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FATIGUE CRACK GROWTH-MICROSTRUCTURAL
RELATIONSHIP OF Ti-6Al-4V

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November 1988

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<p>In a previous effort the fatigue crack growth rate characteristics of Ti-6Al-4V were obtained from two forgings and compared to reference data in the literature. Both the test data and the reference data were from forgings identified as being in the "beta-quenched" condition but the fatigue crack growth rates were different. This project provided an understanding of the cause of the difference by examining the microstructure and developing additional fatigue crack growth rate (FCGR) data for the six inch thick forgings used to develop the test data. The reference data was developed on two inch thick forgings. It was shown there is a through-the-thickness variation in the microstructure of the six-inch-thick forgings from surface to center and that fatigue crack growth rates varied with the change in the microstructure. It was possible to correlate the FCGR to the microstructure. Besides differences in the microstructures, there was also (over)</p>			
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a difference in fracture surface morphology. The surface of the forgings exhibited a beta-quenched microstructure, whereas the center of the forgings had a beta-annealed microstructure. The beta-quenched structure showed a much faster crack growth rate and a smoother fracture surface morphology than the beta-annealed microstructure. It was concluded that knowledge of stress ratio and heat treatment conditions alone may not be sufficient to predict the fatigue crack growth rate, particularly in thick sections; instead, the microstructure must also be examined.

FOREWORD

This effort was conducted over the period of September 1987 to June 1988, as a follow-up to Evaluation Report No. MLS-86-30, "Fatigue Crack Growth Characteristics Of Beta Quenched Ti-6-4 As Used In The Night Hawk Spindle", dated 24 March 1986, authored by Gerald J. Petrak, AFWAL/MLSE.

The author would like to thank Don Woleslagle and Tom Dusz of the University of Dayton Research Institute, Dayton, Ohio for their technical assistance throughout the program.



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SECTION I
INTRODUCTION

In 1986 the Materials Laboratory became involved in an effort designed to answer questions about the damage tolerance properties of Ti-6Al-4V forgings. The effort was prompted by problems with a helicopter spindle previously reported (1). Subsequent investigation showed there was a lack of fatigue crack growth rate data on the specific heat treatment on which to make predictions of the life of the component. The Materials Laboratory's Systems Support Division was tasked with developing fatigue crack growth rate data on the material. The helicopter's manufacturer, Sikorsky Aircraft, provided two pieces of forgings removed from sections of the spindle assembly from the same location which suffered the failure; therefore the forgings' samples had the same composition, thickness, and heat treatment as the spindle. Specimens were removed from varying positions through-the-thickness of both pieces of the forging and tested at two stress ratios, $R=0.1$ and $R=0.7$. The data was compared to data published by Rockwell International (2).

The Ti-6Al-4V provided for the investigation was described as being in the beta-quenched condition. Therefore the Materials Laboratory's data was compared to the beta-quenched data of Rockwell. For the lower stress ratio (minimum stress/maximum stress) of $R=0.1$, the comparison showed a correlation of the data between the two sources. Unfortunately though, at the higher ratio of $R=0.7$, there was a difference between the data

sets. The initial program was completed at that point with only speculations of the cause of the variations in the data being due to position location within the forging or possible forging to forging variations.

This program, which was a follow-on to the original effort, was intended to provide an understanding of the cause of the difference in the results from the two sources. Using the original program's speculations as a starting point, the objective for this project was to determine a relationship between the microstructure and the FCGR in order to provide a correlation of the Materials Laboratory's data to published data. The approach used for this project was four-fold. The first task was to perform an extensive literature search to determine if the Rockwell data was the only and most recent source, or if there were other reports which might be of value. Second, a metallographic examination of the forgings was performed to assess variations in grain size and microstructure from forging-to-forging, and through-the-thickness. The third part of the approach was to perform mechanical property testing on the forgings. This included FCGR testing at near threshold conditions in order to verify the original test data and to expand the range of data. This part of the approach also included hardness testing to determine whether there were any variations from forging-to-forging or through-forging-thickness. The final task involved performing fractography on failed FCGR specimens to examine the surface texture characteristics.

SECTION II
MATERIAL & PROCEDURE

The forgings supplied by Sikorsky Aircraft were approximately six inches in thickness. They were heat treated in accordance with MIL-H-81200 with exceptions being noted in a proprietary Sikorsky Material specification (5).

The literature search was conducted through the Air Force Wright Aeronautical Laboratories Technical Library (AFWAL/ISL).

Metallography was performed in accordance with ASTM E-3. Specimens were removed from locations that were representative of the surface and center of the forgings.

The samples were etched with Kroll's Reagent (5 percent HF, 15 percent HNO₃, 80 percent H₂O), allowing sufficient time for the microstructure to be revealed. Photomicrographs were taken using a Zeiss Metallograph for magnifications of 100X, 250X, and 500X.

