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The Effects of an Aqueous Environment on the Fatigue Crack Propagation Characteristics of Titanium Alloys

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ABSTRACT

Fatigue crack propagation was studied in Ti-6Al-4V, Ti-7Al-2Cb-1Ta, Ti-6Al-6V-2Sn-1Cu-0.5Fe, Ti-6Al-3V-1Mo, and Ti-7Al-2.5Mo alloys. These materials possess yield strengths in excess of 100 ksi, combined with favorable levels of fracture toughness, and they are currently under evaluation for application in large welded structures.

Where an application involves repetitive loading, a knowledge of fatigue crack propagation characteristics is required for failure-safe design against fracture. Fabrication and nondestructive testing procedures cannot guarantee that cracklike defects, which can grow to a critical size, will not be present in plate-thickness sections containing welded joints. In addition, the role of an aggressive environment, such as salt water, in this failure mechanism is of the utmost importance.

Fatigue crack propagation data were taken in both ambient room air and 3.5% salt-water environments. Surface-notched plate bend specimens were cycled in full-reverse (tension-to-compression) sinusoidal loading. The fatigue crack was observed optically, and the crack growth rate was described as an empirical power-law function of the total (elastic-plus-plastic) strain range.

Fatigue crack growth rate relationships were first developed in an air environment and then employed as baselines for establishing the effect of the salt-water environment. Comparisons were made among the fatigue crack propagation characteristics of the several titanium alloys and among a broad spectrum of high-strength structural alloys, both ferrous and nonferrous, previously studied.

PROBLEM STATUS

This report completes one phase of the problem. Work on other aspects of the problem is continuing.

AUTHORIZATION

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THE EFFECTS OF AN AQUEOUS ENVIRONMENT ON THE FATIGUE CRACK PROPAGATION CHARACTERISTICS OF TITANIUM ALLOYS

INTRODUCTION

For the past several years high-strength titanium alloys have been the subject of an intensive research program to develop their usefulness for submersible-vehicle pressure hulls. Titanium alloys are the most promising weldable structural materials currently available for improving strength-to-density ratios beyond the capabilities of high-strength structural steels.

The Metallurgy Division of NRL has assumed a position of leadership in this effort through its broad-based titanium research program. The approach to this research effort is grounded on the philosophy that large, complex welded structures cannot be fabricated, proof-tested, and subsequently put into use for service periods spanning decades without encountering sharp flaws in critically stressed locations. Therefore, the failure-safe design of such structures must take into account a high probability of preexisting flaws whose growth to a critical size under the influence of repeated load and environment must be prevented. To provide the necessary knowledge for such design criteria, this research program's objective is the investigation of high-strength titanium alloys to simultaneously ascertain fracture toughness, weldability, heat treatability, optimization of processing variables, resistance to stress-corrosion cracking, and resistance to fatigue crack propagation. The fatigue research lays particular emphasis on the role of environment in determining fatigue crack propagation characteristics.

This report describes the results of the fatigue crack propagation research conducted to date. However, detailed discussion will be limited to the most promising alloys. The problems of stress-corrosion cracking and corrosion fatigue crack propagation in Ti-7Al-2Cb-1Ta have been the subject of a separate analysis (1) and will not be discussed in this report.

DESCRIPTION OF ALLOYS

The alloys studies in this investigation include the following: Ti-6Al-4V, Ti-7Al-2Cb-1Ta, Ti-6Al-6V-2Sn-1Cu-0.5Fe, Ti-6Al-3V-1Mo, and Ti-7Al-2.5Mo. In summary, all these alloys possess yield strengths in excess of 100 ksi, are weldable, possess favorable levels of fracture toughness, and, with the exception of Ti-7Al-2Cb-1Ta, possess favorable stress-corrosion-cracking characteristics in the heat-treatment condition studied.

Detailed mechanical properties are listed in Table 1, with references to the source of the data. All mechanical properties reported are from 1-in.-thick plate stock, with one exception. The Ti-7Al-2.5Mo test material was taken from 1.25-in.-thick plate stock. Nominal chemical compositions include a maximum oxygen content of 0.08 wt-%.

