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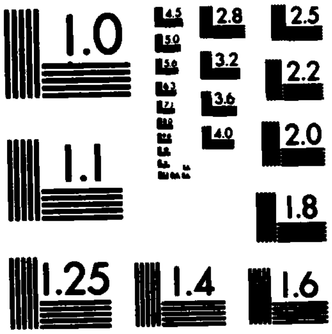

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THE EFFECTS OF DEFORMATION MODE AND MICROSTRUCTURE
FRACTURE - RELATED PROPERTIES OF Ti ALLOYS

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Final Report 11-1-79 - 6-30-83

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Fatigue crack growth has been studied in two binary Ti-Al alloys, an 8 wt.% Al and a 4 wt.% Al alloy. It has been found that the crack growth rate is faster in the 4% Al alloy. The principal difference between these alloys is that the higher Al alloy exhibits planar slip. The effect of this planar slip character is to cause a more irregular crack path. This increase in crack path irregularity causes roughness-induced closure. Back face strain measurements have been used to measure the variation in closure and to calculate an effective ΔK. It also has been shown that the

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crack growth rates for the two alloys coincide if the variations in closure are taken into account. Elevated temperature crack growth experiments have also been conducted and oxide-induced closure effects have been found in this case. This type of closure also affects the crack growth rate. Finally, crack growth experiments at high mean stress have been conducted and it has been found that the closure effects disappear. The implications of this work on the selection of materials for fatigue crack growth limited applications is discussed.

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SUMMARY OF ACCOMPLISHMENTS

The work performed under this program has resulted in several key findings, all of which are related to the understanding of fatigue crack growth. Included in these are the following:

1. slip character affects fatigue crack growth rate;
2. wavy slip materials exhibit faster crack growth rates than do planar slip materials;
3. the principal difference in wavy and planar slip materials is the roughness of the fatigue fracture surfaces;
4. the variations in fracture roughness cause variation in the crack closure loads which affect the effective cyclic stress intensity;
5. when the crack growth rates of the wavy and planar slip materials are plotted against effective cyclic stress intensity, the crack growth rates superimpose;
6. other factors which affect closure such as oxide formation in the crack tip region also alter the crack growth rate;
7. closure does not alter crack growth rate at high mean stresses where the crack cannot close during the unloading portion of the load cycle.

INTRODUCTION

Most if not all of the hardware that the Air Force operates is either partially or totally limited by fatigue. As a result, there has been a significant emphasis placed on fatigue research in Air Force sponsored programs during the past 10 or 15 years. The initial thrust of this work was in the area of fatigue crack initiation. More recently, there has been an increased concern with the concept of damage tolerant design. As a result, much of the emphasis has shifted to fatigue crack growth studies. Although both crack growth and crack initiation are important, the role of microstructure in crack growth has been recognized only quite recently. As the result of several studies, it is now generally agreed that microstructure, as affected by both heat treatment and thermomechanical processing, has a pronounced effect on fatigue crack growth in Ti alloys (1-10). Moreover, this effect extends over the entire range of crack growth rate, not just in the threshold region.

The studies mentioned above, while providing an excellent characterization of microstructure effects, did not provide much insight into the mechanism(s) by which microstructure affects crack growth rate. One of the reasons for this is the complexity of the alloys that were studied. For example, in an alloy such as Ti-6Al-4V, altering the microstructure can simultaneously affect both the slip character and the slip length, making the experimental results very hard to interpret (2,11). In view of this, a study of simpler model alloys was initiated at Carnegie-Mellon University in an attempt to provide am improved insight into the mechanism by which such microstructural features as slip mode affect fatigue crack growth. To do this, two binary Ti-Al alloys were selected because they were known a priori to have a different slip character (11-13). These alloys are Ti-4Al and Ti-8Al. The former has a homogeneous slip character while the latter has a planar slip character. Still lower Al concentrations than 4 Wt.% would have even more homogeneous slip, but twinning becomes prevalent at these lower Al concentrations. These two alloys were used for fatigue crack growth rate studies at room temperature and at 783 K. This report summarizes the results of this study.

EXPERIMENTAL

Two 50 pound heats of Ti-Al alloys were obtained for this study. These alloys contained 4 and 8 wt.% Al and an average Oxygen content of 0.080 wt. %. The alloys were hot rolled into plates approximately 0.5 in. thick. From these plates compact tension specimens were removed for crack growth testing. These tests were run in a MTS servo hydraulic machine at a frequency of 30 Hz. The crack length during the crack growth tests was monitored both by optical measurements and by electric potential drop. The crack growth specimens were heat treated in an Argon atmosphere furnace to achieve a uniform recrystallized grain size prior to testing. Electron fractography was conducted using a JEOL JSM35 scanning electron microscope.