Grain size determination was performed in accordance with ASTM E-112. The average grain diameters were determined using the methods outlined in the standard (see Table 1).

Fatigue crack growth rate (FCGR) testing near the threshold was performed in accordance with ASTM E-647. Compact (CT) specimens 0.35 and 0.5 inches thick and 2.3 inches wide were used. Testing was conducted in lab air using an MTS electrohydraulic test machine and an HP 9825 computer to control load shedding. Crack length was monitored by a Krak-Gage/Fractomat system that was wired to the HP 9825

computer. All of the FCGR data was obtained under load shedding conditions.

Hardness testing was performed using a Wilson Hardness tester and a Rockwell "C" indenter. The specimens were from the surface and the center of both of the forgings (see Table 2).

Fractography was performed on two specimens, one from the surface of one forging and one from the center of the other forging, using failed FCGR specimens. The locations for examination were selected so as to determine if there were any differences in fracture. The locations observed were such that the stress intensity range was the same for both specimens although the crack growth rate might be different. Specimens were examined with a scanning electron microscope (SEM). The entire thickness of the specimen along the location of interest was examined, although photomicrographs were only taken from the center of the thickness.

SECTION III

RESULTS

The literature search provided several articles by the same authors as the work by Rockwell, Mr. James Chesnutt and Mr. John Wert. It had been reported during the original program that some of the early data on Ti-6-4 did not agree with the later results. The data in question was reported in AFML-TR-78-68. This was work by Chesnutt, Thompson, and Williams, of Rockwell International. When it was requested of Chesnutt to send recent information on the subject for the original program, he notified the Materials Laboratory that the earlier data might be questionable. He also provided the most recent work available.

The conclusions of the original program were,

"The results of two FCGR tests performed at $R=0.1$ resulted in different data for the samples. It is suspected the difference is caused by location within the forging even though there is an equal possibility the difference is caused by forging to forging variations. To perform an analysis using the data it would be best to use the data from the sample that exhibited the fastest growth rate. Data from two specimens tested at $R=0.7$ appeared to fall into one scatter band. These two specimens were removed from near the surface of the forging that had the faster growth rate when tested at $R=0.1$.

Reference data on the same alloy and condition, beta quenched Ti-6-4, is close to the faster data for R=0.1. At higher stress ratios there is no correlation between reference data and test data."

Peters, Welpmann, and Doker, (3), showed that grain size has an effect on the FCGR in Ti-6-4. The report also showed that this effect is only seen when there is a large difference in grain size and shape. They reported differences between fine equiaxed grains (1-2 micrometers) and coarse lamellar grains (1-2 mm). Chesnutt and Wert (2) noted that the microstructure of Ti-6-4 forgings which had been water quenched from the beta phase field (as in the forgings examined in this program) could only be controlled for forgings up to 12 mm (approximately one half inch) in thickness. Above this thickness, a consistent through-the-thickness microstructure could not be maintained. It has also been shown (6) that hardenability can only be controlled for thicknesses of up to 25mm. Beyond that thickness, variations in strength and microstructure can occur.

Throughout the remainder of this report the terms beta-quenched and beta-annealed are used to describe the microstructures. These terms refer to the types of microstructures obtained when two-inch thick Ti-6-4 samples are processed by the following schedules, as was done by Chesnutt, et. al.;

- 1) Beta-quenched: 1038 °C/0.5h/water quench
+704 °C/2h/air cool
- 2) Beta-annealed: 1038 °C/0.5h/air cool
+704 °C/2h/air cool

The resulting microstructures can be identified by the relative size of the alpha platelets that form.

In the beta-quenched structure, the alpha platelets were either nonexistent or very fine needles. The beta-annealed structure showed a typical Widmanstätten, or basketweave, structure indicating the alpha platelets had enough time to coarsen and become more evident (see Figs. 1-4). The two samples of Ti-6-4 used in this investigation were six inches thick and arbitrarily identified by the codes AA and BA. There is no significance to these codes. Heat treatment of these samples was done by Sikorsky Aircraft, and is very similar to that described above as the beta-quenched heat treatments.

The grain size studies showed no extreme differences in average grain diameters from surface to center of the forgings. Table 1 shows the results of these studies. Since only large differences in grain size have been shown to cause differences in the FCGR (3), this part of the program was then considered to be not of significance.

FCGR data from the original program was replotted against the data from Chesnutt and Wert for each stress ratio; heat treatment and location in the forgings were the variables. The comparisons of these two sets of data are shown in Figs. 5-8. From these curves the variation of FCGR could be correlated to the published data of Rockwell for a given stress ratio and a given microstructure for all cases. The fatigue crack growth rates, Fig. 8, for beta-quenched microstructure at $R=0.7$ was marginally slower than the data reported by Rockwell. This can

be attributed to the fact that the location the specimen was removed from in the forging was about an inch away from the surface. This location allowed for a small growth in the size of the alpha platelets. These platelets, however, had not grown sufficiently enough for the microstructure to be called beta-annealed. Due to the large number of data points for this specimen, a seven point incremental data reduction routine was used. These points are the ones shown in Fig. 8. The AFWAL FCGR curves shown in Figs. 5, 6, and 7 are curves that were previously reported (1). The data in Fig. 8 was produced during this current effort.