The investigation described in this report was conducted in two phases. The initial phase concerned two samples of Ti-6Al-4V (NRL code numbers T5 and T27) and one sample of Ti-7Al-2Cb-1Ta (code TA2). Work on these alloys was undertaken prior to

Table 1
Mechanical Properties*

Alloy	NRL Code	Fracture Path Orientation	0.2% YS (ksi)	UTS (ksi)	R.A. (%)	ELONG (%)	C_v @ 32°F (ft-lb)	DWTT @ 30°F (ft-lb)	K_{Ic} (ksi $\sqrt{in.}$)	K_{Ix} (ksi $\sqrt{in.}$)	K_{Iscc} (ksi $\sqrt{in.}$)	Remarks
Ti-6Al-4V	T5	RW†	125	131	44	12	29	2075	-	120	105	"Mill annealed" - as received
Ti-6Al-4V	T27	RW†	116	128	26	12	-	1228	-	88	67	"Mill annealed" - as received
Ti-7Al-2Cb-1Ta	TA2	RW†	107	120	28	13	39	2675	-	-	-	"Mill annealed" - as received
Ti-7Al-2Cb-1Ta	T78	RW†	110‡	-	-	-	-	3281	-	130	88	Processing proprietary to TMCA - as received
Ti-6Al-6V-2Sn-1Cu-0.5Fe	T-92	"A"§	122.0	140.4	24.4	10.0	20	681	98	111	96	Circular rolled plate 50% plus reduction below β transus
		"B"	123.8	140.0	18.0	8.9	17	681	-	-	-	
Ti-6Al-3V-1Mo	T-93	"A"§	116.5	128.4	27.5	10.7	23	1173	118	116	110	Circular rolled plate 50% plus reduction below β transus
		"B"	109.8	124.6	21.5	8.9	25	1540	-	-	-	
Ti-7Al-2.5Mo	T-94	"A"§	119.0	133.1	24.1	8.6	27	1540	-	-	-	Circular rolled plate 50% plus reduction below β transus
		"B"	120.5	134.9	20.2	8.6	30	1662	-	101	80	

*Reported in Refs. 4 through 8.
†See Ref. 3.
‡Estimated from producer's data.
§Circular-rolled plate material. Arbitrary orientations designated "A" and "B" are chosen at right angles to each other.

the discovery of serious stress-corrosion-cracking problems in certain titanium alloys, notably Ti-7Al-2Cb-1Ta and Ti-8Al-1Mo-1V. Consequently, the processing and heat treatment given this initial group of alloys was primarily intended to optimize yield strength and fracture toughness. These alloys were tested in the as-received mill-annealed condition. They had been rolled to a 1-in. thickness in the alpha-plus-beta temperature region and air-cooled.

The second phase of this investigation was undertaken after the problem of stress-corrosion cracking had begun to receive considerable attention. The remaining alloys, Ti-7Al-2Cb-1Ta (T78), Ti-6Al-6V-2Sn-1Cu-0.5Fe (T92), Ti-6Al-3V-1Mo (T93), and Ti-7Al-2.5Mo (T94), were tested in the as-received condition, which now included spray quenching after rolling. The spray quenching has the effect of somewhat reducing fracture toughness but greatly enhancing resistance to stress-corrosion-cracking. This procedure produces the best available tradeoff between yield strength, fracture toughness, and stress-corrosion-cracking resistance.

EXPERIMENTAL APPROACH

Apparatus

The experimental data in this report are based on the optically observed growth of fatigue cracks across the surface of center-notched plate bend specimens. A detail drawing of the plate bend specimen is shown in Fig. 1. The specimens are cantilever-loaded in full-reverse (tension-to-compression) strain cycling by hydraulically actuated automatic fatigue machines. Figure 2 is a general view of the test setup.