RESULTS

It has been found that slip character has a significant effect on fatigue crack growth rate at room temperature and at elevated temperature but the effect is larger at room temperature. These results are shown in Figure 1. From this it can be seen that the homogeneous slip material, Ti-4Al, exhibits the more rapid crack growth rate. This figure also shows data for specimens oriented so that the crack growth direction was parallel to both longitudinal and transverse directions of the plate. These data show that the texture in the material used for this study had very little effect on the crack growth rate, at least compared to that of slip character. The data shown in Figure 1 was obtained using the electric potential technique for continuously measuring crack while the crack growth test is in progress. This technique was developed as part of this program and is advantageous for conducting crack growth experiments because it permits the test to run continuously unattended and because it continuously measures crack length so that discontinuities in the crack length-number of cycles curves take on real meaning.

Examination of the fracture surfaces of the crack growth specimens showed that there was a significant difference in the roughness or irregularity of the crack path. Such roughness was readily observable both on a macroscopic and on a microscopic scale. Even at relatively low magnifications the flat cleavage-like facets can be seen in the Ti-8Al alloy whereas these facets are not as well-developed in the Ti-4Al alloy. The correlation between strain localization in the Ti-8Al alloy and the development of planar facets, while circumstantial, is considered to be more than coincidental. This correlation becomes more attractive when it is realized that many of the facets are oriented at an angle to the loading axis so they are the result of a significant shear stress component during crack propagation. Such inclined facets are often referred to as mode II cracks because of this local shear stress component. It is these inclined facets that contribute to the variation in fracture surface roughness between the two alloys studied here. In an attempt to understand the effect of variations in roughness on crack extension, crack tip closure measurements were made by monitoring back face strain on the compact tension crack growth specimens. This is shown schematically in Figure 2. The back face strain measured in this way is sensitive to the point at which the crack opens during loading. At this point the back face strain per unit load increases as shown in Figure 3. The break in the load-strain curve can be located by the intersection of two tangents as shown in Figure 4. The opening load obtained in this way can be used to determine the effective value of the applied load that is available to drive the crack extension process. That is, if the opening load is subtracted from the applied load, the effective load is obtained. If the effective load is used to calculate the effective stress intensity the variations in crack growth rate observed between the Ti-4 and 8Al alloys can be normalized.

An independent way to check on the role of crack closure on the rate of crack growth is to conduct tests at cyclic stress intensities and load ratios (defined as the ratio of minimum load to maximum load) which do not permit the crack to close. In such cases the entire cyclic stress intensity drives the crack and closure does not enter into the crack extension process. The results of crack growth tests run at a load ratio of 0.8 are shown in Figure 6. These results also show that, once the effect of closure is removed from the crack growth process, the crack growth rate in both alloys is essentially the same.

The results presented above show that variations in the extent of crack closure can be used to account for the variations in crack growth rate between the two binary Ti-Al alloys studied. However the reasons for variations in closure between these two alloys is less clear. One possibility is the variation in fracture surface roughness described earlier. If the irregularities on the fracture surface tend to "prop" the crack open, then a relationship between roughness and closure could be established. In an attempt to establish such a relationship, the height of the asperities on the fracture surfaces was measured for each of the alloys. These data were plotted as a function of the opening stress intensity as shown in Figure 7. From this plot it can be seen that there is indeed a good correlation between roughness as measured by asperity height and closure as measured by opening stress intensity. The variations in roughness can also be illustrated by showing the fracture paths by backlighting the specimens and observing the outline of the fracture path as shown in Figure 8. From this it can be seen that the crack path is much more irregular in the Ti-8Al alloy.

It also is interesting to inquire if there can be other sources of closure besides roughness. To examine this point crack growth tests were performed at elevated temperature (783 K) in laboratory air and in an inert environment (Helium). The results of these tests are shown in Figure 9. From these data it is clear that the rate of crack growth is higher at elevated temperature but that the crack stops growing at a rate well above the minimum value achievable at room temperature. The higher growth rate is typical of an environmentally assisted crack growth, possibly as a result of Oxygen. The cessation of crack growth is thought to be a closure-related effect but in this case the closure is the result of oxide formation in crack tip region. Sputtering was used to measure the oxide thickness on the fracture surfaces and the thickness values were consistent with oxide-induced closure at near-threshold crack growth rates. Thus the cessation of crack at 783 K. is also the result of closure effects but in this case the closure is caused by oxide which forms on the fracture during crack growth.

To check the validity of the results obtained on the binary alloys, crack growth experiments were also conducted on a commercial alloy Ti-6Al-2Sn-4Zr-2Mo(0.8Si). Typical results obtained from these tests are shown in Figure 10. From these results it is clear that the early cessation of crack growth at elevated temperature is a general phenomenon.

