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THE EFFECT OF FRETTING DAMAGE ON THE FATIGUE BEHAVIOR OF METALS

Technical Report 1

by

David W. Hoeppner and Gary L. Goss

Office of Naval Research
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Fretting fatigue studies were conducted on Ti-6Al-4V and 7075-T6 aluminum specimens cycled in axial fatigue loading at a fatigue ratio (R) of 0.1. Fatigue loading was applied at 30 Hz in a laboratory environment with the fatigue specimen loaded in fatigue and fretting applied to the specimen central section through a fretting pad made of the same material as the specimen. Tests were conducted at various maximum loads and normal pressures. (U)

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Details of illustrations in
this document may be better
studied on microfiche

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ABSTRACT

Fretting fatigue studies were conducted on Ti-6Al-4V and 7075-T6 aluminum specimens cycled in axial fatigue loading at a fatigue ratio (R) of 0.1. Fatigue loading was applied at 30 Hz in a laboratory environment with the fatigue specimen loaded in fatigue and fretting applied to the specimen central section through a fretting pad made of the same material as the specimen. Tests were conducted at various maximum loads and normal pressures.

The fretting damage that occurred resulted in a significant reduction in fatigue life. The reduction in fatigue strength was greater for both materials in the long life region. A fretting fatigue damage threshold that results from the fretting was found to exist for both materials. At all load levels a given amount of fretting damage is required before any fatigue life reduction occurs. Presumably the damage leads to the development of cracks in the fretted areas. Metallographic studies of the fretted areas have revealed that multiple cracks form in the fretting areas and are propagated by fatigue. Some evidence was found to indicate that fretting debris is forced into the microcracks as they develop, this explaining in part, the significant reduction in life caused by the fretting. Several conclusions are presented based on the studies to date and the direction of the continuing studies is indicated.

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Section 1

INTRODUCTION

When two surfaces held in contact by a normal load (clamping force) undergo a small, relative displacement, even though the two surfaces are presumed to be nominally fixed relative to one another, one or more surfaces may suffer a type of damage referred to as fretting. In the absence of a corrosive media, (e.g., in a vacuum) the process may be purely physical in nature; while in the presence of a corrodent, a chemical surface reaction also may be involved in the process. When one, or both, of the members in contact carry a cyclic load the fretting process may result in a significant reduction in the fatigue stress design allowable. The synergistic combination of fretting and fatigue is herein referred to as fretting-fatigue.

The deleterious nature of fretting on fatigue behavior has recently been recognized as a serious factor in the degradation of load carrying ability of engineering structure. Consequently, increased research and development activity is being devoted to the study of the fretting-fatigue process, with the ultimate goal of eliminating or alleviating the loss of fatigue strength in design or material applications in which fretting is a factor. Various approaches have been taken to study fretting-fatigue. The authors have previously published a summary of some of the research that has improved the level of understanding of the process(1). *

The research effort devoted to fretting-fatigue has primarily taken one of three approaches, namely:

(1) Studies directed toward alleviation and control for a specific application.

(2) Studies that have been devoted toward development of a phenomenological understanding of fretting-fatigue.

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* Numbers in parentheses refer to the references in Section 7.

(3) Studies devoted to an understanding of the fundamentals of fretting-fatigue.

The first item above is discussed extensively in References 2 - 6. Phenomenological aspects are briefly discussed in Reference 1 and extensively summarized in Reference 7.

These first two aspects are not one of the specific goals of the effort reported herein. This research has been directed toward understanding the relationship of fretting damage to the degradation of fatigue load carrying ability. This has been studied by the authors(1), Professor Waterhouse (8 - 10) and others (see Reference 1 or 7). The effort reported herein was thus concentrated in the third area listed above. This report describes the results and analysis completed to date. The analysis and research is continuing.

Section 2

PROGRAM OBJECTIVE AND SCOPE

The broad objective of this research activity is to improve the understanding of the nature of the physical and chemical processes that contribute to fretting-fatigue. In the broad sense, this will allow application of design principles, materials selection and application principles, and alleviation and protection schemes that lead to a reduced incidence of fretting-fatigue failures. The effort reported herein was directed toward the following specific objectives:

(1) Conducting fretting-fatigue tests to establish the reduction of fatigue life caused by fretting damage on Ti-6Al-4V and 7075-T6 as a function of normal load.

(2) Evaluating the effect of the fretting damage by removal of the fretting pad to establish the validity of the fretting damage boundary concept.

(3) Examining the relationship between the initial fretting damage and microstructure.

(4) Establishing the relative role of physical and chemical processes in the fretting-fatigue mechanism.

Section 3

EXPERIMENTAL PROCEDURE

The goal of the experimental program is to produce fretting-fatigue in a controlled manner in order to ascertain the mechanism controlling the failure mode. To conduct controlled fretting-fatigue tests a reproducible test technique and uniformly prepared specimens were utilized. The specimen preparation,test apparatus, and test procedure are respectively described in the following subsections.

3.1 Specimen Preparation

For the first phase of the current study two metal alloys were utilized. These alloys were selected because of their extensive use in aircraft structure. Specimens were fabricated from .050 inch thick sheet Ti-6Al-4V mill-annealed titanium and 7075-T6 aluminum. The fretting pads were machined from .250 inch thick sheet of the same alloys. The specimen and pad dimensions are shown in Figure 1. By using sheet material of proper thickness variables such as grain size, preferred orientation and machining practices were held constant for each alloy.

After the specimens (both coupon and pad) were machined from the sheet they were lapped smooth and highly polished metallographically. This provided a very uniform surface on both the fatigue specimen and pad. Surface finish measurements were taken on a titanium and aluminum specimen surface. Typical values of surface finish in μ inch RMS are presented in Table I. These values are representative of the initial surface condition for all specimens of titanium and aluminum utilized in this study.

3.2 Test Apparatus

The fretting-fatigue apparatus has previously been utilized and details of the operation of the fretting fatigue apparatus are covered elsewhere(1).

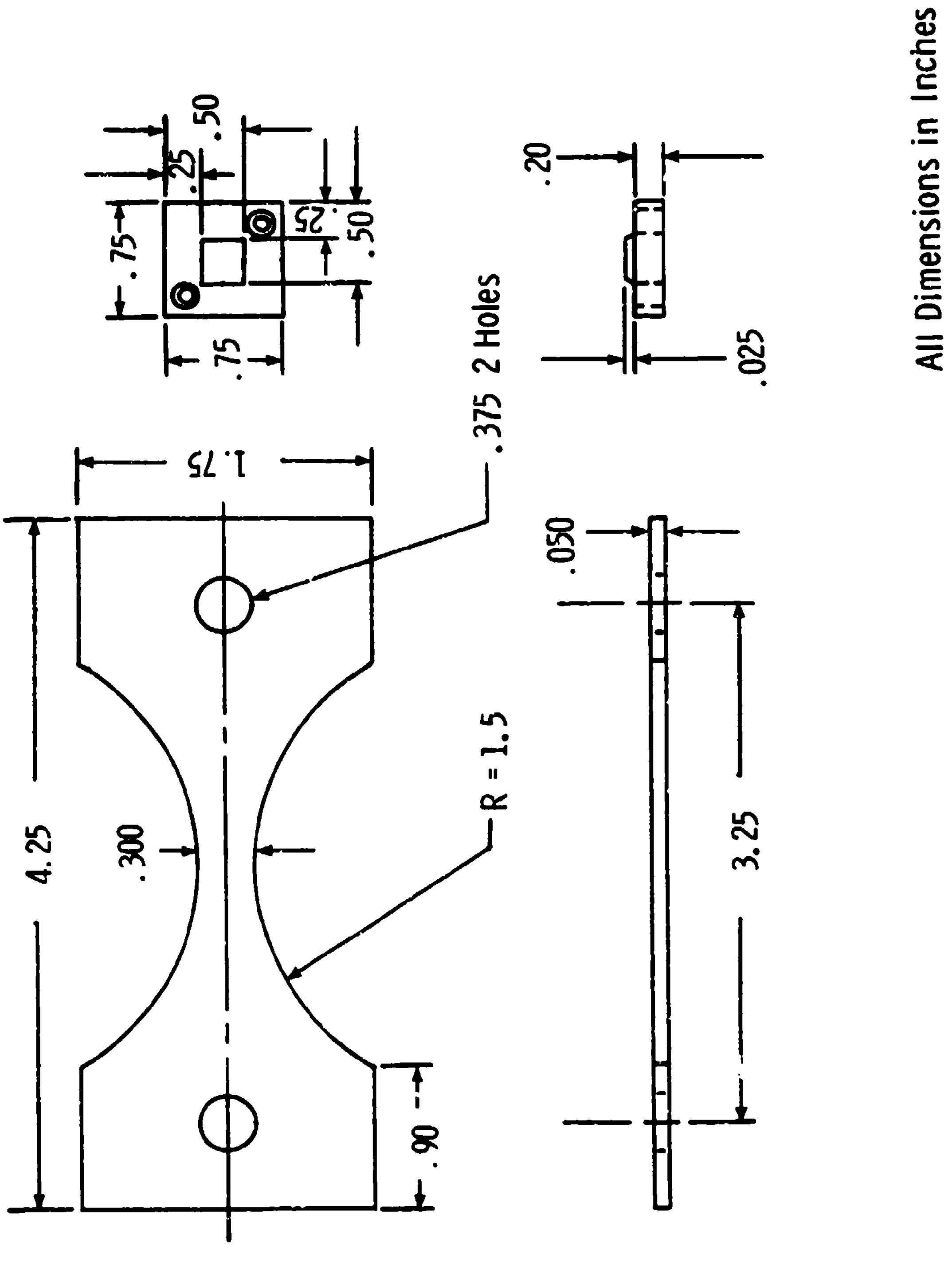


Figure 1. Fretting Fatigue Specimen and Fretting Pad

TABLE I

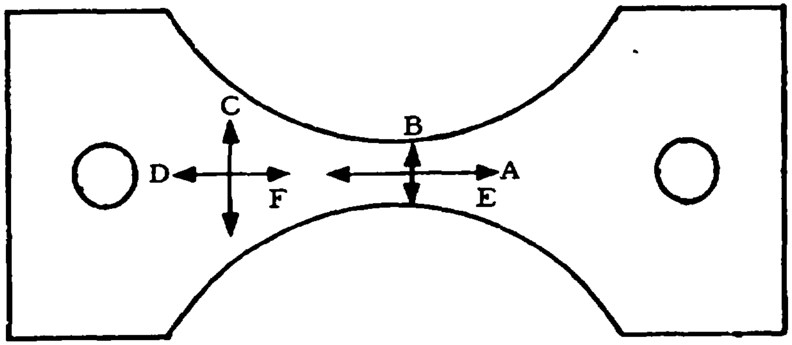
SPECIMEN SURFACE FINISH MEASUREMENTS

Specimen Material	Measurement Location(a)	Surface Finish (μ inch RMS)(b)
Ti-6Al-4V-Mill-Annealed	A	4
	D	6
	B	4
	C	4
	E(c)	6
	F(c)	8
Aluminum 7075-T6	A	3
	D	4
	B	4
	C	4
	E(c)	5
	F(c)	7

(a) All measurements taken in direction indicated by arrows

(b) All measurements taken with a Bendix Profilometer Type QB Model 13 using .0005 in. radius diamond stylus.

(c) Locations E and F refer to readings taken on the lapped backside.



The basic elements are briefly described here. The fretting-fatigue machine was developed to meet the following requirements:

1. (1) A fatigue unit with axial load capability was utilized.
2. (2) The mean load, alternating load, normal load, relative surface displacements, friction load, and frequency would be monitored and controlled, as desired, throughout each test.

An overall view of the test unit is shown in Figure 2. The basic fatigue unit is an electrohydraulic-servo-controlled system. The axial fatigue load (both mean and alternating) are applied through the hydraulic actuator shown in Figure 2. The hydraulic actuator applies a load to the specimen load assembly on the left portion of the figure. A detail of the loading assembly is shown in Figure 3. The normal load is applied through the normal load screw A. The magnitude of the normal load is measured by the load cell in the normal load screw indicated by B in Figure 3. The second load cell, indicated by C, records the lateral load. This load cell is attached to the dead end of a flex plate system that provides rigidity to the normal load screw. The fatigue load is applied axially through the actuator on the right of Figure 3. The magnitude of the fatigue loads is monitored and recorded by the load cell on the right (attached to the hydraulic actuator). The fretting pad is indicated by D and the fatigue specimen by E. A view looking down on the fatigue specimen prior to attachment of the fretting assembly is shown in Figure 4. The entire system is shown schematically in Figure 5. The outputs from all the load cells are monitored continually throughout each test.