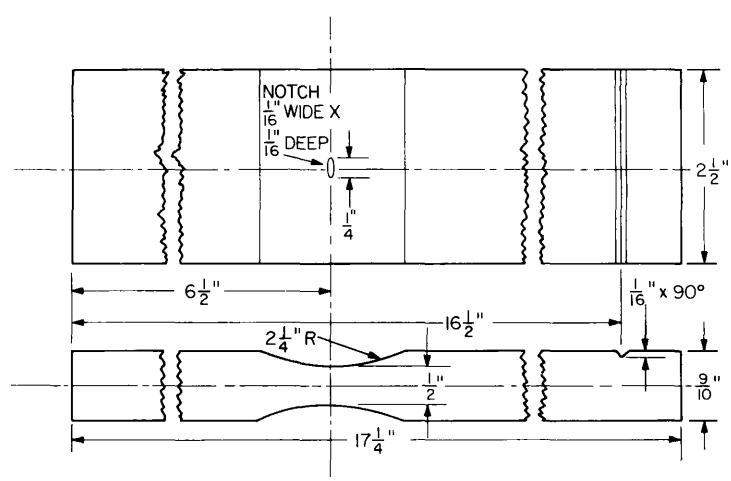

Fig. 1 - Dimensions of the plate bend fatigue specimen

Rapid fatigue crack initiation at relatively low cyclic strain levels is achieved by means of an engraved center surface notch placed at the minimum thickness of the test section. A foil-type resistance strain gage is placed on the test section well ahead of the advancing fatigue crack to monitor nominal surface strains, which are recorded as total (elastic-plus-plastic) strain range values. These details are shown in Fig. 3.

