FATIGUE CRACK INITIATION IN SURFACE GROUND Ti-6Al-4V

Dr. John T. Cammett III
Metcut Research Associates Inc., 3980 Rosslyn Drive
Cincinnati, Ohio 45209 U.S.A.

Abstract

An experimental study was conducted to determine the effects of surface grinding practice on fatigue of Ti-6Al-4V. Variations in fatigue strength as great as 5:1 were experienced as a result of changing grinding parameters over the range typically employed in industry. Extensive microstructural alteration and damage occurred at and near the specimen surfaces as a result of abusive grinding practices involving high metal removal rates. Examination of ground surfaces by optical microscopy, replica transmission electron microscopy, and scanning electron microscopy showed that abusive grinding produced extensive microcracking and smearing of specimen surfaces. Subsequent examination of specimens during the course of fatigue revealed that the low observed fatigue strength obtained with abusively ground surfaces resulted primarily from premature initiation and propagation of fatigue cracks from grinding microcracks.

Introduction

Careful engineering evaluation has shown repeatedly that the mechanical properties of materials, especially fatigue properties, are greatly influenced by surface characteristics. Variations of fatigue strength as great as 5:1 have been observed as a result of machining variations over the range typically employed in industry.[1,2] In general, machining methods involving more rapid rates of metal removal, therefore, higher

Introduction (continued)

rates of energy input to the surface, tend to depress the level of surface integrity. In the current industrial trend of increasing productivity, the danger of producing components with surface sensitive mechanical properties depressed to unacceptable levels is a definite reality. The determination of the basic underlying elements of surface integrity behavior is, therefore, a necessary corollary to engineering programs aimed at increasing productivity via higher metal removal rates in machining. The current study was performed in order to determine the basic features underlying the surface integrity and high cycle fatigue response of surface ground Ti-6Al-4V.

Material

The Ti-6Al-4V material used in this investigation was obtained in the form of 1/4" thick plate in the mill annealed condition. The microstructure consisted of globular and elongated primary alpha phase in a matrix of fine transformed beta phase. The chemical composition in weight percent was as follows:

C-.023, N-.012, H-.005, O-.11, Al-6.00, V-4.10, Fe-.08, Ti-Bal

After a re-annealing heat treatment (1600°F/1 hour), the tensile properties of the material were as follows:

0.2% Y.S.: 143 ksi
U.T.S.: 156 ksi
Elongation: 16%

Specimen Manufacturing

The specimen used for high cycle fatigue testing had a tapered gage section such that a constant elastic bending stress resulted when the specimen was loaded in cantilever bending. The top and bottom surfaces of the specimens were surface ground using either gentle or abusive conditions as specified below:

	Gentle Grinding	Abusive Grinding
Grinding Wheel	C60HV	A46MV
Wheel Speed, ft. /min.	2000	6000
Table Speed, ft. /min.	40	40
Total Depth of Grind, inches	.010	.010
Downfeed, in/pass	First, .008'' @ .0005'' Next, .0008'' @ .004'' Last, .0012'' @ .0002''	.002
Cross Feed, in. /pass	.050	.050
Grinding Fluid	Sol. Oil Emul.	Sol. Oil Emul.

As can be seen in the above, the major difference in the two grinding conditions were grinding wheel grit and hardness, grinding speed, and downfeed. The abusive grinding condition thereby resulted in a much higher metal removal rate than did gentle grinding. There was also a difference in the dressing of the wheel. After machining, the specimen edges were carefully hand polished to eliminate stress concentration

Specimen Manufacturing (continued)

effects and all surfaces outside the gage section were shot peened to insure that fatigue failures occurred in the gage section. The total area of machined surface (both sides) of the specimen gage section was approximately two $in.^2$. This entire area was subjected to constant stress amplitude cycling during fatigue testing.

Results and Discussion

Fatigue testing was performed under constant load amplitude conditions in cantilever bending on a Sonntag SF-02-U fatigue machine. All testing was performed at room temperature in ambient air (approximately 50% relative humidity) at a cyclic frequency of 30 Hz. Results of tests on 30 gently ground and 12 abusively ground specimens are presented as fatigue S-N curves in Figure 1. As can be seen, the 10^7 cycle fatigue strengths were in a ratio of about 5:1 (60-65 ksi for gentle grinding vs. 12 ksi for abusive grinding). Previous residual stress data showed compressive residual stresses in the near surface layers of gently ground specimens. Dominantly tensile residual stresses were found in the near surface layer of abusively ground specimens.

The fatigue specimens used to produce the results in Figure 1 were examined after testing. Visual inspection of fracture surfaces revealed that each gently ground specimen had a single fatigue crack initiation site while abusively ground specimens had numerous fatigue crack initiation sites on the surface. In most cases, several fatigue cracks formed, propagated and subsequently linked together to produce failure of abusively ground specimens.

The above observations were interesting; however, the underlying reason for the differences in behavior between gentle and abusively ground specimens was not apparent. The ground surfaces of both tested and untested specimens were then examined by optical and electron microscopy. Optical photographs of typical areas of both gently and abusively ground surfaces are shown in Figure 2.

It is readily apparent that abusive grinding produced more smearing of metal on the surface than did gentle grinding. The most striking feature observed on abusively ground surfaces, however, was the appearance of numerous small grinding cracks in roughly parallel arrays on many of the smeared areas. Typical cracks were perpendicular to the direction of grinding and were .002-.004 inches in length. An example of grinding cracks on a smeared area is shown in Figure 3. The irregular black cavity in Figure 3 was a microhardness impression used to mark the location for purposes of sectioning through the location. The fact that identical cracks were observed on untested fatigue specimens confirmed that they were grinding cracks and not fatigue cracks. No grinding cracks were observed optically on gently ground specimens.

