DEVELOPMENT OF NONDESTRUCTIVE METHOD FOR PREDICTION OF CRACK INSTABILITY

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ABSTRACT

A method to characterize the deformation zone at a crack tip and predict upcoming fracture under load using white light interference microscopy was developed and studied. Cracks were initiated in notched Ti-6Al-4V specimens through fatigue loading. Following crack initiation, specimens were subjected to static loading during in-situ observation of the deformation area ahead of the crack. Nondestructive in-situ observations were performed using white light interference microscopy. Profilometer measurements quantified the area, volume, and shape of the deformation ahead of the crack front. Results showed an exponential relationship between the area and volume of deformation and the stress intensity factor of the cracked alloy. These findings also indicate that it is possible to determine a critical rate of change in deformation versus the stress intensity factor that can predict oncoming catastrophic failure. In addition, crack front deformation zones were measured as a function of time under sustained load, and crack tip deformation zone enlargement over time was observed.

INTRODUCTION

Current economical circumstances and policies often require that both military and civilian aircraft remain in service well beyond their design life. This approach leads to the use of nondestructive evaluation of key components and application of fatigue crack damage tolerance models to predict the residual life of any critical components that may have detectable flaws. Current damage models are conservative and thus lead to a lower level of utilization or more frequent and costly inspection [1]. This work provides a new method to relate surface deformation at a crack front to possible failure under static load. Such findings will allow for a more efficient approach to aircraft maintenance.

This work is one of the first laboratory applications of white light interference microscopy. White light interferometry enables topographical measurements with 3 nm vertical resolution and at highest magnifications lateral surface resolutions of 0.2 μm. Such precision provides detailed topographic images. In addition, imaging cycle time for medium resolution scans, up to a square millimeter in size, is less than 5 minutes. Short scanning time requirements enable in-situ measurements such as the time dependent measurements of the crack front deformation performed in this work.

Ti-6Al-4V was chosen for this work because it is the most commonly used titanium alloy in airframe applications. It is used in high performance primary components because of its toughness and fatigue strength [2, 3]. Specific aerospace applications of Ti-6Al-4V include turbine engine blades, parts of the fuselage of some high performance jet aircraft and the lower skin of aircraft wings.

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EXPERIMENT

Material

Ti-6Al-4V alloy was investigated in this project. The primary microstructure in this study was mill-annealed sheet with grain sizes of approximately 5 μm in the transverse direction and 20 μm in the longitudinal direction (Figure 1a). Both longitudinal and transverse orientation behavior of this material was investigated. A duplex microstructure from $\alpha+\beta$ forged and solution treated plate, with grain sizes of approximately 10-20 μm, was also examined (Figure 1b). All specimens were flat 79 mm dogbone specimen with a 0.4 mm notch initiated in the center of the reduced section of the specimen. Prior to testing all specimens were polished to a low surface roughness (RMS $\approx$ 250 nm) to enable detailed examination of changes in surface topography.

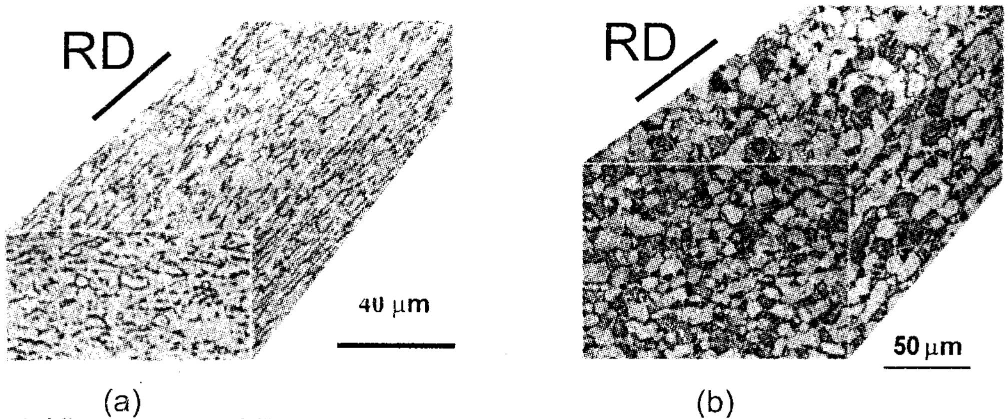


Figure 1: Microstructure of Ti-6Al-4V specimens (a) mill annealed sheet and (b) duplex microstructure forged plate

Mechanical Testing

Fatigue cracks were initiated from the notch of each sample by high cycle fatigue loading. As soon as a crack was visually detected the stress was reduced by 10% and the specimen was subjected to an additional 1000 cycles. This stress reduction was repeated several times to sharpen the crack front and reduce the surface deformation area. The precracked specimen was then loaded into a portable static load frame. The load frame was placed under a white light interference microscope for in-situ topographical data acquisition.