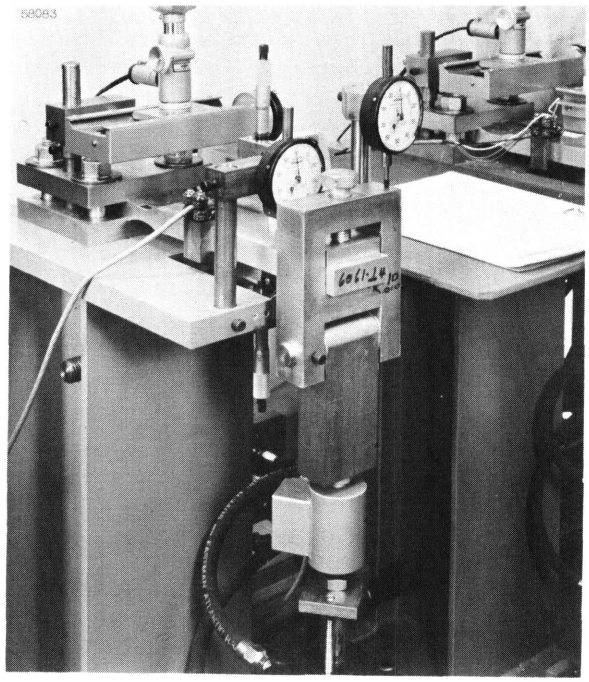

Fig. 2 - The plate bend fatigue test setup

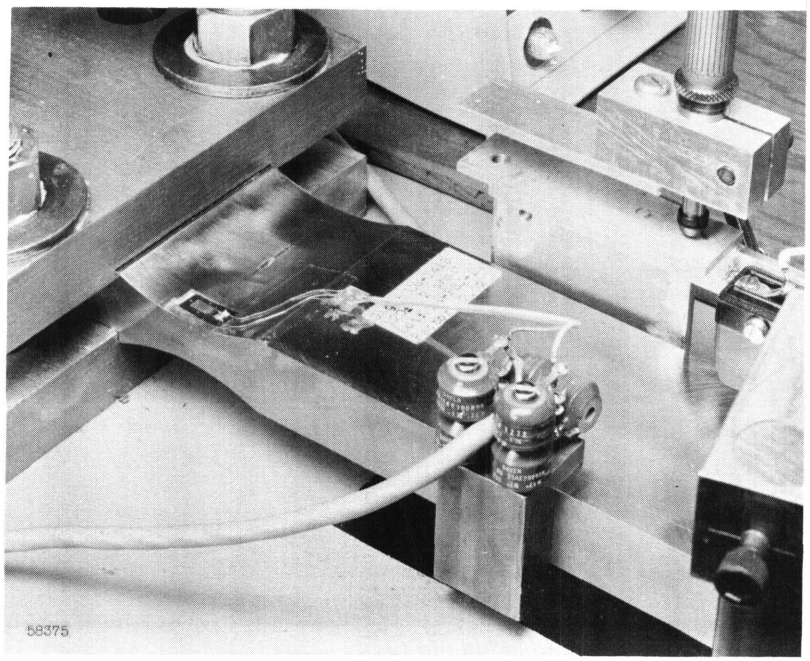

Fig. 3 - The plate bend fatigue specimen. Note the machined surface notch to facilitate crack initiation and the foil resistance-type strain gage for measuring the strain range.

The progress of the fatigue crack across the test section is observed from directly above through a slide-mounted optical micrometer. Extensions at both ends of the crack are monitored, and the sum is reported. Automatic deflection control of the test is obtained through micrometer-adjusted microswitches which contact the specimen arm at the maximum and minimum points in the loading cycle. The automatic operation provides a sinusoidal loading pattern at a cycling rate of approximately 5 cycles/min.

In the salt-water environment tests a corrosion cell is placed over the portion of the test section containing the fatigue crack. The corrosion cell is made of molded polyurethane, which is relatively soft and flexes with the specimen. The 3.5% salt-water solution is constantly circulated through the corrosion cell, from a reservoir, by a small electric pump. The solution undergoes filtering and periodic monitoring of its pH value and salt content. A glass cover at the top of the corrosion cell permits optical observation of the fatigue crack.

Procedure

Based on extensive experience with this test method described in Ref. 2, it has been found that constant, total strain-range cycling in the plate bend specimen results in a constant value of fatigue crack growth rate. For this reason all tests described here were conducted under constant, total strain-range loading. Such loading is obtained by gradually reducing the deflection control limits as the fatigue crack increases in size.

The general procedure followed is schematically illustrated in Fig. 4. Cycling is begun at the lowest desired strain range and is continued until a fatigue crack is initiated, propagates away from the mechanical notch, and establishes a constant growth rate. Then the specimen is loaded to the next higher strain-range level desired and cycled until the new, higher growth rate is established. Using this procedure, one specimen can be used to generate several successive data points. Data on a given material are first taken in air, and then the test procedures are repeated with fresh specimens under salt water.

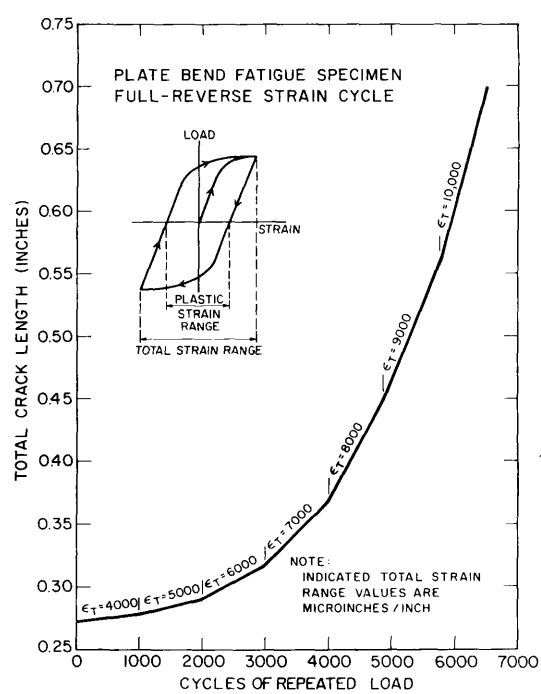

Fig. 4 - Illustration showing the experimental procedure of increasing total strain range at given intervals

Upon completion of fatigue testing, the plate bend specimens are pulled apart, in tension, to expose the fatigue surface. Basically, the fatigue crack grows radially from the notch until its downward growth is inhibited by the low-stress region near the neutral bending axis. Beyond this point the outward growth continues. The shape of the crack front near the test surface remains nearly constant throughout the various stages of growth. This is probably the reason for the singular correlation between the fatigue crack growth rate and total strain range, irrespective of flaw size.