A metallographic cross-section parallel to the grinding direction through the area in Figure 3 is shown in Figure 4. The small cracks, seen in profile, were typically .0002 inches in depth and extended only to the interface between the heavily smeared layer on the surface and the bulk material beneath. Other observations on similar metallographic sections revealed that the smeared layers were not contiguous with the bulk material over most of their area; however, they were attached at some point. It appeared that these layers consisted of material which was plowed up from the surface during grinding and then was extruded out over the surface as a thin leaf-like covering. This type of formation has been referred to as plastically deformed debris.[3]

Results and Discussion (continued)

Severe microstructural alterations in the near surface layers of the material are apparent in Figure 4. In addition to the severe plastic deformation at the surface, mechanical twins are evident approximately .002-.003 inches below the surface. Some grain growth occurred at depths of .003-.004 inches below the surface. This latter phenomenon may be inferred by comparison with the normal microstructure of the gently ground specimen shown in Figure 5. The white layer in Figure 4 is a manifestation of oxygen absorption which occurred as a result of overheating of the specimen during the grinding operation. Further evidence of overheating may be inferred from the abusively ground specimen in Figure 5 in which evidence of beta transformation can be seen at about .001-.002 inches below the surface. The gently ground specimen in Figure 5 also showed evidence of some overheating during grinding as manifested by a thin white layer typically about .0001 inches in depth at the surface. The photomicrograph of the abusively ground specimen in Figure 5 is typical. Apparently the grinding cracks (Figure 4) occurred in areas which were most severely overheated as evidenced by the greater depth of microstructural alteration in that location (compare Figures 4 and 5).

Specimens were also examined by scanning electron microscopy and replica transmission electron microscopy. Representative photographs are shown in Figures 6 and 7. The scanning electron microscopy photographs give an excellent photographic representation of the surfaces. As can be seen, the greater smearing which occurs when abusive grinding is readily apparent. No grinding microcracks, known to be present, were resolved by the scanning electron microscopy technique. On the other hand, the replication transmission electron microscopy technique did not permit as good a photographic representation of the surfaces as did the scanning electron microscopy technique. The replica transmission electron microscopy technique, however, did reveal grinding cracks even smaller than those which were observed optically. Examples of these may be seen in Figure 7.

It was noted previously that fatigue tested abusively ground specimens exhibited many fatigue origins. Moreover, the fatigue strength associated with abusive surface grinding was only one-fifth that associated with gentle surface grinding. It was suspected that the reason for this low strength was that fatigue cracks were initiated from the grinding cracks introduced during machining. Direct evidence to support this idea was not immediately at hand. A surface photograph shown in Figure 8, however, exhibits a fatigue crack on an abusively ground surface which apparently initiated within an array of small grinding cracks.

To establish whether or not fatigue cracks initiate from pre-existing grinding cracks in abusively ground Ti-6Al-4V, additional experiments were performed involving fatigue testing an abusively ground specimen and replicating the specimen at various times during the test from beginning to end. After the test was completed, the replicas were examined and a fatigue crack at a given location was traced through its various stages of growth from replica to replica. A series of photographs of the replicas showing the crack at different stages in the fatigue process is presented in Figure 9. As can be seen from the photograph representing zero cycles, i.e., before fatigue testing, the fatigue crack initiation site was, in fact, a small grinding crack. It was concluded, therefore, that grinding cracks resulting from abusive grinding are responsible for the low fatigue strength of abusively ground Ti-6Al-4V relative to the strength obtained by gentle grinding.

References

1. Koster, et al, "Surface Integrity in Machining of 4340 Steel and Ti-6Al-4V," SME Technical Paper No. 1Q71-237, 1971.

2. Koster, et al, "Surface Integrity of Machined Structural Components," AFML-TR-70-11, March 1970.

3. Field, M.F., "Plastically Deformed Debris and Built-Up Edge Produced on Surfaces by Chip Removal and Abrasive Machining Processes," to be published in CIRP Annals, Vol. 23/1, 1974.

Acknowledgement

The author wishes to thank Metcut Research Associates Inc. for financial sponsorship of this work. Technical discussions with Dr. Michael Field of Metcut were of significant benefit during the course of the program.

