NUCLEAR DIVISION

Report No. RN-S-0461

PLANE STRAIN FRACTURE TOUGHNESS, AND
FATIGUE TESTS OF A LARGE Ti-5 Al-2.5 SN ELI (GRADE)
FORGING IN LIQUID HYDROGEN

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NERVA Program

Contract SNP-1

April 1968

NUCLEAR ROCKET OPERATIONS

MASTER

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA

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AEROJET - GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

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FORGING IN LIQUID HYDROGEN

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ABSTRACT

A series of tests was carried out on a large titanium forging to determine the suitability of the material for use in rotating machinery at cryogenic operating temperatures. The radial and tangential tensile properties of the forging were found to be satisfactory on the basis of -423°F notched (K_T 5-6) to unnotched tensile strength ratios in excess of 1.00 and tensile elongations in excess of 8%. Part-through-precracked tensile fracture toughness testing at -423°F resulted in K_{Ic} values in excess of 71 ksi - in^{1/2}. Axial fatigue testing in liquid hydrogen at -423°F produced close to expected results at the low load ratio (A) but less than the expected results at higher load ratios. This condition was attributed to the adverse effect of coarse grain size.

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I. INTRODUCTION

A 20-in.-diameter by 13-in.-high forging was evaluated relative to its suitability as a high-speed rotating component in a liquid hydrogen turbopump.

Plane strain fracture toughness, K_{Ic} , tensile properties, and axial fatigue in liquid hydrogen were determined.

II. CONCLUSIONS

1. The selection of Ti-5 Al-2.5 SN ELI for high-speed, cryogenic-pump applications was supported by the tensile, fatigue, and fracture-toughness data.

2. Tensile tests at -423°F resulted in anisotropic tensile strengths and ductility in excess of 8%. Notched-unnotched tensile ratios were in excess of 1.00 in both portions of the forging tested and part-through-cracked tensile fracture toughness tests resulted in K_{Ic} in excess of $71 \text{ ksi-in}^{1/2}$.

3. Axial fatigue tests at -423°F resulted in 10^6 cycle endurance of $127 \pm 25.5 \text{ ksi}$ at load ratio A of 0.20 and $46.5 \pm 44.5 \text{ ksi}$ at load ratio A of 0.95. The latter value was lower than expected due to the coarse grain of the material. This value can probably be increased with improved grain-size control during the forging process. These results were considered adequate justification for use of this material in critical rotating applications. However, control of the forging and heat-treating processes are required to achieve an optimum grain structure.

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III. TECHNICAL DISCUSSION

A. BACKGROUND INFORMATION

The forging, AGC P/N 289997, was press forged from a 16-in. in dia by 32-in.-long billet supplied by Titanium Metals Corp. of America. The billet was reduced approximately 50% in length by press forging in two heating cycles at 1850°F. The final forged dimensions were 22-in. in dia by 16 1/2-in. in height. Rough machining reduced the part to 20-in. in dia by 13 in. in height. Chemical analysis of the forging is presented in Table 1.

B. TENSILE TESTING

1. Top Section

The part was originally procured for application in the M-1 liquid-hydrogen turbopump development program. A single-stage centrifugal fuel (LH₂) impeller/inducer approximately 10 in. in height was to have been fabricated from the forging. Consequently, only the top three inches of the forging was available for 40°R property tests in support of this application. A total of 19 specimens was machined from the top 3-in.-thick slice. Tensile tests were made to test the radial and tangential properties at 80°F and -423°F. The results presented in Table 2 show good F_{tn}/F_{tu} ratios of 1.4 and 1.2 at 80°F and -423°F, respectively, and average elongations greater than 8%.

2. Center Section

The preceding test specimens described were removed from the top 2.5-in. slice designated MI on Figure 1. In addition, 20 radial fatigue specimens that were fabricated as shown in Figure 2, were removed from this area of the forging.

