NRL Report 6330

Fractographic Analysis of Ti-7Al-2Cb-1Ta and Ti-6Al-4V Fractures Developed in "Wet" Fatigue

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Strength of Metals Branch
Metallurgy Division

January 14, 1966

U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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Fractographic studies show that the increase in crack-growth rate is due to a change from the ductile mode of fatigue fracture, usually found in "dry" low-cycle fatigue tests of titanium alloys, to the brittle quasi-cleavage mode of fracture—a fracture mechanism of stress-corrosion cracking. The amount of quasi-cleavage seen on the fatigued fracture surface generally corresponds to the crack-growth-rate increase; thus, it is indicative of the degree of stress-corrosion cracking sensitivity.

INTRODUCTION

The safe and dependable use of high-strength metals in large, cyclically loaded structures requires a knowledge of low-cycle fatigue. In complex welded structures, small flaws and cracks are formed during manufacture and fabrication and frequently escape detection despite the use of the best inspection techniques. Therefore, the only practical recourse for safe and dependable use of this type structure is to provide design criteria which preclude the growth of such flaws to a critical size during its expected service life. The U.S. Naval Research Laboratory has a program to determine the low-cycle-fatigue characteristics of a wide variety of high-strength structural materials. The results of the study reported here are only a small portion of this program.

TEST PROCEDURES

Low Cycle Fatigue

During the period of September to December 1964, center-notched plate bend specimens of Ti-7Al-2Cb-1Ta (7-2-1) and Ti-6Al-4V (6-4) alloys were subjected to low-cycle fatigue tests in air and a 3.5 percent salt-water solution (1,2). In addition, a 7-2-1 specimen was tested in distilled water. This specimen configuration has a test section 2.5 in. wide by 0.5 in. thick, formed by 2.25-in.-radius opposing cuts across the width. A sharpened notch is machined into the specimen at the center of the test section to initiate a fatigue crack with a low number of loading cycles (Fig. 1). The specimen is loaded in cantilever fashion by a test machine built for this purpose. The growth of the crack is monitored by a micrometer slide comparator, while loading conditions are monitored by a strain gage at the test section. In "wet" fatigue tests, a soft, flexible corrosion cell is clamped to the test section; the corrosive solution is circulated through the cell from a reservoir. After completion of the test, the specimen is pulled in tension to failure to expose the fatigued fracture surface for fractographic examination. The tensile fracture surface is also examined fractographically.

The object of the plate-bend test is the determination of the rate of fatigue-crack propagation through the material in question at varying degrees of strain. Therefore, the test is begun with a deliberately introduced fatigue crack. The specimen is cyclically loaded at a controlled constant total strain range until the crack-growth rate at that strain range has been determined;

NRL Problem M01-05; Projects SF 020-01-01-0724, RR 007-01-46-5405, and WW-041 (R05-24A). NRL Problem M01-18; Projects SF 020-01-05-0731, RR 007-01-46-5420, and WW-041 (R05-24B). NRL Problem F01-17; Project SP-00405. This is an interim report; work is continuing. Manuscript submitted July 26, 1965.

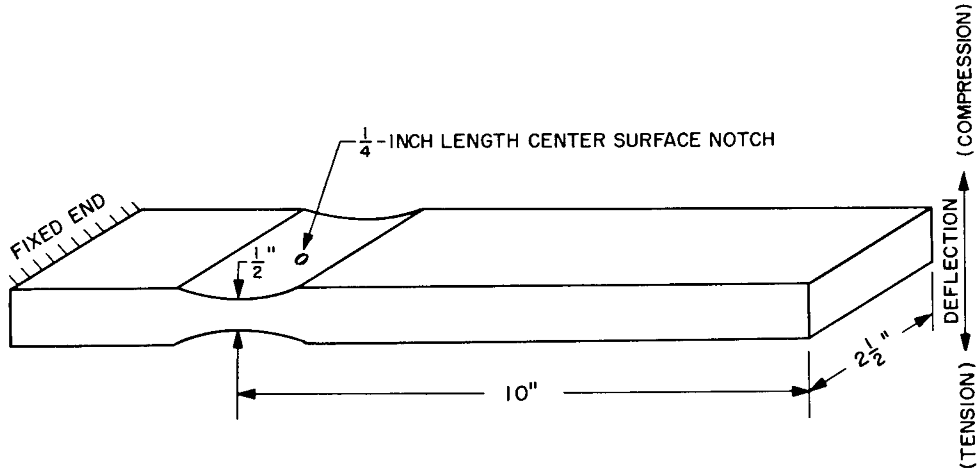

Fig. 1 — Illustration of Lehigh plate-bend fatigue specimen

the strain range is increased in a stepwise fashion, the crack-growth rate being determined at each step until the crack length becomes so great that the results are no longer meaningful. Empirical relations which have been evolved are of the form $\Delta L/\Delta N = C(\epsilon_T)^m$, where $\Delta L/\Delta N$ = crack-growth rate, (ϵ_T) = total strain range, and C and m are constants which vary with different materials and different environmental conditions (2).