3.3 Test Procedure

In preparation for testing, the fatigue specimen is placed in the test unit described previously and pretensioned so that axial alignment of the specimen is assured during final loading and the grip ends can be tightened and fretting in the grips prevented. Steel plates and emery cloth also are used in the specimen-grip interface to prevent slippage and/or fretting in the

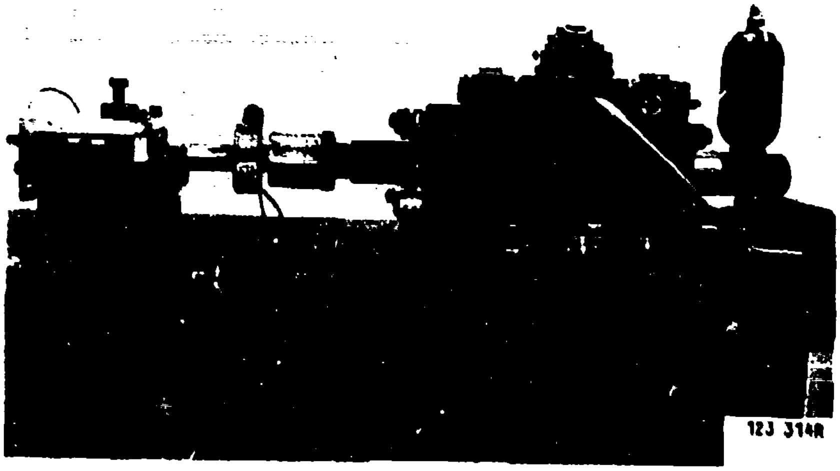


Figure 2. Overall View of the Fretting-Fatigue Test Machine(11)

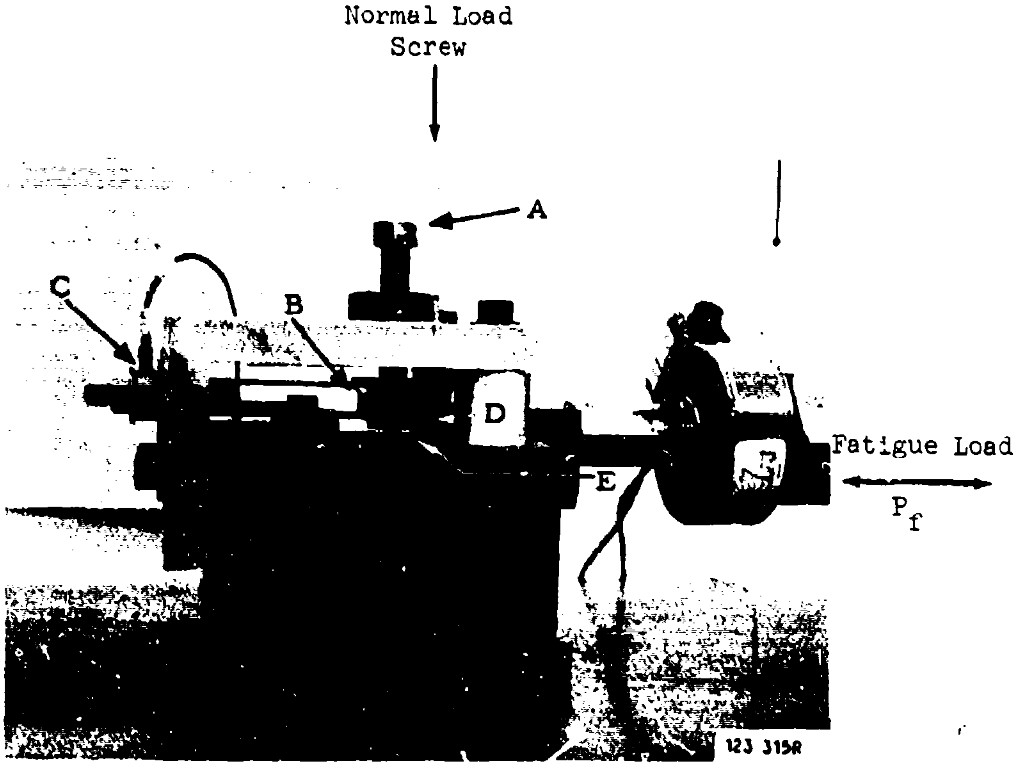


Figure 3. Detail of the Specimen Load Assembly

A. Normal Load Screw
B. Load Cell - Normal Load
C. Load Cell at Rear of Flex Plate
D. Fretting Pad
E. Fatigue Specimen

Figure 4. A View Looking Down on the Fatigue Specimen Prior to Attachment of the Fretting Assembly

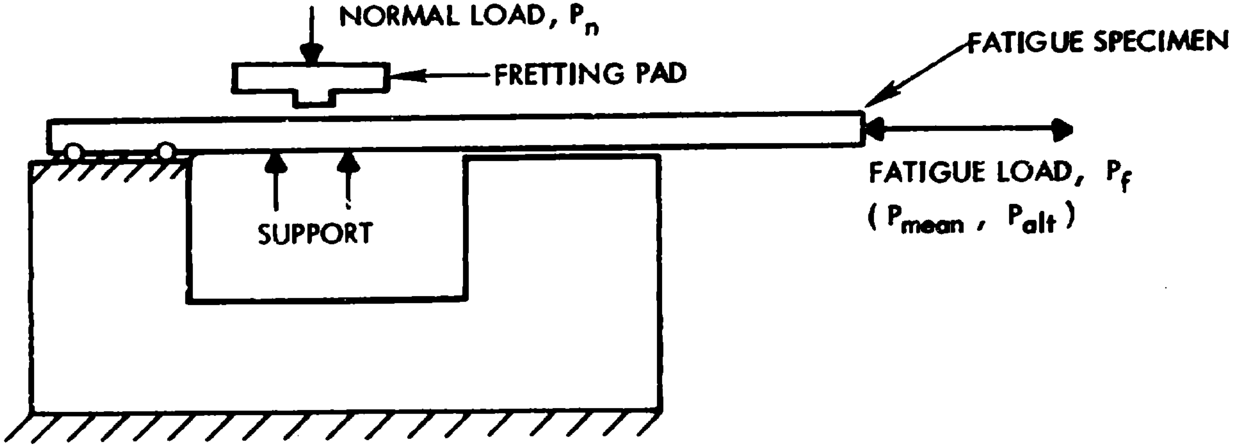


Figure 5. Schematic of the Fretting-Fatigue Loading Assembly

grips. After the fatigue specimen is in the grips it is in a fatigue test configuration and axial load fatigue baseline data can be generated. This procedure was utilized for generation of all of the baseline data presented in the next section.

Fretting-fatigue tests require an additional support block and rollers placed beneath the specimen test section to prevent bending of the specimen due to the normal load. Molybdenum disulfide is used as a lubricant between the support block and the specimen to prevent fretting on the fatigue specimen's undersurface. The fretting pad is fastened to the normal load screw and lowered into position above the fatigue specimen. The desired normal load then is applied with only a slight pretension on the fatigue specimen. As previously indicated, the normal load applicator is highly restrained from moving in the horizontal direction, i.e., with the movement of the fatigue specimen. Since the fatigue specimen deforms during the application of the fatigue cycle, a relative movement occurs between the fatigue specimen and fretting pad upon application of the alternating fatigue load. This motion acting under the various magnitudes of applied normal and fatigue loads results in fretting.

Two tests are used to study the damage produced by fretting. The first is a complete fretting-fatigue life test where the fretting pad is left on during the entire test (until failure or run-out). The data produced gives the fretting-fatigue baseline curve that demonstrates the degradation of fatigue life at various fatigue stresses. The second test is the so-called interrupted fretting-fatigue test where at some predetermined number of fretting-fatigue cycles the fretting pad is removed. The specimen can then either be removed for examination or cycled to failure with no additional fretting applied. This type of test yields information concerning the amount and kind of damage produced as a function of cycles and also its effect on fatigue life.

Subsequent to testing the pad and specimen are stored in vacuum when not being examined. Damage analysis is made by macroscopic and microscopic study.

Analysis of the fracture surfaces and fretting damage is made utilizing scanning electron microscopy and transmission electron fractographic analysis. After the surface observations are completed the specimens are placed in metallographic mounts to study the following:

- Failure mode
- Relationship of fretting damage to the base material
- Crack propagation mode
- Multiplicity of cracks

The following section presents all of the test results generated to date. A discussion of the results and the metallographic analysis conducted to date are presented in Section 5.

Section 4

RESULTS

Baseline fatigue tests have been conducted on both Ti-6Al-4V mill-annealed material and 7075-T6 aluminum alloy at a fatigue ratio R*, of +0.1. All fatigue and fretting fatigue tests conducted to date have been conducted at a test frequency of 1800 cpm (30 Hz). The results obtained on the Ti-6Al-4V material to date are summarized in Table II in order of decreasing maximum fatigue stress. Most of the data presented are for a normal pressure of 3000 psi. Two tests have been conducted at a normal pressure of 6000 psi in order to begin to develop an understanding of the role of normal pressure on fretting-fatigue. In Table II two columns are presented related to cycles (the two right-hand columns). The second column from the right lists the fretting-fatigue cycles. This is the cycles of fatigue with the fretting pad in contact with the fatigue specimen. In the right-hand column the total cycles to failure (or test termination) are listed. In some cases the number of cycles listed in both columns is the same. This means that the fretting pad was in place until failure occurs, i.e. 100 percent of the life.

The data presented in Table II are plotted in various forms in Figures 6 through 9. Figure 6 shows the significant degradation in fatigue behavior of Ti-6Al-4V at a normal pressure of 3000 psi. At 5×10^6 cycles the reduction in runout maximum stress is approximately 80,000 psi. At 10^5 cycles the corresponding reduction is approximately 60,000 psi. It may be noted that the two curves converge on the left. Thus, with fretting present, the reduction in allowable fatigue stress is much greater at longer lifetimes for this normal pressure. Between the baseline condition and normal pressure

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$* \; R = \frac{S_{min}}{S_{max}}$

TABLE II

RESULTS OF FRETTING-FATIGUE TESTS CONDUCTED ON Ti-6Al-4V MILL-ANNEALED MATERIAL

Specimen Identification	Maximum Fatigue Stress, psi x 1000	Normal Pressure psi x 1000	Fretting-Fatigue Cycles	Total Cycles, to Failure
70-5	125	3	32,000	32,000
70-8	125	3	11,500	11,500
72-18	125	3	13,000	13,000
72-19	125	3	14,000	14,000
72-21	125	3	12,600	34,000
72-33	125	3	12,600	20,200
72-23	125	3	9,500	37,800
72-29	125	3	6,300	13,141
72-38	125	3	6,300	33,000
72-39	125	3	3,900	70,500
72-30	125	3	3,000	679,000
70-7	115	3	56,900	56,900
71-1	110	3	16,000	16,000
70-6	105	3	20,500	20,500
70-4	100	3	13,600	13,600
70-3	75	3	75,000	75,000
71-2	70	3	69,500	69,500
71-10	70	3	55,000	84,000
71-3	70	3	45,000	62,200
71-4	70	3	45,000	58,300
71-7	70	3	32,000	101,900
71-5	70	3	20,000	198,000
71-8	70	3	15,000	680,000
71-9	70	3	15,000	5 x 10^6 (No Fail)
70-2	60	3	195,000	195,000
70-1	50	3	620,000	620,000
71-11	35	3	4 x 10^6	4 x 10^6 (No Fail)
71-12	35	6	5 x 10^6	5 x 10^6 (No Fail)
72-14	50	6	533,000	533,000