DISCUSSION AND SUMMARY

The crack growth experiments conducted in this study have shown that fracture roughness is affected by the slip character of the material under test. Moreover, it has been shown that variations in fracture roughness correlate with variations in crack growth rate. The variations in roughness in turn relate to variable extents of crack closure and this causes the effective stress intensity to vary. At elevated temperatures a separate crack closure effect is caused by the oxide layer which forms on the fracture surface. Thus the variations in crack as a function of alloy content or microstructure appear to be the result of variations in the extent of crack tip closure. It also has been shown that closure effects disappear in crack growth tests run at high load ratios. The practical consequences of this observation are substantial. That is, components which operate with a high mean stress cannot benefit by being constructed of crack growth resistant materials. Fortunately, there is a considerable amount of hardware that operates in stress environments where slip character, microstructure and oxide affect the crack growth rate. In all of these cases, the results of this study provide some useful guidelines for selection of materials that will have improved fatigue crack growth resistance.

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(Through October 1982)

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J. E. Allison - Ph.D. Metallurgical Engineering and Materials Science, October 1982

PUBLICATIONS

1. H. M. Kim and J. C. Williams, "The Effects of Composition and Temperature on the Dislocation Structure of Cyclically Deformed Ti-Al Alloys," Strength of Metals and Alloys, (R. C. Gifkins, ed.), Vol. 3, p. 1, Pergamon Press, Oxford, England, 1983.

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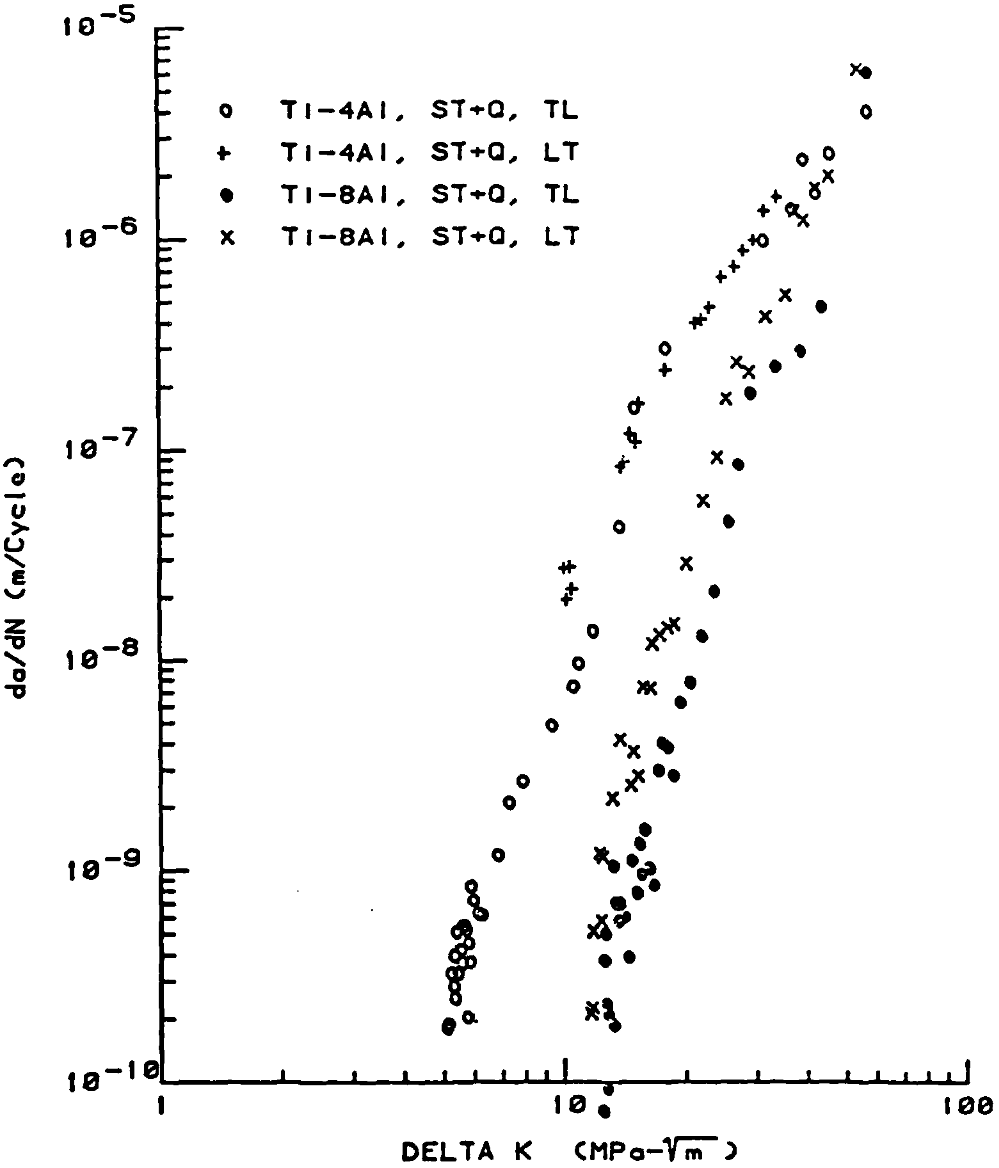


o TI-4Al, ST+Q, TL
+ TI-4Al, ST+Q, LT
● TI-8Al, ST+Q, TL
x TI-8Al, ST+Q, LT
da/dN (m/Cycle)
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
1
10
100
DELTA K (MPa-√m)