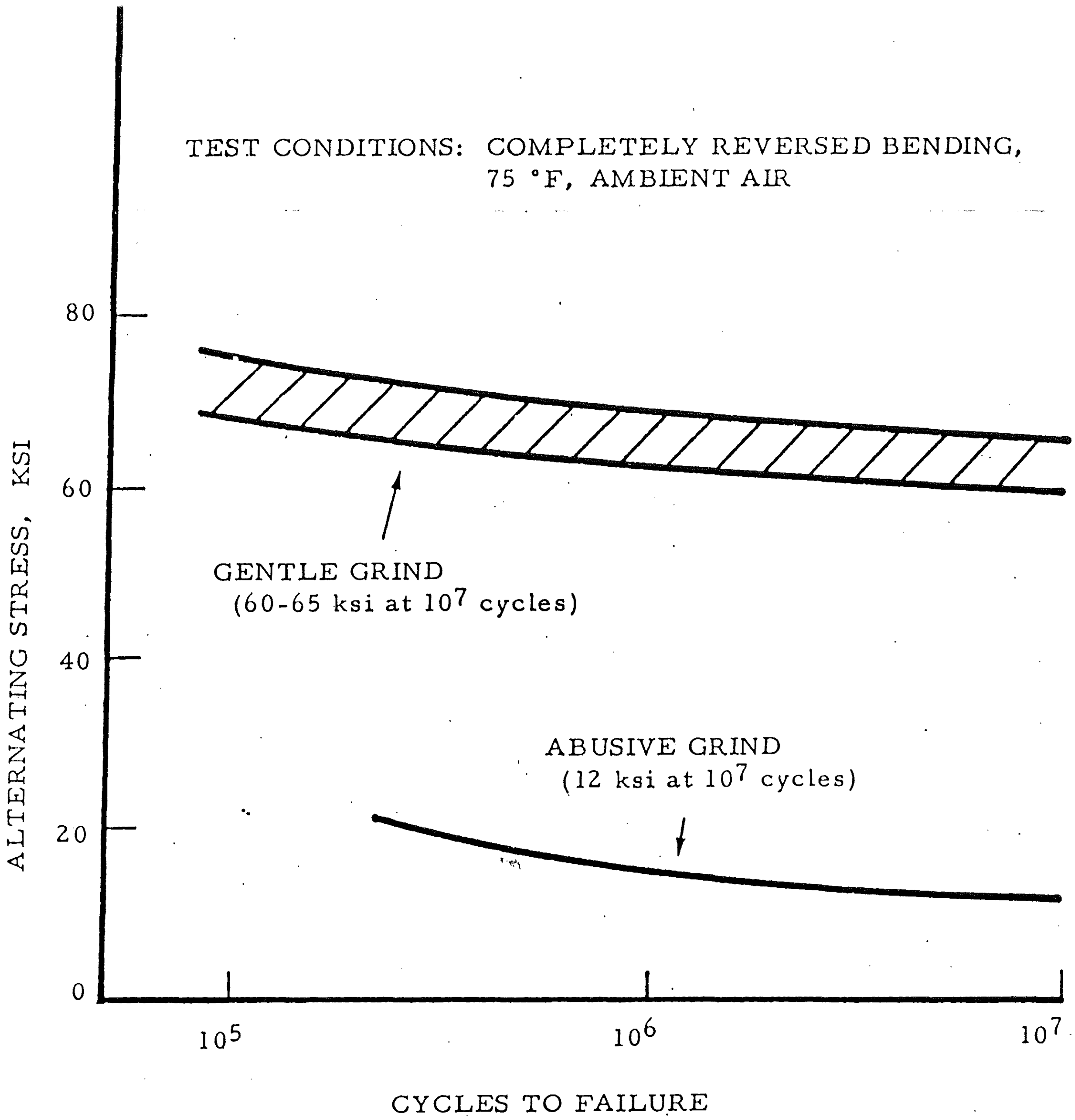
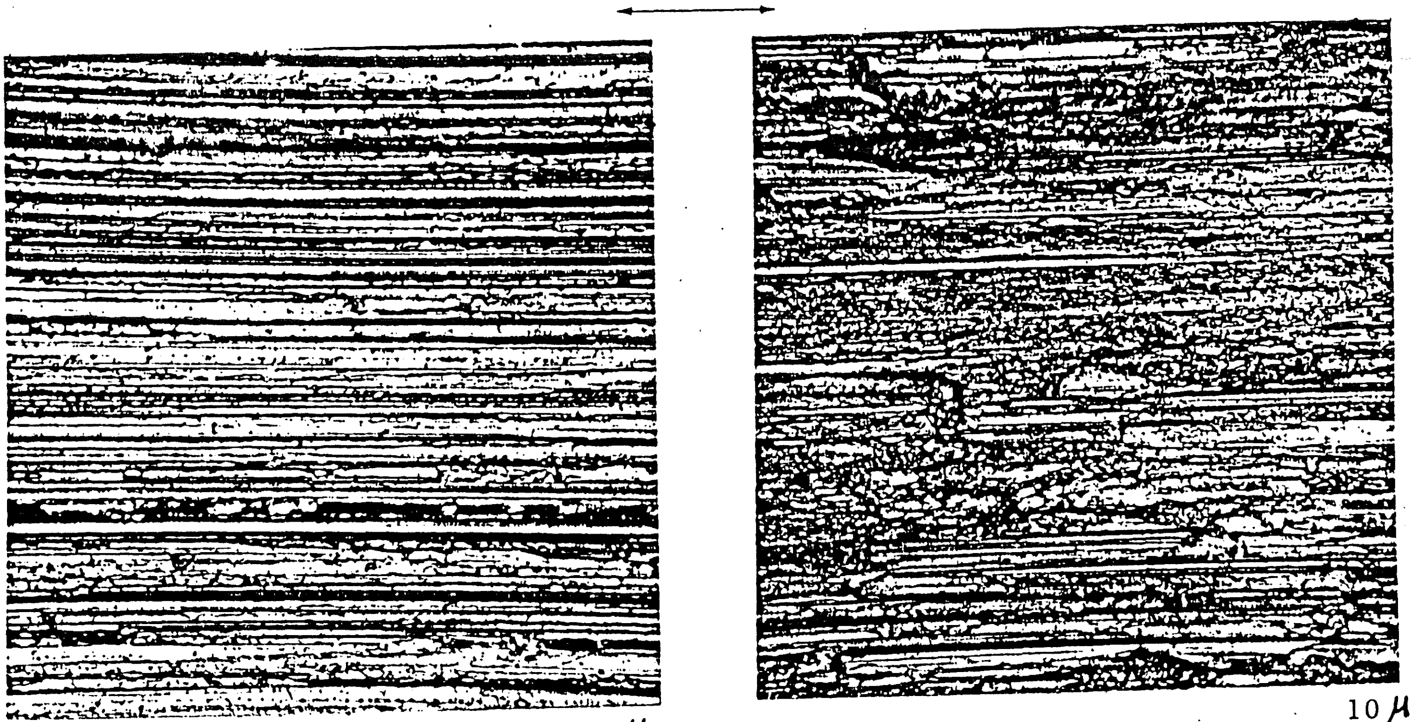