Profilometry

White light interference microscopy was used to document topographical changes at the crack front of each specimen. The micropsope is a Michelson interferometer [4] with one of the mirrors replaced by the surface being examined (Figure 2) [5]. The white light

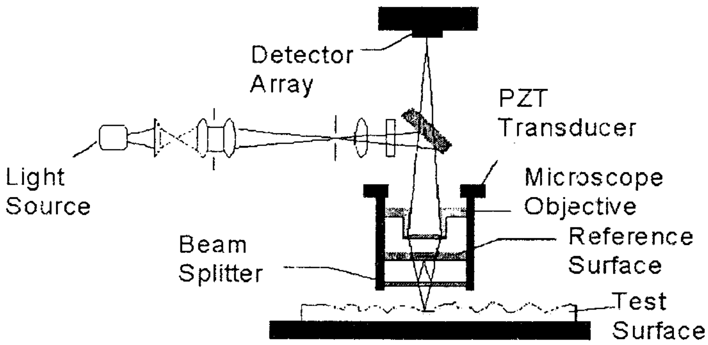


Figure 2: Schematic of White Light Interference Profilometer

source for vertical scanning interferometry is unfiltered white light with a short coherence length. The beam is split between the reference mirror and the specimen surface. After reflecting from these surfaces the beams recombine. Interference regions occur when the optical path difference for the combined beams closely nears or equals zero. During each scan the reference mirror is moved along the z-axis by a linearized piezoelectric transducer, causing the height of interference to change. The region of interference is then recorded for each pixel and related to the location of the reference mirror along the z-axis [4, 5].

The instrument is capable of 3 nm vertical resolution and has a lateral surface resolution of 0.2 μm. The profilometer also has an image analysis package that enables automated topographical calculations including height profiles, threshold surface area, and surface depression volume analysis, along with other calculable parameters which are not used in the present analysis.

Observation of crack tip deformation zone

The material directly ahead of a crack tip is under a triaxial state of stress. This stress state, along with crack tip deformation, led to an area of depressed material ahead of the crack tip. This depression can be imaged, characterized, and quantified (Figures 3 & 4) with white light interference microscopy. Through out this work the observed depression is referred to as a deformation zone.

RESULTS AND DISCUSSION

Deformation area and depression volume as a function of load

Results of the incrementally increased static load tests are shown in Figure 3. Area and volume data were calculated through analysis of images like those contained in Figure 5. All images taken after or during application of load show a distinct region of deformation ahead of the crack. This deformation zone increases exponentially both in area and volume with the increasing stress intensity factor. Figure 3 shows that relationships predicting failure exist for both area and volume of deformation. The volume comparison (Figure 3b) contains less data scatter than the area comparison (Figure 3a). As failure approaches the area of deformation slightly retracts. This is documented in Figure 3a by the area values leveling out directly prior to failure. The Transverse Mill Annealed curve shows the greatest amount of area retraction.

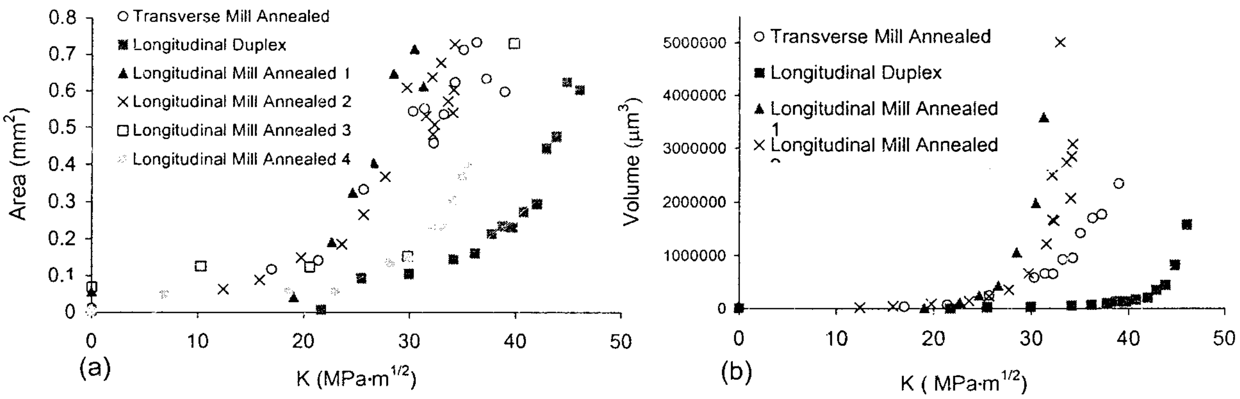


Figure 3: Deformation and stress factor relationship for Ti-6Al-4V for (a) area and (b) volume

Unlike area, the volume continually increases with K until the final failure (Figure 3b).