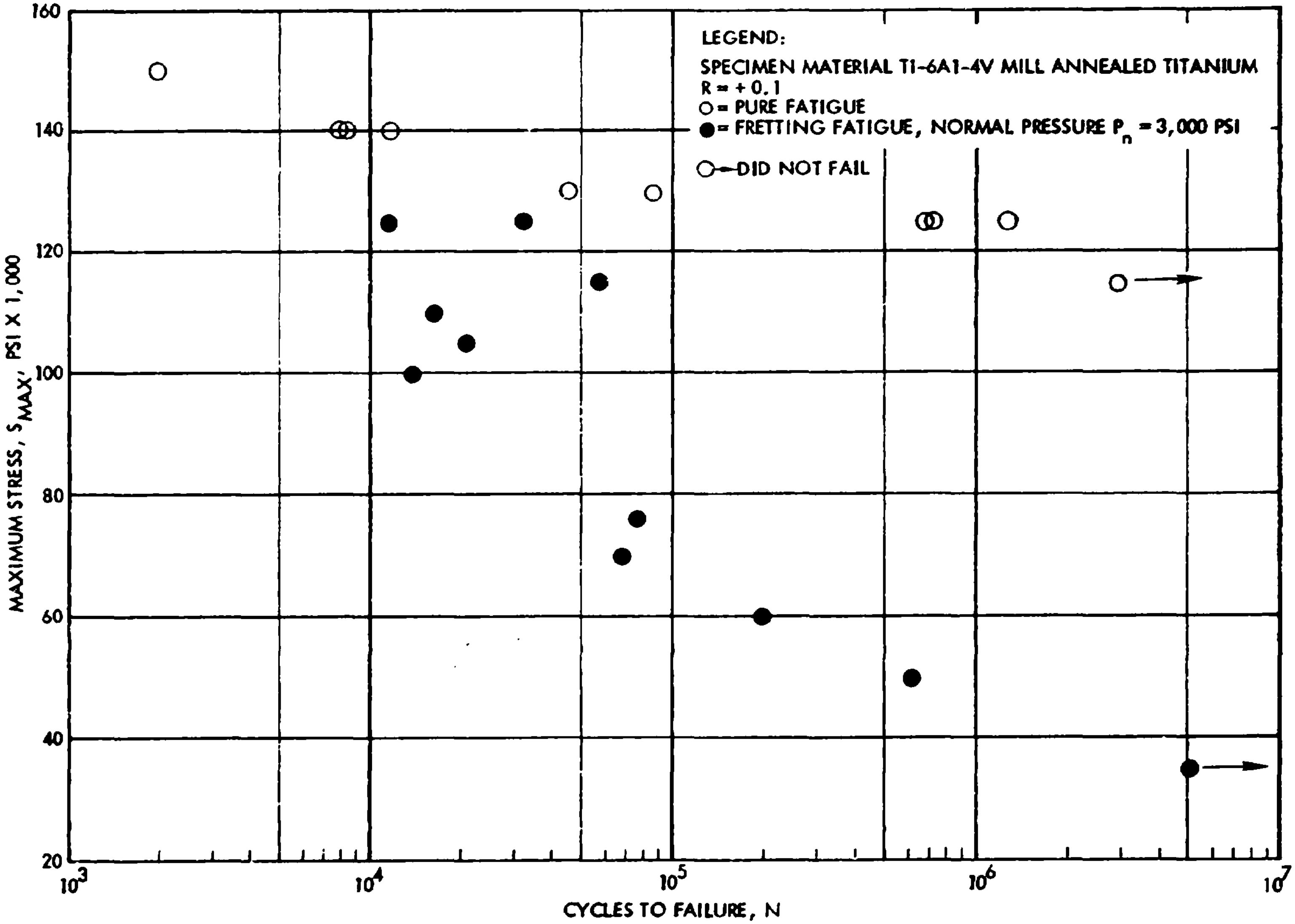


Figure 6. Maximum Stress Versus Cycles to Failure for Titanium 6Al-4V Alloy for Baseline and Fretting Conditions as Indicated

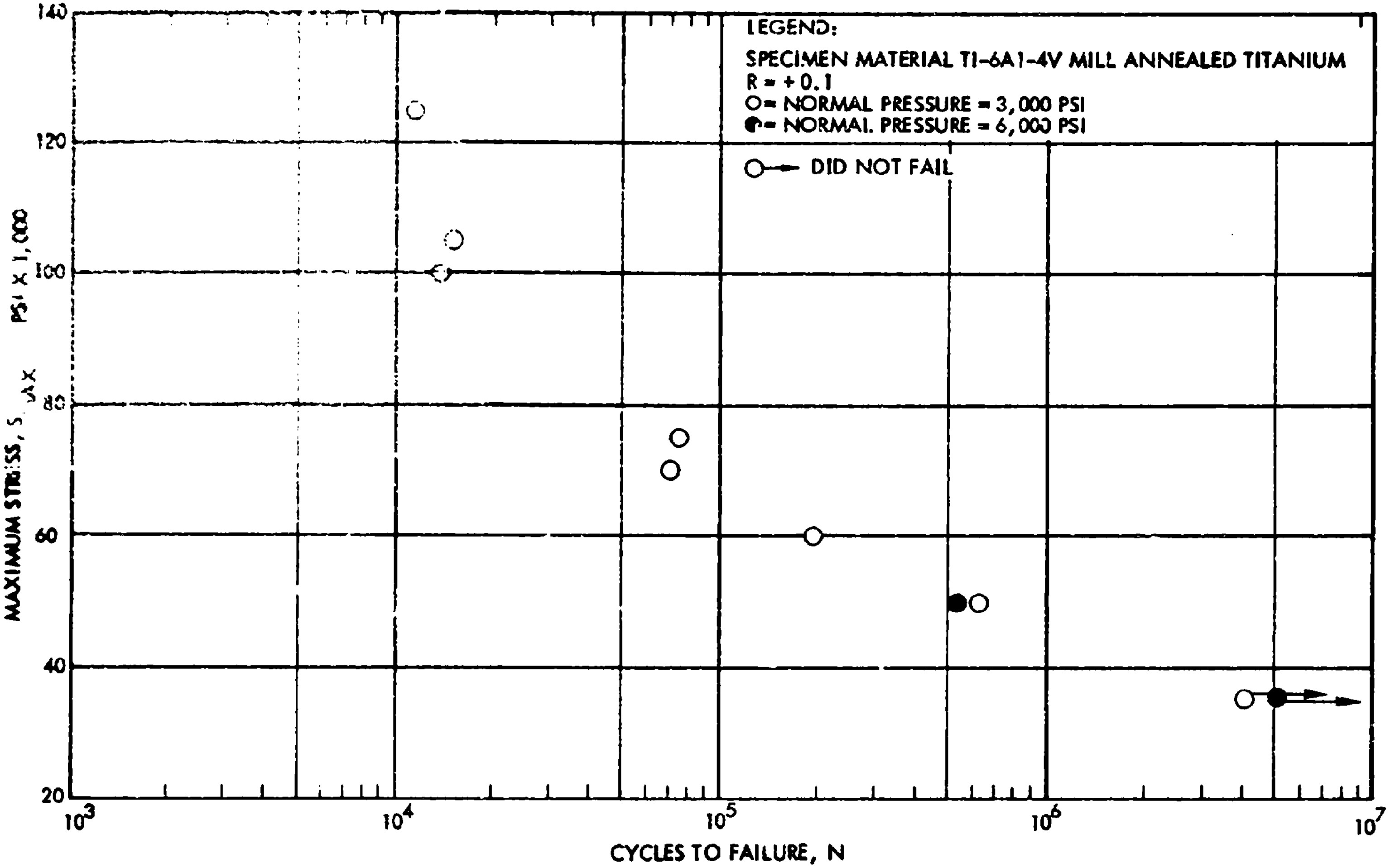


Figure 7. Maximum Stress Versus Cycles to Failure for Titanium 6A1-4V Alloy for Two Normal Pressures as Indicated

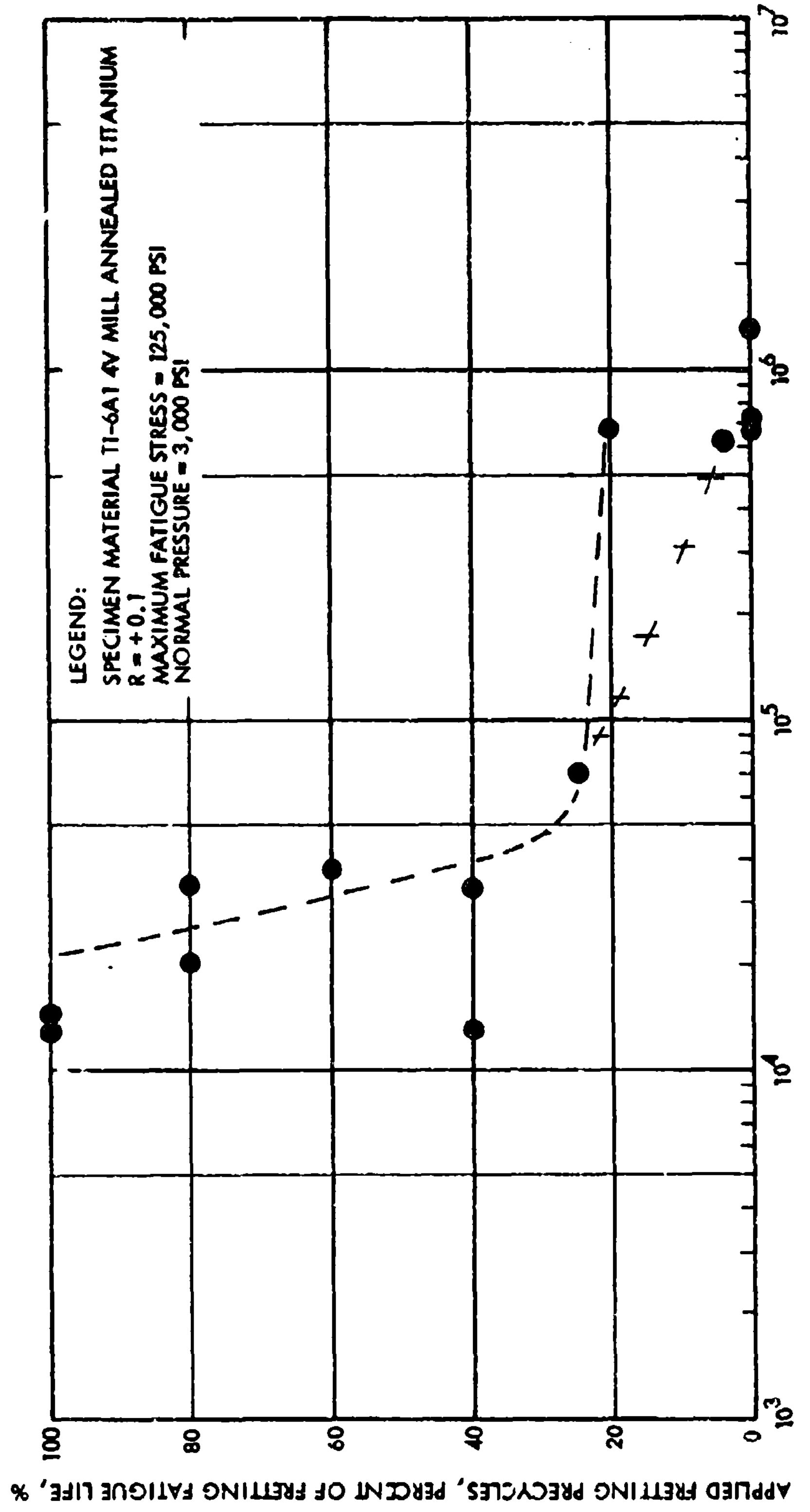


Figure 8. Interrupted Fretting Fatigue Test Results

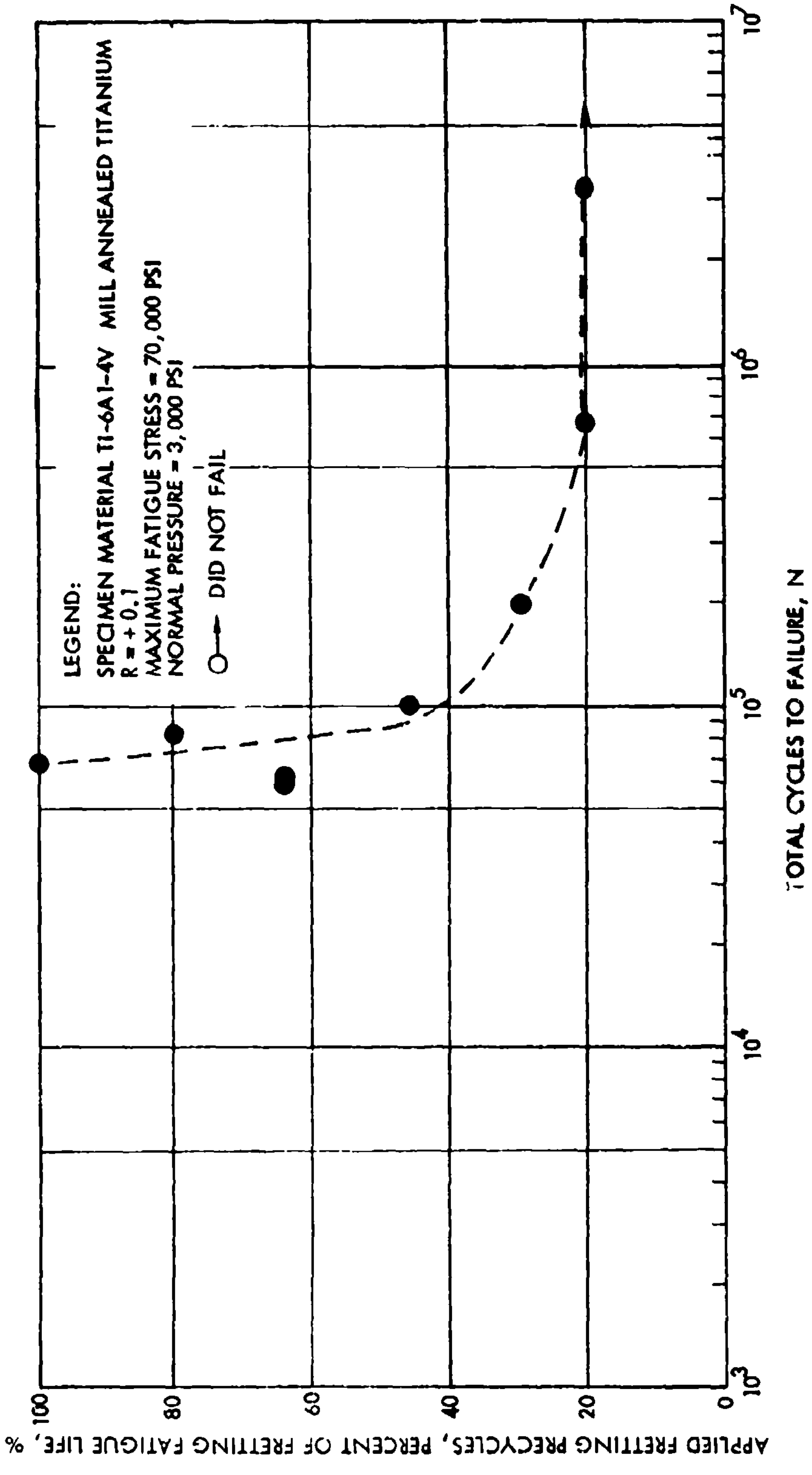
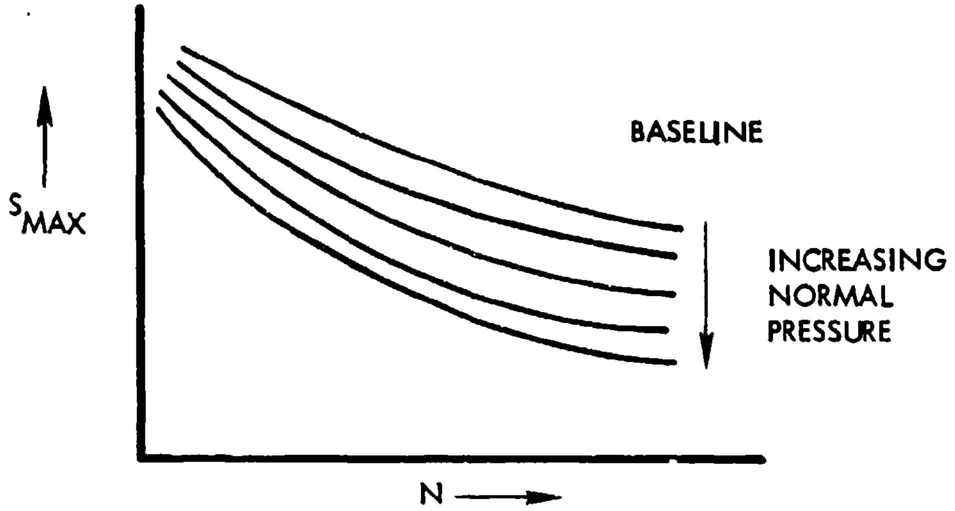