Figure 1 - FATIGUE CHARACTERISTICS OF ANNEALED Ti-6Al-4V PRODUCED BY GENTLE AND ABUSIVE SURFACE GRINDING

Grinding Direction



10 μ

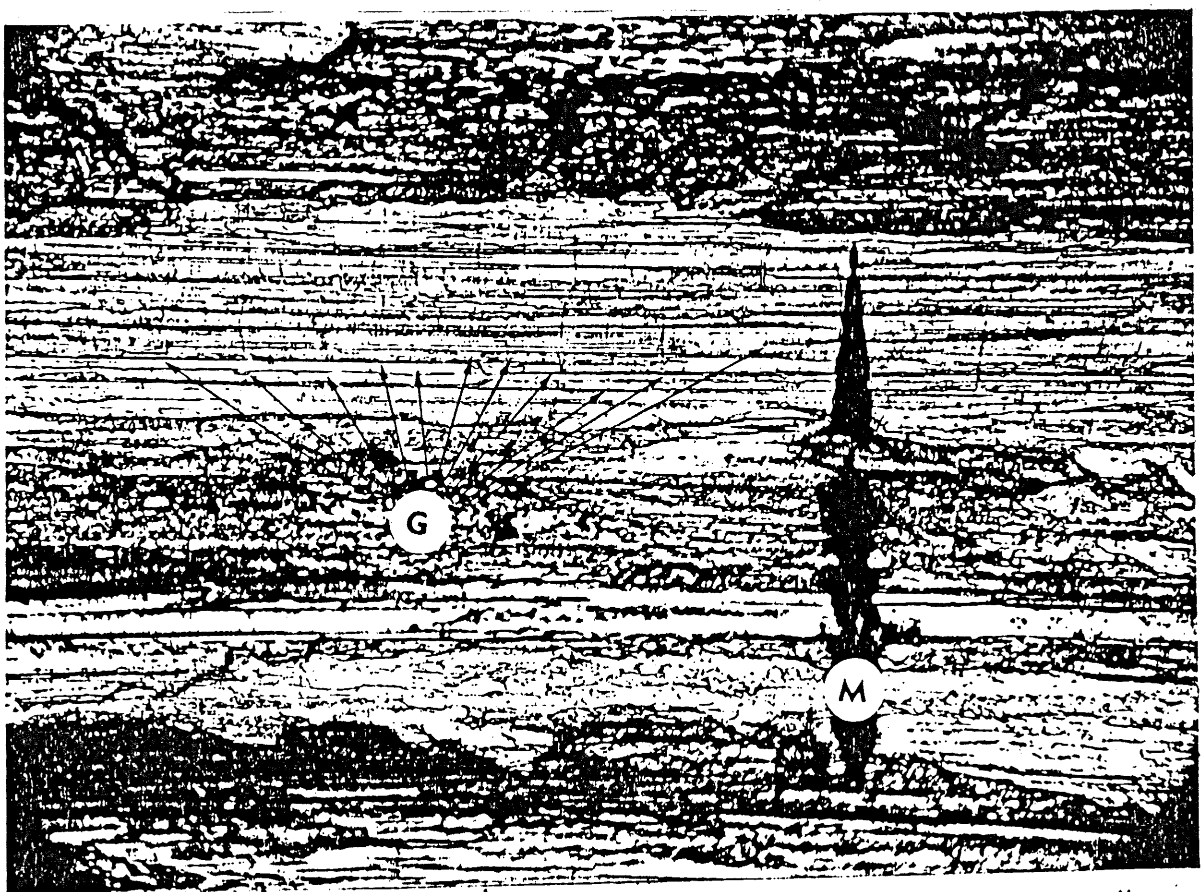
(a) Gentle Grind

10 μ

(b) Abusive Grind

Figure 2 - PHOTOMICROGRAPHS SHOWING TYPICAL SURFACE APPEARANCE OF GENTLY AND ABUSIVELY GROUND Ti-6Al-4V

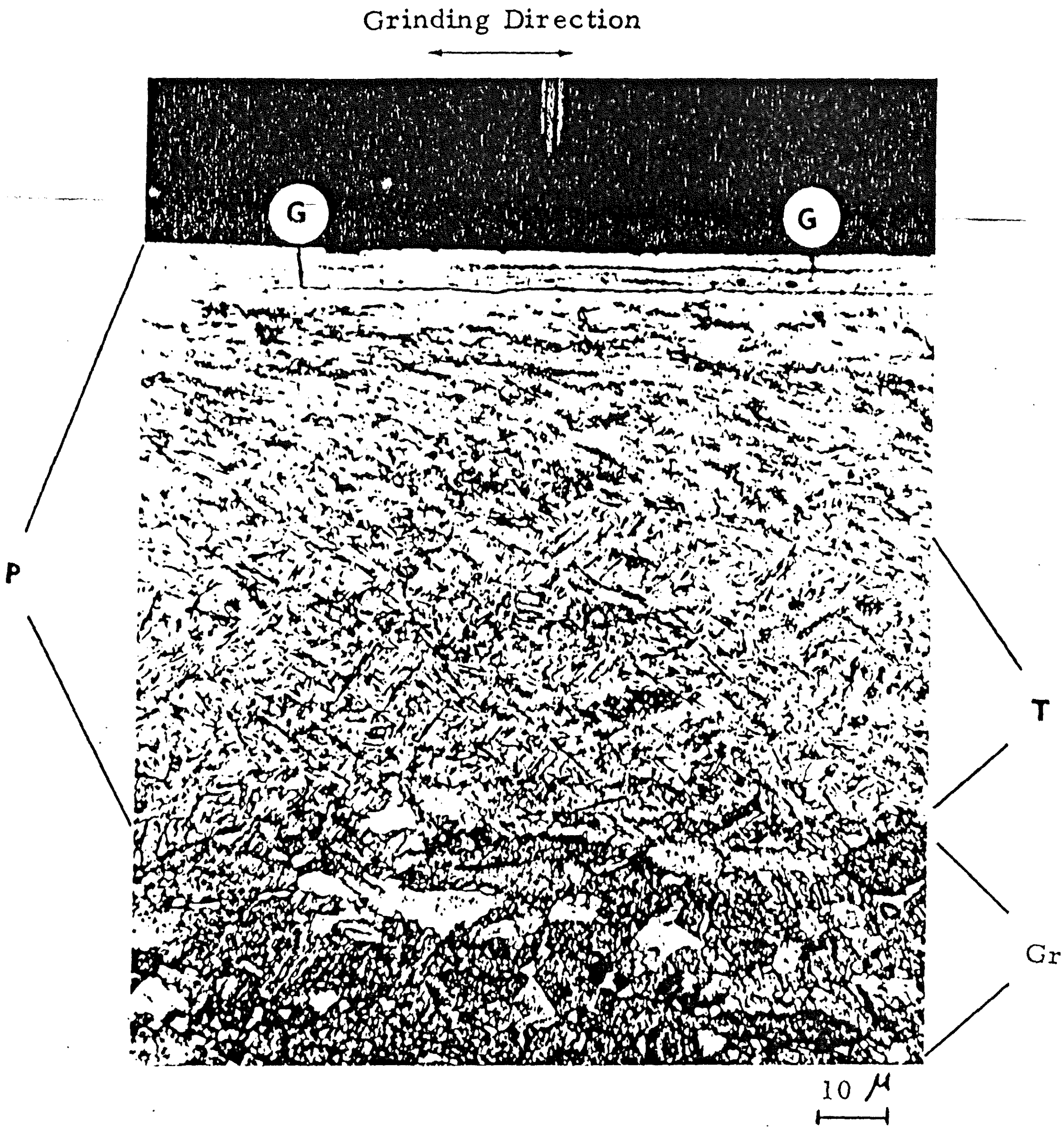
Grinding Direction



10 μ

