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The Effect of Thickness Upon Sustained Load Crack Propagation in Ti-6Al-4V Alloy Tested in 3-1/2% NaCl Solution

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The titanium alloy Ti-6Al-4V was found to be susceptible to sustained load cracking in 3-1/2% NaCl solution, and this susceptibility increased with increased specimen thickness. The sensitivity to thickness was found in the thickness range near that required for plane strain crack propagation. Cracking rates were also found to increase with increasing specimen thickness.

The mechanism for the sustained load cracking may have been either a stress corrosion cracking mechanism arising from the presence of the salt water or a hydrogen-assisted cracking mechanism arising from the hydrogen content of the alloy.

Details of illustrations in
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CONTENTS

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THE EFFECT OF THICKNESS UPON SUSTAINED LOAD CRACK PROPAGATION IN Ti-6Al-4V ALLOY TESTED IN 3-1/2% NaCl SOLUTION

INTRODUCTION

Sustained load cracking of titanium alloys is of considerable interest in the application of these alloys to aerospace and hydrospace environments. The effects of both dissolved hydrogen and aggressive environments upon slow crack growth are being intensively studied in an effort to establish the key causative factors which may be experienced in practice. A parallel effort is directed toward understanding the crack-tip propagation mechanisms.

The present investigation was directed primarily toward evaluating the effect of thickness upon sustained load crack growth characteristics in the titanium alloy Ti-6Al-4V stressed in 3-1/2% salt water. Secondary aims were to (a) briefly compare these results in salt water with results in air, (b) evaluate a thickness effect suggested previously (1), and (c) briefly check the rising load fracture toughness.

MATERIAL AND EVALUATION PROCEDURES

Specimens of 2, 1.5, and 3/4 in. thicknesses were cut from a 3-in.-thick plate of Ti-6Al-4V, whose chemical analysis is given in Table 1. This plate was from a 12,000-lb ingot which had been prepared by triple melting in vacuum by the consumable electrode process. Forging the final plate was initiated at 2050°F, with final rolling at 1750°F and finishing at 1440°F. Slices were cut from the plate, with neighboring specimens alternating between the three thicknesses in order to minimize the possibility that specimens of a given thickness would have significantly different microstructures from those of another thickness. Specimens which were cut initially to the full plate thickness had to be reduced to the above 2 in. thickness to better approach the ASTM requirement (2) that the depth of the specimen be at least twice the thickness.

The specimens were of the design shown in Fig. 1 and were tested by three-point bending as shown in Fig. 2. Side grooves of 5% of the specimen thickness were machined as shown in Fig. 1. The final dimensions of the specimens were (a) 3/4 × 2 × 9 in., (b) 1.5 × 3 × 12 in., and (c) 2 × 3 × 12 in. These specimens were oriented such that the cracks would propagate in the TS direction (3) – previously the WT (4), or long transverse direction – and the smaller specimens were machined such that the tips of the fatigue cracks were positioned at the same depth into the plate as the larger specimens (at 1/4 plate thickness). The specimens were precracked by fatigue to a depth of 3/4 in., which gave a notch-plus-crack length of about 1 in. During the fatigue precracking the fatigue loads were gradually reduced to comply with ASTM suggested standards (2). Most of the specimens were tested in 3-1/2% NaCl solution, using cells cemented to the sides of the specimens as shown in Figs. 2 and 3. The distances between the upper loading points

Table 1
Chemical Content of the Ti-6Al-4V Alloy

Element	Composition (wt-%)
Al	6.0
Mo	–
V	4.1
Fe	0.5
C	0.023
O_2	0.07
N_2	0.008
Ti	Balance