Fractography

Advantages of the use of the electron microscope in preference to the optical microscope are the greater depth of field and the higher magnifications which can be attained with the electron microscope. Considerable work has been done in the relatively new field of fractography, which is based on the use of the electron microscope. As a result of this work, the basic fracture mechanisms have been identified, and descriptive terminology has been assigned to each failure mode. The terminology used in this report is taken from the work of C. D. Beachem (3,4).

In the process of electron fractography, the first step is the making of a replica of a portion of the fracture surface. This is done by pressing a strip of softened plastic against the fracture surface, allowing the plastic to harden, and then mechanically stripping it from the fracture surface. The plastic, which is now an accurate mold of the fracture surface, is angle-shadowed with a heavy metal and backed with a carbon film. The plastic is next dissolved away, leaving a film whose point-to-point variations in density accurately reflect the topography of the fracture surface. This film is placed into the electron microscope, where a beam of electrons is passed through it. The variations in density of the film are shown on a fluorescent screen as a representation of the fracture surface. Photographs of the replica (fractographs) can be made directly in the electron microscope.

EXPERIMENTAL RESULTS

Low Cycle Fatigue

The low-cycle-fatigue test results on the 7-2-1 and 6-4 alloys were surprising, since the 7-2-1 alloy exhibited a greatly increased crack-growth rate with a change from normal air environment to an aqueous environment at comparable elastic stress levels, while the 6-4 alloys showed no change in crack-growth rate for the same environmental change (2). It can be seen in Fig. 2 (top) that the data for the 6-4 alloys exhibit some scatter which does not seem to be related to any change in environment. The scatter in this case is more indicative of differences in the materials which had the same nominal composition and were obtained from the same manufacturer, but which were taken from different heats and consequently had different mechanical properties. Alloy T-27 was lower than T-5 in yield strength (YS) and fracture toughness, as measured by the NRL drop-weight tear test (DWTT) (Table 1).

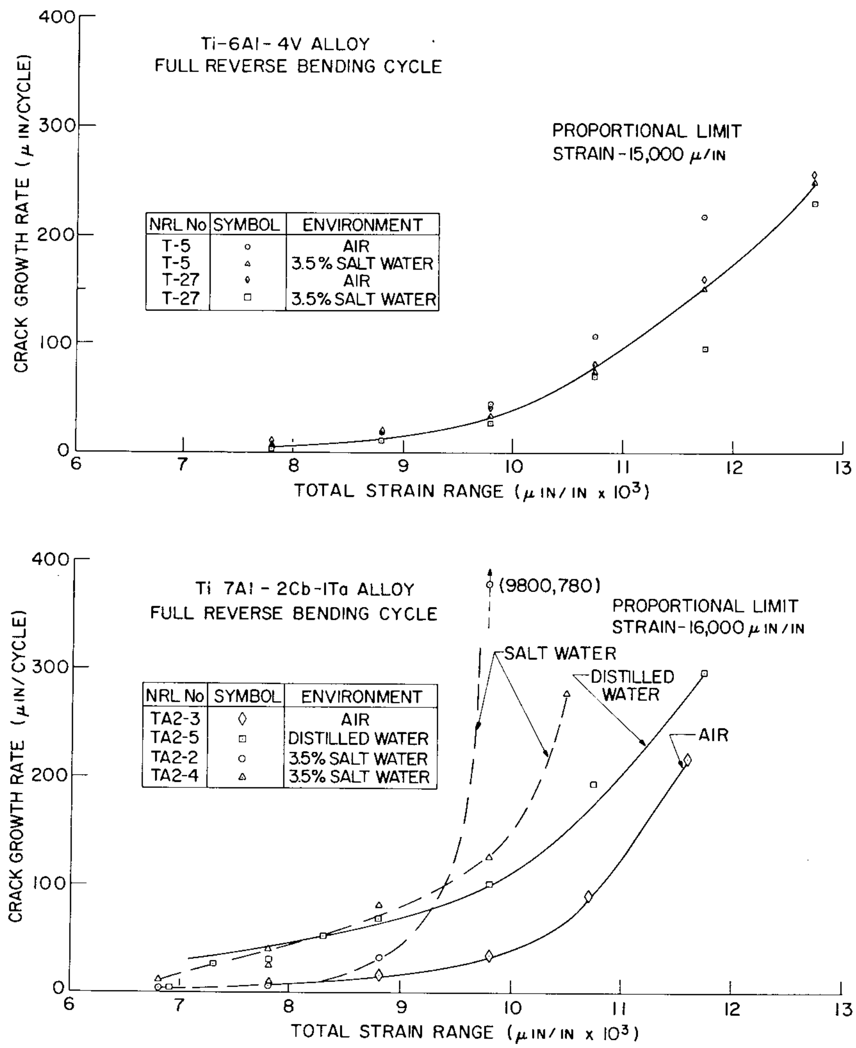

Fig. 2 — Comparison of crack-growth rates for Ti-7Al-2Cb-1Ta and Ti-6Al-4V alloys. Note increase in crack-growth rates with a change in environment in the 7-2-1 alloy, while the 6-4 alloys do not show appreciable change in crack-growth rate.