M = Microhardness Impression
G = Grinding Crack

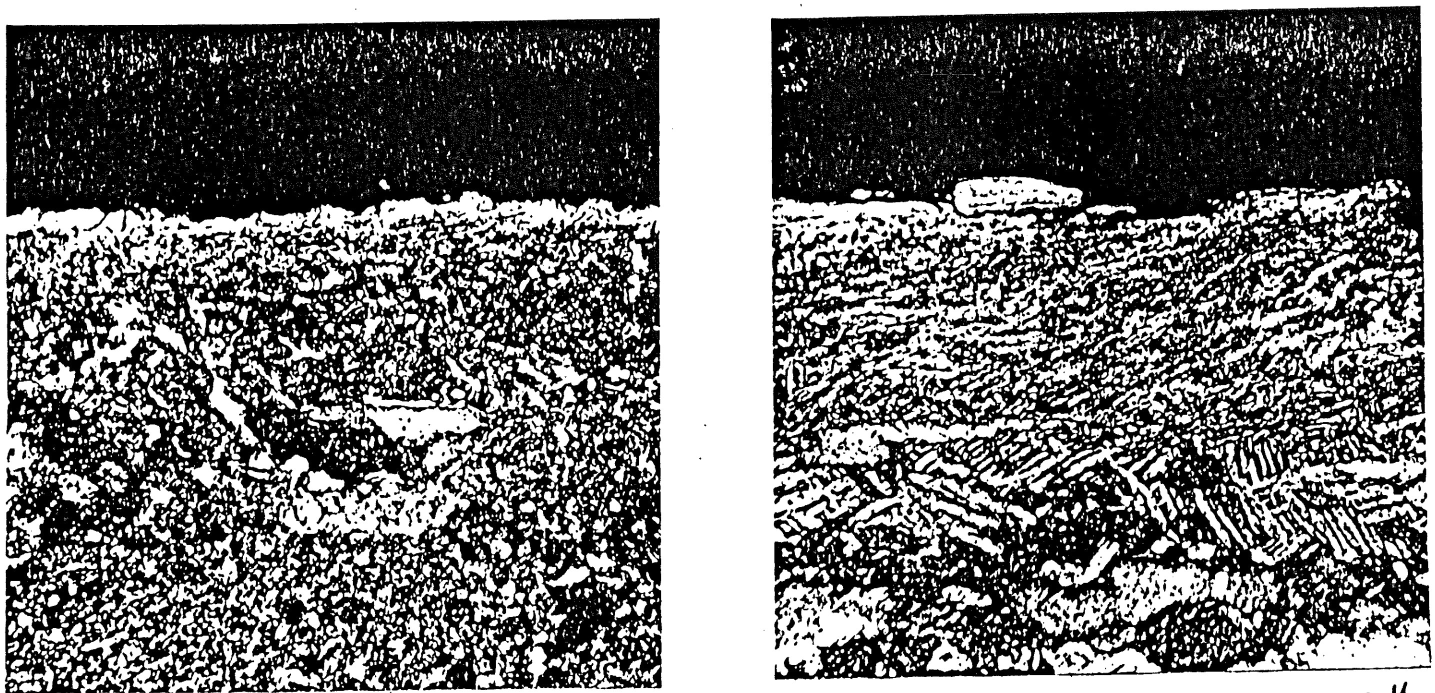
Figure 3 - AREA ON ABUSIVELY GROUND Ti-6Al-4V SURFACE SHOWING ARRAY OF GRINDING CRACKS



G = Grinding Crack
P = Plastic Deformation Area
T = Mechanically Twinned Area
Gr = Grain Growth Area

Figure 4 - PHOTOMICROGRAPH OF SECTION THROUGH SURFACE OF ABUSIVELY GROUND Ti-6Al-4V SPECIMEN (Same Area as Shown in Figure 3)