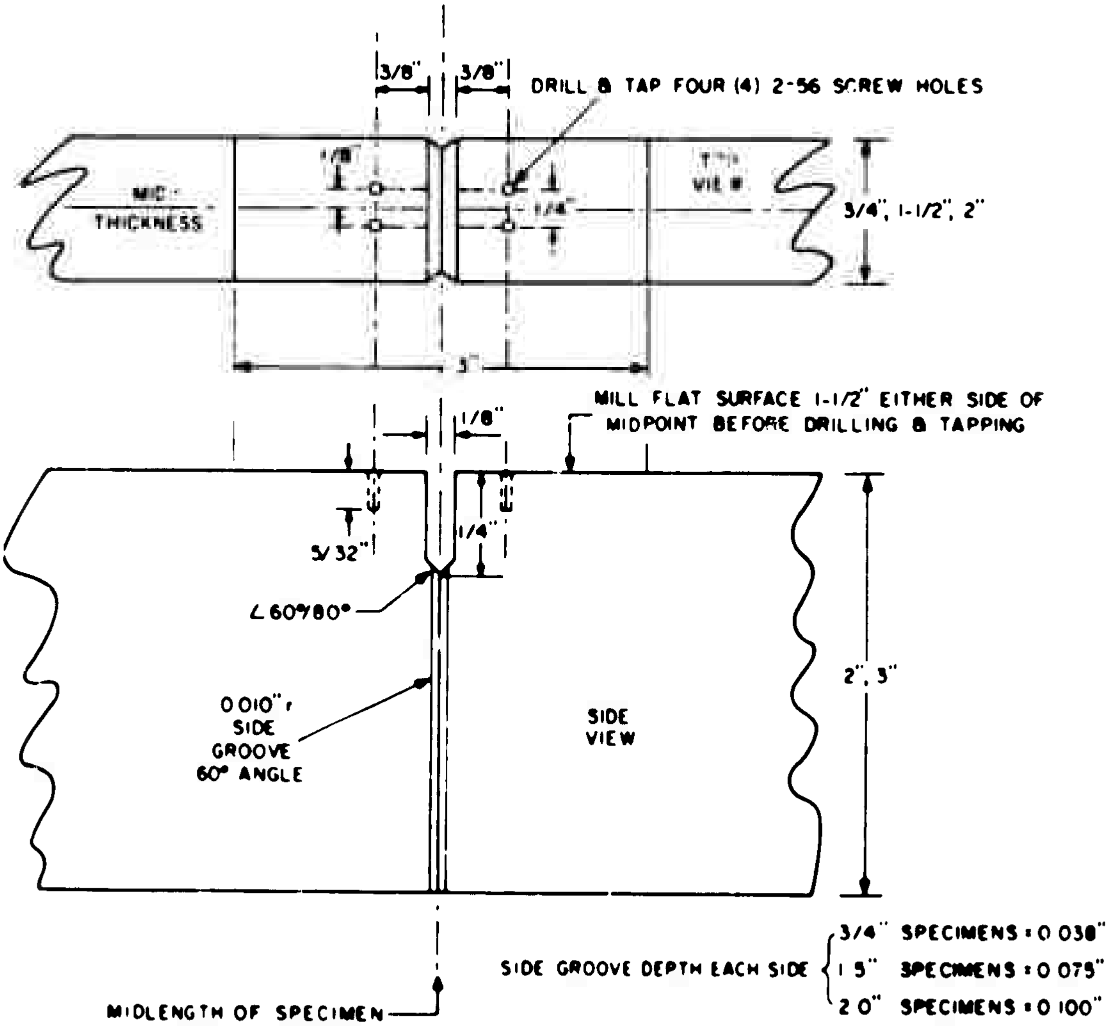


Fig. 1 — Design of three-point bending specimens

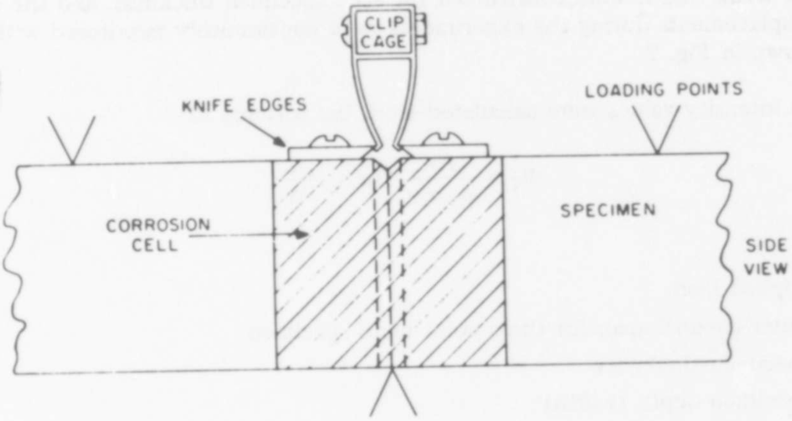


Fig. 2 — Specimen loading arrangement and corrosion cell

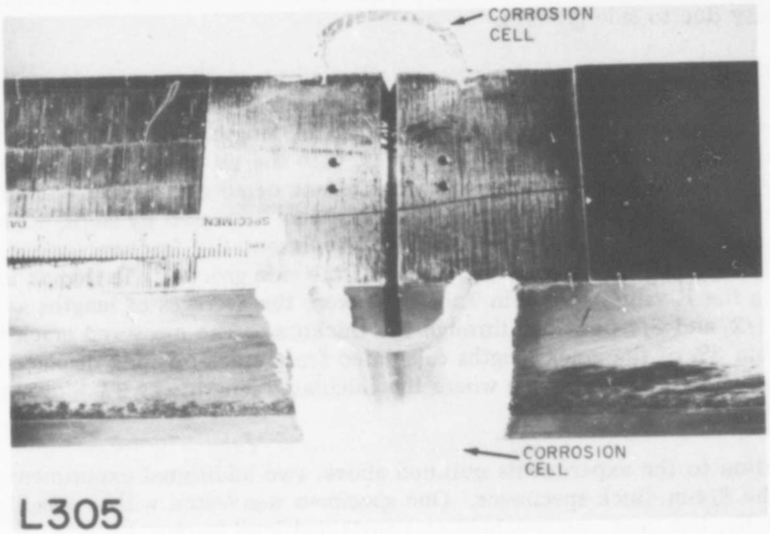


Fig. 3 — Corrosion cell in place on a 2-in.-thick specimen

shown in Fig. 2 were 8 in. for the 3/4-in.-thick specimens and 12 in. for the other two thicknesses. Calibration curves relating the crack opening displacement and the applied load to the crack length were constructed for each specimen thickness, and the crack opening displacements during the experiments were continuously monitored with a clip gage as shown in Fig. 2.

Stress intensity values were calculated from the formula (2)

$$K_I = \frac{PS}{BW^{3/2}} \sqrt{B/B_n}\, f\left(\frac{a}{w}\right)$$

where

P = applied load

S = outer support span for three-point bend specimen

B = specimen thickness

W = specimen depth (width)

B_n = net thickness after machining side grooves

$f\left(\frac{a}{w}\right)$ is obtained from Ref. 2.

The term $\sqrt{B/B_n}$ is suggested by Freed and Krafft (5) to correct for the elevation of effective stress intensity due to side grooves.

The first specimen of each thickness was loaded by small increments, with 1/2-hr holds at each load until cracking started. The approximate threshold values K_{Ith} for each thickness were established from these loads and crack lengths. Succeeding specimens were loaded immediately to selected lower K_I values, with the intention of holding these loads until crack growth occurred. If crack growth did not occur after a day at load, as was the case with many of the experiments, the loads were increased by steps, with hold times of several hours, until crack growth did occur. Representative fracture surfaces are shown in Fig. 4. The fatigue cracks are seen to lead at the side grooves. The crack lengths used in calculating the K values shown in Tables 2-4 were the averages of lengths as measured at the 1/4, 1/2, and 3/4 positions through the thickness. The measured crack lengths were to within 3% of the crack lengths calculated from crack-opening displacement measurements, except for one instance where the calculated length was 9% longer than the actual length.