TABLE 1
Mechanical Properties of Titanium Alloys

Alloy No.	Nominal Composition	UTS (ksi)	YS (ksi)	Charpy V −80°F (ft-lb)	Charpy V 32°F (ft-lb)	DWTT (ft-lb)
TA2	Ti-7Al-2Cb-1Ta	120.5	107.5	30.5	38.7	2676
T5	Ti-6Al-4V	131	125.5	24	29	<~2000
T27	Ti-6Al-4V	126 RW 129 WR	115.5 RW 120 WR	— 22	— 26	1228 RW 931 WR

The influence of an aqueous environment on the 7-2-1 alloy can be seen very clearly in Fig. 2 (bottom). The specimen tested in air represents the base-line performance for this alloy in low-cycle fatigue tests. The specimens tested in a salt-water or a distilled-water environment exhibited an increased crack-growth rate at all strain levels. The crack-growth rate was more accelerated in the salt-water environment than in either the air or distilled-water environments, and the salt-water specimens appeared to be more sensitive to the environment at the higher strain ranges. An acceleration of the crack-growth rate, as shown by the increasing slope of the curves, of the salt-water specimens can be seen at 9000 to 10,000 μin./in. strain range (60 percent of yield strength). This acceleration was attributed to corrosion cracking which appeared to be the dominant crack-growth mechanism at this and higher levels of strain range. This "threshold" strain-level effect was particularly evident in specimen TA2-2, which was unaffected by the salt-water environment until the strain range was increased to 9800 μin./in. At this point, the crack-growth rate increased from 30 μin./cycle at 8800 μin./in. strain range to 780 μin./cycle at 9800 μin./in. strain range, an increase of about two orders of magnitude. The behavior of this specimen is discussed in more detail later in this report.

The unusual behavior of the 7-2-1 alloy in these tests and the importance of this particular alloy to the BuShips titanium program indicated that an investigation of the micromechanisms of the fatigue-crack propagation be conducted. Accordingly, the specimens of the two alloys were broken in tension to expose the "fatigue" surfaces (Fig. 3), which were then studied in the electron microscope.

Fractography

The specimen tested in air (TA2-3) fractured with the typical fatigue appearance (Fig. 4) in the low-cycle fatigue portion of the fracture surface. The tensile-fracture portion of this specimen was composed of dimpled rupture and stretching (Fig. 5) (4), which are the normal overload-tearing failure modes for titanium alloys (5). The zone along the interface between the tensile-fracture and fatigue-fracture portions of the specimen (Fig. 3), however, contained scattered facets of quasi-cleavage fracture (Fig. 6). This was very unusual, since quasi-cleavage fracture had not been reported as a fracture mechanism for titanium alloys. The mechanisms of quasi-cleavage are not fully understood, but they appear to vary with material and fracture conditions. The term "quasi-cleavage" is employed to describe fracture surfaces that resemble cleavage but are not known to be parallel to cleavage planes. Quasi-cleavage at this location may have been due to the presence of condensate at the root of the fatigue crack when the specimen was broken in tension. The specimen was broken apart several days after the fatigue tests were finished, which allowed time for moisture to condense and collect at the root of the notch.

The fatigued surface of the 7-2-1 specimen tested in distilled water (TA2-5) was a mixture of fatigue striations and quasi-cleavage fracture (Fig. 7). The distance of crack propagation covered by each quasi-cleavage facet was several times greater than the distance between fatigue striations. Therefore, the presence of the quasi-cleavage facets would account for the rate of crack growth being both greater and more erratic than that observed under the same loading conditions in an air environment.

The amount of quasi-cleavage observed on the fracture surface of the 7-2-1 specimens (TA2-2 and TA2-4) tested in a salt-water solution was greater than the amount found on specimen TA2-5, fatigued in distilled water (Figs. 8,9). This difference may be correlated to the differences in fatigue-crack growth rate and the amount of low-energy (quasi-cleavage) fracture found in the fatigued zone of the fracture.

In Fig. 2 (bottom), it can be seen that specimen TA2-2 was more severely affected at higher strain range by salt water than was specimen TA2-4. The reason for this discrepancy is not known; there was no noticeable difference in the amount of quasi-cleavage fracture between the two specimens. However, a marked transition from stepwise crack propagation, as evidenced by fatigue striations, to essentially exclusive quasi-cleavage fracture was found near the fatigue-crack initiation notch in specimen TA2-2. This transition was found on two separate replicas taken near the mechanical notch (Fig. 3). Figure 10 shows the transition, which seems to occur at the point where the strain range was changed from 8000