Figure 9. Interrupted Fretting Fatigue Test Results

studied, it is anticipated that increasing normal pressure will produce a more significant reduction in allowable stress as shown in the sketch below.



To establish the effect of normal load two tests were conducted at a normal pressure of 6000 psi. These two points are indicated by the solid circles in Figure 7 where the data for fretting at 3000 psi also are presented for comparison. Note that the two test results for 6000 psi fall on the curve for 3000 psi. Apparently the pressure of 3000 psi produces the maximum reduction as discussed above. Further verification of the normal pressure variation effect is required, as well as study of normal pressures less than 3000 psi.

The concept of the fretting damage threshold hypothesized in Reference 1 was also one of the factors studied in the research to date. To develop the damage threshold concept interrupted fretting tests were conducted on the Ti-6Al-4V material at two values of maximum fatigue stress. These results are plotted in Figures 8 and 9 for the maximum fatigue stresses of 125,000 psi and 70,000 psi. The value of 125,000 psi was selected since it is slightly above the normal runout baseline fatigue stress of 115,000 to 120,000 psi as shown in Figure 6. The value of 70,000 psi was selected because it is well below the normal runout stress. The ordinate in Figures 8 and 9 is plotted as fretting precycles, percent of fretting life. The abscissa is total cycles to failure. The value of total cycles to failure at 100 percent precycles is the total number of cycles to cause failure with the fretting pad in place. In future work normalized values will be presented. The effect of the fretting damage can be assessed from Figure 8 or Figure 9 by noting the remaining life after the pad is removed. Note the resulting data in Figure 8 follow (approximately) the dashed line drawn through the data. At 60 percent fretting precycles ($0.6 \times \sim 1.5 \times 10^4$ cycles) the specimen does not fail until 4×10^4 cycles. Slightly more than the 100 percent value of $\sim 1.5 \times 10^4$ cycles. However, at 20 percent fretting precycles the damage generated does not result in any fatigue life reduction since the cycles to failure is the same as if no fretting damage had been produced. The value at 20 and zero (0) percent fretting precycles on Figure 8 are comparable. A similar trend can be noted in Figure 9 for the maximum cyclic stress of 70,000 psi. The fretting precycle concept may be a quantitative way to assess the effectiveness of a fretting alleviation system. This could be similar to plotting a stress-number of cycles-flaw size diagram proposed for fatigue by the authors(1,12,13) and others(14,15) previously. In this case, it may be desirable to plot stress-number of cycles-percent fretting precycles, i.e. generate an S-N-F_{pc} (respectively), diagram.

The data generated to date on 7075-T6 aluminum alloy are presented in Table III and plotted in Figures 10 and 11. Studies similar to those on titanium have been conducted and are underway. The data plotted in Figure 10 compare fretting at a normal pressure of 3000 psi to the baseline (R = +0.1) 7075-T6 condition. Once again, a significant reduction in life is noted due to the fretting. In another program a statistical analysis of these, and other, fretting data are underway (the results will be presented at a later date) to evaluate and compare the reduction in titanium and aluminum alloys caused by fretting. The data presented in Figure 11 are for interrupted tests at a maximum fatigue stress of 60,000 psi, well above the normal baseline runout (pure) fatigue value for this alloy shown in Figure 10. Additional studies are underway at lower maximum fatigue stresses. The data shown in Figure 11 indicate, for the tests conducted to date, that the

TABLE III

RESULTS OF FRETTING FATIGUE TESTS CONDUCTED ON 7075-T6 ALUMINUM MATERIAL

Specimen Identification	Maximum Fatigue Stress, psi x 1000	Normal Pressure psi x 1000	Fretting-Fatigue Cycles	Total Cycles
71-5A	60	3	15,500	15,500
72-14A	60	3	19,800	19,800
72-15A	60	3	21,700	21,700
72-23A	60	3	9,000	42,700
71-2A	50	3	18,000	18,000
71-6A	50	3	34,600	34,600
71-1A	40	3	137,000	137,000
71-3A	40	3	26,000	26,000
71-7A	35	3	67,800	67,800
71-8A	30	3	103,000	103,000
71-9A	30	3	208,000	208,000
71-10A	25	3	455,000	455,000
71-11A	20	3	611,000	611,000
71-12A	15	3	2,400,000	2,400,000 (No Fail)

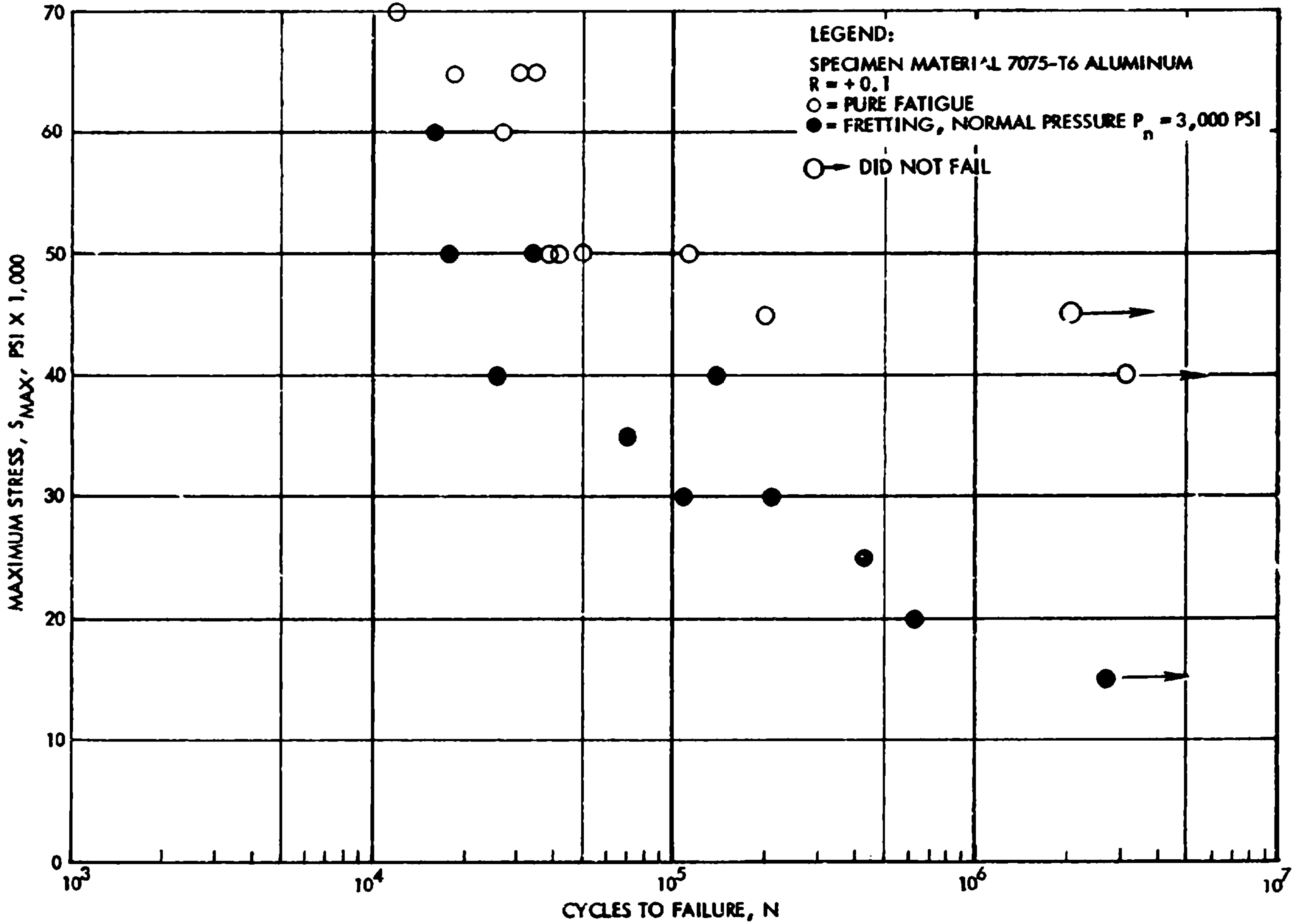


Figure 10. Maximum Stress Versus Cycles to Failure for 7075-T6 Aluminum Alloy for Baseline and Fretting Conditions as Indicated

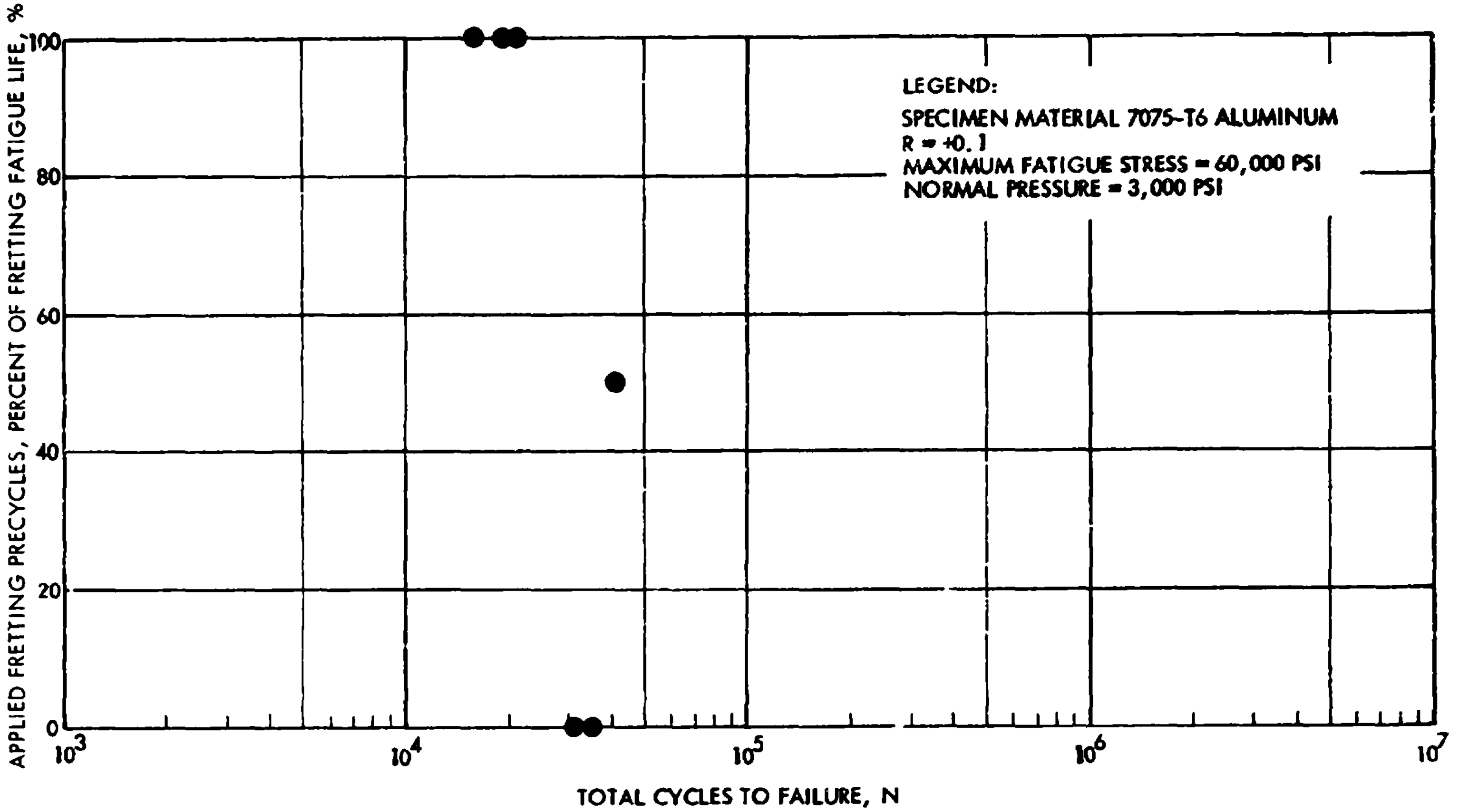


Figure 11. Interrupted Fretting Fatigue Test Results

fretting effect at this maximum fatigue stress value does not appear to be significant. Additional studies are required to verify the damage threshold concept in the 7075-T6 aluminum alloy.

