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MECHANICAL PROPERTIES OF Ti-6Al-4V ANNEALED FORGINGS

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R. R. Cervay

FOREWORD

This report was prepared by the University of Dayton Research Institute, Dayton, Ohio. The work herein described was performed under USAF Contract No. F33615-72-C-1282. It was initiated under Project No. 7381, "Materials Applications", Task No. 738106, "Engineering and Design Data". The program was administered by the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, Mr. David C. Watson (AFML/MXE), Program Monitor.

The materials used in this program were commercial items, which were not developed or manufactured to meet government specifications, or to withstand the tests to which they were subjected. Any failure to meet the objectives of this study is no reflection on any of the commercial items or the manufacturing process.

The author would like to acknowledge the support provided to this program by Messrs. D. Woleslagle and J. Eblin of the University of Dayton Research Institute.

This report covers work conducted from June 1971 to October 1973. It was submitted by the author in December 1973. The contractors report number is UDRI-TR-73-16.

This technical report has been reviewed and is approved for publication.

David C. Watson
Project Monitor

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ABSTRACT

Tests were conducted to determine the mechanical properties of titanium 6Al-4V annealed forgings. Tensile, fracture toughness, and constant amplitude cyclic crack growth properties were obtained along with limited corrosion studies of fastener installations. The tensile properties were determined for three orientations and the fracture toughness properties for four orientations. Some of the tensile and fracture toughness specimens were subjected to a time-temperature exposure before being tested at room temperature. The mechanical properties of the annealed material were similar to those in the literature. The time-temperature exposure cycle slightly altered the mechanical properties of the material. The corrosion tests conducted on the fastener installations did not produce any cracking in the material under the test conditions.

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SECTION I

INTRODUCTION

One of the first titanium alloys developed and put into widespread use in the aircraft industry was Ti-6Al-4V. Although the titanium industry has continually developed new alloys, most new airframes using titanium are still extensively designed around the Ti-6Al-4V alloy. Although this alloy has been well documented in the past, there are gaps in the fracture and crack propagation data. Also, much of the existing data is on material in heat treatments or annealed conditions which are modifications of present MIL specifications. In order to obtain better base line data on the Ti-6Al-4V alloy, this effort was undertaken.

This program is related to effort on beta forged titanium reported in Reference 1. For the current effort four closed-die forgings in the annealed condition were purchased from the Wyman-Gordon Company. Their die designated as R-475, was the same as used in the effort reported in Reference 1. The material properties investigated in this program were tensile, fracture toughness, cyclic crack growth, time-temperature exposure effects on the tensile and toughness properties, and environmental induced corrosion cracking in an interference fit fastener installation.

In Reference 2 the effect of a time-temperature exposure on the mechanical properties was examined. This experience with titanium 6Al-2Sn-4Zr-6Mo indicated that with some time-temperature exposures there was a reduction in toughness with no change in strength. These findings made it desirable to determine the effect of a prolonged thermal cycle on the mechanical properties of titanium alloy 6Al-4V.

Interference-fit fasteners have had remarkable success in retarding crack initiation and growth in fastener holes and consequently are in wide-spread use throughout the aircraft industry. However, the corrosion properties of such fastener installations have not received extensive evaluation.

SECTION II

MATERIALS AND SPECIMENS

Four forgings of Ti-6Al-4V were purchased from the Wyman-Gordon Company. The test material was prepared by conventional forging technique. The forgings have two sections: a thin section (0.5 inch) and a thick section (2.3 inches). See Figure 1. The forgings were produced in accordance with MIL-T-9047E and were annealed at 1300°F for two hours in accordance with MIL-L-81200A. The chemical composition of the material is as follows:

Chemical Composition (Weight %)

C	Fe	O_2	H_2	N	V	Al	Ti
0.026	0.13	0.140	0.0062	0.015	4.20	6.40	Bal.

The chemical composition is in variance with MIL-T-9047E with respect to the aluminum content being below 6.50 per cent by weight. The MIL SPEC calls for the aluminum to be in the range of 6.50 to 6.75.

The interface fit fasteners used in the stress corrosion work were Taper-Lok® fasteners provided by Briles Manufacturing Company, who also did the hole preparation for the fasteners. The sample configuration for the interference fit fasteners is shown in Figure 2.

The specimen configuration used for tensile testing is shown in Figure 3. The compact tension fracture toughness specimens were machined to the configuration shown in Figure 4. The 3/4-inch size was used for the specimens taken from the thick section and the 1/2-inch size was employed for the specimens prepared from the thin section. The compact tension specimens utilized in the crack growth work were the same as the 3/4-inch size compact tension specimen in Figure 4. The contoured double cantilever beam specimen used for the cyclic crack growth work is shown in Figure 5.