Deformation area and depression volume as a function of time

The deformation investigated includes both the plastic and the elastic deformation contributions. A substantial amount of elastic deformation was expected to relax upon release of the static load. To track this phenomenon, images were taken of the specimen under load and then directly following release of the load. Measurements showed a minimal decrease in the deformation area. This strain release was time dependent and could be traced over a period of several hours.

At high loads (~ 3000 N) the amount of deformation accumulating due to static loading during the scan resulted in an increase in the degree of deformation rather than a decrease as was expected due to elastic relaxation. This increase in deformation led to additional experiments in which time-dependent deformation growth was investigated. Examination of this phenomenon revealed that the deformation zone continues to expand during the first several hours under static load. After several hours the deformation zone size levels out and remains nearly constant (Figure 4).

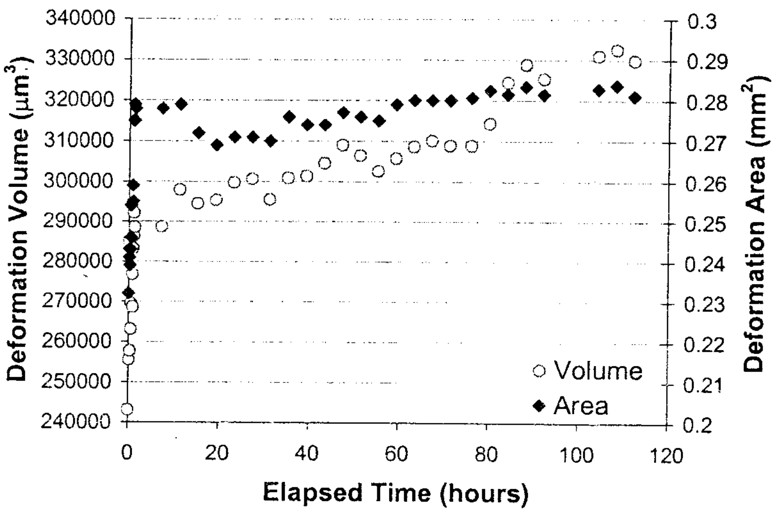
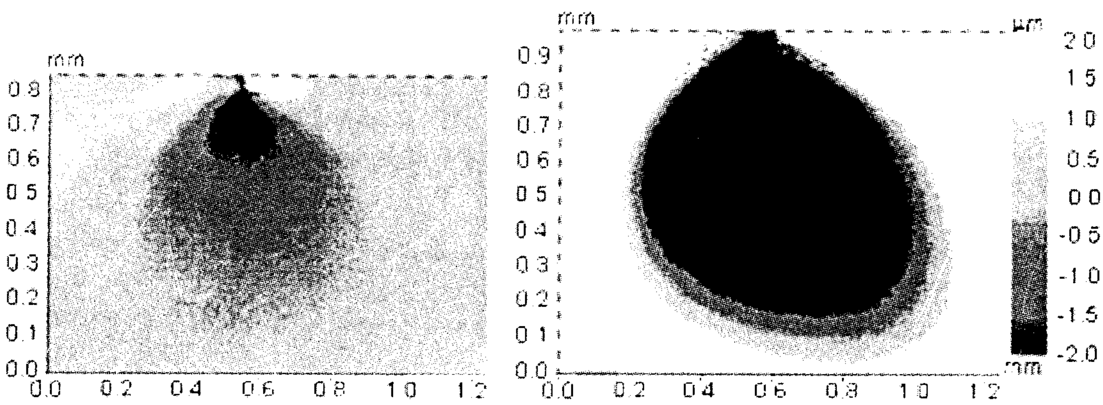


Figure 4: Deformation as a function of time (3000 N)

Deformation shape

Topographical data shows a distinct deformation shape that is common for all specimens tested. This shape is shown in Figure 5 at two stages of deformation development. The general shape of the deformation remains the same from the beginning of loading all of the way through



(a) (b)

Figure 5: Deformation zones under loads of (a) 2500 N and (b) 3500 N (directly before failure)

development of crack instability. The deformation continues to grow as the magnitude of load is increased. Original investigations included efforts to relate deformation symmetry to failure prediction. This correlation was not reproducible due to the affect of microstructure on the symmetry of the deformation.

