001\}$  ferrite planes. Beachem argued that the modifier “quasi”- was no longer necessary as its primary purpose was due to the uncertainty of the fracture plane.

Further, it is noted that the quasi-cleavage fractures observed by Beachem and Pelloux [30,37] were in monotonically loaded samples. Aita and Weertman [38] were among the first to report the presence of quasi-cleavage facets on the fracture surface of a Fe–0.64C fatigue specimen. The facets resembled those observed by Beachem and Pelloux and were termed quasi-cleavage facets because there was uncertainty regarding the crystallographic orientation of the facets. There were, however, a few differences between the facets formed during monotonic testing and the facets produced by fatigue loading raising doubts as to whether they are truly quasi-cleavage facets. Aita and Weertman [38] reported that crack extension occurred at the crack tip and not by linking up microcracks ahead of the crack tip. There was also a clear initiation point at the edge of the facet with steps parallel to the direction of crack propagation and it was stated that cracks were arrested at facet boundaries. There was no clear indication if each facet was formed by a single or multiple load cycles. This mechanism of crack growth during cyclic loading, even in a similar material, was still quite different than the quasi-cleavage crack extension mechanism proposed by Beachem and Pelloux [30].

In the present study, while some attributes of quasi-cleavage are present on the facets, others are not. First, the crack initiation sites are found on the edges of facets, not internally. This is consistent with what has previously been observed on both surface and subsurface initiation sites in other Ti alloys [35]. The absence of inclusions and hard second phases in Ti alloys, which act as microcrack initiation sites ahead of the crack tip in steels, make it unlikely that the crack propagates by the quasi-cleavage mechanism. The absence of tear ridges on the facets from the continuously cycled samples (no overloads) supports this argument. Analyzing complementary fracture surfaces of continuously cycled samples revealed step-to-step matching over a range of maximum stress levels in the cast + HIP condition. Though occasional step-to-step matching is found in quasi-cleavage [30,35], Thompson [35] has pointed out that ridge-to-ridge matching is a diagnostic of quasi-cleavage.

The primary purpose of the modifier quasi-, according to Beachem [37], was that it distinguished that there was uncertainty regarding the crystallographic plane of fracture. With respect to the orientation of the facets relative to the hcp crystal structure in near- $\alpha$  and  $\alpha + \beta$  titanium alloys, it is agreed that the facets have basal or “near” basal orientation [18,20–22]. This means that the  $[0001]_{\alpha}$  direction in the crystal is either parallel or nearly parallel to the facet normal direction (Fig. 5a). The presence of steps on the facets can account for the occurrence of facets with “near” basal orientations. Wojcik et al. [5] have suggested that the steps form as a result of cracks propagating on both basal and prism planes. As shown schematically in Fig. 5, a facet can have an apparent non-basal orientation while still forming on the basal plane. A series of steps are present on the facet which produce an apparent facet plane that can deviate from the basal plane. In general, the steps are parallel to one of the  $\langle a \rangle$  slip directions in the basal plane [5,39]. The orientation of the  $\beta$  platelet with respect to the crack growth direction will depend on which basal slip system is active. The terraces between the steps are generally planar and appear smooth in the present material; occasionally finer steps parallel

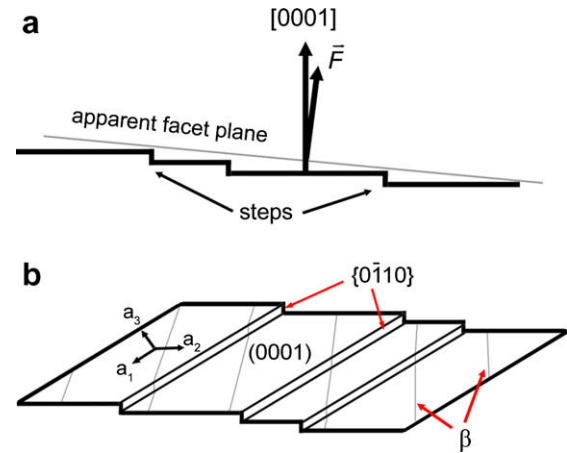
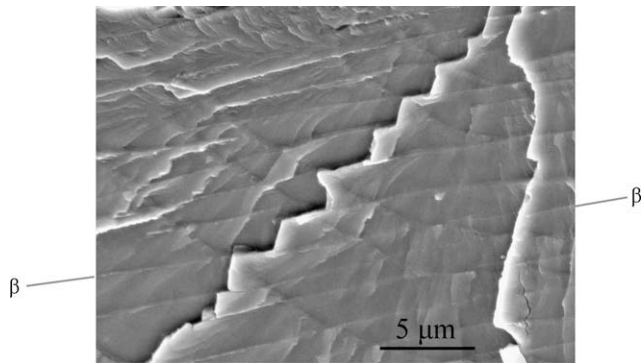


Fig. 5. (a) A schematic diagram of the steps that are commonly found on the facets Ti alloys viewing along  $(2\bar{1}10)$ . The basal plane normal and the direction normal to the facet plane are designated by  $[0001]$  and  $\vec{F}$ , respectively. (b) The schematic shown from an oblique angle. The steps are generally parallel to one of the  $\langle a \rangle$  slip directions.