One of the major aspects of the effort is oriented toward delineation of the microstructural and surface damage caused by the fretting. In the discussion section some results of this effort are presented. All of the specimens listed in Tables II and III are available for damage analysis. However, certain specimens have been selected for the initial characterization studies. These specimens are summarized in Table III. It is important to note the specimen history on the right. In addition, a large group of specimens that have been subjected to fretting precycles have been reserved for analysis. All of the specimen results shown in Figures 8, 9 and 11 have a duplicate specimen that has not been failed but reserved for analysis. The damage analysis to date has yielded several significant features relative to fretting and its role in fatigue. These results are presented in the following section and discussed as they relate to the fretting process in metallic systems studied to date.

TABLE IV

FRETTING-FATIGUE SPECIMENS UNDERGOING FRETTING DAMAGE ANALYSIS

Specimen Identification	Maximum Fatigue Stress psi x 1000	Normal Pressure psi x 1000	Fretting Fatigue Cycles	Specimen History
Ti-6Al-4V				
72-19	125	3	14,000	100% Fretting Fatigue Life at 60,000 psi
72-20	125	3	14,000	100% Fretting Fatigue Life at 60,000 psi
72-21	125	3	12,600	80% of 100% Fretting Fatigue Cycles Applied - Pad Removed - Run to Failure
72-22	125	3	12,600	80% of 100% Fretting Fatigue Cycles Applied - Test Stopped
72-23	125	3	9,500	60% of 100% Fretting Fatigue Cycles Applied - Pad Removed - Run to Failure
72-34	125	3	9,500	60% of 100% Fretting Fatigue Cycles Applied - Test Stopped
72-29	125	3	6,300	40% of 100% Fretting Fatigue Cycles Applied - Pad Removed - Test Continued
72-35	125	3	6,300	40% of 100% Fretting Fatigue Cycles Applied - Test Stopped
72-30	125	3	6,300	20% of 100% Fretting Fatigue Cycles Applied - Pad Removed - Test Continued
7075-T6 Aluminum				
72-22A	60	3	18,300	100% Fretting Fatigue Life at 60,000 psi
72-23A	60	3	9,000	50% of 100% Fretting Fatigue Cycles Applied - Pad Removed - Test Continued

Section 5

DISCUSSION

Scanning electron micrographs of the fretted surfaces are presented in Figures 12 through 15. Results on the titanium surfaces are shown in Figures 12 and 13 from previous work presented by the authors(15). The micrographs presented are for two different maximum fatigue stresses, 125,000 psi and 50,000 psi, respectively. Cracking is apparent in both figures although the fretting debris changes character for the lower stress case (Figure 13). Similar micrographs are presented for the aluminum material in Figures 14 and 15 for maximum fatigue stresses of 20,000 psi and 15,000 psi, respectively. Once again the surface cracking in the fretted area is apparent and the character of the debris changes for the different stresses.

Two photomicrographs of a titanium specimen tested at a maximum fatigue stress of 125,000 psi are presented in Figure 16. These views can be compared to the scanning micrographs presented in Figure 12. As expected, the depth seems to be lost in the photomicrographs of Figure 16 although the definition of the surface cracking appears better in Figure 16B. In an attempt to ascertain if the obvious surface cracking was associated with the fretting debris or if it was cracking in the specimen, metallographic sections were taken through the fracture surface and damage area to reveal salient characteristics of the damage. Typical sections and photomicrographs are presented in Figures 17 and 18 for the titanium and Figures 19 through 23 for the aluminum.

In Figure 18 several features are evident:

- The fracture surface is transcrystalline, indicative of a typical fatigue failure

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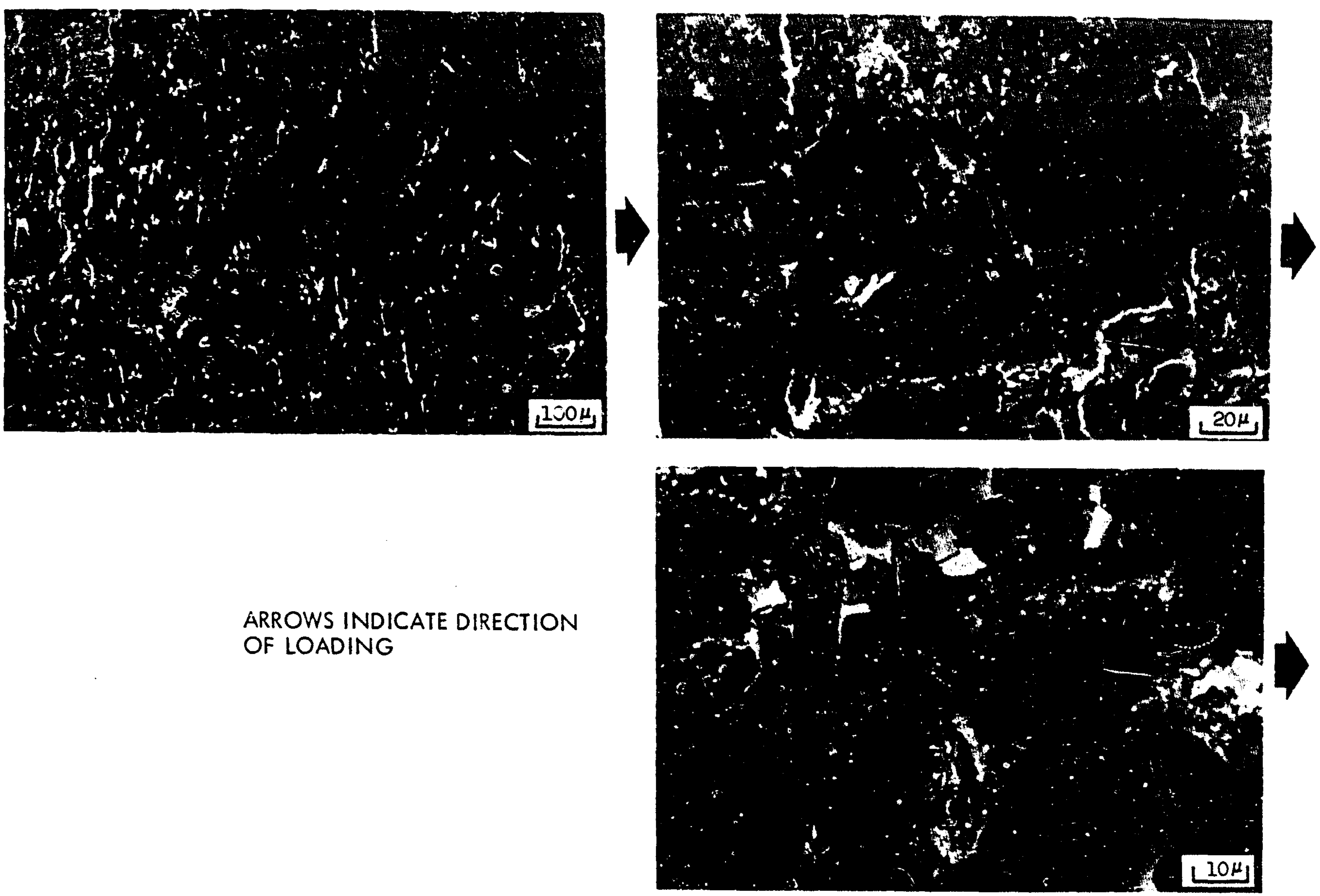
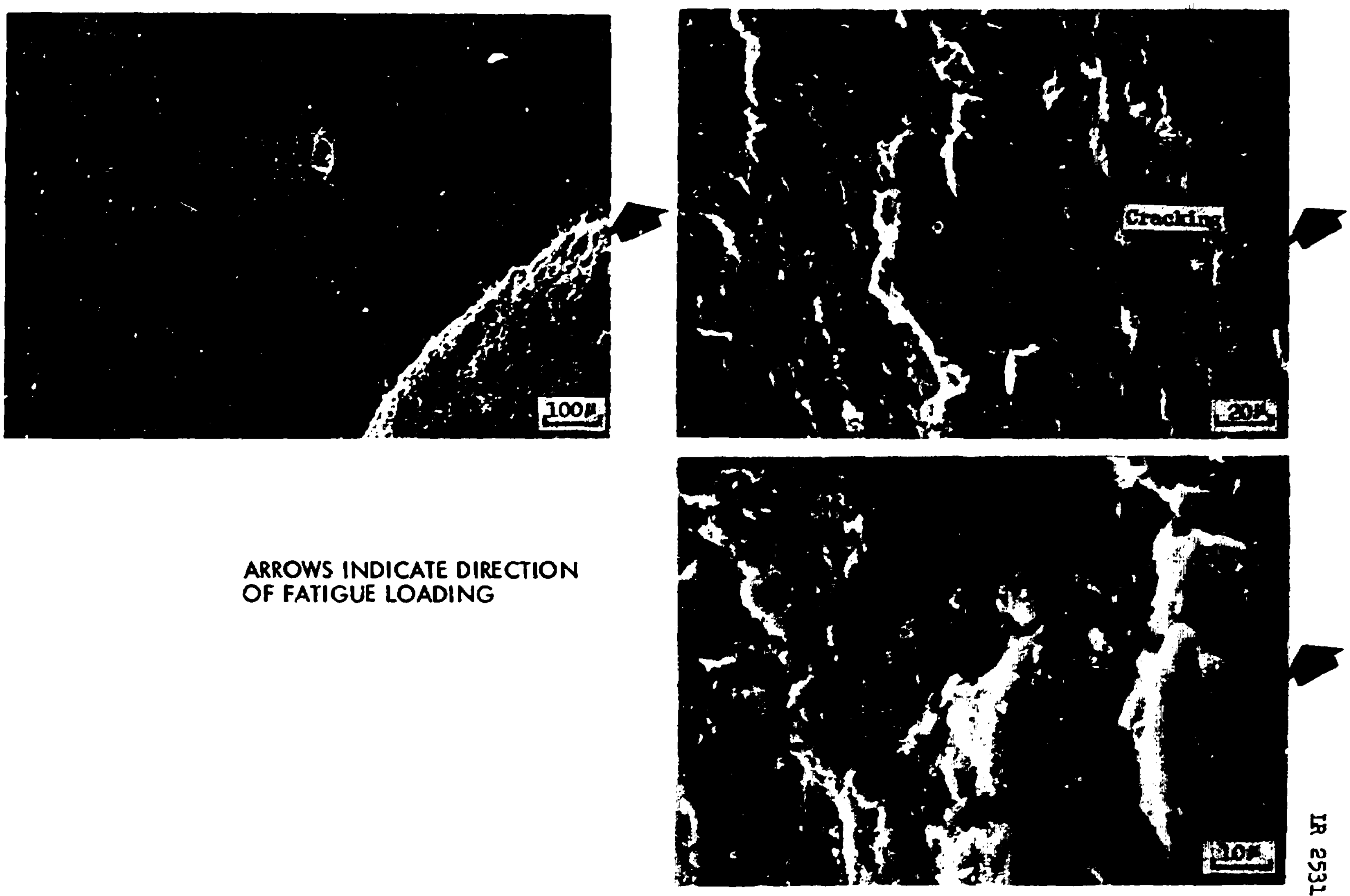


ARROWS INDICATE DIRECTION
OF LOADING

Figure 12. Scanning Electron Microscopy Views of a Fretting Fatigue Specimen After 32,000 Cycles (Failure), Ti-6AL-4V S_{max} = 125,000 psi, R = + 0-1 (15)