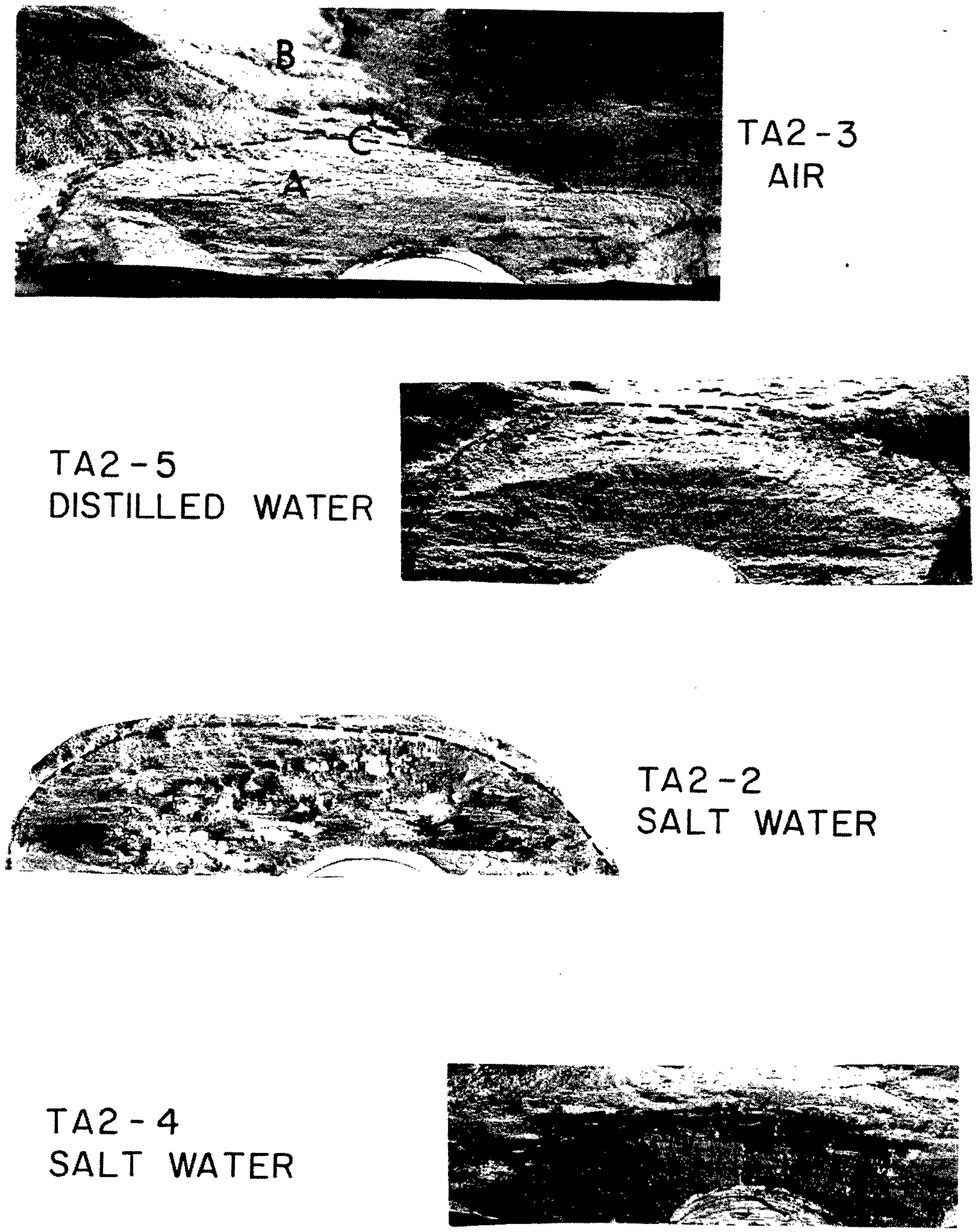

Fig. 3 — Fracture surfaces of the Ti-7Al-2Cb-1Ta specimens. In specimen TA2-3, typical areas are shown. Area A immediately around the mechanical notch is the fatigued zone. Area B is the surface created when the specimen was broken in tension. Area C is the interface between fatigue and tensile fracture. Approximately 5X magnification.

Fig. 4 — Stepwise crack propagation and dimpled rupture in the fatigued area (Area A, Fig. 3) of the 7-2-1 specimen TA2-3 (air). Striations illustrate normal fatigue-fracture appearance. 3000X.

Fig. 5 – Fractograph of tensile fracture area (Area B, Fig. 3) of the 7-2-1 specimen tested in air (TA2-3). Area composed of small and large dimples can be seen between vertical arrows, while serpentine glide can be seen between horizontal arrows. This appearance is indicative of the ductile failure usually seen in titanium fractures and is typical of the fast-fracture portion of all the specimens in this study. 6000X.

Fig. 6 — Quasi-cleavage fracture at interface of fatigue and fast fracture (Area C, Fig. 3) in the 7-2-1 specimen TA2-3 (air). Large facets (bounded by large arrows) are planes inclined at different angles. Small-scale markings (small arrows) are typical steps or tear ridges. 6000X.