Figure 1

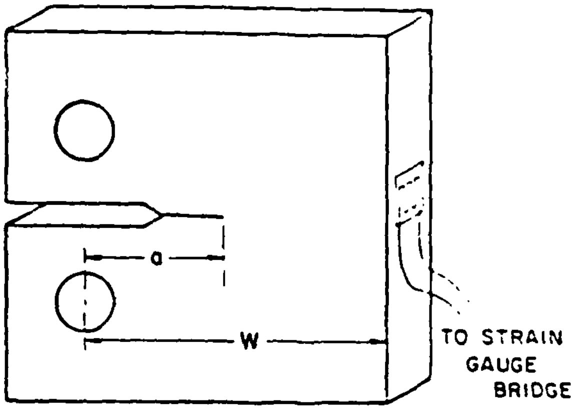
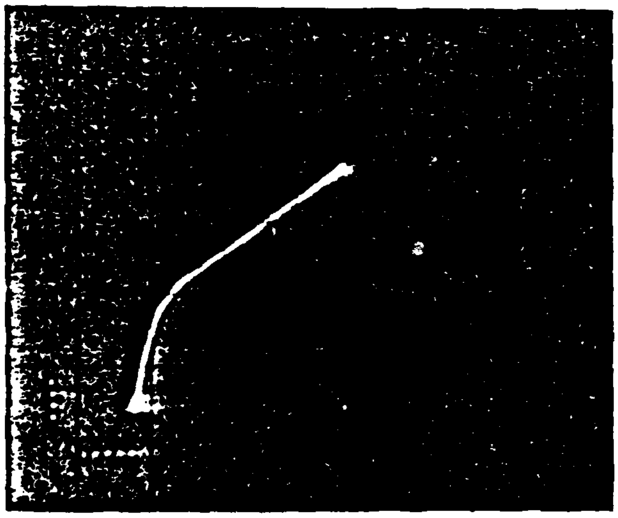


Figure 2



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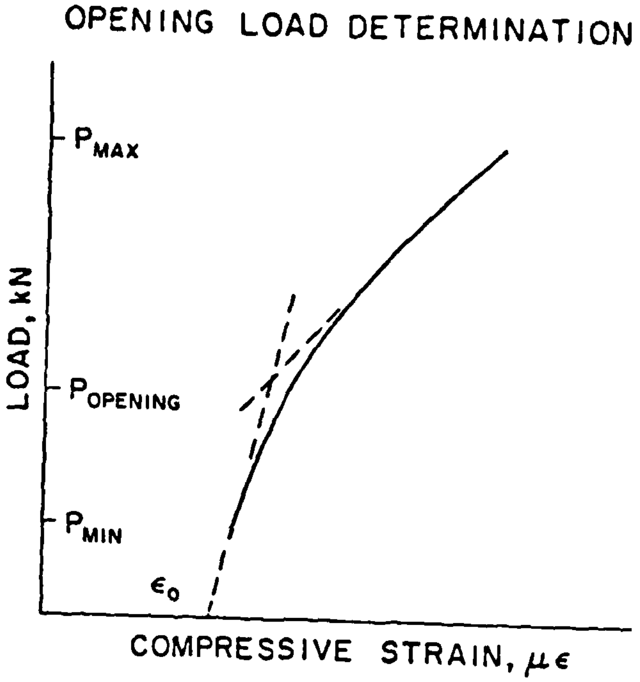