The hardness testing showed that there was a variance in the hardness from surface to center of the forgings, as is shown in Table 2. This was of no surprise since a beta-quenched microstructure is similar to that of titanium martensite, which is a hard structure. Therefore it would be expected to see a harder structure at the surface of the forging than in the center.

Fractography of the failed FCGR specimens with the use of an SEM showed that the beta-annealed morphology has a much coarser morphology than the beta-quenched. This is also obvious in visual observations of the fracture face (see Fig. 9).

SECTION IV

DISCUSSION

Because of the thickness of the spindle forgings and the heat treatment applied to them, the variations in fatigue crack growth rate was not surprising. Chesnutt and Wert (2) reported that the maximum thickness that could be quenched and still maintain a uniform microstructure was 12 mm, which is just under one half inch. Therefore it could not be expected of the six inch spindle forgings to have a uniform microstructure from surface to center. The center of the forging retains enough heat after quenching to allow the alpha platelets to grow and produce the annealed structure. This was shown by the metallography. The Rockwell forgings were two inches in thickness which produced a more consistent microstructure, although some slight variances could be expected. The FCGR curves were able to be correlated with microstructure. The beta-annealed structure had a slower FCGR than the beta-quenched for a given stress ratio because of the fact that the coarser alpha structure in the annealed state had the tendency to deflect the crack away from the crack growth plane which is consistent with previous findings (4), and the present results of the fractography, Fig. 9. This resulted in a slower crack growth rate. Since the crack was deflected for the beta-annealed case, the fracture face showed a rougher texture than that of the beta-quenched case, which did not have nearly as many of these deflections. A higher stress ratio usually produces a faster FCGR irrespective of microstructure because there is a higher mean stress applied to the specimen. Therefore

for these forgings, the fastest FCGR would be seen in the beta-quenched structures with a stress ratio of $R=0.7$.

Two of the four original approaches in this program were found to have no significance. The first was the case of the grain size, which has already be discussed. The other was the variations in the hardness of the forgings. The hardness changed along with the microstructure. However, there does not appear to be justification for relying solely on hardness as an indicator of FCGR characteristics in Ti-6-4.

A report released by Rockwell International after the technical effort of this program had been completed tends to agree with the results discussed above. (4) This latest effort by Rhodes, Chesnutt, Wert, and Ghosh concluded that crack propagation rates at $R=0.1$ are microstructure dependent at stress intensity levels up to about $18 \text{ ksi } \sqrt{\text{in}}$. However, microstructural effects become less significant at stress intensity levels above $9 \text{ ksi } \sqrt{\text{in}}$. for $R=0.7$ testing. They conclude that the difference between $R=0.1$ and $R=0.7$ test conditions is most likely associated with crack closure effects. They also stated that the crack direction would be determined by the orientation of the Widmanstatten colony with respect to the applied stress axis.

SECTION V
CONCLUSIONS

It can be concluded that the fatigue crack growth rate of Ti-6-4 may not be solely determined by the heat treatment schedule. The microstructure must also be examined in order to completely understand all the factors involved. Examinations, either visually or with the use of a scanning electron microscope (SEM) of the fracture surface texture can serve as a guide to the FCGR but could not be relied upon as an exact indicator. In the case of the Ti-6-4 spindle forgings, different microstructures produced different fracture surface morphologies.

The reason the original program showed different growth rates for the two forgings was the fact of comparing a specimen removed from near the center of one forging to a specimen removed from near the surface of the other forging. This follow-up program could not find any evidence of forging-to-forging variations.

The problem of test data and reference data not correlating at higher stress ratios has been solved by simply identifying the microstructure and comparing the test data to the reference data based upon this microstructure.

The other conclusion drawn from this effort supports previous findings that thick sections of Ti-6-4 can not be heat treated to the same microstructure throughout.

SECTION VI

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- (3) Peters, M., Welpmann, K., and Doker, H.; Fatigue Crack Growth Behaviour of Two Extreme Microstructures of Ti-6Al-4V, Titanium -- Science and Technology, Volume 4, 1984, pp. 2267-2274.

- (4) Rhodes, C. G., Chesnutt, J. C., Wert, J. A., and Ghosh, A. K. Processing and Properties of Airframe Materials, AFOSR-TR-87-0815, June 1987.

- (5) Sikorsky Material and Process Specification, SS No. 8452, Titanium Alloy 6Al-4V Forgings, Beta Solution Heat Treated and Overaged.

- (6) Polmear, I. J. Light Alloys-Metallurgy of the Light Metals, pp. 162-209, c. 1981, Edward Arnold (Publishers) Ltd.