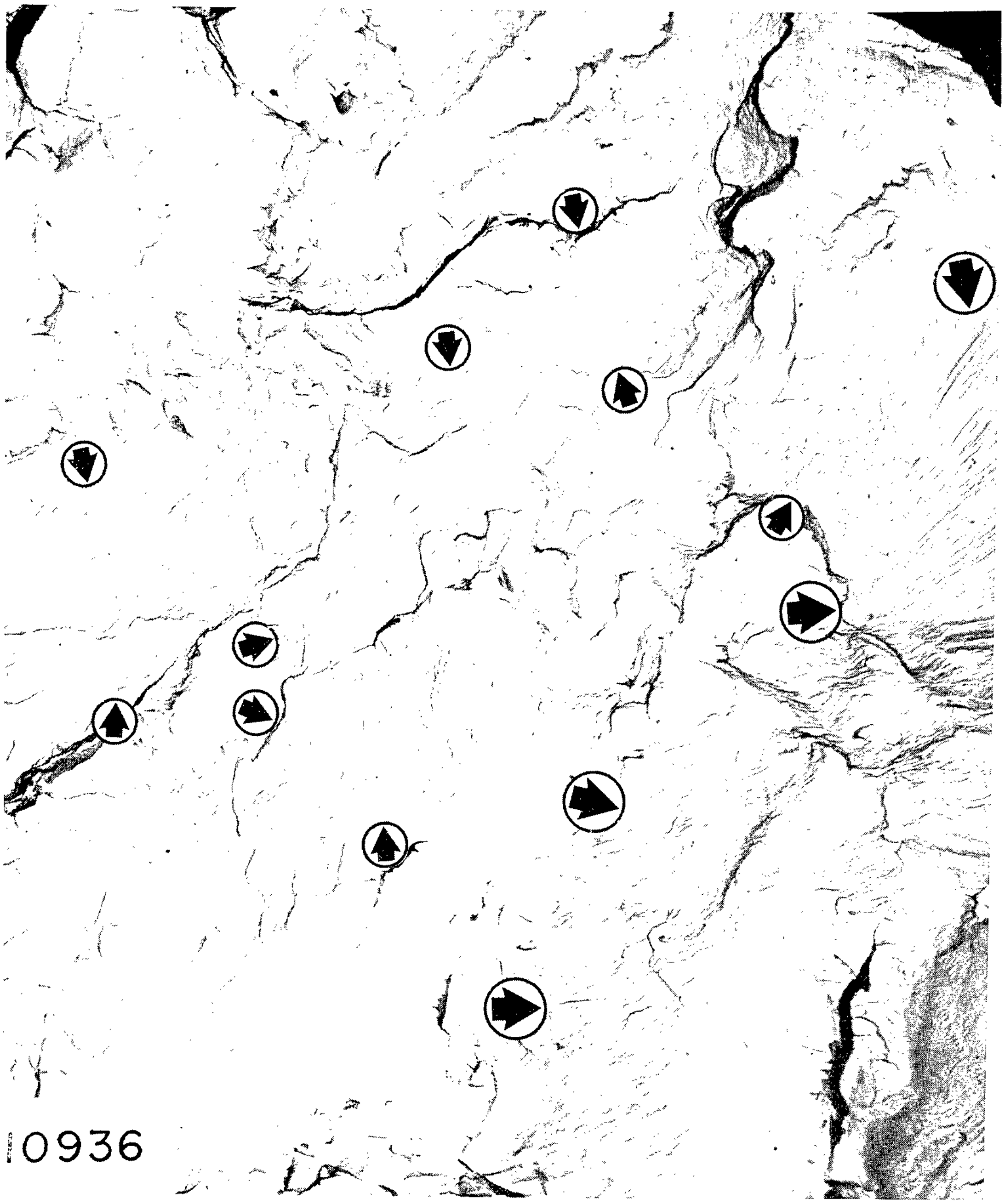

Fig. 7 – Quasi-cleavage (small arrows) and fatigue striations (large arrows) in the 7-2-1 specimen TA2-5 (fatigued in distilled water). 3000X.