ARROWS INDICATE DIRECTION
OF FATIGUE LOADING

Figure 13. Scanning Electron Microscope Views of a Fretting Fatigue Specimen After 700,000 Cycles (Failure) at a Maximum Fatigue Stress of 50,000 psi, R = + 0-1 Ti-6AL-4V Milannealed (15)

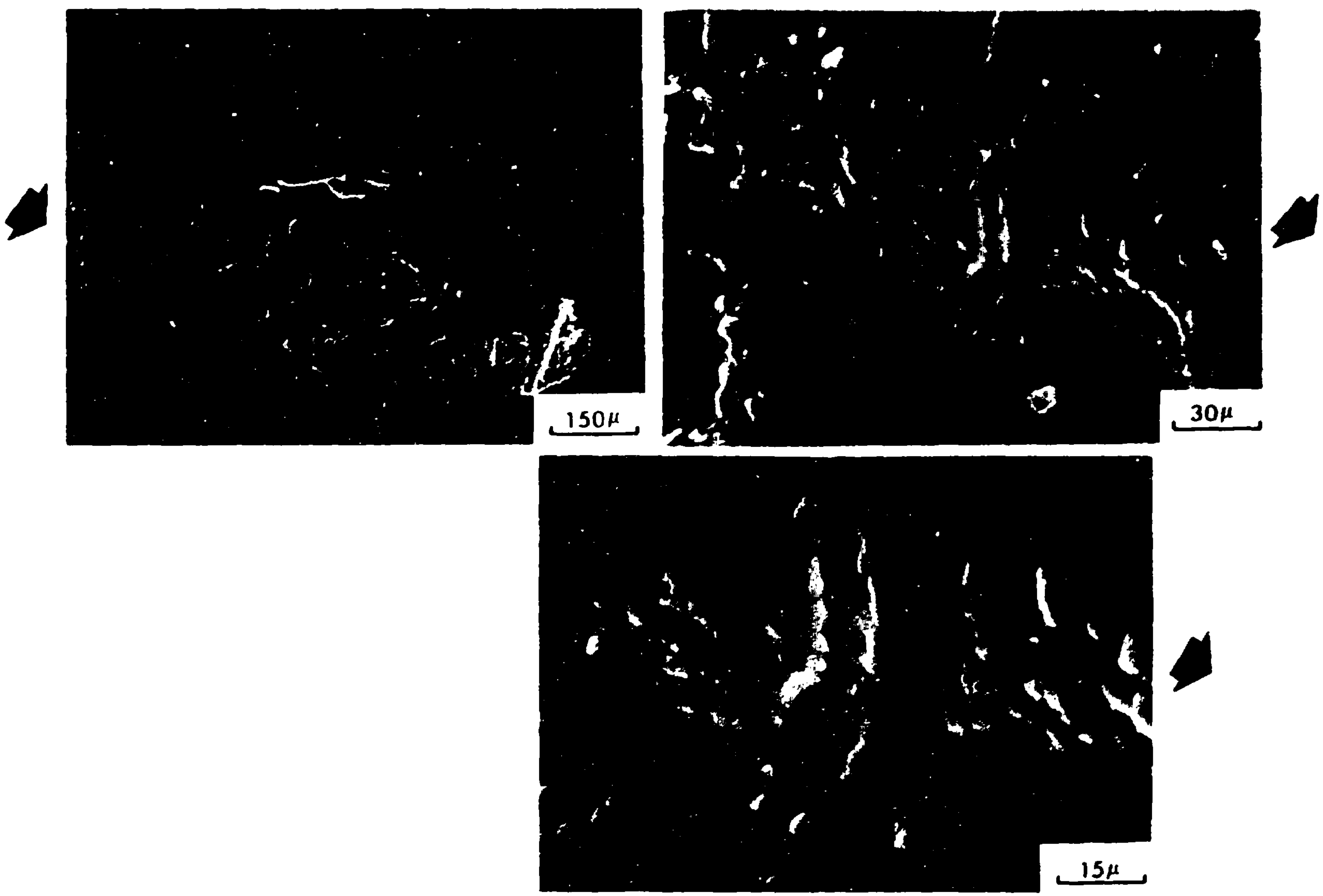


Figure 14. Scanning Electron Microscope Views of a Fretted Surface of 7075-T6 Aluminum After 611,000 Cycles (Failure) at a Maximum Fatigue Stress of 20,000 psi (R = + 0.1)

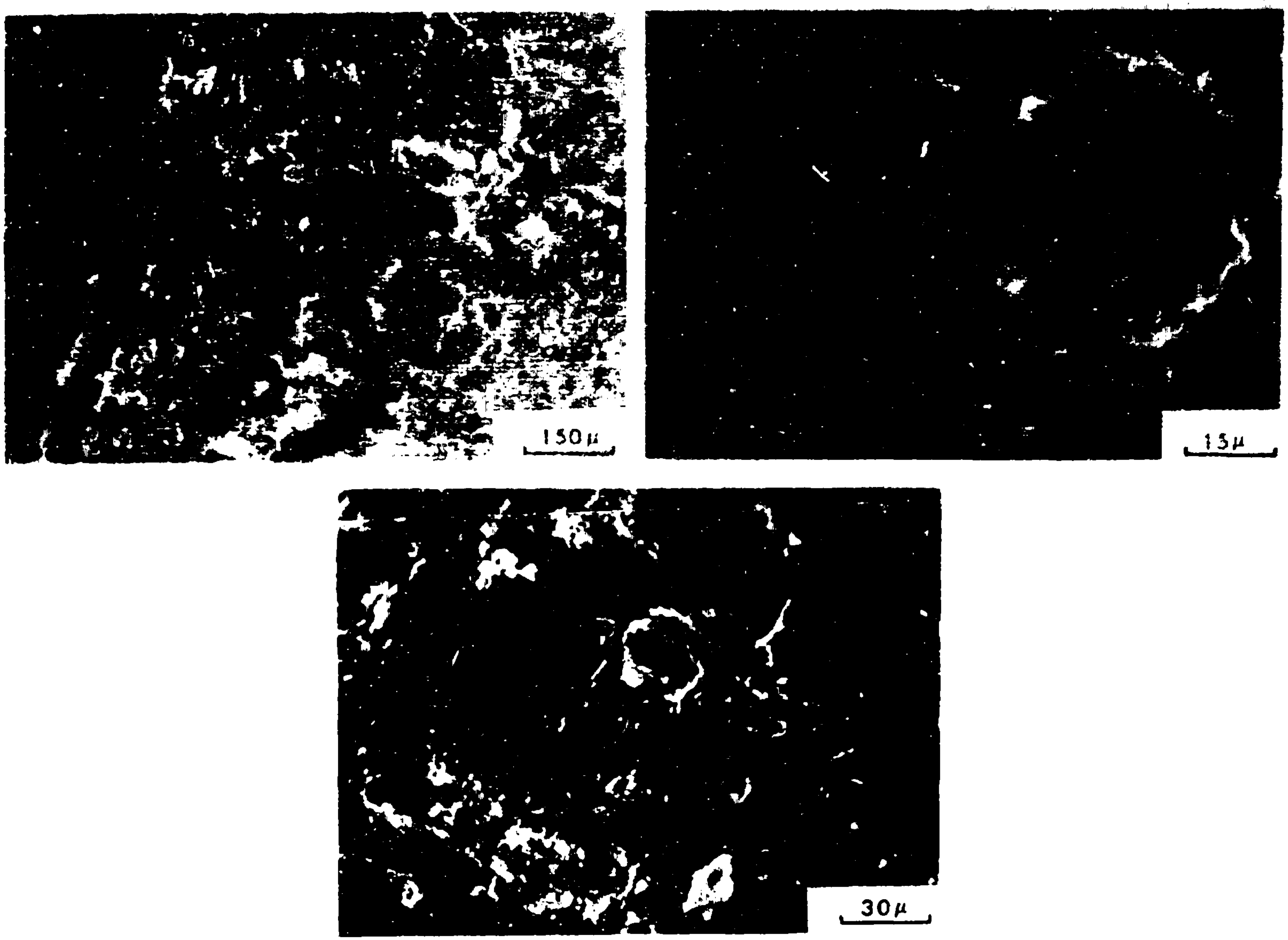
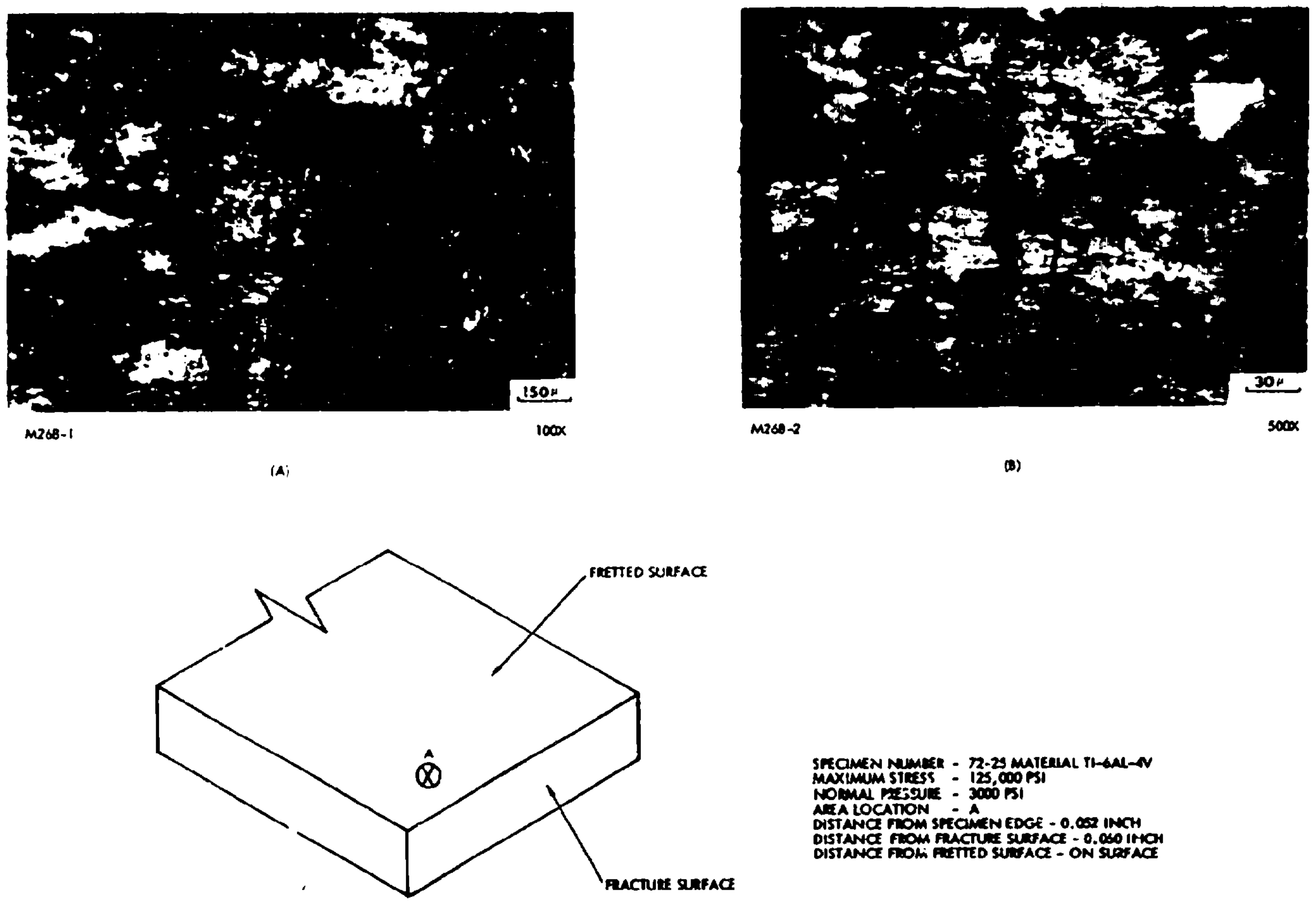
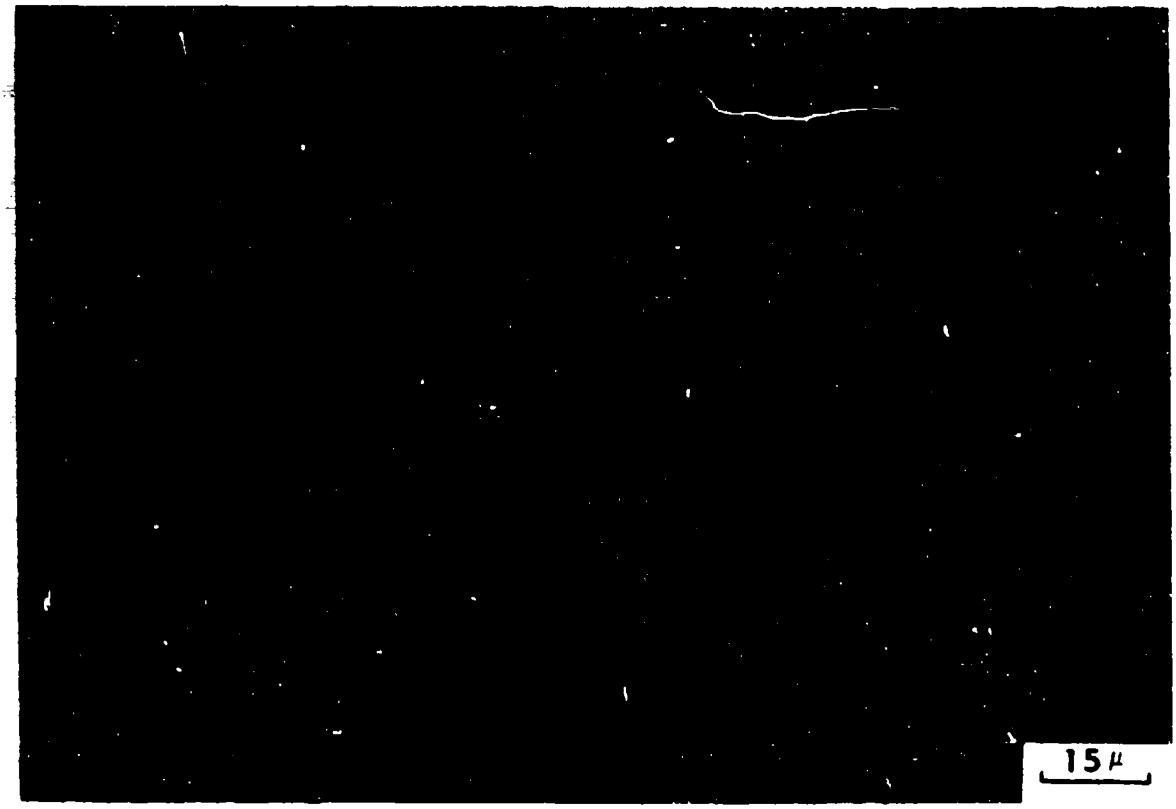