TABLE 1
CHEMISTRY OF TITANIUM FORGING

<u>Element</u>	<u>Forging, wt%</u>	<u>Recommended, wt%</u>
O ₂	0.086	0.12 max
H ₂	0.002	0.0125 max
C	0.063	0.05 max
Fe	0.080	0.25 max
N ₂	0.047	0.04 max
Al	4.9	4.75/5.75
Sn	2.6	2.2/2.8
Mn, V, Mo, Cr	<0.010 each	0.05 max each

TABLE 2

TENSILE PROPERTIES OF Ti-5 Al-2.5 Sn (ELI) FORGING AT 80°F AND -423°F*

<u>80°F Test Temperature</u>						
<u>Direction</u>	<u>F_{tu}, ksi</u>	<u>F_{ty}, ksi</u>	<u>Elong % in 4D</u>	<u>R.A., %</u>	<u>F_{tn}/K_t=5.4</u>	<u>F_{tn}/F_{tu}</u>
Radial	109.4	102.1	11.5	22.0	151.3	--
Radial	111.2	105.6	13.0	17.6	148.5	--
Radial	_____	_____	_____	_____	<u>152.9</u>	
Average	110.3	103.9	12.3	19.8	150.9	1.37
Tangential	103.5	97.3	11.0	28.4	147.8	--
Tangential	106.6	98.4	12.5	29.3	146.9	--
Tangential	_____	_____	_____	_____	<u>157.2</u>	
Average	105.1	97.9	11.8	28.9	150.6	1.43
<u>-423°F Test Temperature</u>						
Radial	198.0	173.8	8.0	14.5	235.5	--
Radial	200.0	175.9	10.0	16.0	239.5	--
Radial	_____	_____	_____	_____	<u>231.5</u>	
Average	199.0	174.9	9.0	15.8	235.5	1.18
Tangential	196.0	175.8	6.0	14.1	224.0	--
Tangential	200.5	171.5	10.5	16.8	239.8	--
Average	_____	_____	_____	_____	_____	
	198.3	173.7	8.3	15.5	231.9	1.17

*R-3 specimens Fed. Test Meth. Std 151

Figure 1 - Titanium Forging Section Sequence

Figure 2 - Tension-Compression Fatigue Specimen

Further tests were made to determine if top section properties developed by M-1 were representative of properties in other areas of this large forging. Since properties could be expected to be worst at the center of the forging, a 3-in.-thick section, including the original longitudinal centerline (prior to removal of the MI test section) of the forging, was removed from the part. The forward half of this section in Figure 1, designated Section 2, was used for smooth and notched -423°F tensile tests. The back half, designated Section 5, was used for fracture-toughness testing.

Six smooth R3 tensile specimens and six notched R3 specimens were removed from Section 2 along the mid-radius line to represent the top, center, and bottom areas of the section.

As indicated in Table 3, the center section properties of the forging compared favorably with data obtained from the top slice. The greatest deviations from the data presented in Table 3 pertained to the radial notched tensile strength and notched/unnotched ratio. However, the notched/unnotched ratio was above 1.0 in both test directions at a K_T of 5.1 to 5.7.

Four specimens, fabricated in accordance with Figure 3, were tested at -423°F to test the effect of a very sharp notch ($K_T \sim 17$) on the notched/unnotched tensile ratio. Results of these four tests were combined with the average smooth tangential tensile strength (Table 3) to determine the notched/unnotched ratio. The ratio dropped from 1.21 (average) to 0.749 (average), indicating a moderate increase in the material's sensitivity of the material under high stress concentration. Data are presented in Table 4.