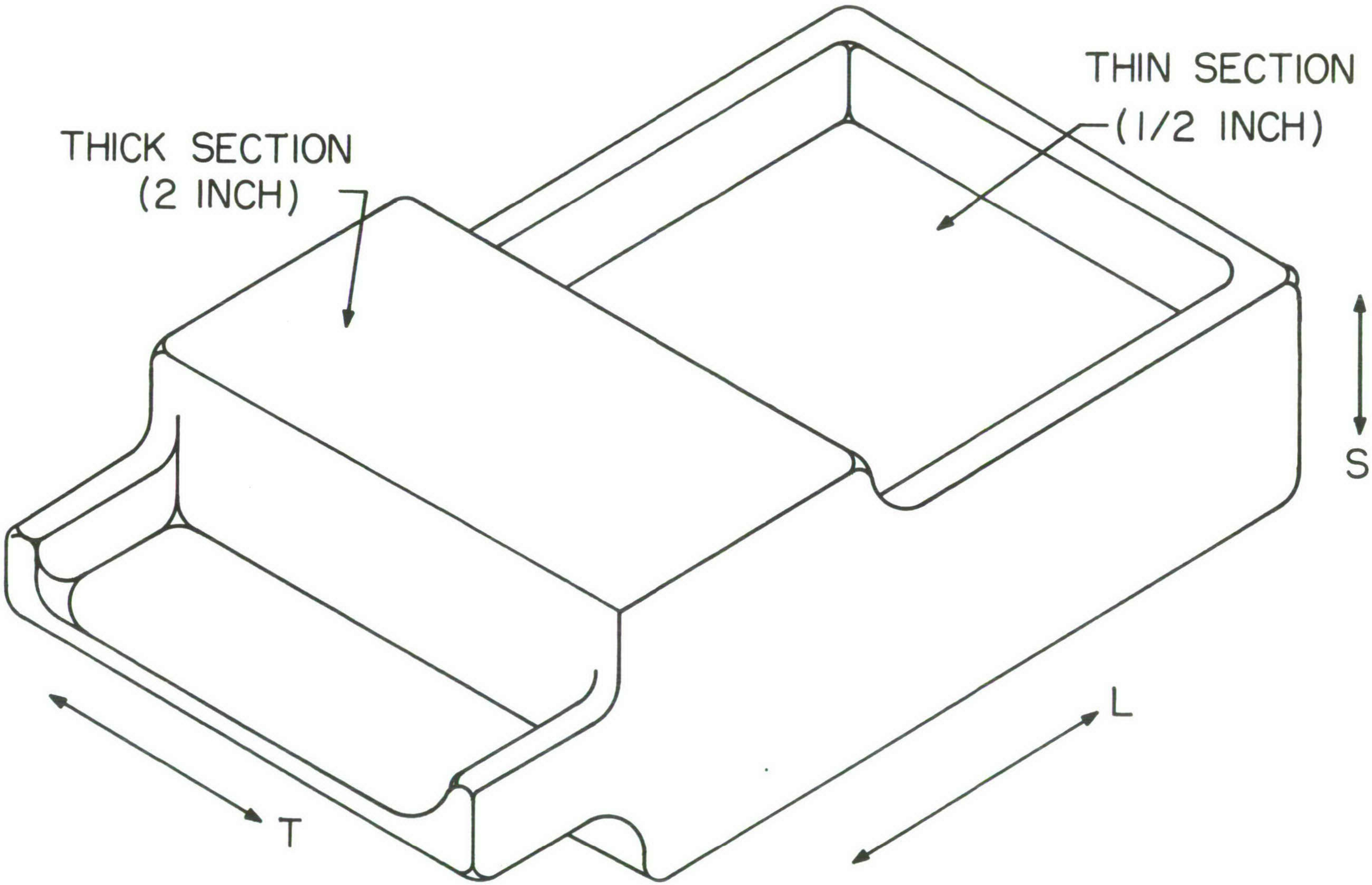


Figure 1. Forging Configuration.

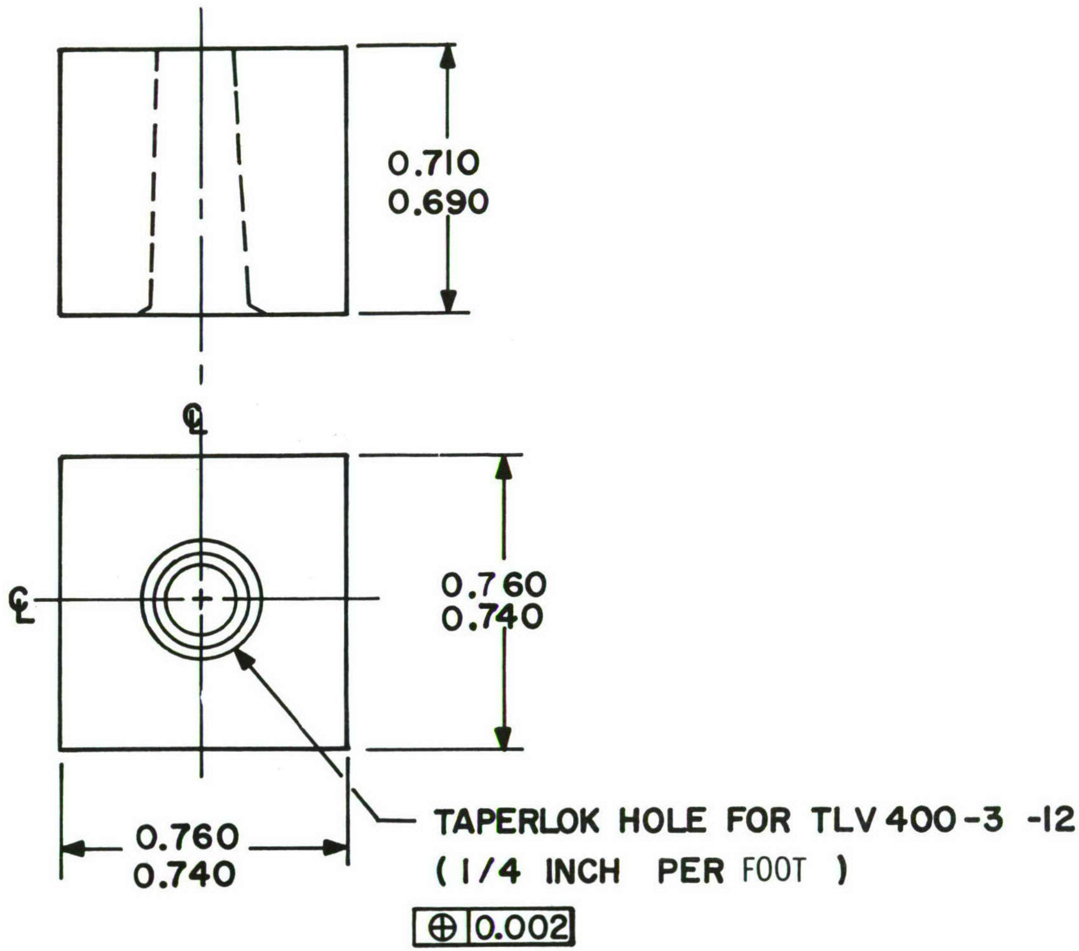


Figure 2. Taper Lok Specimen.