RESULTS AND DISCUSSION

Air Environment Data

The air environment fatigue crack propagation data for all titanium alloys studied in this program are shown in Fig. 5. With the exception of Ti-6Al-6V-2Sn-1Cu-0.5Fe (T92), all the data are grouped within a single scatter band and will be treated collectively to avoid dealing with small individual differences. Seven samples of titanium alloys are included in this plot, and a legend is provided on Fig. 5 for individual indentification.

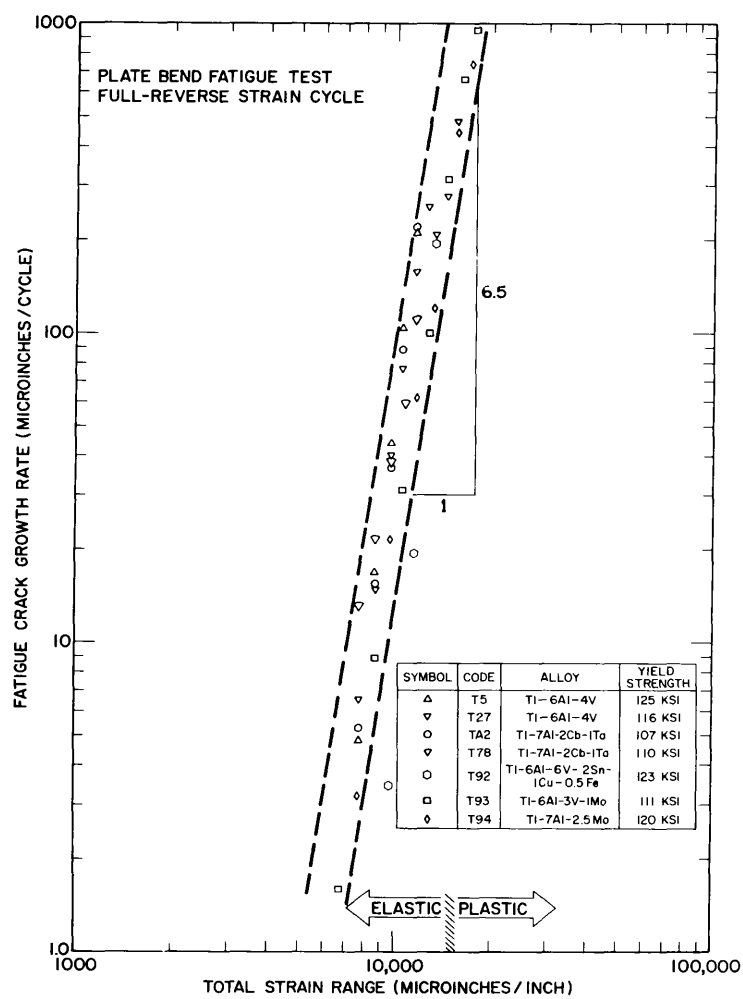

Fig. 5 - Log-log plot of fatigue crack growth rate versus total strain range for titanium alloys in an air environment

With regard to the fatigue crack propagation characteristics of these alloys, Fig. 5 reveals two points of general discussion. First, and most obvious, there are no broad differences in fatigue crack propagation behavior among these alloys. For the most part these alloys possess similar strength and toughness properties despite their differences in chemical composition. The range of fatigue properties illustrated by the width of the scatter band in Fig. 5 would seem to be consistent with variations in other mechanical properties among this group of alloys. Based on the small number of data available the behavior of Ti-6Al-6V-2Sn-1Cu-0.5Fe (T92) is considered to be anomalous and bears further investigation. This alloy was highly resistant to the initiation of fatigue cracks, but once underway the crack growth rates rapidly increased to similar values measured for the other alloys in the group shown.