TABLE 3
TENSILE PROPERTIES OF Ti-5 Al-2.5 Sn (ELI) FORGING AT -423°F

Direction/ Location**	<u>Center Section</u>						
	F_{tu} , ksi	F_{ty} , ksi	Elong, % in 4D	R.A., %	F_{tn}	F_{tn}/F_{tu}	K_t
Radial-Top	203.2	173.0	14.0	14.5	226.4	1.12	5.2
Radial-Center	198.0	169.3	8.5	17.4	215.8	1.09	5.7
Radial-Bottom	187.9	170.2	4.0*	7.7*	188.7	1.00	5.1
Average	196.3	170.8	11.2	15.9	210.3	1.07	
σ	7.8	1.9	--	--	19.4	0.06	
Tangential-Top	182.6	167.7	7.0	19.6	234.6	1.28	5.7
Tangential-Center	181.8	170.1	6.0	16.2	220.6	1.21	5.2
Tangential-Bottom	196.1	174.2	11.5	18.0	226.8	1.15	5.1
Average	186.8	170.6	8.1	17.9	227.3	1.21	
σ	7.3	3.3	2.9	7.6	7.2	0.065	

* Failed outside gage marks.

** See Figure 1

Figure 3 - Notched Tensile Specimen with $K_T \sim 17$

TABLE 4
 LH₂ NOTCHED-TENSILE PROPERTIES, $K_T \sim 17$, of Ti-5 Al-2.5 Sn (ELI)
 FORGING, CENTER SECTION

<u>Direction</u>	<u>F_{tu}, ksi</u>	<u>F_{tn}/F_{tu} *</u>	<u>K_t</u>
Tangential	135.2	0.724	15.5
Tangential	141.8	0.759	17.4
Tangential	130.3	0.698	17.5
Tangential	152.8	0.818	17.5
Average	140.0	0.749	--
σ	9.7	0.052	--

* Based on average tangential tensile strength of 186.8 ksi, Table 3.

C. FRACTURE TOUGHNESS TESTING

1. Specimen Design

The part-through-crack (PTC) tensile specimen shown in Figure 4 was used to determine the plane strain (K_{Ic}) fracture toughness of the Ti-5 Al-2.5 Sn ELI alloy. This specimen was designed to obtain K_{Ic} data in accordance with ASTM recommended practice, while not exceeding the maximum specimen dimensions permitted by available cryogenic testing facilities. The latter criteria were determined by the cryostat and corresponded to the following:

Maximum specimen length - 11 in.
Maximum specimen width - 3 in.
Maximum load - Approximately 30,000 lb

The following equation was used to determine the approximate test section width (1.1-in.) and thickness (0.2-in.) of the PTC tensile specimen shown in Figure 1.

$$K_{Ic}^2 = 1.21 \pi (a/Q)F^2 \quad \text{Equation (1)}$$

where:

K_{Ic} = Plane strain fracture toughness (ksi-in.^{1/2})
a = The fatigue crack depth (in.)
F = Gross fracture stress (ksi)
Q = Flaw shape parameter obtained from Figure 5 (dimensionless)

In order to obtain valid K_{Ic} values in accordance with previous ASTM recommended fracture testing requirements, the following criteria were met in designing the specimen and during specimen fatigue precracking and testing:

Figure 4 - Part-Through-Crack Tensile Specimen, Ti-5Al-2.5 Sn (ELI Grade)
Material Tested at -423°F

- a. Precrack depth (a) less than 50% of the specimen thickness.
- b. Precrack area less than 10% of the specimen area. For semi-elliptical cracks, the area is $\frac{\pi (a)(2c)}{4}$ where 2c is the crack length.
- c. Gross fracture stress less than the material 0.2% offset yield strength.

In designing the test specimen (Figure 4) for this program, the gross dimensions (overall length and width) were fixed by the cryostat dimensions. Also, it was desirable not to exceed a maximum load of approximately 30,000 lb which, for this material (yield strength = 170.6 ksi), meant the specimen test section should not exceed approximately $(30,000/170,600) \text{ in.}^2$ or 0.175 in.^2 .