FORGING LOCATION	AA	BA
SURFACE	0.014"	0.020"
CENTER	0.015"	0.016"

Table 1 - Average Grain Diameters at Different Locations
in Six-Inch-Thick Ti-6Al-4V Forgings

FORGING LOCATION	AA	BA
SURFACE	42	43
CENTER	36	31

Table 2 - Rockwell "C" Hardness Data at Different Locations
in Six-Inch-Thick Ti-6Al-4V Forgings

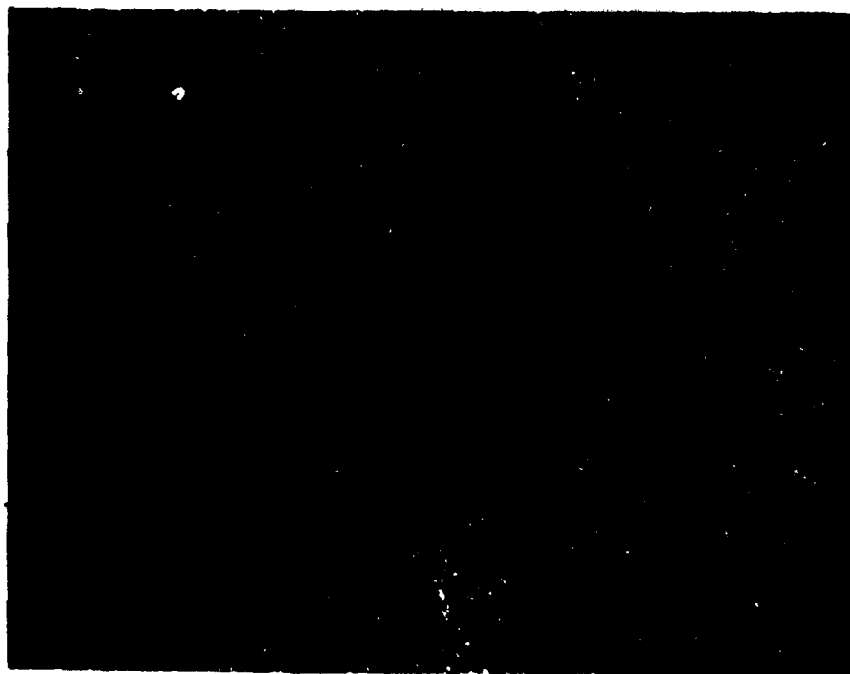


Figure 1. Microstructure of 6-inch-thick Forging AA from near the surface; the lack of large alpha platelets is indicative of a Beta-Quenched microstructure. (100X-top, 500X-bottom)

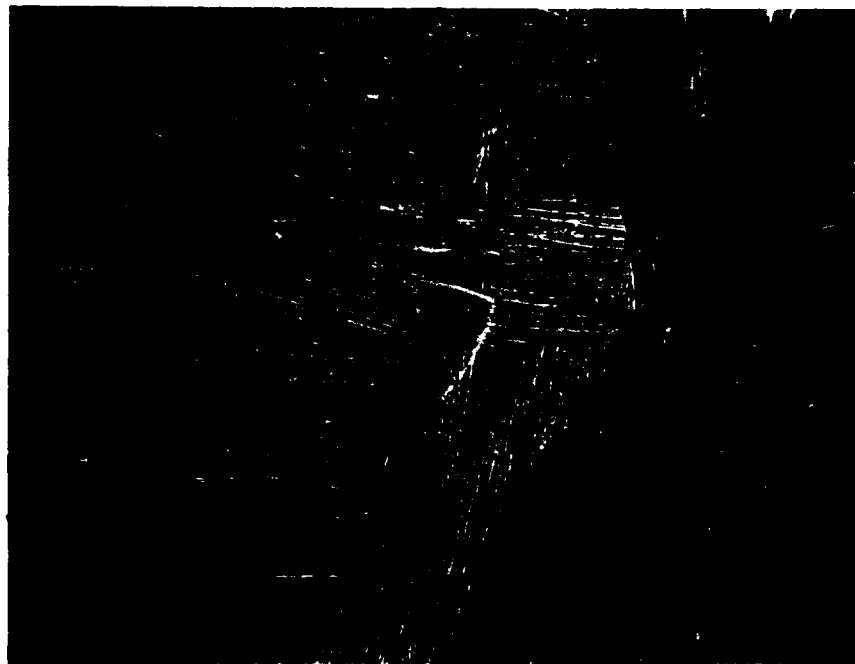
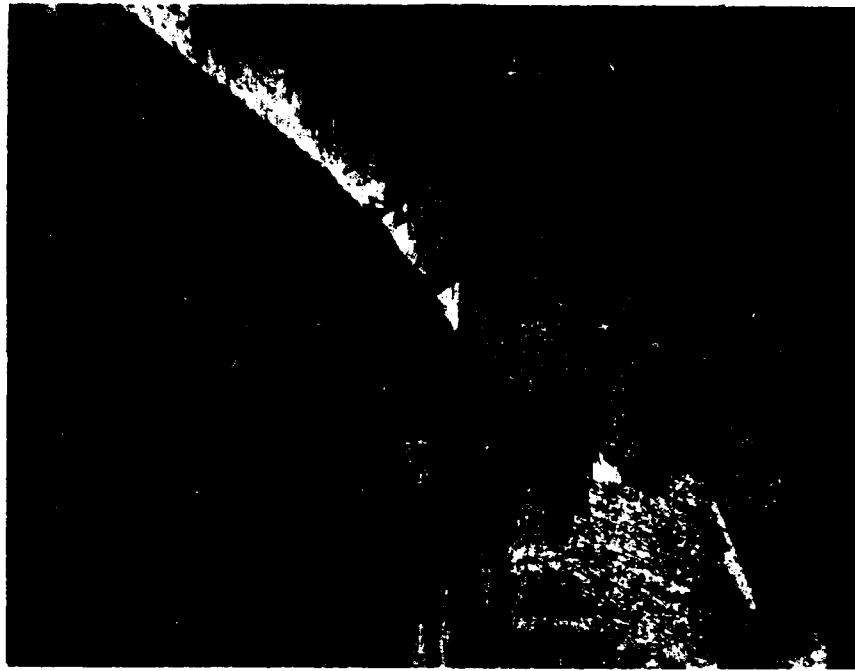