Perhaps the most important common characteristic of the data in Fig. 5 is the steepness of the slopes of the individual relationships which fall within the indicated scatter band. The equations between fatigue crack growth rate and total strain range established by this plot have the form

$$\frac{d(2a)}{dN} \propto (\epsilon_T)^m \tag{1}$$

where $d(2a)/dN$ is the fatigue crack growth rate, ϵ_T is the total strain range, and m is the power-law exponent, or slope of the curves. The slopes of these relationships range from 6:1 to 7:1 for this group of titanium alloys. By way of comparison, 4:1 is the common slope of the fatigue crack propagation relationships for most martensitic structural steels evaluated by this test method.

Figure 6 illustrates the asymptotic form of these steep power-law relationships for fatigue crack propagation in titanium alloys. This typical plot rises rapidly from almost immeasurably slow rates of crack growth to rates nearly 1000 times greater, as the total strain range increases by less than a factor of three. Behavior of this sort suggests that designing titanium structures against failure by subcritical flaw growth in fatigue might best be approached as a "threshold phenomenon." Below a certain critical level of load intensity, as measured by total strain range or other suitable parameter, subcritical flaw growth by fatigue could be considered harmless; above this critical level of load intensity an increasingly dangerous potential for failure would exist.

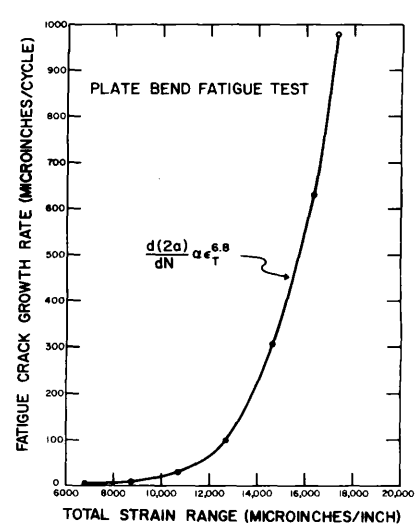

Fig. 6 - Linear plot of fatigue crack growth rate versus total strain range for Ti-6Al-3V-1Mo in air environment

Finally, it should be noted that in considering the data of Fig. 5 the total strain range values employed in these tests are well within the nominal working stress levels anticipated for these alloys. The elastic-plastic transition region for these materials in the plate bend specimen configuration is indicated in Fig. 5 for reference. The total strain range values employed are approximately equivalent to cyclic stress amplitudes of 50% to 100% of yield strength for these alloys.

Aqueous Environment Data

The results of the fatigue crack propagation tests conducted in a 3.5% salt-water environment are shown in Fig. 7. This plot is identical to the air environment summary data display, Fig. 5. The scatter band from the air environment data display is reproduced in Fig. 7 for reference purposes. No data from salt-water environment tests of Ti-7Al-2Cb-1Ta alloys are included, since the stress-corrosion-cracking phenomenon in these alloys has been documented previously (1).