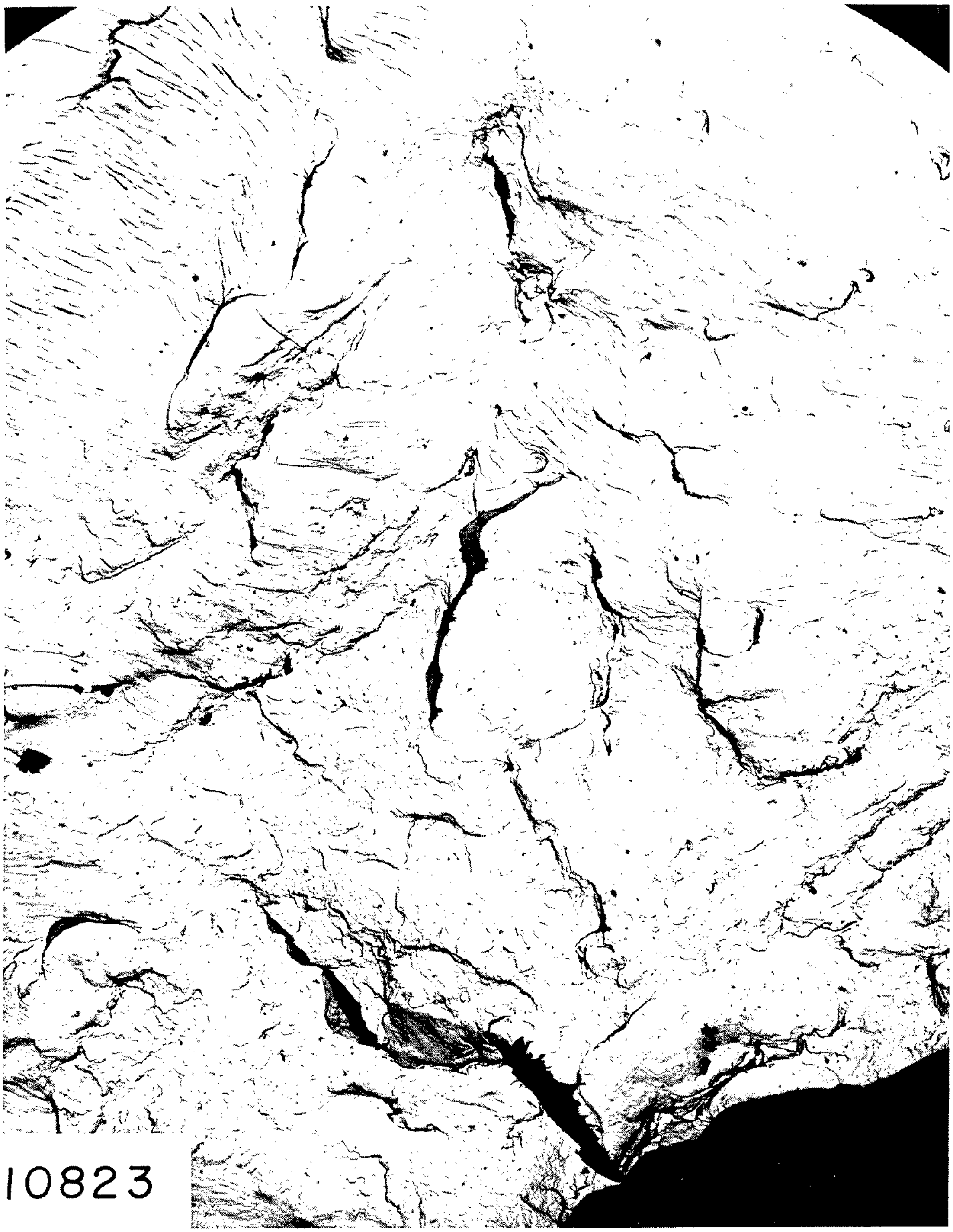

Fig. 8 — Fatigue striations and quasi-cleavage in the fatigued area of 7-2-1 specimen TA2-4 (salt water). 3000X.

Fig. 9 — Quasi-cleavage in 7-2-1 specimen TA2-4 (salt water). 3000X.