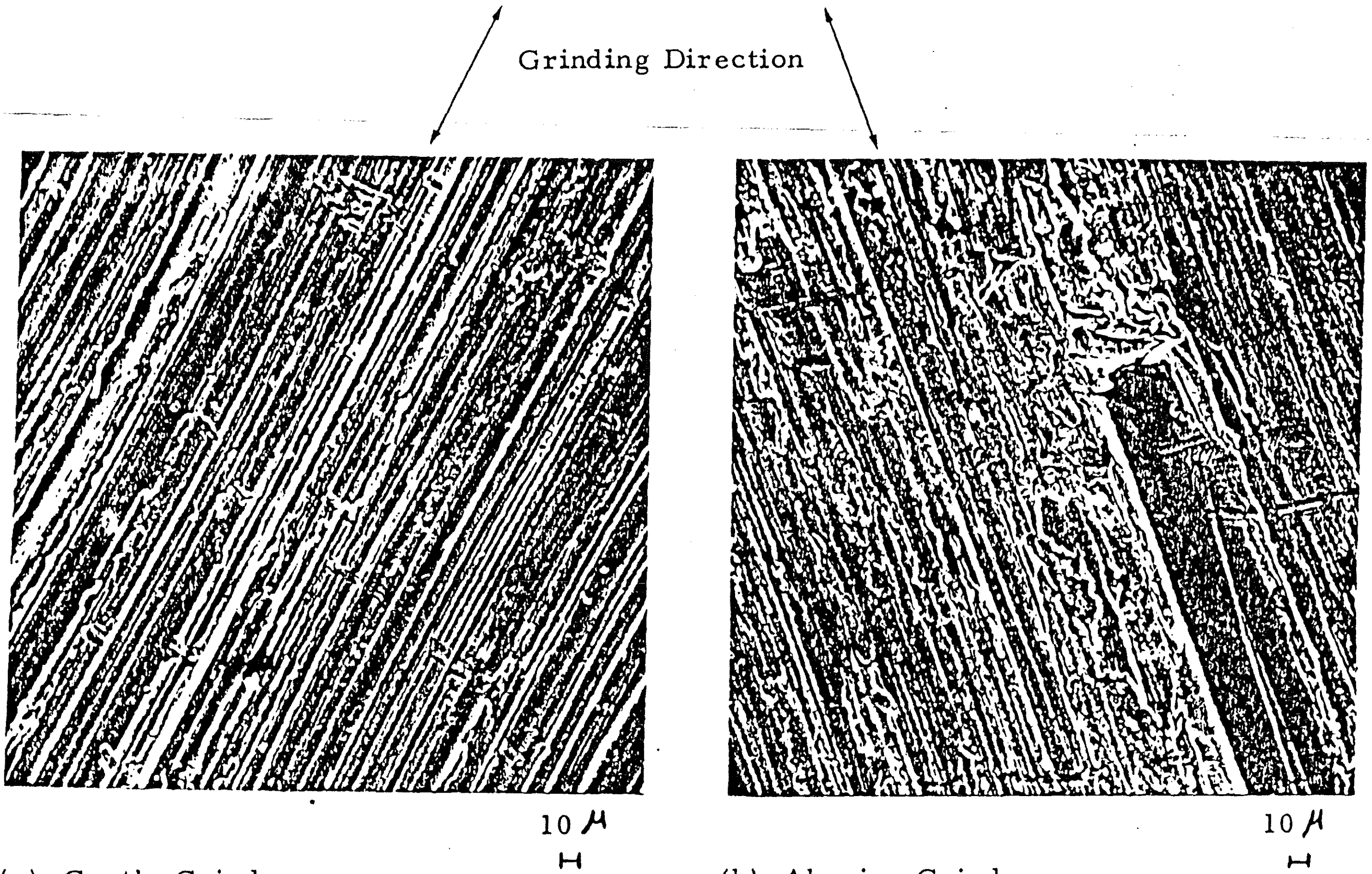
Grinding Direction



10 μ   10 μ

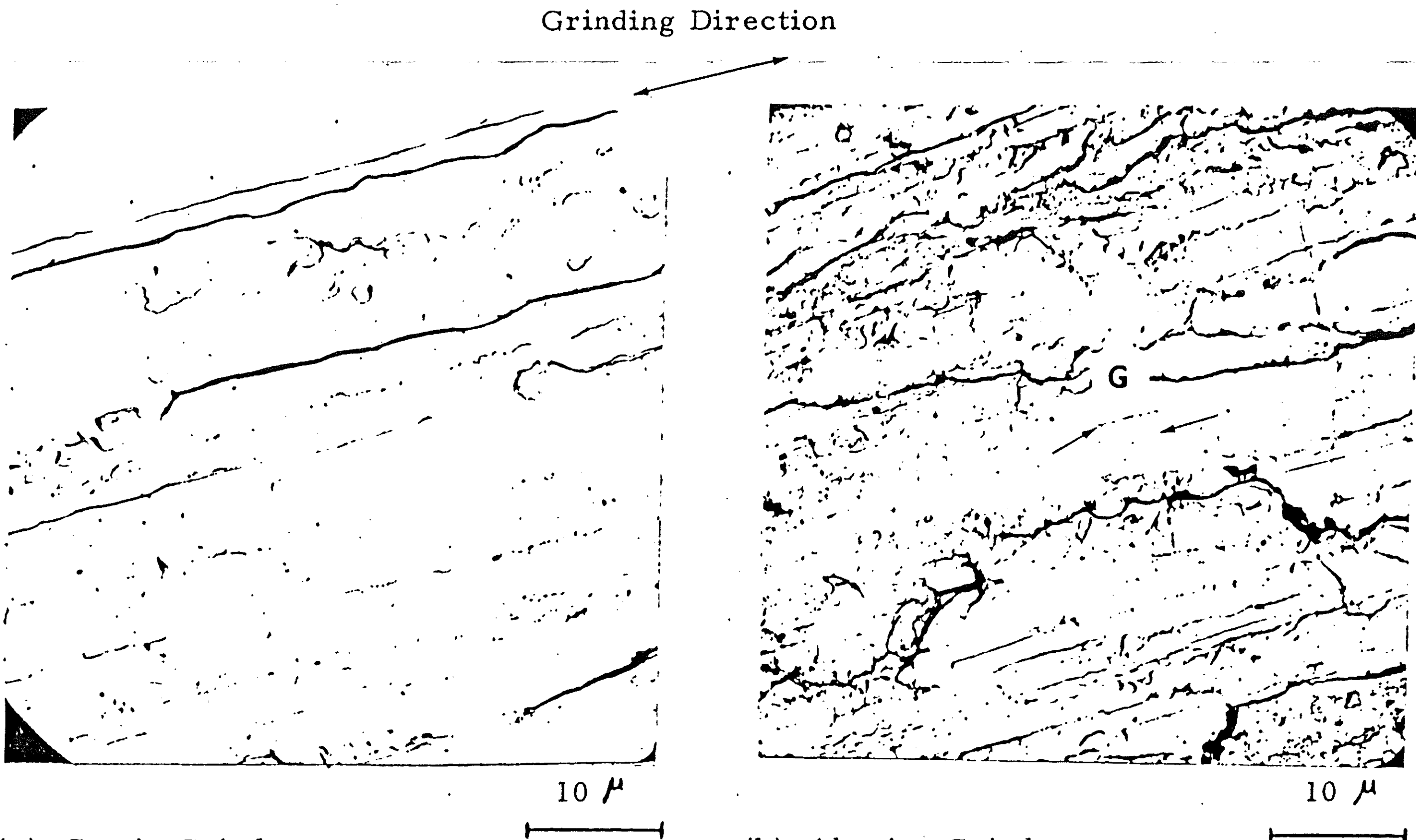
(a) Gentle Grind   (b) Abusive Grind

Figure 5 - PHOTOMICROGRAPHS OF SECTIONS THROUGH SURFACES OF GENTLY AND ABUSIVELY GROUND Ti-6Al-4V SPECIMENS



(a) Gentle Grind (b) Abusive Grind

Figure 6 - SCANNING ELECTRON MICROGRAPHS OF GENTLY AND ABUSIVELY GROUND Ti-6Al-4V SURFACES

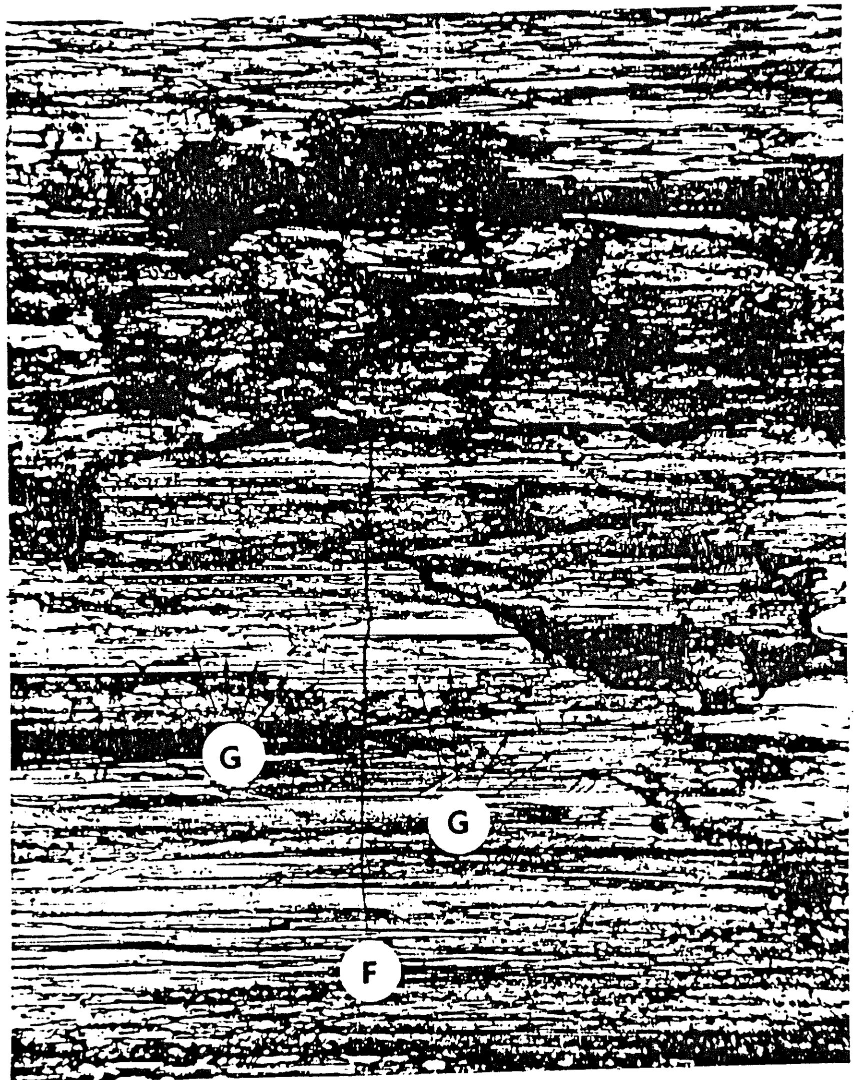


(a) Gentle Grind (b) Abusive Grind