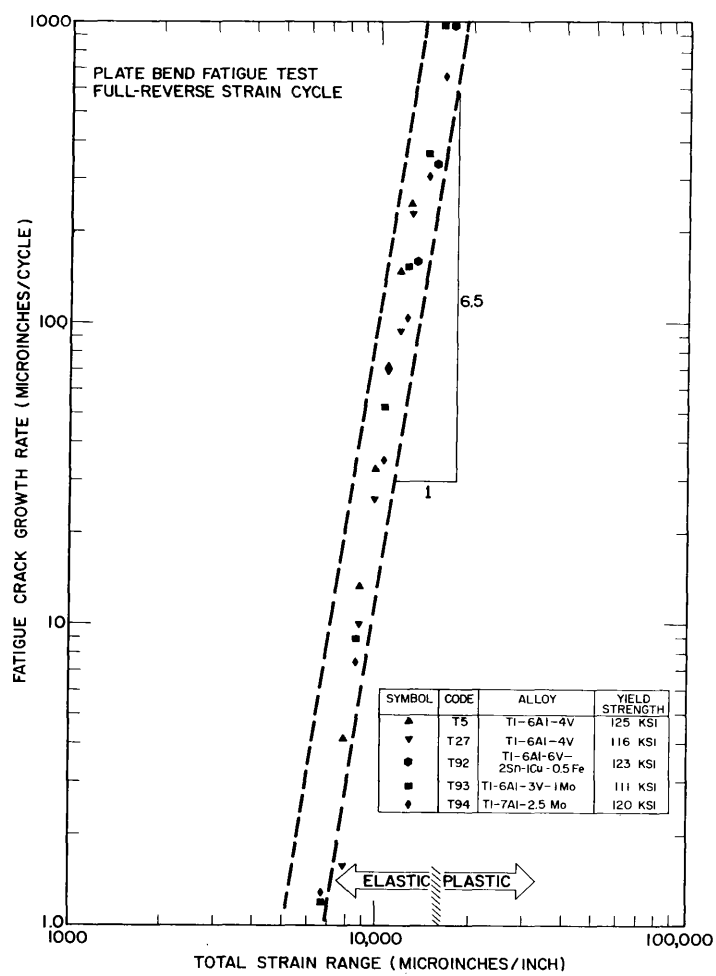

Fig. 7 - Log-log plot of fatigue crack growth rate versus total strain range for titanium alloys in a 3.5% salt-water environment. The scatter band limits are reproduced from the air environment data plot for reference.

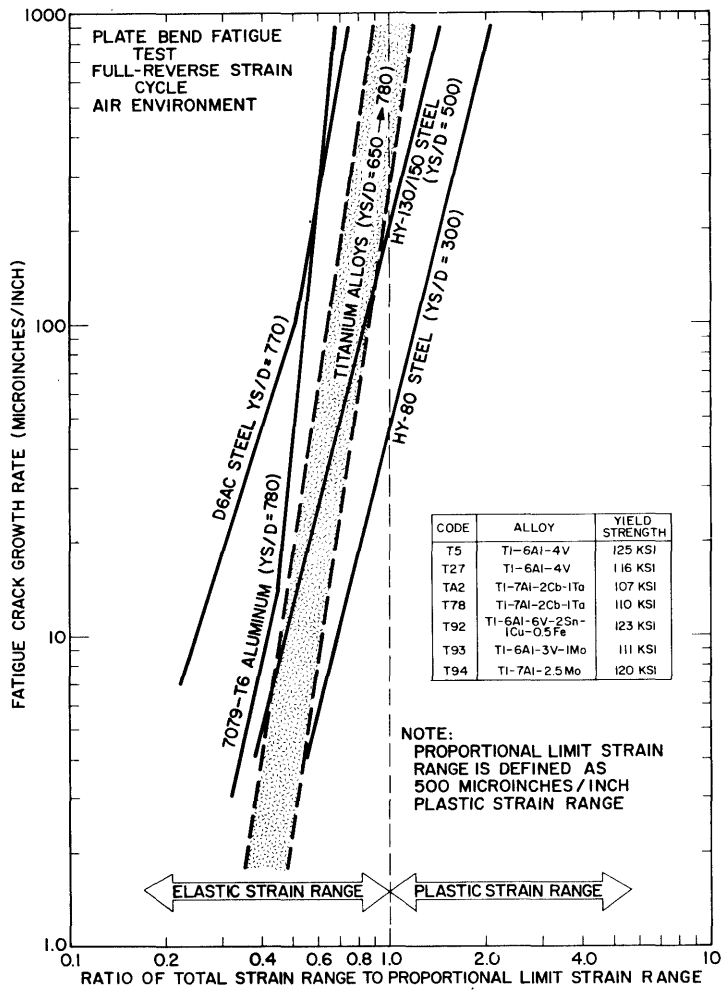

Fig. 8 - Log-log plot of fatigue crack growth rate versus the ratio of total strain range to proportional-limit strain range for titanium alloys and several conventional structural materials. Yield strength-to-density ratios are indicated for each material.