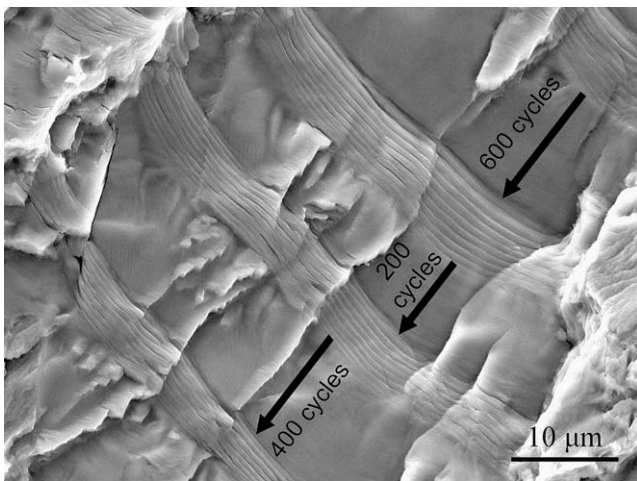
to the major step are resolvable indicating that this fracture mechanism may be occurring on multiple length scales. As a consequence of the steps, the basal pole makes an angle with the apparent fracture plane normal. Recent work combining electron backscatter diffraction (EBSD) and quantitative tilt fractography has allowed for accurate measurements of crystallography to be made by also considering the spatial orientation of the facet from which the crystallographic data was obtained. EBSD patterns can be taken directly from the as-fractured surface [22] or from a polished plane perpendicular to the fracture surface [31]. An inverse pole figure is plotted relative to the facet normal vector to identify the crystallographic plane exposed to the fracture surface. Ro et al. [40] have reported an accuracy of about  $3^\circ$  using the combined EBSD-tilt fractography technique. Sinha et al. [21] noted that the deviation of the basal plane from the apparent facet plane was largest for static loading ( $\sim 20^\circ$ ) and smallest for continuously cycled fatigue samples ( $< 5^\circ$ ) and was an intermediate value for dwell-loading conditions ( $10^\circ$ – $15^\circ$ ). Sinha et al. [21] also reported that the density of steps on the static loaded samples was higher than in the dwell loaded samples. The smallest deviations from the basal plane were found in the continuously cycled samples, which also had the lowest density of steps.

In Fig. 4, a second  $\alpha$  colony is identified in the lower left corner of the image. In order to account for faceted growth over multiple colonies, it is essential that the colonies share a common basal plane. This can occur when both colonies have  $\alpha$  that forms along the same  $\{110\}_{\beta}$  plane but with different  $\langle 111 \rangle_{\beta}$  directions within that plane. Both colonies satisfy the BOR and are just different variants that are misoriented by  $10.5^\circ$  about  $[0001]$ . This phenomenon has been discussed in previous studies [14,26,41].

An example of the effect of microstructure on faceted crack growth behavior is evident in Fig. 6. Two well defined steps are present on the facet. The step on the left travels nearly parallel to the  $\alpha/\beta$  interfaces as well as across the  $\alpha$  lamellae. The step traverses the  $\alpha$  lamellae until it encounters the  $\alpha/\beta$  interface on the other side of the lath and is deflected again. While in some instances the overload cycles seem to influence the crack propagation direction, they certainly are not a requirement to deflect the crack either to or from  $\alpha/\beta$  interfaces. The traces of these two crack paths make an angle of  $\sim 60^\circ$  with one another, which also corresponds to the angular distance between the close packed slip directions in the basal plane. The step on the right seems to choose a



**Fig. 6.** A high magnification secondary electron image near the initiation site of the facet shown in Fig. 3. Several overload markers are visible and the orientation of the  $\beta$  laths is shown. The crack path on the left often changes direction, though not always, when an overload spike is applied.



**Fig. 7.** The effect of  $\Delta K$  on fracture topography. Very fine striations that resemble faceted topography at lower magnification are observed during the normal cycling periods and well defined striations are present for each overload cycle.

path that seems independent of overload spikes and appears to transfer easily across  $\alpha/\beta$  interfaces. Based on the approach angles to the  $\beta$  platelets, the step on the right should be parallel to  $\langle a_2 \rangle$  while the step on the left seems to alternate between the  $\langle a_1 \rangle$  and  $\langle a_2 \rangle$  directions.

At longer crack lengths, the overload markers demonstrate the effect of increased  $\Delta K$  on fracture topography. In Fig. 7,  $\Delta K$  during the overload cycles is large enough to create distinct striations. One striation is present for each overload cycle. At higher  $\Delta K$ , the increased crack tip opening displacement causes the crack tip to become blunted during loading while it is resharpened during unloading. It is this resharpening process that creates the features on the fracture surface that we recognize as fatigue striations [42].

#### 4. Conclusions

The literature contains a range of nomenclature used to describe facets observed on fatigue fracture surfaces in Ti alloys. Some of the features on the facets are similar, or identical, to cleavage fracture and quasi-cleavage fracture yet have wholly different origins. We propose that the term “low  $\Delta K$  faceted growth” be adopted to describe this type of fatigue crack growth in Ti alloys. This is consistent with the reports that facets only occur at low stress intensity ranges, which corresponds to small crack lengths.

Also, this term is intended to be a phenomenological descriptor that does not imply anything about the number of load cycles required to produce the facet.

In summary:

- (1) Low  $\Delta K$  crack advance in Ti alloys can occur along basal planes creating flat faceted features on the fracture surface. Thousands of cycles can contribute to the formation of a single facet.
- (2) Low  $\Delta K$  faceted growth can occur over differently oriented  $\alpha$  lamellae if the colonies share a common basal plane orientation.
- (3) We suggest that all terminology with the word cleavage be abandoned in favor of “low  $\Delta K$  faceted growth”.

#### Acknowledgements

This work was performed with support from the Office of Naval Research under contract N00014-06-1-0089 and from the Federal Aviation Administration (FAA) under Grant GRT869261. We also acknowledge J. Ault at Precision Castparts Corp. for providing the material for this study and R.E.A. Williams at OSU for many thought provoking discussions.

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