Figure 2. Microstructure of 6-inch-thick Forging AA from near the center; the presence of large alpha platelets and colonies is indicative of a Beta-Annealed microstructure. (100X-top, 500X-bottom)

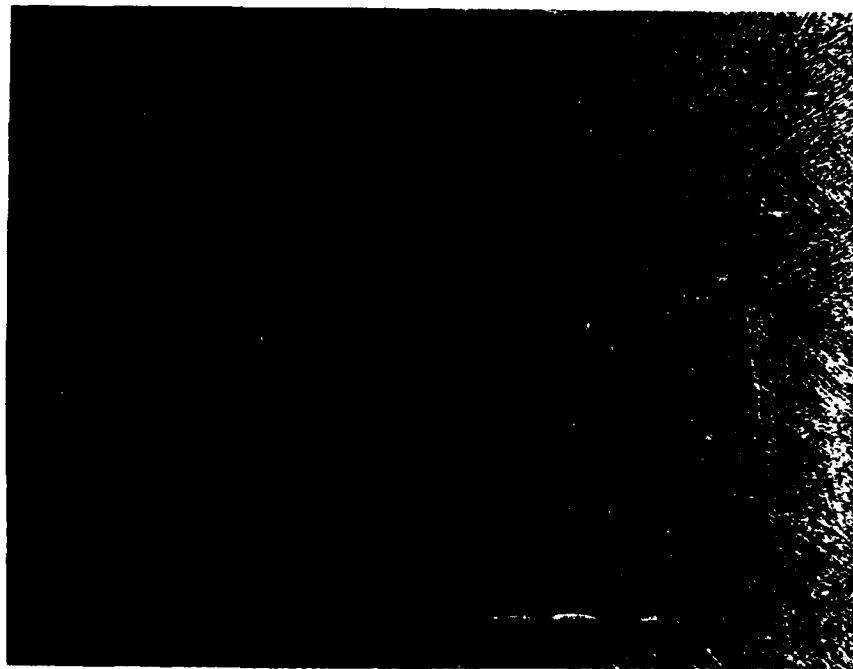


Figure 3. Microstructure of 6-inch-thick Forging BA from near the surface; the lack of large alpha platelets is indicative of a Beta-Quenched microstructure. (100X-top, 500X-bottom)