In addition to the experiments outlined above, two additional experiments were conducted on the 3/4-in.-thick specimens. One specimen was tested with a steadily rising load, as in a K_{Ic} test, and one was held at a sustained load in air.

RESULTS

The lowest, or threshold, levels of stress intensity at which cracking occurred in this Ti-6Al-4V alloy in 3-1/2% NaCl solution are shown in Fig. 5. The effect of specimen thickness is pronounced, with the threshold K_{Ith} decreasing about 30 ksi$\sqrt{\text{in.}}$ with an increase in thickness from 3/4-in. to 2-in. The scatter of the results for a given thickness is probably due to the heterogeneity of the alloy plate, which shows up on the fracture surfaces in Fig. 4.

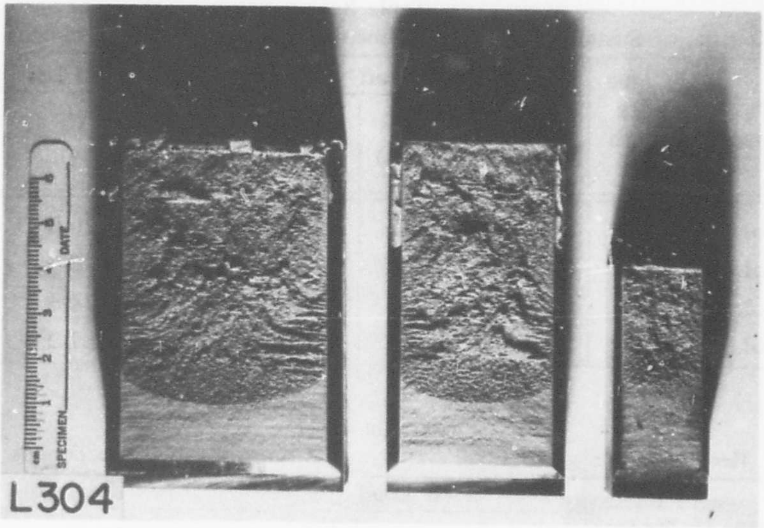


Fig. 4 — Examples of the fracture surfaces of the three titanium specimen thicknesses (2, 1.5, and 3/4 in., left to right)

Table 2
Results of Sustained Load Experiments on 3/4-in.-Thick Specimens

Crack-Tip Environment	Fatigue Crack Length (in.)	First Load			Final Load		
		Load (lb)	K_I (ksi$\sqrt{\text{in.}}$)	Time at Load (min.)	Cracking Load (lb)	Cracking K_I (ksi$\sqrt{\text{in.}}$)	Time to Break (min.)
NaCl Sol.	0.053	4,580	40.0	120	11,000	96.0	65
NaCl Sol.	0.903	10,600	94.6	60	10,600	94.6	60
NaCl Sol.	0.916	10,550	90.1	86	10,550	90.1	86
NaCl Sol.	0.965	9,750	85.0	1200	10,880	95.0	12
Dry	0.981	9,200	96.0	40	9,200	96.0	40
Dry	0.907	12,100	116.0	3.25	—	—	—

Table 3
Results of Sustained Load Experiments on 1.5-in.-Thick Specimens

Crack-Tip Environment	Fatigue Crack Length (in.)	First Load			Final Load		
		Load (lb)	K_I (ksi$\sqrt{in.}$)	Time at Load (min.)	Load (lb)	K_I (ksi$\sqrt{in.}$)	Time to Break (min.)
NaCl Sol.	0.855	18,000	42.2	1,098	33,750	79.6	120
NaCl Sol.	0.793	30,160	68.1	990	34,800	78.6	485
NaCl Sol.	0.801	31,550	71.5	312	32,850	74.5	553
NaCl Sol.	0.913	26,950	67.0	1,055	35,000	87.2	414