G = Grinding Cracks

Figure 7 - REPLICA TRANSMISSION ELECTRON MICROGRAPHS OF GENTLY AND ABUSIVELY GROUND Ti-6Al-4V SURFACES

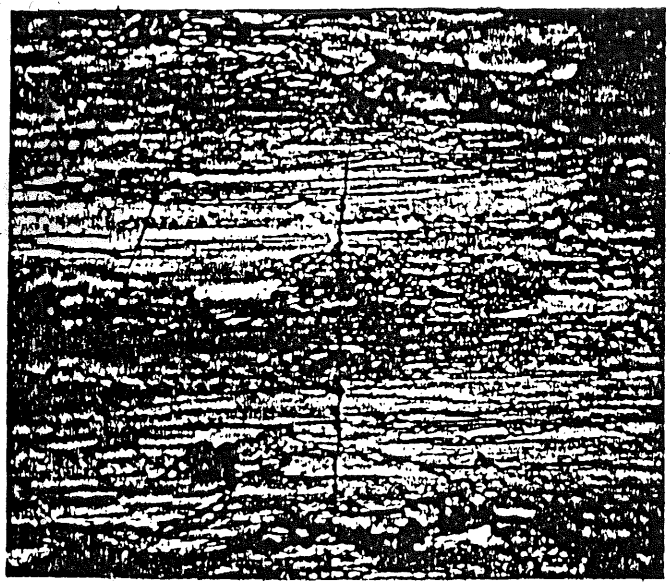
Grinding Direction



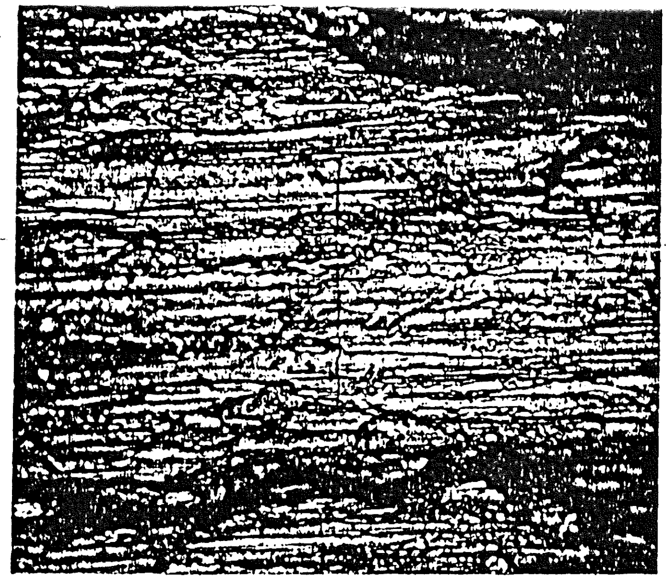
10 μ

F = Fatigue Cracks
G = Grinding Cracks

Figure 8 - FATIGUE CRACK IN MIDST OF ARRAY OF GRINDING CRACKS ON ABUSIVELY GROUND Ti-6Al-4V SURFACE



(e) 60,000 Cycles



(f) 20,000 Cycles

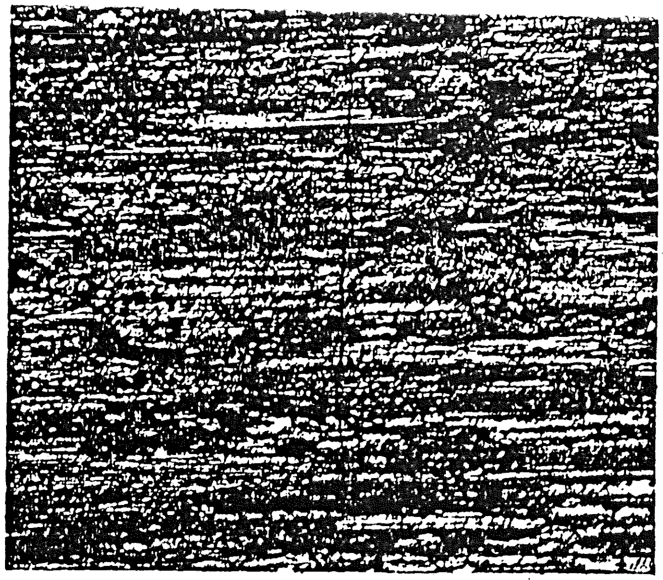
(g) 0 Cycles

(h) 0 Cycles