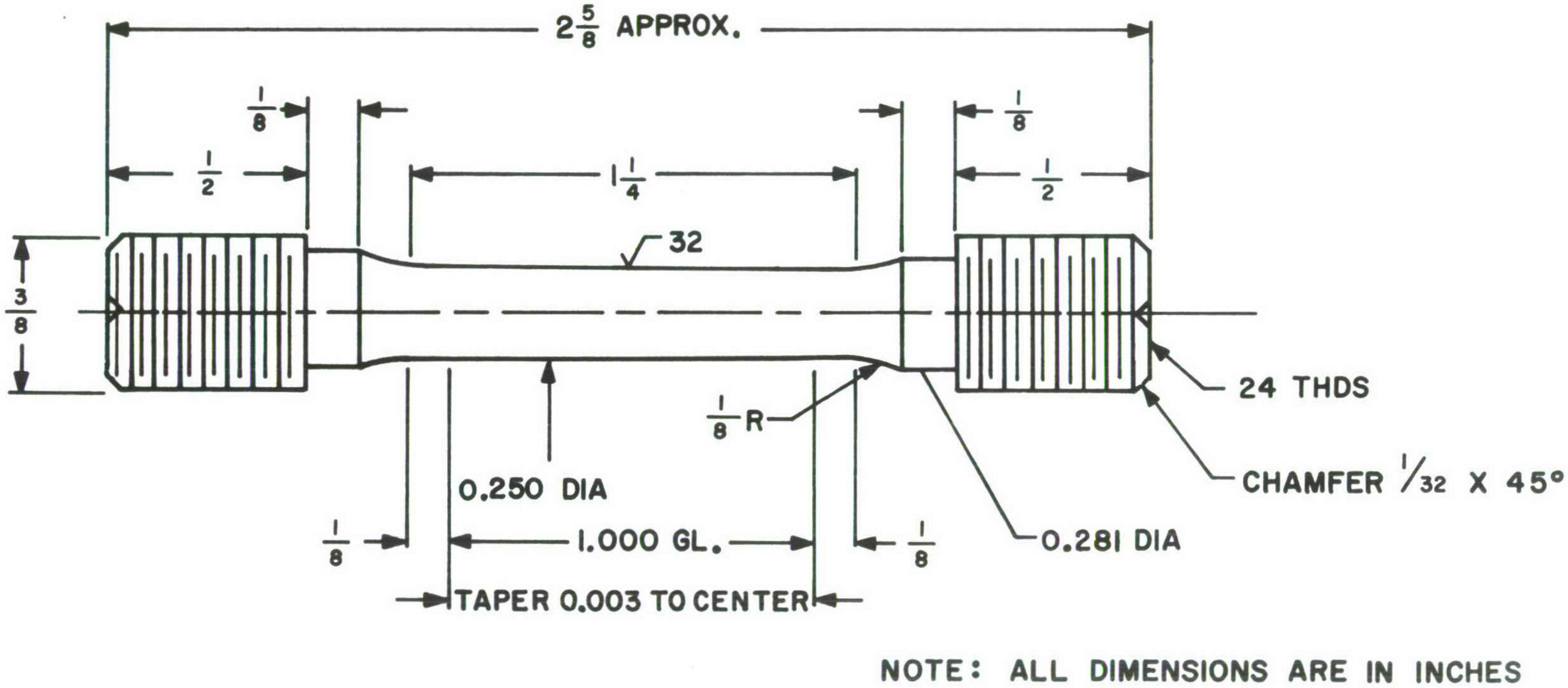
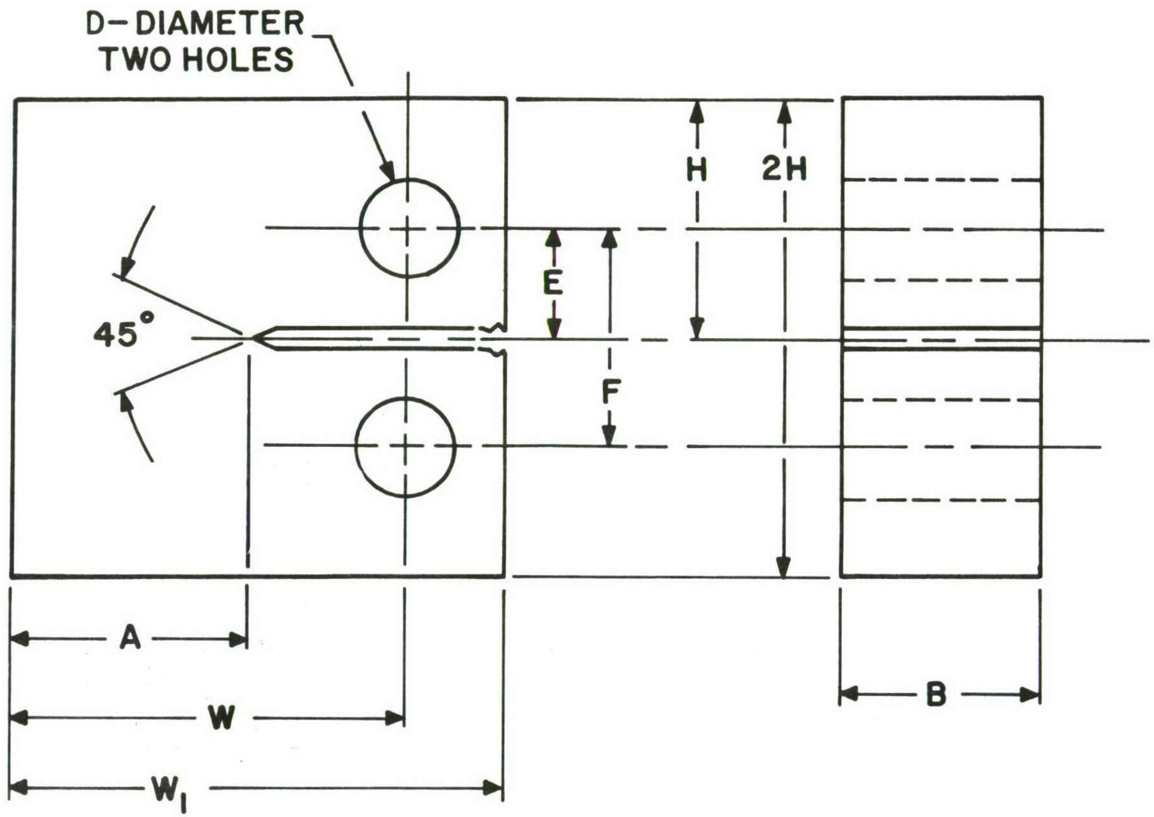


Figure 3. Tensile Specimen.



SPECIMEN SIZE	B	A	W	W_1	S	E	F	H	D
3/4	0.750	0.915	1.500	1.875	0.625	0.413	0.825	0.900	0.375
1/2	0.500	0.610	1.000	1.250	0.625	0.275	0.550	0.60	0.250

Figure 4. Fracture Toughness Specimen.