The salt-water-environment fatigue data shown in Fig. 7 lie well within the same scatter band as was drawn for the air-environment fatigue data. Whether viewed individually or collectively, these alloys show no evidence of degradation in fatigue crack propagation resistance due to the presence of a 3.5% salt-water environment. However, a statement of caution is in order. The sinusoidal loading pattern employed in these tests did not include a hold period at peak load. Also, laboratory 3.5% salt-water solution has been found to be a less aggressive environment than actual sea water. These two facts should be remembered when evaluating the favorable results indicated by the data in Fig. 7.

Comparative Evaluations

A comparative evaluation of the fatigue crack propagation characteristics of these titanium alloys is shown in Fig. 8. By converting strain units to the ratio of total strain range to proportional-limit strain range, a normalized basis is established for comparing

the fatigue crack propagation behavior of materials possessing widely different elastic moduli and yield strengths. The curves in Fig. 8 are based on the results of plate bend fatigue tests conducted in an air environment.

As in previous plots the titanium data are treated collectively, and the scatter band limits from Fig. 5 are reproduced for reference purposes. Relationships for four additional structural materials, HY-80, HY-130/150, and D6AC steels plus 7079-T6 aluminum are indicated in Fig. 8 as a basis for comparative evaluations. In addition, yield strength-to-density ratios are listed for each material, since this is a critical criterion in aerospace and hydrospace structural applications.

In brief summary, Fig. 8 suggests that this group of titanium alloys possesses inferior fatigue crack propagation resistance when compared to HY-80 or HY-130/150 (5Ni-Cr-Mo-V) steels, which have lower yield-strength-to-density ratios. This observation is based on the tendency of these titanium alloys to develop much more rapid rates of fatigue crack growth at cyclic strain levels approaching proportional-limit strains. However, these titanium alloys are definitely superior in this regard when compared to conventional high-strength steels or aluminum alloys which possess equivalent yield-strength-to-density ratios. The relationships shown for D6AC steel and 7079-T6 aluminum illustrate this point. In addition, all the materials shown in Fig. 8, for comparative purposes, are sensitive to aqueous environments. The presence of an aqueous environment can increase fatigue crack growth rates in HY-80 and HY-130/150 steels by a factor of 5 and by a factor of 10 in D6AC steel and 7079-T6 aluminum, whereas no increases in crack growth rates due to environment were observed in these titanium alloys, except for Ti-7Al-2Cb-1Ta. Therefore, from a fatigue crack propagation standpoint, these titanium alloys appear to merit consideration among the promising new materials currently under evaluation for structural applications requiring high strength-to-density ratios and resistance to aqueous environmental attack.

SUMMARY AND CONCLUSIONS

A fatigue crack propagation study was conducted on the following high-strength titanium alloys: Ti-6Al-4V, Ti-7Al-2Cb-1Ta, Ti-6Al-6V-2Sn-1Cu-0.5Fe, Ti-6Al-3V-1Mo, and Ti-7Al-2.5Mo. Plate bend specimens were employed using sinusoidal tension-to-compression strain cycling at a rate of approximately 5 cycles/min. Data based on optical measurements of fatigue crack growth were taken in both ambient room air and 3.5% salt-water environments. The following conclusions were reached.

1. In an air environment all the titanium alloys tested exhibited similar fatigue crack propagation characteristics, as determined by empirical power-law relationships between fatigue crack growth rate and total strain range of the form $d(2a)/dN \propto (\epsilon_T)^m$. The average exponent value for these relationships was 6.5, which indicates that fatigue crack propagation in these titanium alloys is highly sensitive to cyclic strain.

2. With the exception of Ti-7Al-2Cb-1Ta no degradation in fatigue crack propagation resistance was observed with the introduction of the 3.5% salt-water environment. This is considered to be a highly favorable resultant, but it must be tempered by the knowledge that the test conditions, i.e., sinusoidal loading pattern and laboratory salt-water solution, are not potentially as severe as many actual service situations.

3. The fatigue crack propagation characteristics of these titanium alloys compare favorably with competitive high-strength structural materials. For applications which require high yield-strength-to-density ratios and resistance to aqueous environmental attack, these titanium alloys merit consideration.

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13. ABSTRACT

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Strain cycle loading						
Fatigue crack growth rate						

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