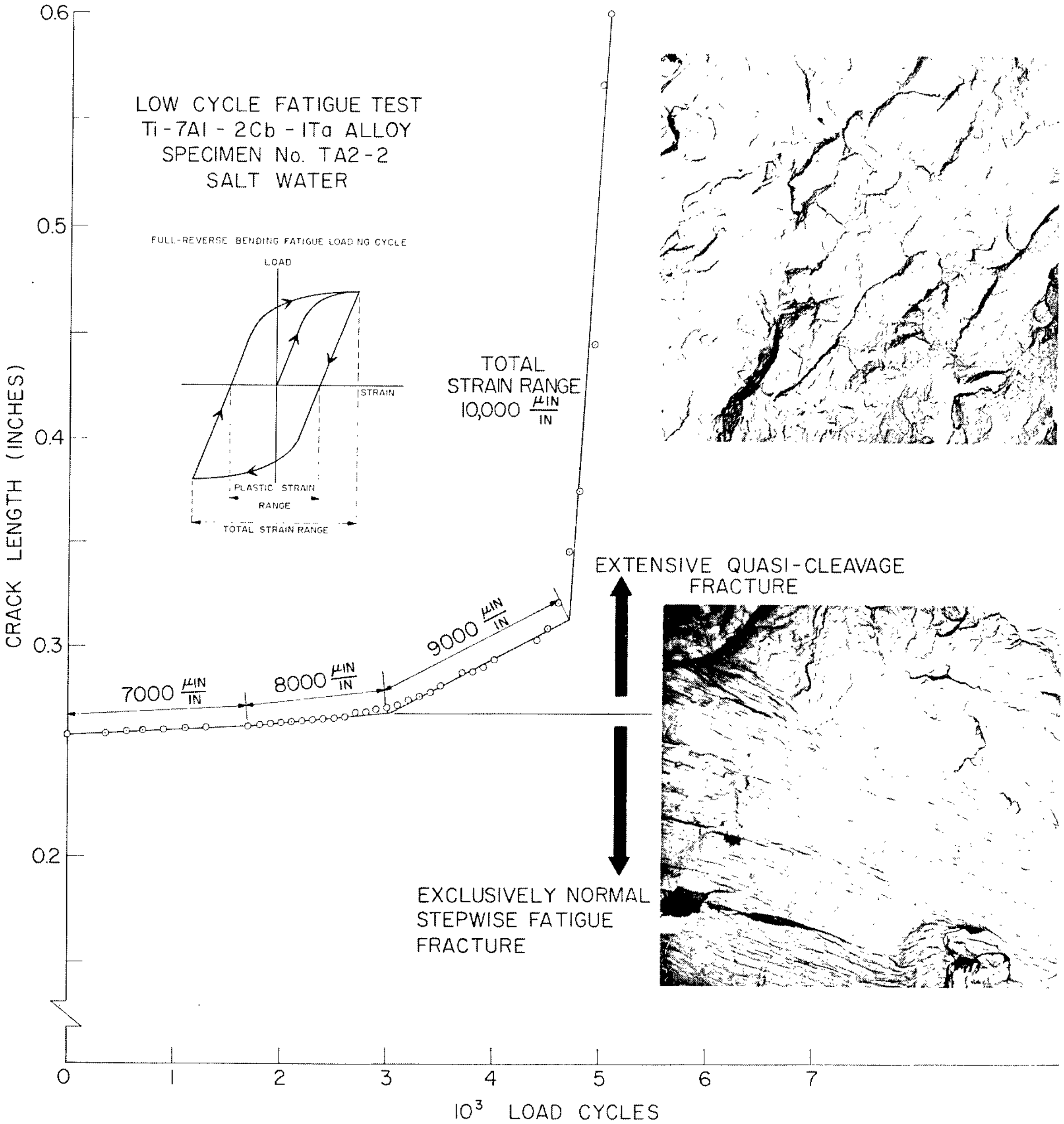

Fig. 10 — Illustration of fracture-mode transition from stepwise crack advance to quasi-cleavage fracture for the 7-2-1 alloy. The transition is placed near the beginning of the 9000 μin./in. strain range (60-percent yield strength) phase of the test by relative positions of fatigue fracture and quasi-cleavage on grid. 3000X.

to 9000 μin./in. during the normal course of the test. The correlation is shown by the relative position of the fatigue striations and quasi-cleavage areas on the grid.

Since T-27 was considered to be more representative of available Ti-6Al-4V plate material than T-5, the fracture surfaces of the T-27 specimens were chosen for study. Electron fractography revealed no apparent differences between the specimens tested in different environments. In both cases, the major failure mode was normal fatigue fracture by stepwise crack propagation (Figs. 11,12). This was not surprising in view of the lack of change of crack-growth rate with a change in environment (Fig. 2, top).

DISCUSSION

It was apparent from the fractographs that the presence of quasi-cleavage in the 7-2-1 specimens tested in an aqueous environment led to a considerably greater crack-growth rate in these specimens than in the 7-2-1 specimens tested in air under comparable loading conditions. The increase in crack-growth rate is due to the size of the quasi-cleavage facets in relation to the distance between fatigue striations, which distance has been proven to represent one loading cycle for some materials (6), and certainly has some relation to the number of loading cycles per unit distance on the surface of the specimen. Each quasi-cleavage facet was several times greater than the distance between fatigue striations seen in the same general area.

The transition from fatigue fracture to quasi-cleavage fracture seen on specimen TA2-2 – fatigued in salt water (Fig. 10) – partially explains the behavior of the crack-growth rate in the specimen. It can be seen in Fig. 2 (lower) that the crack-growth rate for this specimen was the lowest of all observed at lower strain ranges. The abrupt increase in crack-growth rate at 9000 μin./in. strain range can be attributed to the introduction of quasi-cleavage fracture at that point. Another factor contributing to this sudden increase in crack-growth rate is the possibility of the growth of the initial crack at the surface lagging the growth of the submerged portion of the crack. The fatigued portion of this specimen (Fig. 3) was very rough, which indicated that considerable submerged crack growth could have occurred before the surface crack appeared. Such behavior of the crack front would lead to conservative values of crack-growth rate. In any case, the significant observation from the data is the great increase in the crack-growth rate due to the introduction of a salt-water environment.

The same dramatic decrease in resistance to fracture propagation has been observed for the same 7-2-1 alloy in stress-corrosion cracking (SCC) tests by B. F. Brown (7). In these studies, a change in the basic mode of fracture is also associated with the decrease in fracture propagation resistance. This change is from the dimpled rupture, a ductile mode always seen in Charpy V, drop-weight tear, and "dry" fracture mechanics tests, to quasi-cleavage in the "wet" tests. Brown's studies show a threshold level of stress intensity (K_I) below which SCC is not observed, with the mode of fracture of the ductile type. At stress intensities above the threshold level, failure due to SCC occurs in a matter of a few minutes, and quasi-cleavage is seen as the fracture mode. The abrupt increase in crack-growth rate at 9000 μin./in. strain range (60-percent yield strength) for the 7-2-1 in the low-cycle fatigue test generally corresponds to the SCC results in the terms of a K_{ISCC} (threshold level of stress intensity for SCC) of about 35 ksi $\sqrt{\text{in.}}$ for similar material that had a "dry" value of about 120 ksi $\sqrt{\text{in.}}$

CONCLUSIONS

The increase in crack-growth rate from wet fatigue and increased scatter of observed data (erratic crack growth) in the Ti-7Al-2Cb-1Ta alloy was due to the low-energy fracture of portions of the material while other portions of the material fractured by stepwise crack propagation. The increase in crack-growth rate for any specimen corresponded roughly to the relative amount of quasi-cleavage fracture found in that specimen. In one specimen, tested in salt water, a sharp transition from stepwise (classical fatigue) crack extension to largely quasi-cleavage fracture was shown to occur very near a point where the strain range was changed from 8000 to 9000 μin./in. (60 percent of yield strength) in the normal course of the test. No change in failure mode was observed in examination of air and salt-water fatigued specimens of Ti-6Al-4V alloy.