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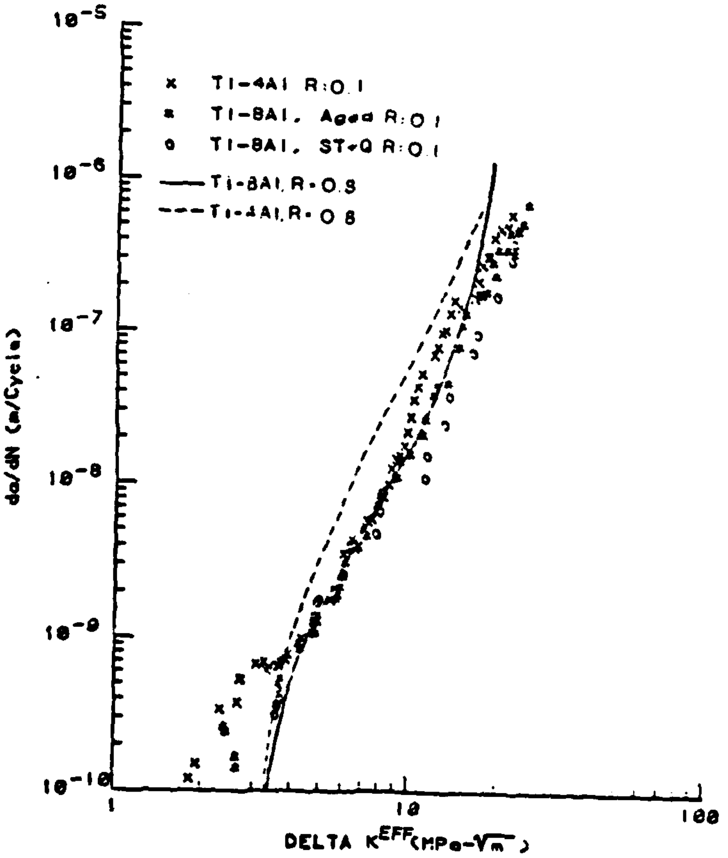

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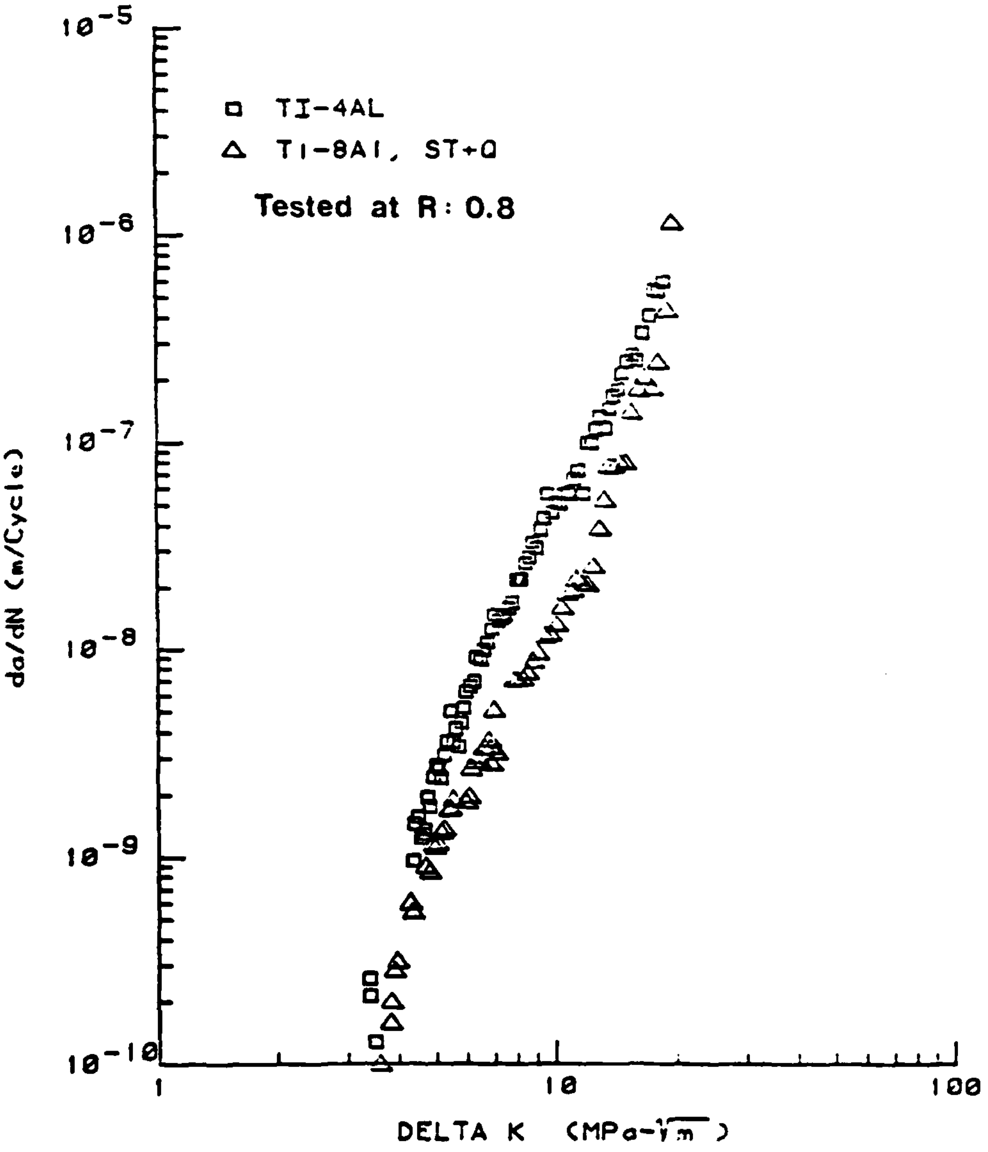