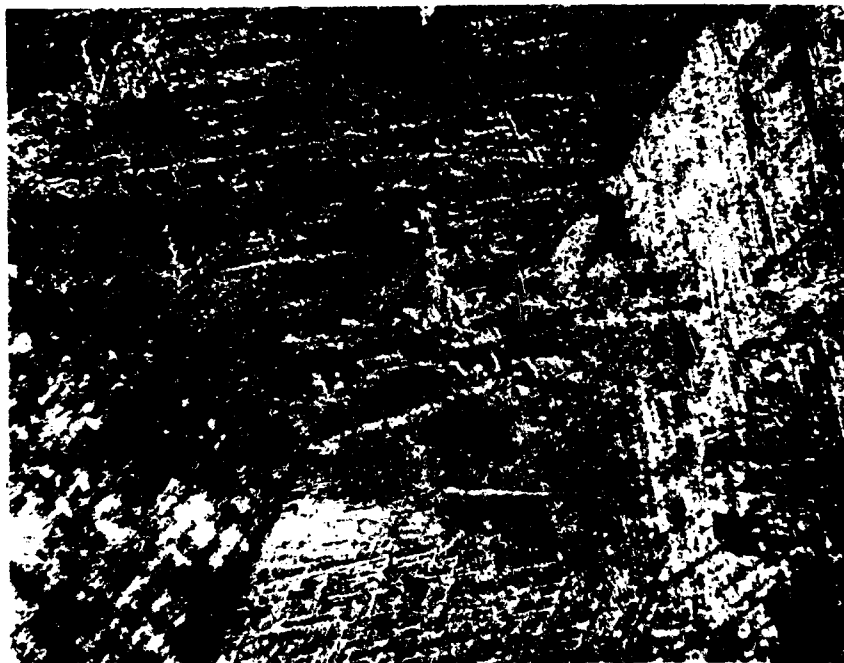
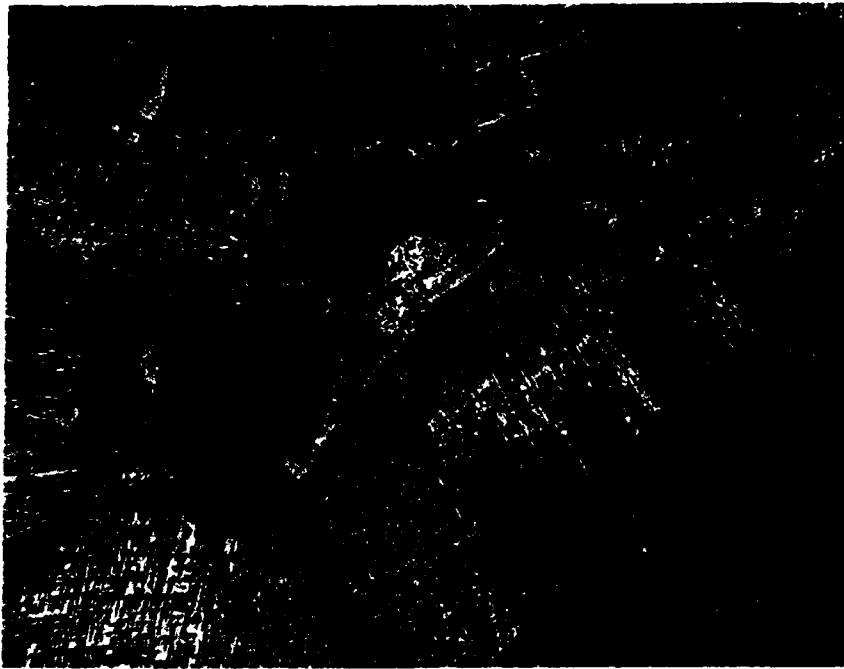


Figure 4. Microstructure of 6-inch-thick Forging BA from near the center; the presence of large alpha platelets and colonies is indicative of a Beta-Annealed microstructure. (100X-top, 500X-bottom)