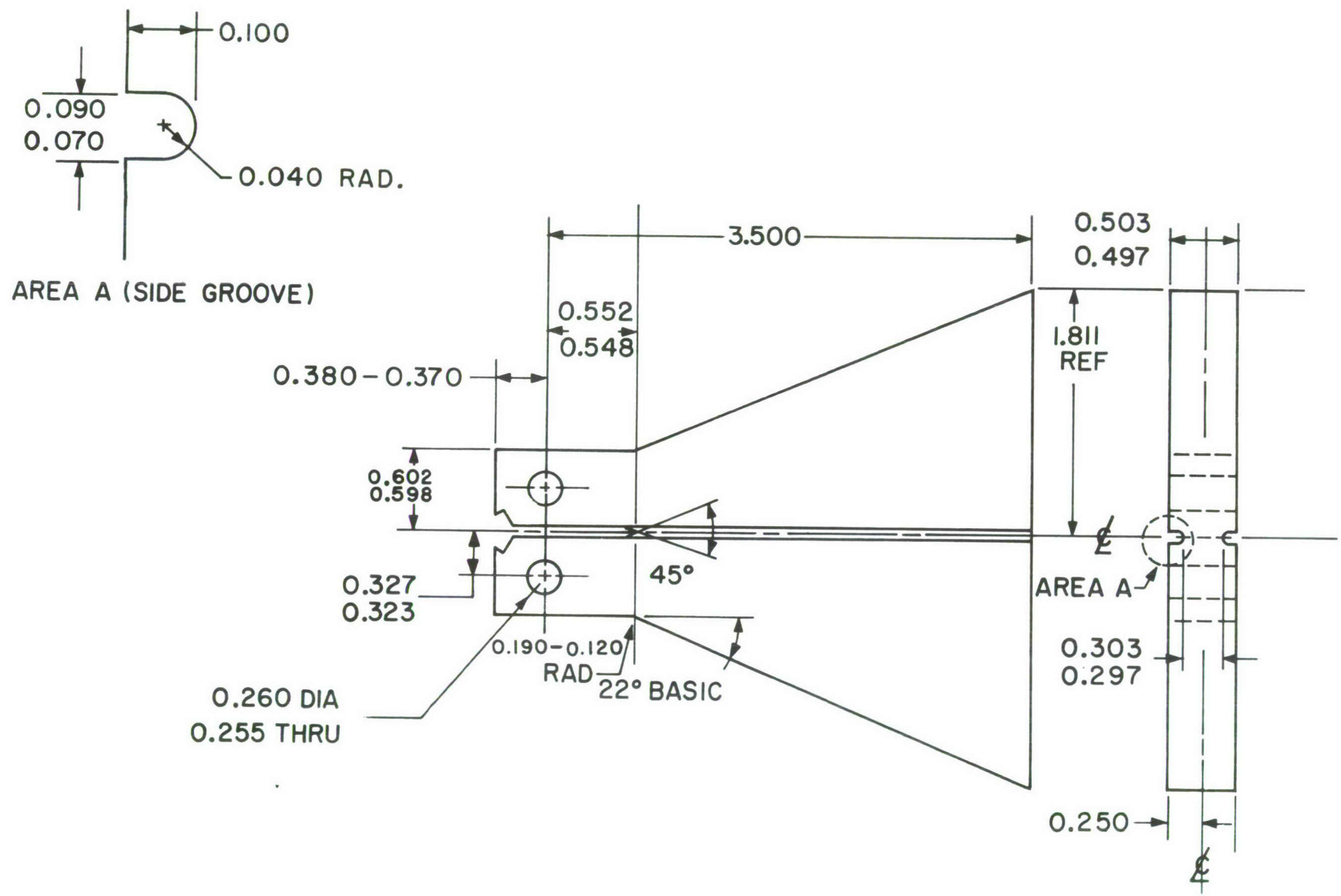


Figure 5. Double Cantilever Beam Specimen.

SECTION III

TEST PROGRAM

The test program was divided into four parts: (1) tensile testing, (2) plane strain fracture toughness (K_{IC}) testing, (3) cyclic crack growth testing (da/dn vs. ΔK), and (4) stress corrosion testing of interference fit fastener installations. Tensile data were generated from the thin and thick section areas in the forgings at temperatures of -65°F, room temperature, and 200°F. The specimens from the thick section were removed from the longitudinal, transverse, and short transverse directions. Tensile tests from the thin section were from the longitudinal direction only.

The effect of a time-temperature exposure on the tensile strength was determined by exposing specimens to temperatures of 600°F and 800°F for 1000 hours before testing at room temperature. These specimens were made from the thin section of the forging.

Thick section fracture toughness properties were obtained at -65°F, room temperature, and 200°F in four orientations: longitudinal (LT), transverse (TL), and short transverse (with SL and ST crack orientations). Thin section specimens were taken from the longitudinal orientation (LT) and tested at room temperature and 200°F. The effect of a time-temperature exposure on the fracture toughness was explored by exposing compact tension specimens taken from the thin section of the forging to 600°F and 800°F for 1000 hours before precracking and testing at room temperature.

Constant amplitude fatigue crack growth rate tests were performed on specimens with longitudinal (LT) orientation. Two types of specimens were prepared for these tests. A tapered double cantilever beam specimen was employed for testing the material as it was supplied by the manufacturer. Since the double cantilever beam specimens were too large to fit in the available furnaces, compact tension specimens were used to check the effect of a time-temperature exposure on the fatigue crack growth rate; these specimens were exposed to 800°F for 1000 hours before being tested at room temperature.

Stress corrosion cracking testing was done on small samples of the forging with Ti-6Al-4V interference fit fasteners installed in accordance with the manufacturer's recommended procedure. The environments that were investigated were distilled water, saltwater, JP-4 fuel, and trichloroethane.

SECTION IV

TEST EQUIPMENT AND PROCEDURE

The tensile tests were performed in a 50,000 lb. Wiedeman tensile testing machine in accordance with the technique recommended by ASTM.

The Wiedeman tensile machine was also used for the fracture toughness testing. Precracking was accomplished on an Amsler fatigue machine. The test procedures adherend to ASTM recommendations (Reference 3). A Conrad Missimer Environmental Chamber was used for the 200°F and -65°F tensile and fracture toughness testing.

All dynamic crack growth testing was accomplished on an MTS servocontrolled hydraulic machine. The load was cycled at 600 cycles per minute. A contoured double cantilever beam (DCB) specimen was used for some of the cyclic crack growth testing. The stress intensity for the DCB specimen is:

$$K_I - P \sqrt{\frac{E(dc/da)}{2b_n(1-u^2)}}$$

where:

P = load
E = modulus of elasticity
dc/da = change in compliance per change in crack length
b_n = material thickness in the notch
u = Poisson's ratio

A compliance calibration was performed on two DCB specimens to establish the coefficient (dc/da).

The calibration was accomplished as follows. Specimens with a known crack length were load cycled. Using a clip on strain gage the load vs. crack opening displacement was recorded on an x-y recorder. After a given number of cycles the operation was repeated for successively larger crack lengths. The crack length was monitored with a 30x travel microscope. For the DCB specimen used in this program, the change in compliance with a change in crack length was determined to be $dc/da = 1.02 \times 10^{-5}$ (in/lb)/in.

Taper-Lok® fasteners were first installed into the specimen thumb tight while immersed in the adverse liquid environments examined in this program. They were then secured in the test material by pulling the fastener into the samples with an Instron tensile machine. A dial indicator was used to determine the distance the fasteners were pulled into the samples. These data were then used to determine the extent of the interference fit in the installation. The manufacturer's installation recommendations were followed (Reference 4).