10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
da/dN (m/Cycle)
□ TI-4AL
△ TI-8AI, ST+Q
Tested at R: 0.8
1
10
100
DELTA K (MPa-√m)

Figure 6

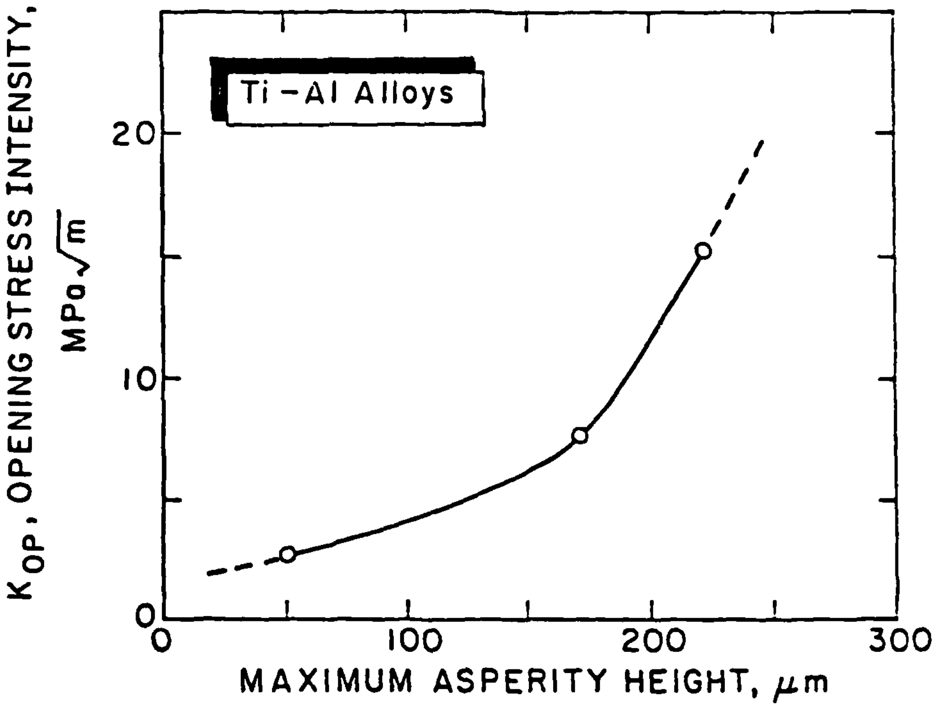

Ti – Al Alloys
K_{OP}, OPENING STRESS INTENSITY, MPa$\sqrt{m}$
0
10
20
0
100
200
300
MAXIMUM ASPERITY HEIGHT, μm