Table 4
Results of Sustained Load Experiments on 2-in.-Thick Specimens

Crack-Tip Environment	Fatigue Crack Length (in.)	First Load			Final Load		
		Load (lb)	K_I (ksi$\sqrt{in.}$)	Time at Load (min.)	Load (lb)	K_I (ksi$\sqrt{in.}$)	Time at Break (min.)
NaCl Sol.	0.670	36,093	54.7	1,134	40,600	61.5	1,788
NaCl Sol.	0.755	33,500	55.0	1,072	47,500	78.0	495
NaCl Sol.	0.709	38,000	59.7	257	46,950	73.7	232

The observed decrease in K_{Ith} with increased thickness is thought to be due to the increased lateral constraint at the crack tip with increased thickness. The cracking occurred at K_I values close to the partial criterion for plane strain, as defined by the equation

$$B < 2.5\left(\frac{K_I}{\sigma_{ys}}\right)^2 .$$

If σ_{ys} is taken as 114 ksi, then the highest stress intensities for which this condition is satisfied are 62.5 ksi$\sqrt{in.}$ for the 3/4-in.-thick specimens, 88.5 ksi$\sqrt{in.}$ for the 1.5-in.-thick specimens, and 102 ksi$\sqrt{in.}$ for the 2-in.-thick specimens. The ratios of these values to the lowest K_I measured for each of the thicknesses were therefore 0.7, 1.2, and 1.7 for the 3/4, 1.5, and 2-in. thicknesses, respectively. The effect of increased thickness lowering the K_{Ith} value is not surprising in this range of thicknesses since it is probable that the maximum lateral constraint along the crack front is not a constant in this range.

Crack growth rate measurements were made during these experiments and the results are shown in Fig. 6, where it is seen that the cracks grew faster in the thicker specimens.

CONCLUSIONS

There is a pronounced effect of thickness upon the slow crack growth characteristics of this Ti-6Al-4V alloy for thicknesses close to those required for valid plane strain