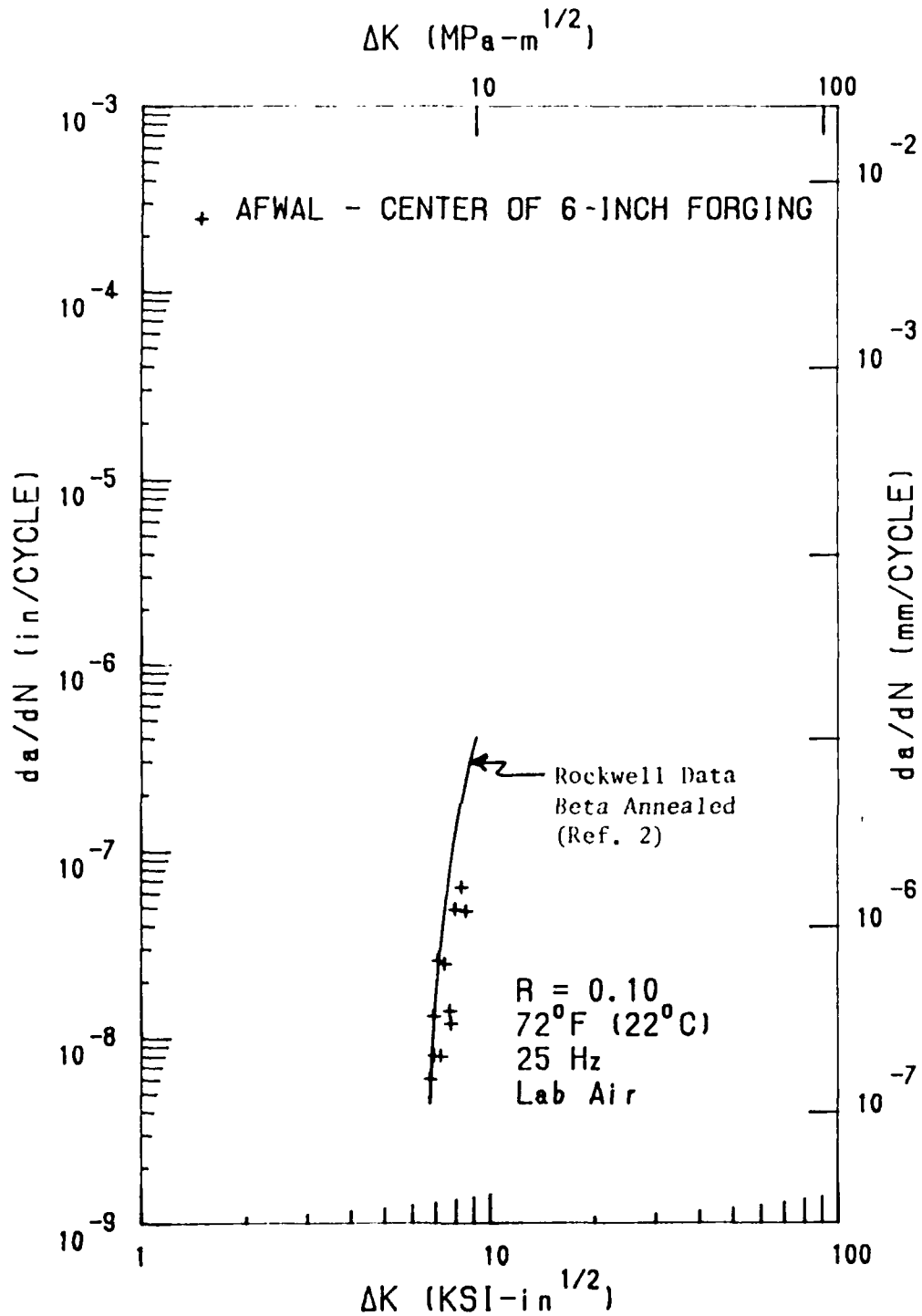


Figure 5. FCGR results for specimen removed from the center of a six-inch forging and reference data for a two-inch-thick Beta-Annealed forging.