SECTION V

RESULTS AND ANALYSIS

Individual tensile test results are presented in Table I and average tensile values are presented in Table II. The specimen orientation listed in these tables correspond to those shown in Figure 1 and do not necessarily refer to the localized grain orientation in the forgings. The tensile properties of the three different orientations of the thick section of the forgings are about equal and about the same as those found in Reference 1 for similar Ti-6Al-4V material in the same thickness. See Table III. The test specimens taken from the thin section of the forging have slightly higher tensile properties than the specimens taken from the thick section of the forging, but approximately the same strength as that reported in Reference 5 for material of similar thickness. The longitudinal tensile strength varied from 152.7 to 130.0 KSI over the temperature range of $-65^{o}F$ to $200^{o}F$. See Figure 6. The time-temperature exposure appeared to cause a slight increase in the ultimate strength (7.8 per cent) without sacrificing any ductility. There is more scatter in the tensile data than is normally found in a homogeneous product form. However, this is common in forgings. See Reference 1.

The results of the fracture toughness testing are reported in Table IV, with average values shown in Table V. For both the thin and thick sections, the reference material (see Table III) had similar toughness to the test material. The short transverse orientations (SL) taken from the thick section displayed noticeably higher toughness than the longitudinal (LT) or transverse (TL) orientation specimens for the assumed coordinate system. The specimens taken from the thin section had lower toughness than the specimens taken from the thick section of the forging. This of course is understandable in light of the previously observed difference in strength level discussed above and the well known inverse relationship between strength and toughness. As with the tensile data, there is appreciable scatter in the fracture toughness test results for duplicate tests. The ten per cent variation in toughness is not uncommon in forgings and extrusions. Similar variations are reported in Reference 6.

An increase in test temperature from $-65^{o}F$ to $200^{o}F$ resulted in an increase in plane strain fracture toughness, K_{IC}, from 48 KSI $\sqrt{IN}$ to 67 KSI $\sqrt{IN}$ (see Figure 6). It can also be observed from Table V that the time-temperature exposure had little effect on the fracture toughness of the material. The K_{IC} data scatter band for the exposed specimen overlaps the scatter band of the unexposed specimens. See Table IV.

The fatigue crack growth test results are presented in Figures 7 and 8. The time-temperature exposure slightly reduced the resistance to crack growth (see Figure 7). The crack growth resistance of the unexposed material is slightly better than that reported for plate material in Reference 5 (see Figure 8).

There was no corrosion cracking failures in the Taper-Lok® fastener installation. The installations were disassembled to visually examine the fastener and hole interface surfaces approximately two thousand hours after installation. There was no evidence of corrosion in any of the specimens or fastener surfaces caused by the environments: distilled water, salt water, JP-4 fuel, and trichloroethane.

TABLE I

TENSILE PROPERTIES OF Ti-6Al-4V FORGING

Specimen No.	Thickness (in.)	Orientation *	Test Temperature (°F)	Yield Strength (KSI)	Ultimate Strength (KSI)	Elong. (%)	R.A. (%)	Exposure
L4	2.3	L	RT	133.2	142.4	12.8	43	None
L5	2.3	L	RT	128.2	137.9	15.3	44	None
L6	2.3	L	RT	125.2	135.1	14.0	42	None
T4	2.3	T	RT	136.5	144.7	16.7	42	None
T5	2.3	T	RT	131.3	141.8	15.4	42	None
T6	2.3	T	RT	129.4	139.9	16.8	41	None
S4	2.3	ST	RT	132.9	142.4	15.0	45	None
S5	2.3	ST	RT	127.7	139.5	13.8	32	None
S6	2.3	ST	RT	124.0	137.2	12.2	41	None
L13	0.5	L	RT	138.8	147.2	15.3	42	None
L14	0.5	L	RT	136.6	144.7	14.8	43	None
L15	0.5	L	RT	137.5	145.4	15.0	37	None
L2	2.3	L	-65	146.8	153.3	15.9	37	None
L3	2.3	L	-65	142.8	152.0	14.7	45	None
T1	2.3	T	-65	156.5	163.2	10.0	37.2	None
T2	2.3	T	-65	154.3	162.0	13.0	38	None
T3	2.3	T	-65	142.2	149.7	11.3	34	None
S1	2.3	ST	-65	149.5	156.6	6.3	19.2	None
S2	2.3	ST	-65	144.7	154.3	10.2	28.2	None
S3	2.3	ST	-65	143.0	154.6	10.8	35.4	None
L10	0.5	L	-65	-----	162.0	13.7	39.9	None
L11	0.5	L	-65	154.0	161.7	13.4	40.2	None
L12	0.5	L	-65	157.2	164.2	11.6	32.0	None
L18	0.5	L	-65	156.1	164.8	11.6	31.4	None
L7	2.3	L	200	-----	132.5	18.0	52.4	None
L8	2.3	L	200	117.0	128.0	16.5	52.0	None
L9	2.3	L	200	118.2	129.6	18.3	52.4	None

TABLE I (concluded)

TENSILE PROPERTIES OF Ti-6Al-4V FORGING

Specimen No.	Thickness (in.)	Orientation *	Test Temperature (^{o}F)	Yield Strength KSI	Ultimate Strength (KSI)	Elong. (%)	R.A. (%)	Exposure
T7	2.3	T	200	-----	131.9	16.5	49.3	None
T8	2.3	T	200	-----	125.8	15.0	46.0	None
T9	2.3	T	200	121.1	131.9	16.9	50.3	None
S7	2.3	ST	200	118.0	129.2	18.8	58.4	None
S8	2.3	ST	200	111.7	127.7	15.4	36.6	None
S9	2.3	ST	200	110.4	126.0	15.9	42.8	None
L16	0.5	L	200	124.2	133.6	16.2	52.6	None
L17	0.5	L	200	122.0	133.1	16.2	52.8	None
L22	0.5	L	RT	137.7	148.0	14.8	38.7	$600^{o}F$ - 1000 hrs.
L23	0.5	L	RT	136.7	146.6	13.3	39.8	$600^{o}F$ - 1000 hrs.
L24	0.5	L	RT	137.0	147.5	14.2	40.6	$600^{o}F$ - 1000 hrs.
L19	0.5	L	RT	143.0	149.8	14.6	39.7	$800^{o}F$ - 1000 hrs.
L20	0.5	L	RT	142.0	149.3	14.3	38.7	$800^{o}F$ - 1000 hrs.
L21	0.5	L	RT	141.8	148.7	15.3	36.9	$800^{o}F$ - 1000 hrs.