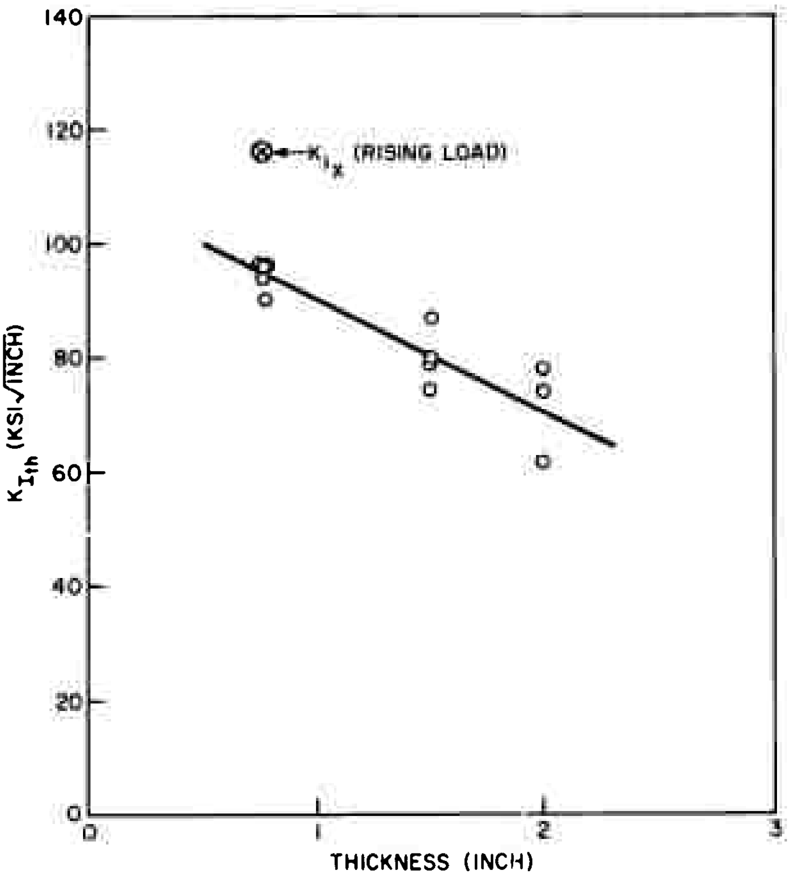
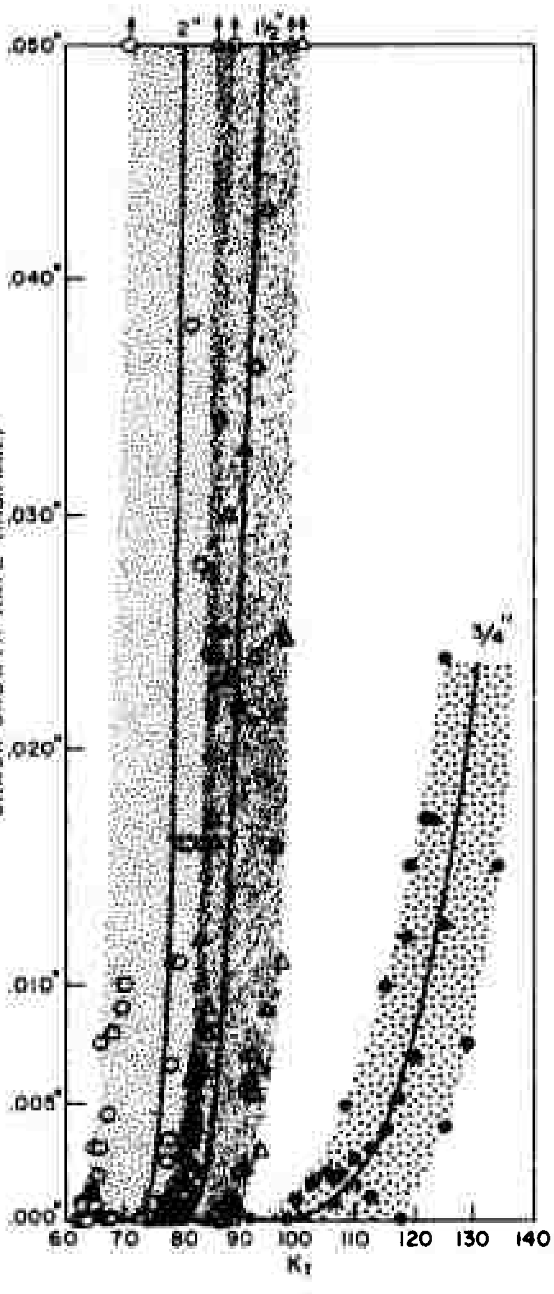


Fig. 5 — Effect of specimen thickness upon the threshold stress intensity value K_{Ith}

conditions. The effects are that (a) increased thicknesses cause sustained load cracking at lower stress intensity levels, and (b) faster cracking rates occur in the thicker sections. The effects of the salt water upon cracking are not clear, since it is known that hydrogen in titanium causes sustained load cracking (6), and since the 3/4-in. specimen, which was stressed at sustained load in laboratory air, cracked at about the same K_I at which the specimens loaded in salt water cracked. In other words, the sustained load cracking may have been caused by hydrogen-assisted cracking from hydrogen already dissolved in the lattice instead of from some stress corrosion mechanisms at the crack tip. No effect of step loading on K_{Ith} was found.

The fact that the 3/4-in.-thick specimen, which was broken with an increasing load, fractured at a higher stress intensity than those held at constant loads (116 ksi$\sqrt{\text{in.}}$ versus an average of 93.9 ksi$\sqrt{\text{in.}}$) suggests that the alloy is significantly sensitive to either stress corrosion cracking or to sustained load cracking due to internally dissolved hydrogen.

Fig. 6 — Crack growth rate versus stress intensity factor K_I for the three titanium specimen thicknesses



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