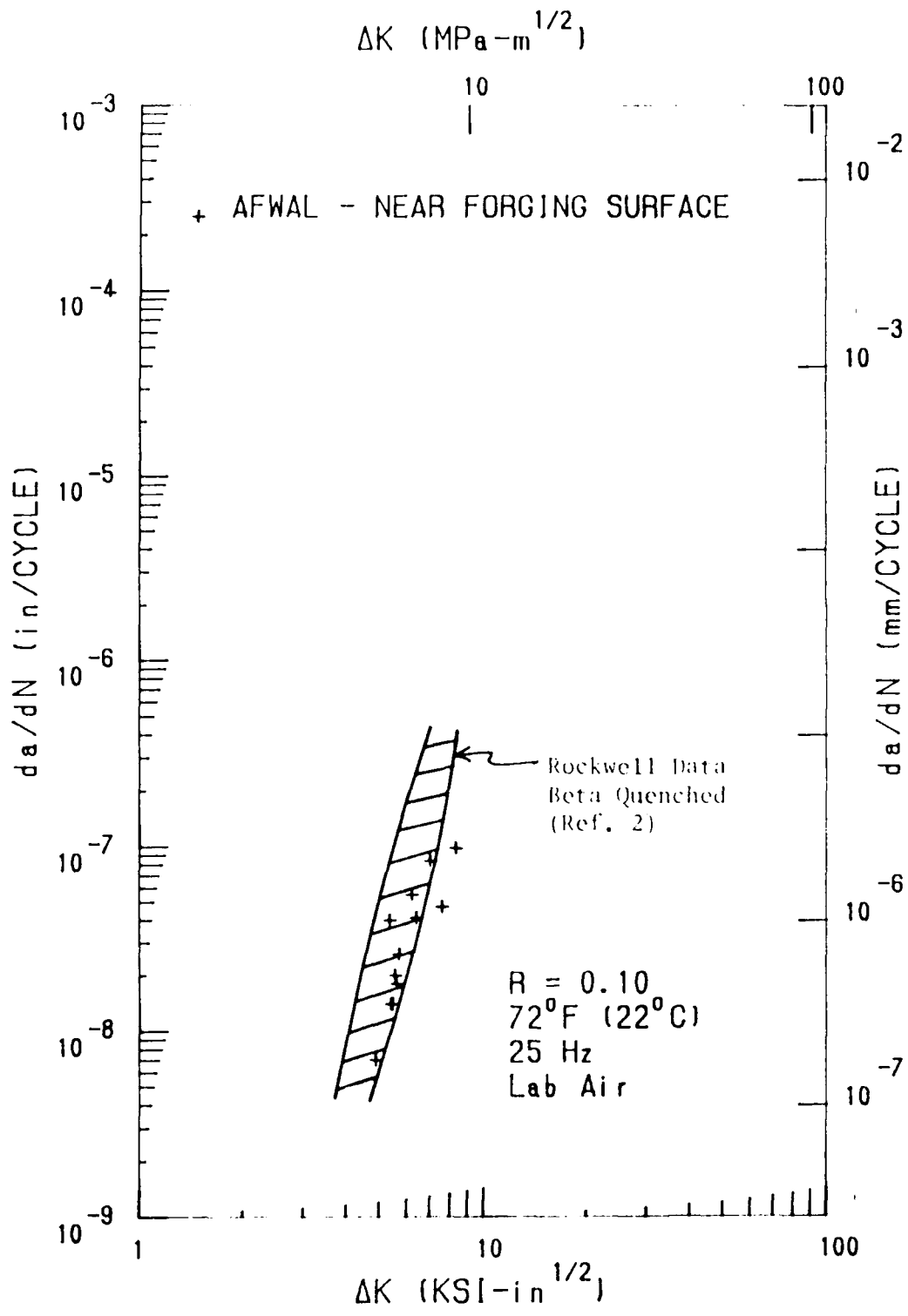


Figure 7. FCGR results for specimen removed from near the surface of a six-inch forging and reference data for a two-inch-thick Beta-Quenched forging.

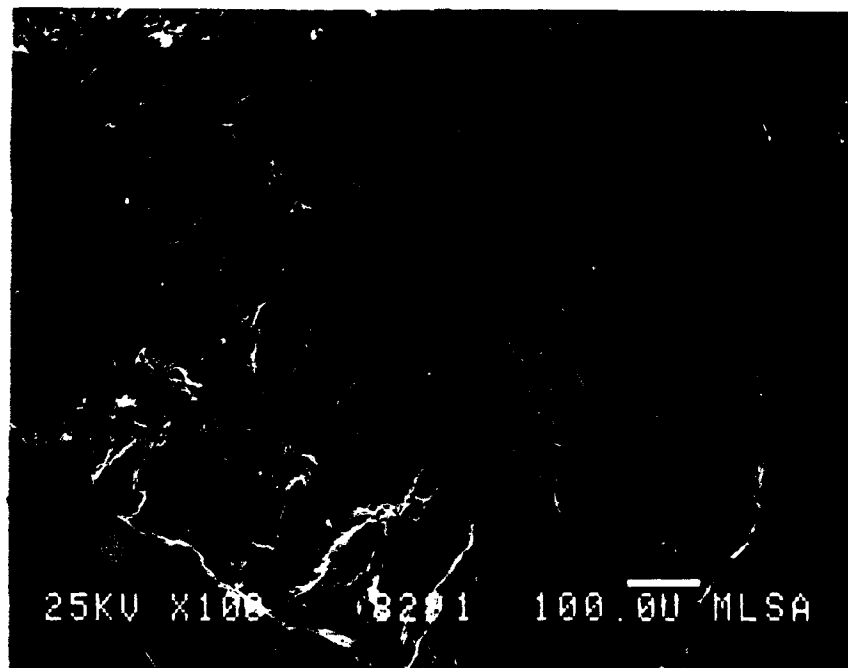
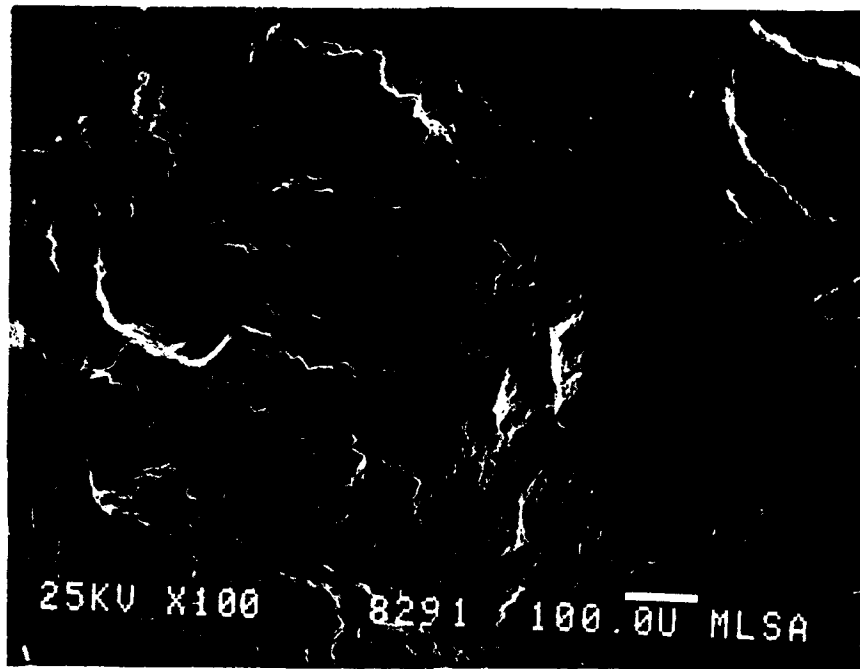


Figure 9. SEM fractography of fracture faces of samples removed from a six-inch-thick Ti-6-4 forging.

Top: Near surface of forging.

Bottom: Near center of forging.