*See Figure 1

TABLE II

AVERAGE TENSILE PROPERTIES OF Ti-6Al-4V FORGING

Forging Thickness (in.)	Orientation *	Test Temperature (°F)	Yield Strength (KSI)	Ultimate Strength (KSI)	Elongation (%)	R.A. (%)	Exposure
2.3	L	RT	128.9	138.5	14.0	43.0	None
2.3	T	RT	132.4	139.4	16.3	41.7	None
2.3	S	RT	128.2	139.7	13.7	39.3	None
0.5	L	RT	137.6	145.8	15.0	40.7	None
2.3	L	-65	144.8	152.7	15.3	41.0	None
2.3	T	-65	151.0	158.3	11.4	36.4	None
2.3	S	-65	145.7	155.2	9.1	27.6	None
0.5	L	-65	155.7	163.2	12.6	35.9	None
2.3	L	200	117.6	130.0	17.6	52.3	None
2.3	T	200	121.1	129.9	16.1	48.5	None
2.3	S	200	113.4	127.6	16.7	45.9	None
0.5	L	200	123.1	133.4	16.2	52.7	None
0.5	L	RT	137.1	147.4	14.1	39.7	600°F - 1000 hrs.
0.5	L	RT	142.3	149.3	14.7	38.4	800°F - 1000 hrs.

*See Figure 1

TABLE III

Ti-6Al-4V MECHANICAL PROPERTIES

Material	Ultimate Strength (KSI)	Yield Strength (KSI)	K_{IC} KSI $\sqrt{IN}$
Forging (this report) [2.3 in. thick]	138	129	58
Forging (Reference 1) [2 1/2 in. thick]	140	133	49
Forging (this report) [1/2 inch thick]	146	138	48
Plate (Reference 5) [1/2 inch thick]	147	142	38

TABLE IV

FRACTURE TOUGHNESS PROPERTIES OF Ti-6Al-4V FORGINGS

Specimen	Specimen Orientation	Forging Thickness (in.)	Test Temperature (°F)	K_{IC} (KSI$\sqrt{IN}$)	Exposure
LW4	Long. (LT)	2.3	R.T.	57.6	None
LW5	Long. (LT)	2.3	R.T.	57.2	None
LW6	Long. (LT)	2.3	R.T.	59.4	None
WL4	Trans. (TL)	2.3	R.T.	65.2	None
WL5	Trans. (TL)	2.3	R.T.	62.1	None
WL6	Trans. (TL)	2.3	R.T.	59.2	None
TL4	Sh. Tran. (SL)	2.3	R.T.	67.4	None
TL5	Sh. Tran. (SL)	2.3	R.T.	7212	None
TL6	Sh. Tran. (SL)	2.3	R.T.	68.8	None
TW4	Sh. Tran. (ST)	2.3	R.T.	59.0	None
TW5	Sh. Tran. (ST)	2.3	R.T.	58.4	None
TW6	Sh. Tran. (ST)	2.3	R.T.	56.9	None
LW15	Long. (LT)	0.5	R.T.	52.4	None
LW16	Long. (LT)	0.5	R.T.	43.9	None
LW17	Long. (LT)	0.5	R.T.	47.8	None
LW20	Long. (LT)	0.5	R.T.	41.5	None
LW21	Long. (LT)	0.5	R.T.	53.1	None
LW10	Long. (LT)	0.5	R.T.	54.6	800°F for 1000 hrs.
LW11	Long. (LT)	0.5	R.T.	46.9	800°F for 1000 hrs.
LW12	Long. (LT)	0.5	R.T.	52.1	800°F for 1000 hrs.
LW14	Long. (LT)	0.5	R.T.	52.1	600°F for 1000 hrs.
LW2	Long. (LT)	2.3	-65	65.1	None
LW3	Long. (LT)	2.3	-65	48.4	None
WL1	Trans. (TL)	2.3	-65	50.4	None
WL2	Trans. (TL)	2.3	-65	70.9	None
WL3	Trans. (TL)	2.3	-65	52.2	None
TL1	Sh. Tran. (SL)	2.3	-65	59.7	None
TL2	Sh. Tran. (SL)	2.3	-65	58.3	None
TL3	Sh. Tran. (SL)	2.3	-65	55.0	None
TW1	Sh. Tran. (ST)	2.3	-65	49.0	None
TW2	Sh. Tran. (ST)	2.3	-65	56.6	None
TW3	Sh. Tran. (ST)	2.3	-65	65.0	None

Table IV (concluded)

FRACTURE TOUGHNESS PROPERTIES OF Ti-6Al-4V FORGINGS

Specimen	Specimen Orientation	Forging Thickness (in.)	Test Temperature (°F)	K_{IC} (KSI$\sqrt{IN}$)	Exposure
LW7	Long. (LT)	2.3	200	65.8	None
LW8	Long. (LT)	2.3	200	81.7	None
LW9	Long. (LT)	2.3	200	67.9	None
WL7	Trans. (TL)	2.3	200	75.5	None
WL8	Trans. (TL)	2.3	200	79.0	None
WL9	Trans. (TL)	2.3	200	67.6	None
TL7	Sh. Tran. (SL)	2.3	200	78.1	None
TL8	Sh. Tran. (SL)	2.3	200	80.1	None
TL9	Sh. Tran. (SL)	2.3	200	75.5	None
TW7	Sh. Tran. (ST)	2.3	200	75.4	None
TW8	Sh. Tran. (ST)	2.3	200	69.2	None
TW9	Sh. Tran. (ST)	2.3	200	68.4	None
LW23	Long. (LT)	0.5	200	58.9	None

TABLE V

AVERAGE FRACTURE TOUGHNESS PROPERTIES OF

Ti-6Al-4V FORGING

Forging Thickness (in)	Specimen Orientation *	Test Temperature (°F)	K_{IC} (KSI$\sqrt{IN}$)	Exposure
2.3	LT	R.T.	58.1	None
2.3	TL	R.T.	62.2	None
2.3	SL	R.T.	69.5	None
2.3	SL	R.T.	58.1	None
0.5	LT	R.T.	47.7	None
0.5	LT	R.T.	51.2	800°F for 1000 hrs.
0.5	LT	R.T.	52.1	600°F for 1000 hrs.
2.3	LT	-65	56.8	None
2.3	TL	-65	57.8	None
2.3	SL	-65	57.8	None
2.3	ST	-65	56.9	None
2.3	LT	200	71.8	None
2.3	TL	200	74.0	None
2.3	SL	200	77.9	None
2.3	ST	200	71.0	None
0.5	LT	200	58.9	None