Figure 15. Scanning Electron Microscope Views of a Fretted Surface of 7075-T6 Aluminum After 2,410,000 Cycles (No Failure) at a Maximum Fatigue Stress of 15,000 psi (R = + 0.1)



SPECIMEN NUMBER - 72-25 MATERIAL TI-6AL-4V
MAXIMUM STRESS - 125,000 PSI
NORMAL PRESSURE - 3000 PSI
AREA LOCATION - A
DISTANCE FROM SPECIMEN EDGE - 0.052 INCH
DISTANCE FROM FRACTURE SURFACE - 0.060 INCH
DISTANCE FROM FRETTED SURFACE - ON SURFACE

Figure 16. Photomicrographs of a Fretted Region on Ti-6AL-4V Showing Apparent Multiple Cracks on the Fretted Surface at the Indicated Location



SPECIMEN NUMBER - 71-10, MATERIAL-TI-6AL-4V
MAXIMUM STRESS - 70,000 PSI
NORMAL PRESSURE - 3000 PSI
AREA LOCATION - SECTION A-A
DISTANCE FROM SPECIMEN EDGE - 0.030 INCH
DISTANCE FROM FRACTURE SURFACE - 0.0.03 INCH
DISTANCE FROM FRETTED SURFACE - ON SURFACE

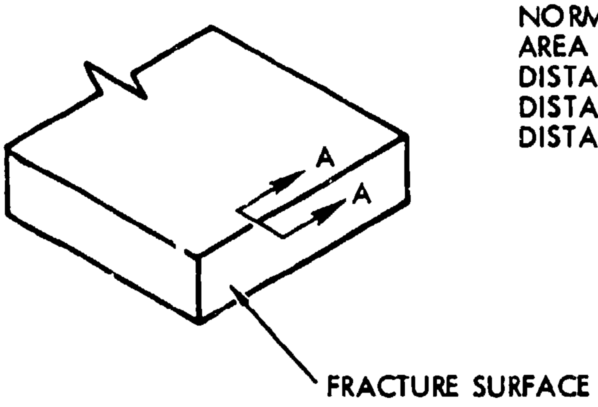


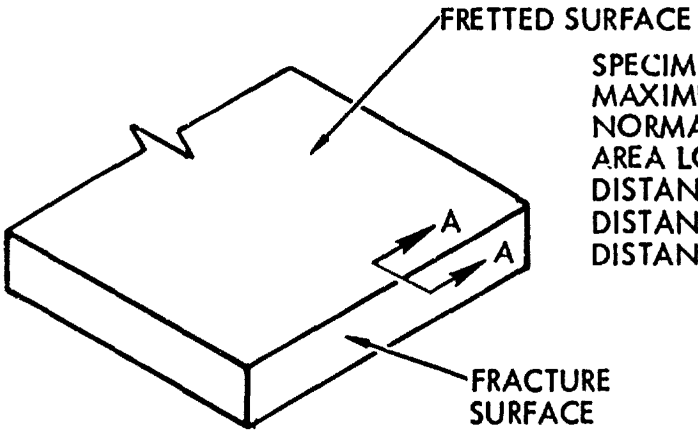
Figure 17. Photomicrograph of a Section Through a Failed Specimen Showing Edge of Fracture Surface (Right) and Fretted Surface (Top)

- There is evidence of secondary cracking associated with the accumulated fretting debris
- Significant surface roughening is apparent from the fretting

Figure 18 shows a crack that extends through a fretted area but does not extend into the specimen. Obviously the question is now raised as to whether the surface cracking evident in Figures 12 and 13 only extends through the oxide layer. The damage that results from the fretting appears, as proposed by the authors in Reference 1, to simply result in surface damage that is sufficient to accelerate the "initiation" stage of cracking.

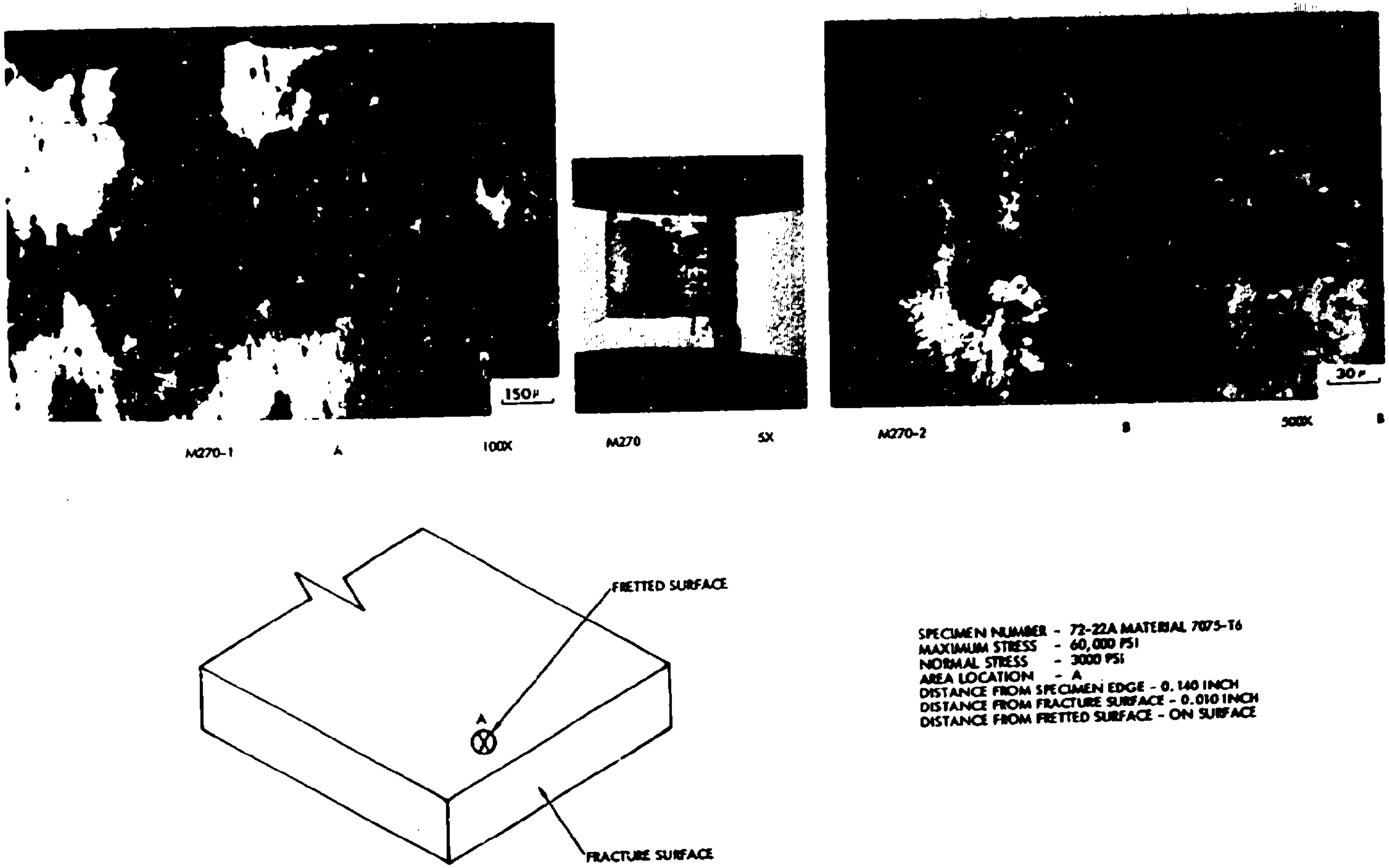
The photomicrographs shown in Figure 19 for the aluminum can be compared to the scanning micrographs shown in Figures 14 and 15. A difference in damage character between the titanium and aluminum is obvious from the views presented of the fretted surfaces. The amount of surface cracking on the fretted aluminum does not appear as extensive as on the titanium. This observation from the surface damage is interesting when Figures 20 through 23 are examined. Figure 20 shows a cross section through a fretted specimen. The fracture propagation mode is again observed to be transcrystalline. In the figure there are evident at least five secondary cracks. This is interesting when the surface micrographs of the aluminum did not show as much evidence of cracking as with the titanium. This might indicate that the cracking evident on the fretted areas is, in the main, associated with cracking in the oxide layer and not necessarily in the specimen per se. All the cracks evident in Figure 20 are associated with the fretting damage. This is more obvious in Figures 21 and 22 where higher magnification views of the two major secondary cracks evident in Figure 20 are presented. This multiplicity of cracks is similar to corrosion fatigue but not typical of normal fatigue in a non-corrosive media. This is further evidence of the apparent similarities between fretting fatigue and corrosion fatigue discussed in References 1, 8-10, and 12. It appears obvious at this time that, in the absence of an extremely aggressive corrosive media, the major effect of fretting damage is the production of surface damage that reduces the

801-1 A-A 1000X



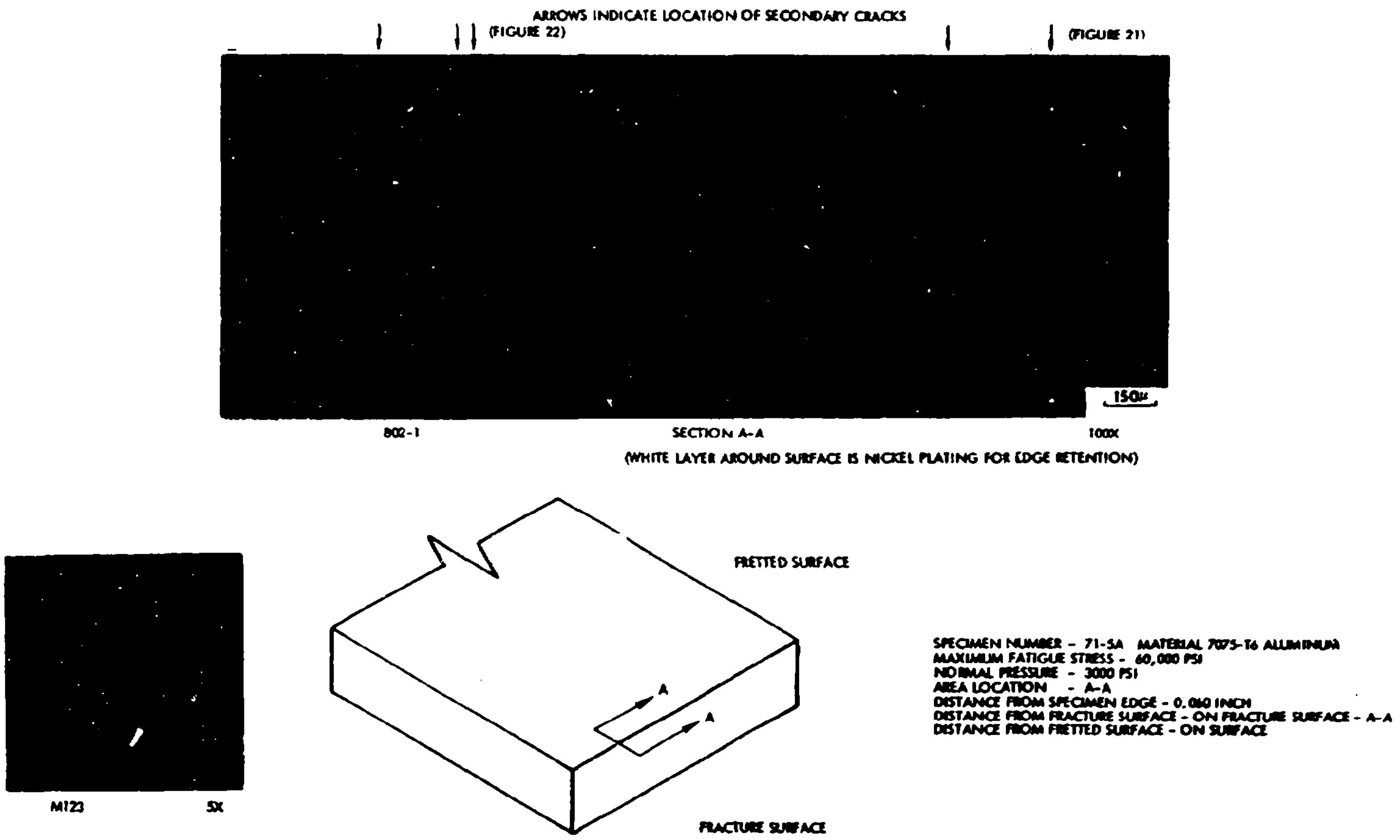
SPECIMEN NUMBER - 71-7 MATERIAL-TI-6AL-4V
MAXIMUM STRESS - SECTION A-A
NORMAL STRESS - 70000 PSI
AREA LOCATION - 3000 PSI
DISTANCE FROM SPECIMEN EDGE-0.095 INCH
DISTANCE FROM FRACTURE SURFACE-0.030 INCH
DISTANCE FROM FRETTED SURFACE-SURFACE