Figure 9 - PHOTOMICROGRAPHS FROM SURFACE REPLICAS TAKEN AT VARIOUS STAGES OF FATIGUE CRACK PROPAGATION IN ABUSIVELY GROUND Ti-6Al-4V SPECIMENS (cont.)

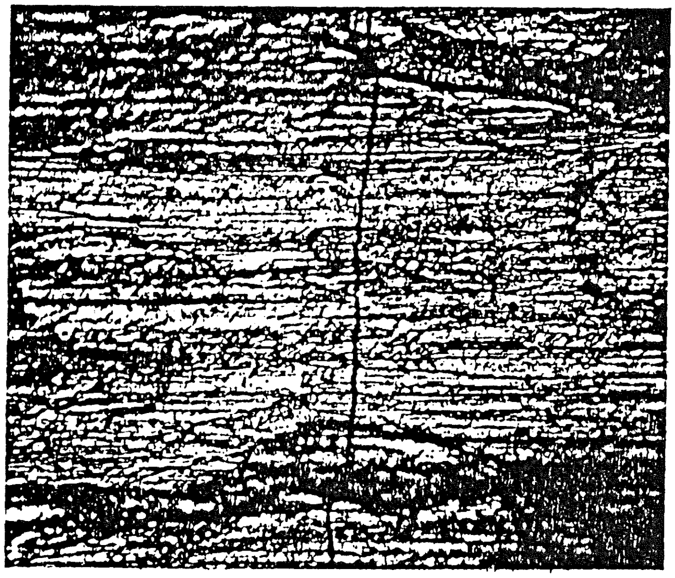
100 μ

(a) 220,000 Cycles



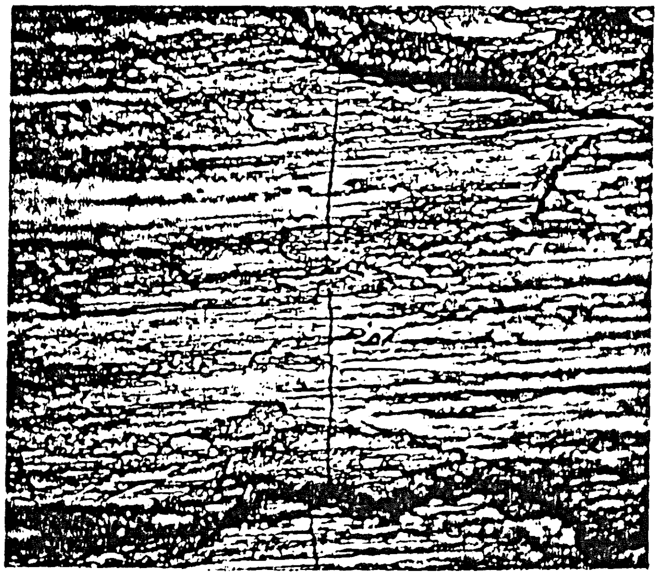
100 μ

(b) 140,000 Cycles



10 μ

(c) 140,000 Cycles



10 μ

(d) 100,000 Cycles

Figure 9 - PHOTOMICROGRAPHS FROM SURFACE REPLICAS TAKEN AT VARIOUS STAGES OF FATIGUE CRACK PROPAGATION IN ABUSIVELY GROUND Ti-6Al-4V SPECIMENS