* See Figure 1

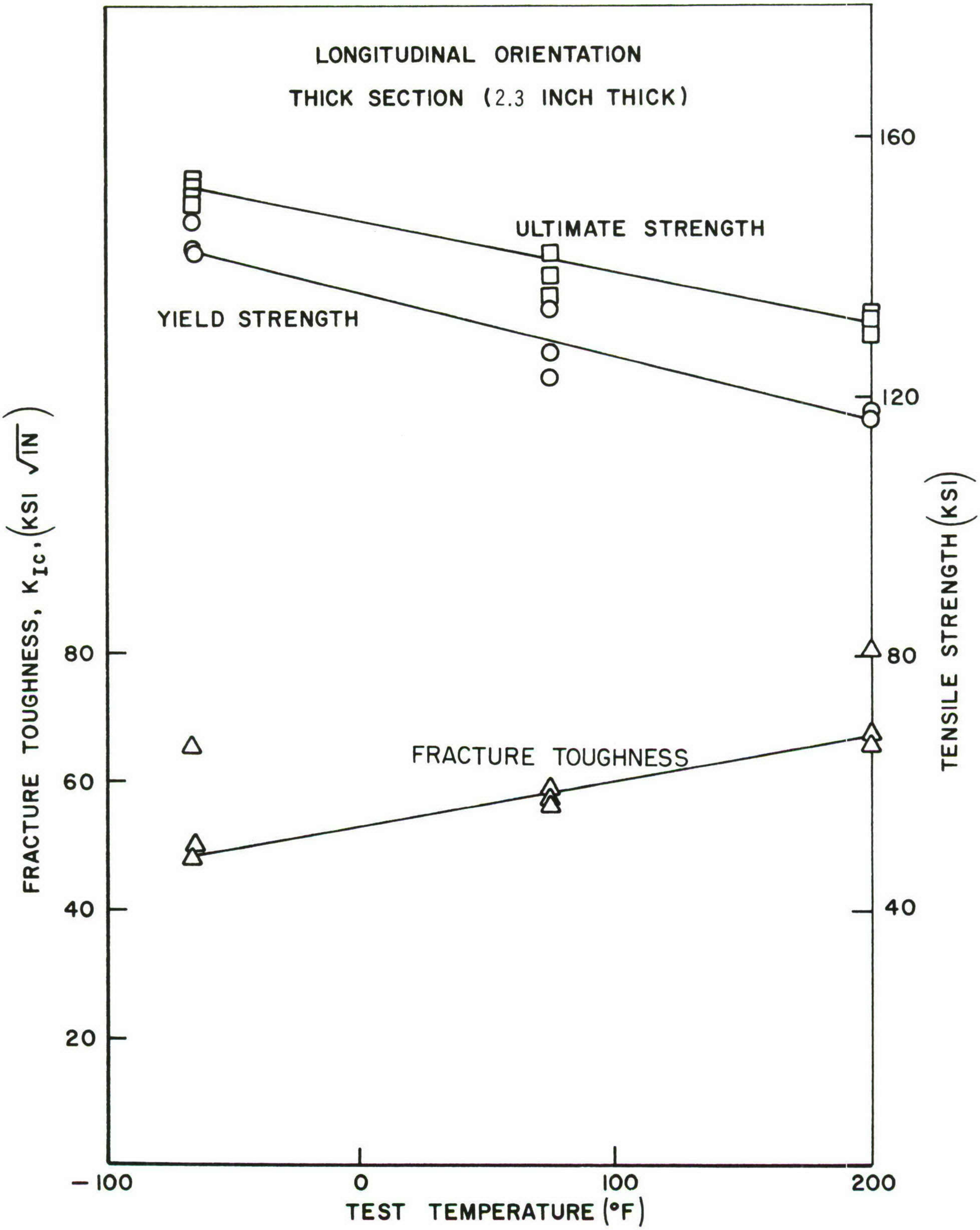


Figure 6. Ti-6Al-4V Forging Mechanical Properties variation with temperature.