Figure 7

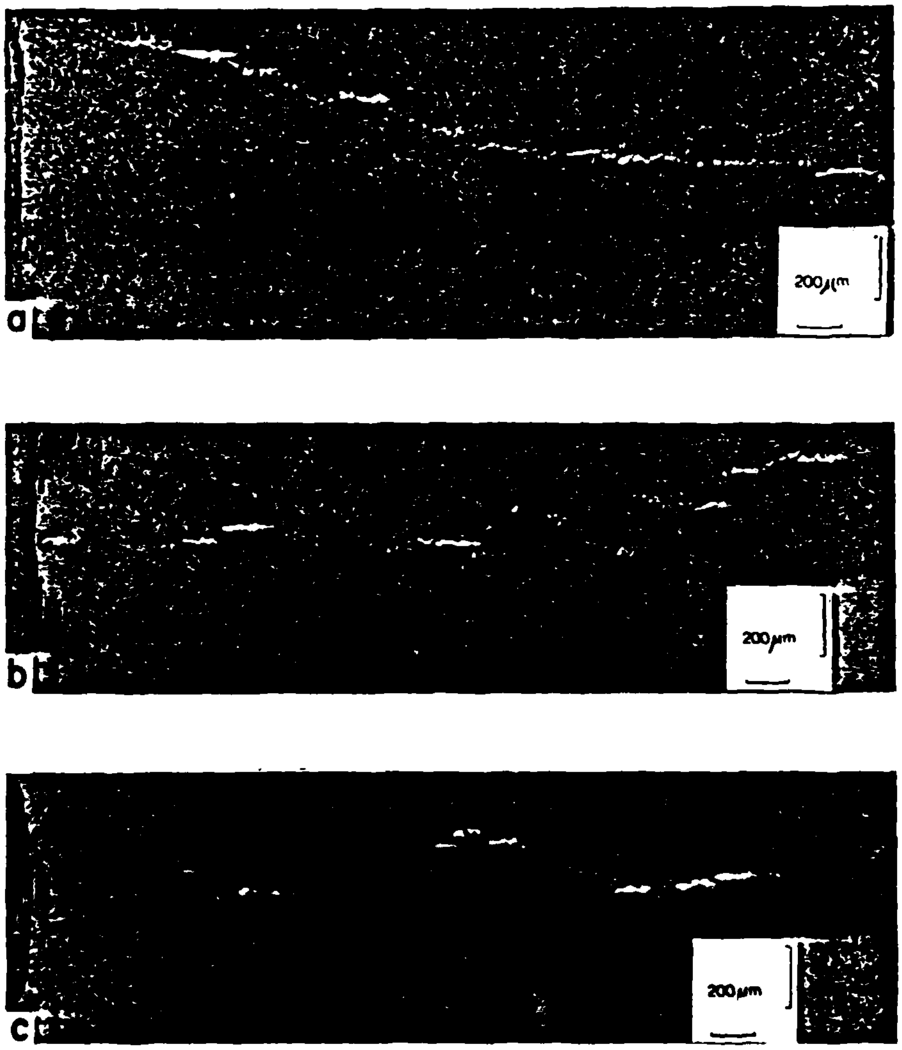
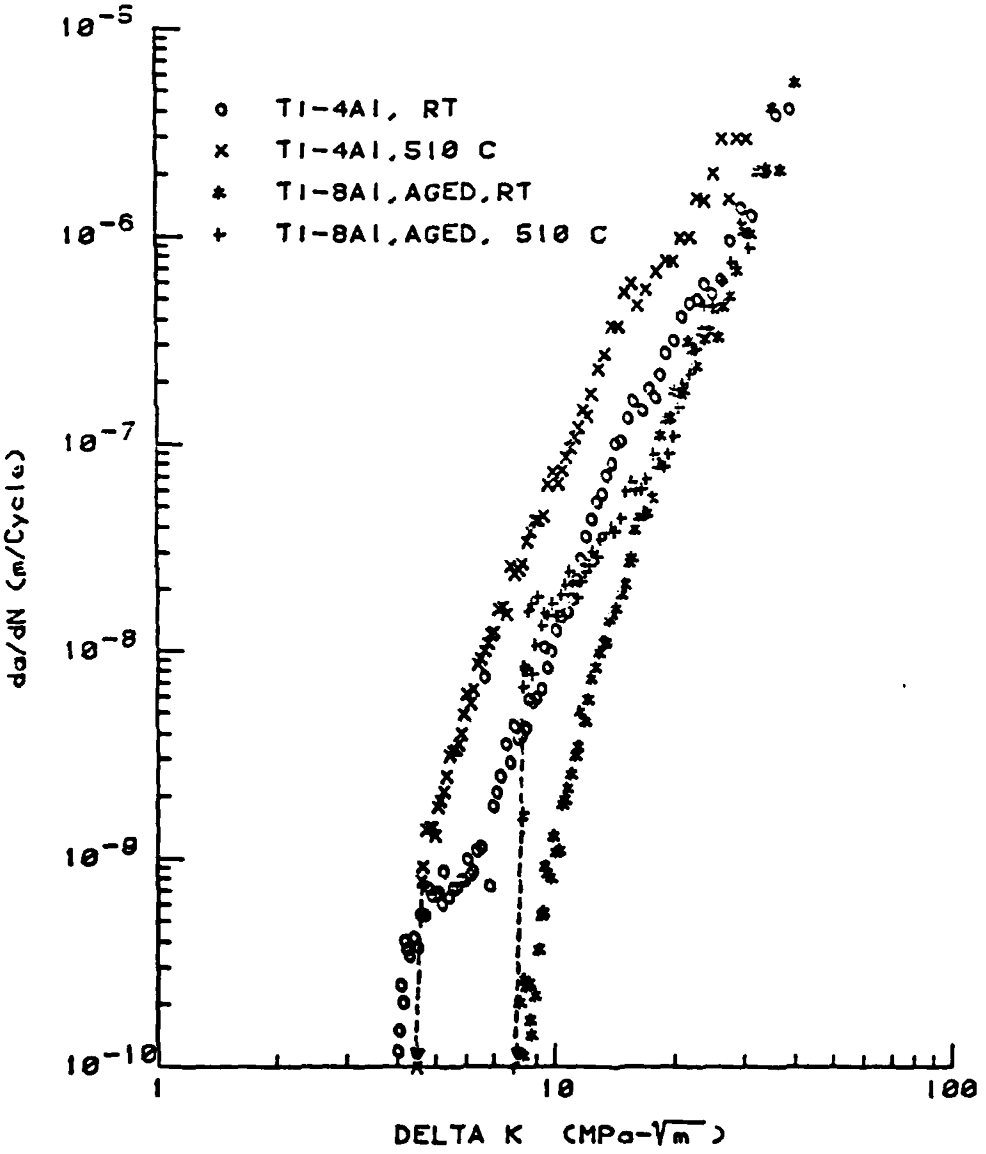