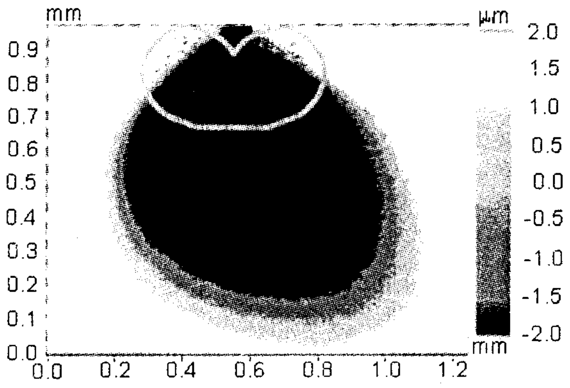


Figure 6: Theoretical plastic zone at K=30 MPa•m$^{1/2}$ compared to surface deformation at same K level

A comparison of theoretical plastic deformation and surface deformation was created by plotting the radius of plastic deformation developed from the classical equation for plane stress plastic deformation [6]. The radius was calculated at the stress intensity level represented by the figure over which it is overlaid and plotted as a function of θ. This theoretical shape was validated through etch pit studies by Hahn and Rosenfield [6], but it inadequately represents the surface deformation shown in Figure 6.

Microstructure effect on deformation

Two microstructures and two material orientations have been tested. Each material variance causes a slight change in the magnitude of relationship between the deformation size and stress intensity, but all materials tested follow the same behavior. This behavior and magnitude change is shown in Figure 3, but is clearly schematically represented in Figure 7.

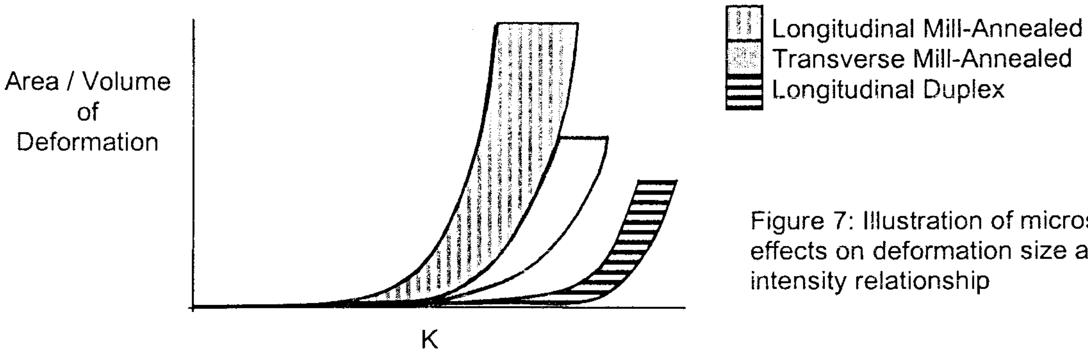


Figure 7: Illustration of microstructure effects on deformation size and stress intensity relationship

Criteria for failure prediction

Examination of the common relationship between deformation zone size and the stress intensity factor indicates that criteria for failure may be extracted from such data. The suggested criterion for failure is a critical rate of change (r_c). This rate is the slope of the size of deformation over the stress intensity factor at a determined point prior to failure. A schematic of this rate is shown if Figure 8.

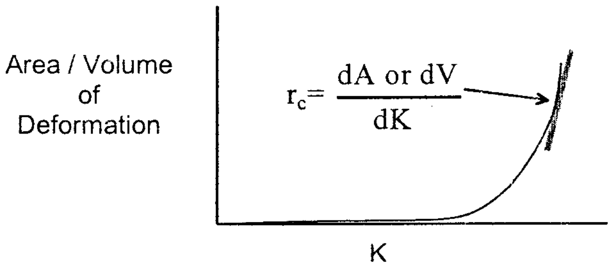


Figure 8: Criteria for failure: critical rate of deformation growth with respect to change in stress intensity factor

CONCLUSIONS

The objective of this work was to develop a method to characterize the deformation zone ahead of a crack tip and predict upcoming fracture.

1. White light interference microscopy was successfully used to measure the topography of crack tip deformation.
2. A distinct deformation shape resulted for all specimens tested. The surface deformation shape shared limited similarities with the theoretical plastic zone shape.
3. The area and volume of deformation increased as both a function of load and a function of time. The deformation trends for both a mill-annealed and duplex microstructure of Ti-6Al-4V are similar but differed in magnitude. Transverse and longitudinal orientations of the mill-annealed microstructure shared similar trends with a minimal magnitude difference.
4. Results suggest that a critical rate of change between the size of the crack tip deformation (surface area or volume) and the stress intensity factor may be developed to predict crack instability. This rate of change (r_c) may be the basis for development of a nondestructive evaluation method to predict oncoming crack instability of visible flaws.

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