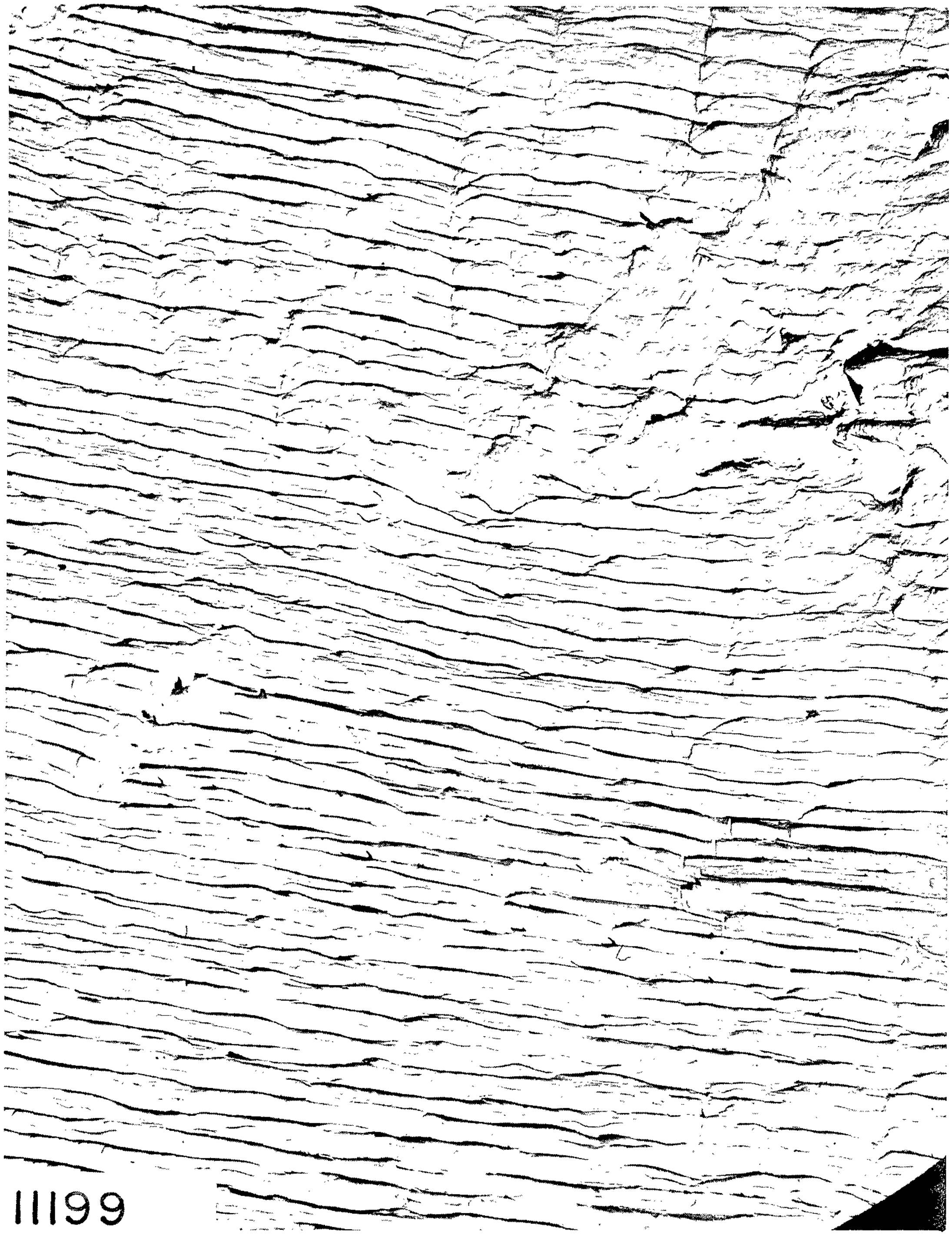

Fig. 11 — Fatigue striations in a 6-4 specimen tested in air. 3000X.

Fig. 12 — Fatigue striations in a 6-4 specimen tested in salt water. Replica was taken from area of higher strain range, which may account for wide spacing of striations. 3000X.

ACKNOWLEDGMENT

The authors are grateful for the interest and helpful suggestions of Mr. C. D. Beachem in the fractographic aspects of this study.

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Security Classification

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1. ORIGINATING ACTIVITY *(Corporate author)* U.S. Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

FRACTOGRAPHIC ANALYSIS OF Ti-7Al-2Cb-1Ta AND Ti-6Al-4V FRACTURES DEVELOPED IN "WET" FATIGUE

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

An interim report on one phase of problem.

5. AUTHOR(S) *(Last name, first name, initial)*

Judy, Ralph W., Jr., Crooker, Thomas W., Morey, Robert E., Lange, Eugene A., and Goode, Robert J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 14, 1966	20	7

8a. CONTRACT OR GRANT NO. M01-05, M01-18, F01-17, R05-24A and R05-24B b. PROJECT NO. SF 020-01-01-0724, SF020-01-05-0731, WW-041, c. RR 007-01-46-5405 & -5420, and SP-00405 d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6330 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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