Figure 8



10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
o TI-4AI, RT
x TI-4AI,510 C
* TI-8AI,AGED,RT
+ TI-8AI,AGED, 510 C
da/dN (m/Cycle)
1
10
100
DELTA K (MPa-√m)

Figure 9

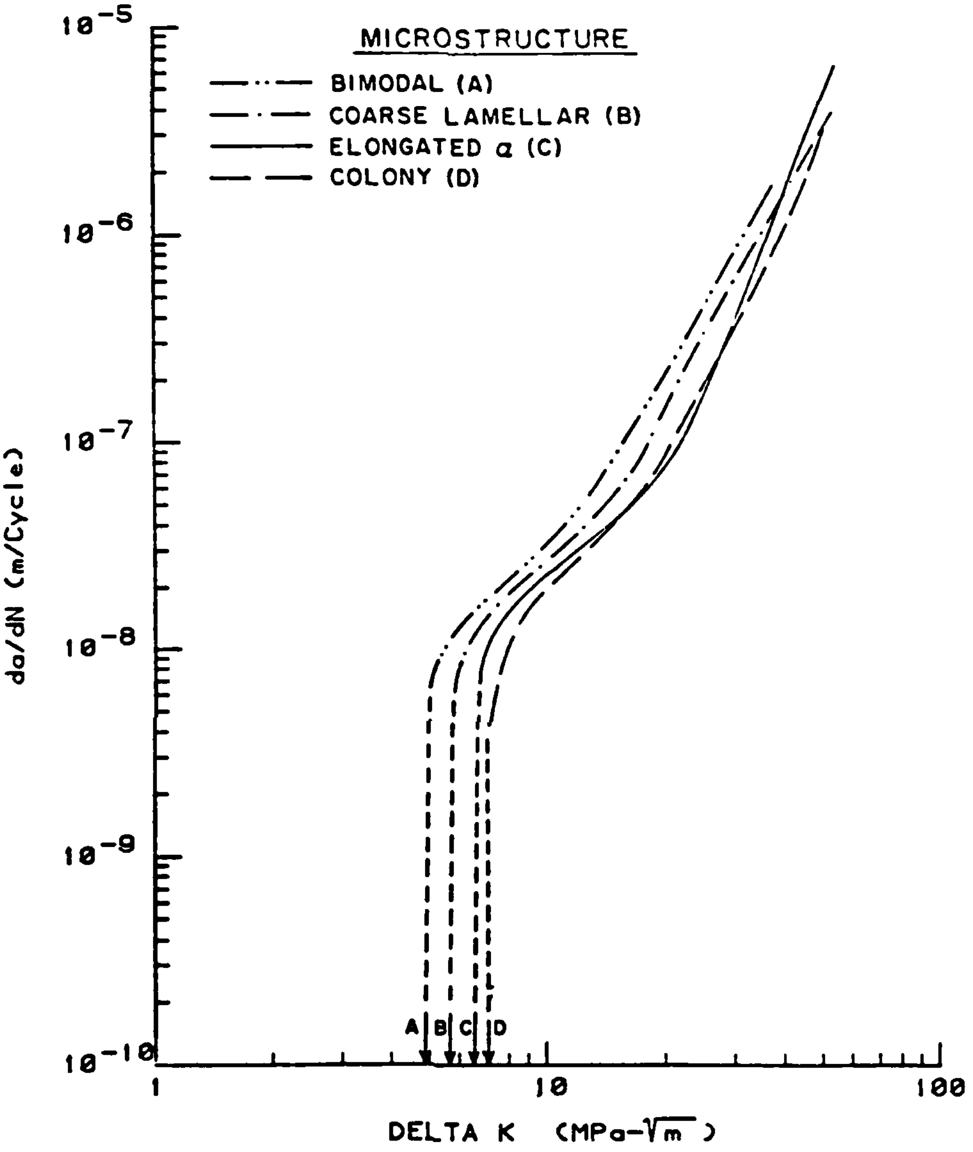

MICROSTRUCTURE
BIMODAL (A)
COARSE LAMELLAR (B)
ELONGATED α (C)
COLONY (D)
da/dN (m/Cycle)
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
A
B
C
D
1
10
100
DELTA K (MPa-√m)

Figure 10