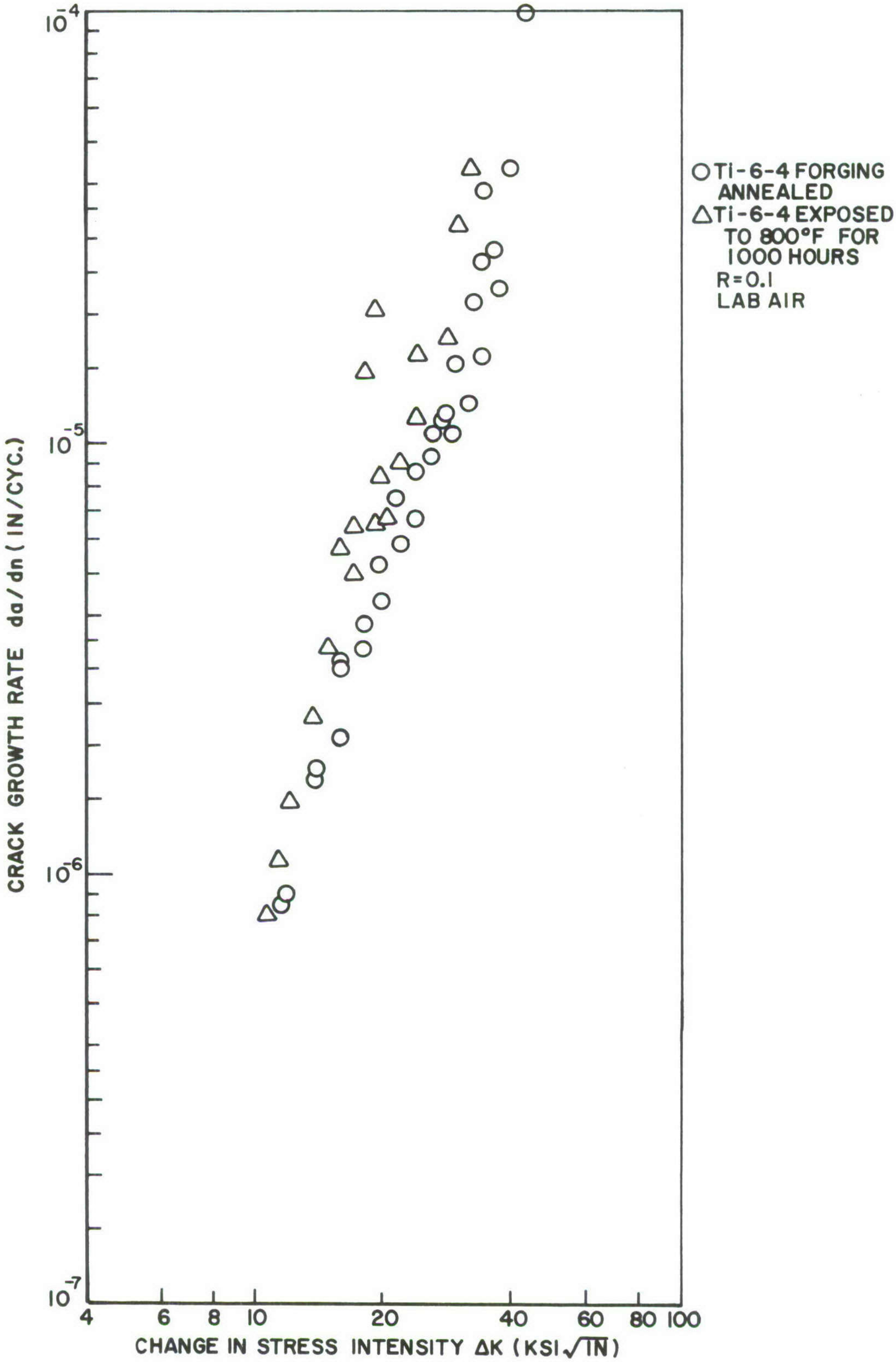


Figure 7. Crack Growth Rates of Ti-6Al-4V Forging.

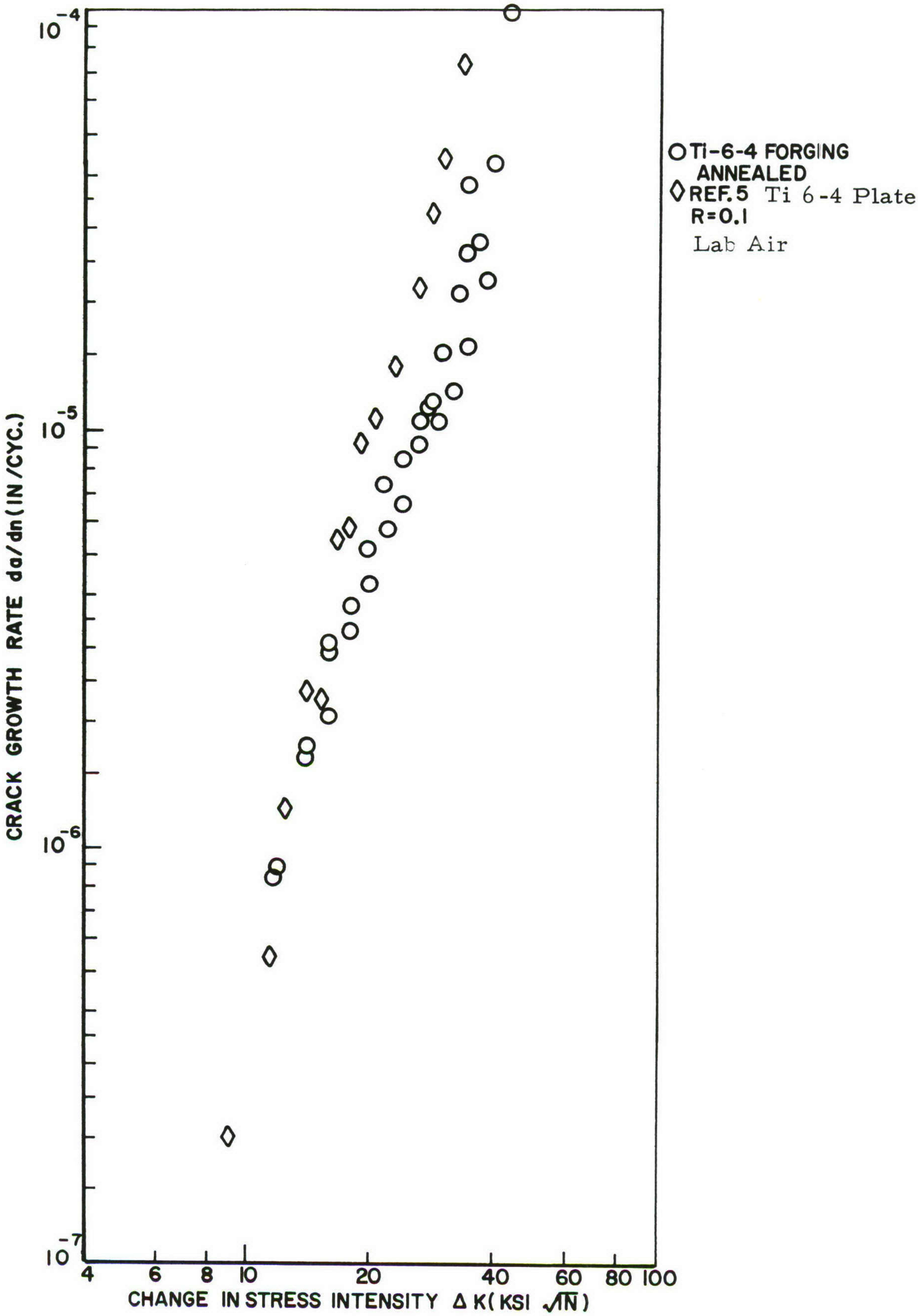


Figure 8. Crack Growth Rates of Ti-6Al-4V Forging and Plate (Reference 5).

SECTION VI

SUMMARY

In general, the test material was directly comparable in strength and in toughness with the reference data found on the same alloy. There was more scatter in the tensile and toughness test results than is normally found in a homogeneous plate material but not an uncommon amount for a forging or extrusion product form. The toughness of the assumed short transverse orientation was higher than the other two orientations. Toughness did not vary appreciably with the time-temperature exposures incorporated in this program.

The fatigue crack growth rate increased slightly following the material's exposure to a high temperature environment (800°F) for 1000 hours.

The test material did not appear to be corrosion sensitive to the environment and test conditions incorporated in this test program. Test environments employed in this investigation were: distilled water, salt water, JP-4 fuel, and trichloroethane.

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13. ABSTRACT

Tests were conducted to determine the mechanical properties of titanium 6Al-4V annealed forgings. Tensile, fracture toughness, and constant amplitude cyclic crack growth properties were obtained along with limited corrosion studies of fastener installations. The tensile properties were determined for three orientations and the fracture toughness properties for four orientations. Some of the tensile and fracture toughness specimens were subjected to a time-temperature exposure before being tested at room temperature. The mechanical properties of the annealed material were similar to those in the literature. The time-temperature exposure cycle slightly altered the mechanical properties of the material. The corrosion tests conducted on the fastener installations did not produce any cracking in the material under the test conditions.

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