Figure 18. Photomicrograph of a Section Through Fretting Debris that is Cracked



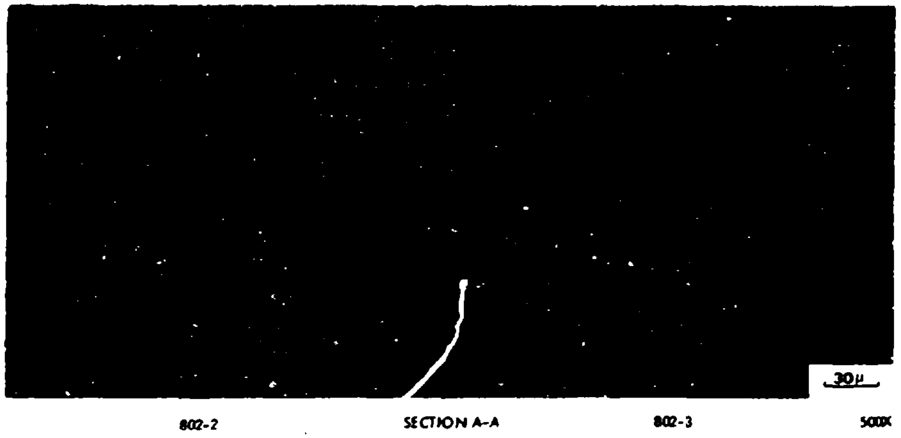
SPECIMEN NUMBER - 72-22A MATERIAL 7075-T6
MAXIMUM STRESS - 60,000 PSI
NORMAL STRESS - 3000 PSI
AREA LOCATION - A
DISTANCE FROM SPECIMEN EDGE - 0.140 INCH
DISTANCE FROM FRACTURE SURFACE - 0.010 INCH
DISTANCE FROM FRETTED SURFACE - ON SURFACE

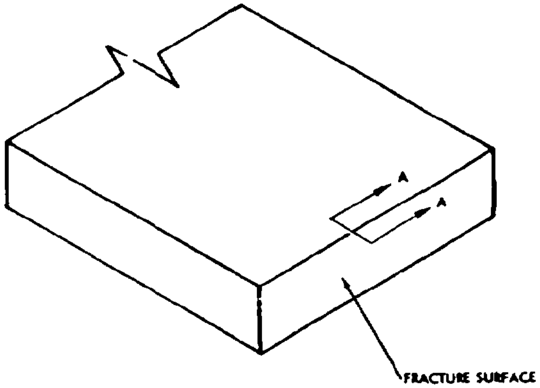
Figure 19. Photomicrographs of a Fretted Region on 7075-T6 Aluminum



SPECIMEN NUMBER - 71-5A MATERIAL 7075-T6 ALUMINUM
MAXIMUM FATIGUE STRESS - 60,000 PSI
NORMAL PRESSURE - 3000 PSI
AREA LOCATION - A-A
DISTANCE FROM SPECIMEN EDGE - 0.060 INCH
DISTANCE FROM FRACTURE SURFACE - ON FRACTURE SURFACE - A-A
DISTANCE FROM FRETTED SURFACE - ON SURFACE

Figure 20. Photomicrograph Showing Location of Frature and Secondary Cracking





SPECIMEN NUMBER - 71-5A MATERIAL 7075-T6 ALUMINUM
MAXIMUM STRESS - 60,000 PSI
NORMAL PRESSURE - 3000 PSI
AREA LOCATION - A-A
DISTANCE FROM SPECIMEN EDGE - 0.060 INCH
DISTANCE FROM FRACTURE SURFACE - FRACTURE SURFACE - 0.010 INCH
DISTANCE FROM FRETTED SURFACE - ON SURFACE

Figure 21. Photomicrograph Showing Details of Major Secondary Crack Shown in Figure 20

802-4 SECTION C-C 500X

SPECIMEN NUMBER - 71-5A, 7075-T6
MAXIMUM STRESS - 60000 PSI
NORMAL PRESSURE - 3000 PSI
AREA LOCATION - C-C
DISTANCE FROM SPECIMEN EDGE - 0.060 INCH
DISTANCE FROM FRACTURE SURFACE - 0.078 INCH
DISTANCE FROM FRETTED SURFACE - ON SURFACE

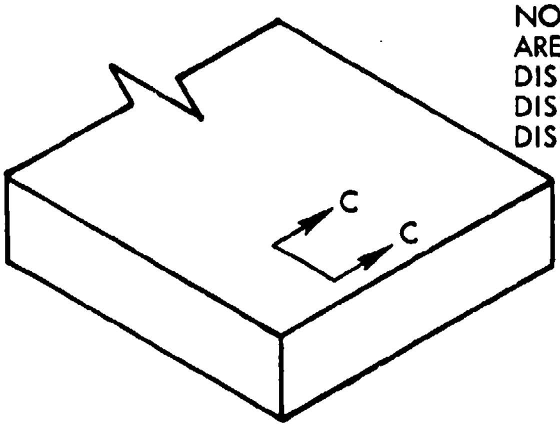
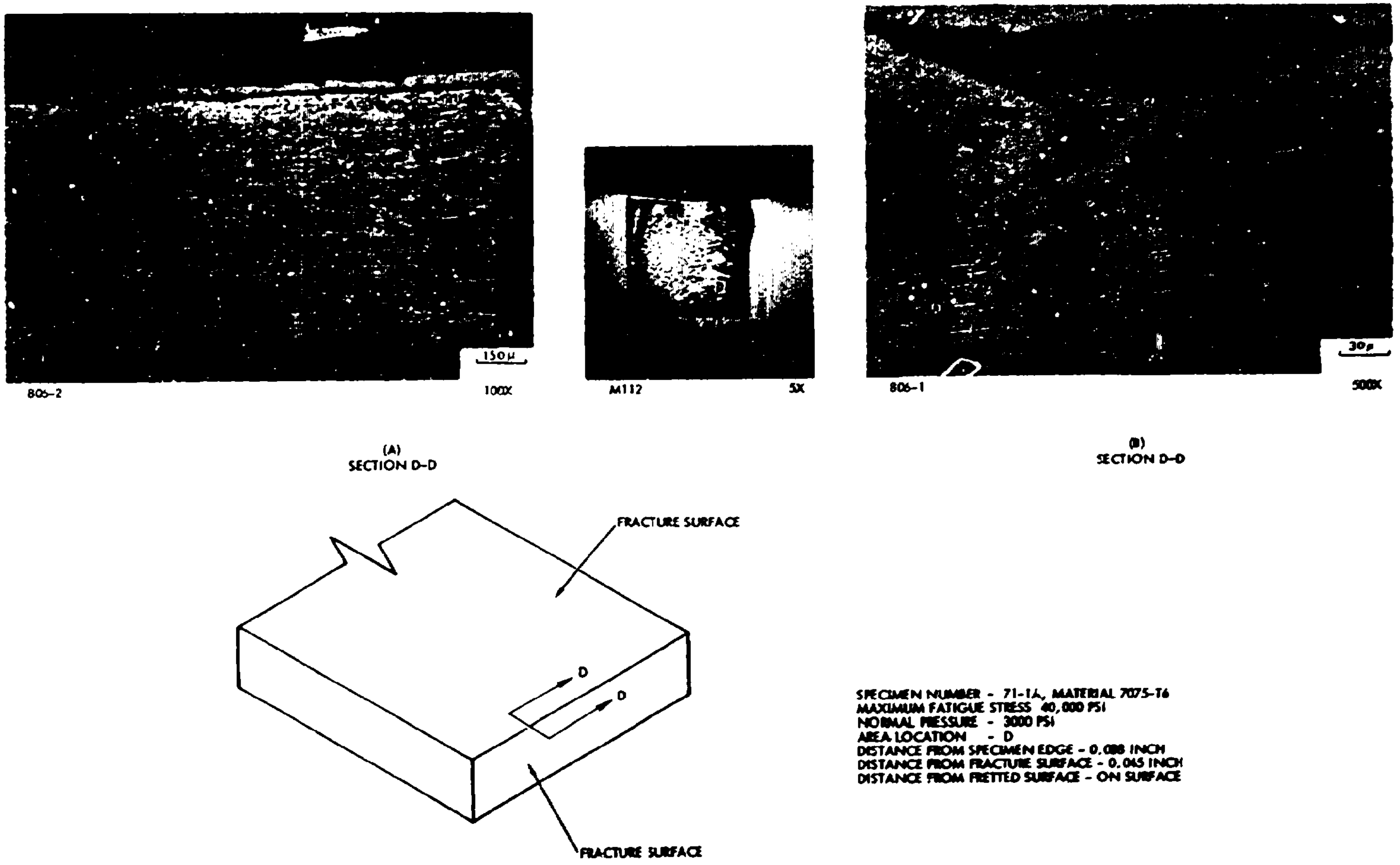


Figure 22. Photomicrograph Showing Additional Secondary Crack in Figure 20



SPECIMEN NUMBER - 71-1A, MATERIAL 7075-T6
MAXIMUM FATIGUE STRESS 40,000 PSI
NORMAL PRESSURE - 3000 PSI
AREA LOCATION - D
DISTANCE FROM SPECIMEN EDGE - 0.088 INCH
DISTANCE FROM FRACTURE SURFACE - 0.065 INCH
DISTANCE FROM FRETTED SURFACE - ON SURFACE

Figure 23. Photomicrographs Showing Secondary Cracks in Another Specimen of 7075-T6

initiation stage of fatigue. These metallographic observations are further support of the damage hypothesis of the authors(1).

Figure 23 is another set of photomicrographs for another aluminum specimen tested at a lower fatigue stress. It is expected that the number of cracks formed as a result of the fretting will increase as the maximum cyclic stress is lowered. This point needs further verification. The only difference in damage obvious when comparing two secondary cracks (Figures 21 to 23B) at the same magnification is an apparent widening of the secondary cracks evidenced in Figure 23B. In Figure 23B it appears that a greater number of secondary cracks may be present. Further verification of this point is required however.

The significant reduction in fretting life evident from the figures presented in the results section can be interpreted as resulting from the production of mechanical surface damage that leads to numerous crack initiation sites. These initiated areas then appear to have surface oxide debris that is produced forced into them and result in an apparent widening of the initiated crack. This could be the explanation for the significant reduction of fatigue life when fretting occurs and may eventually aid in establishing the effect of normal pressure and environment on fretting. The obvious threshold evident from this work is in consonance with the concept that a crack of size sufficient to exceed a stress intensity to propagate must be developed by the fretting. In future work this aspect will receive more attention.

Even though the metallographic analysis is in its initial stages it has already provided considerable insight in the fretting process. Additional metallographic analysis of the damage and cracking is underway in an attempt to more clearly understand where the damage leads to cracking.

Section 6

CONCLUSIONS

Several conclusions are possible from the research performed to date; these are:

1. Both titanium and aluminum undergo a significant reduction in fatigue life in the presence of fretting.
2. The fretting damage produced results in a large number of cracks that form in the presence of the fretting.
3. The cracks formed differ in character as a function of applied stress level.
4. A fretting fatigue threshold exists.
5. After fretting damage has occurred above the fretting threshold, removal of the fretting has no effect on the remaining life.

Additional analysis and research is progressing in all of the above areas.

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Section 7

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