The actual specimen net section and precrack configuration was determined using equation (1). This was accomplished by assuming a K_{Ic} value based on data available in the literature, setting the gross fracture stress (F) equivalent to the 0.2% offset yield strength, and solving equation (1) for a/Q. A flaw depth (a)-to-length (2c) ratio is then assumed based on past experience and Figure 5 is used to determine Q at $(\sigma/\sigma_{ys}) = 1$, since the applied fracture stress (σ) = the yield strength (σ_{ys}). With this data, it is possible to calculate the minimum flaw depth (a), flaw length (2c) and flaw area $(\frac{\pi (a)(2c)}{4})$ for valid toughness measurements and determine their conformity with the requirements shown above. Depending on the calculated values, modifications in specimen design can then be made to enable testing of the largest practical specimen, since this approach permits testing of material having high toughness, which may be desirable depending on the accuracy of the assumed toughness values. A sample calculation of this type leading to the actual specimen dimensions shown in Figure 4 is presented below, although several calculations of the type shown were required before the final dimensions were established.

Figure 5 - Flaw-Shape Parameter for Surface and Embedded Flaws

The only available K_{Ic} data (Ref. 1) for the Ti-5 Al-2.5 Sn alloy (which was not ELI grade), at -423°F prior to the tests in this program, indicated a K_{Ic} value of approximately $55 \text{ ksi-in.}^{1/2}$. The tensile properties (-423°F) for the actual material to be tested in this program were reported in Table 3, as follows:

Ultimate strength, tangential	= 186.8 ksi
0.2% offset yield strength	= 170.6 ksi
Elongation in 4D	= 8.1%

Using equation (1), a/Q is calculated as follows, assuming that the gross fracture stress (F) corresponds to the 0.2% offset yield strength.

$$K_{Ic}^2 = 1.21 \pi (a/Q) F^2 \quad \text{Equation (1)}$$

$$(55,000)^2 = 3.8 (a/Q) (170,600)^2$$

$$a/Q = 0.0273 \text{ in.}$$

Assuming $a/2c = 0.3$, which is a reasonable assumption based on previous Aerojet precrack test experience for many different structural metals, and $\sigma/\sigma_{ys} = 1$, from Figure 5, $Q = 1.41$. Therefore $a = 0.039 \text{ in.}$; $2c = 0.13 \text{ in.}$; and the corresponding crack area is

$$\frac{\pi (a)(2c)}{4} = 0.78(0.039) (0.13) = 0.004 \text{ in.}^2$$

Consequently, the minimum specimen cross section for valid tests would be 10 times the crack area or approximately 0.04 in.^2 .

However, the maximum desirable load for the cryostat available for these tests approximated 30,000 lb. Assuming a material yield strength of 170.6 ksi, a specimen with a cross section of approximately 0.178 in.^2 can be tested. Since the larger specimen cross section (with a larger precrack) will

permit valid measurements of higher K_{Ic} values, it was considered desirable to use the maximum cross section permitted by the cryostat. This was particularly true in this program where previous K_{Ic} data were not available for ELI-grade material, which generally gives higher K_{Ic} values compared with material of standard interstitial content.

Consequently, a specimen cross section of 0.2 x 1.1-in.; a flaw depth (a) of 0.075-in. (<50% of the specimen thickness) and a flaw depth/length ratio (a/2c) of 0.3 was assumed. With $F = 170.6$ ksi

$$K_{Ic}^2 = 1.21 \pi (a/Q) F^2$$

$$K_{Ic}^2 = 3.8 \left(\frac{0.075}{1.41} \right) (170.6)^2$$

$$K_{Ic} = 77 \text{ ksi-in.}^{1/2}$$

Assuming $a/2c = 0.3$; $2c = 0.25$ and the crack area = 0.0147 in.^2 . Therefore, with the following specimen parameters it is possible to obtain valid K_{Ic} values as high as $77 \text{ ksi-in.}^{1/2}$

Specimen thickness	=	0.2-in.
Specimen width	=	1.1-in.
Precrack depth	=	0.075-in.
Precrack length	=	0.25-in.

Although the gross load at this toughness level ($77 \text{ ksi-in.}^{1/2}$) slightly exceeds 30,000 lb, it was not considered likely on the basis of available information that the K_{Ic} value would exceed $65 \text{ ksi-in.}^{1/2}$. In this case, the failure load would be below 30,000 lb. However, if an exceptionally high K_{Ic} value was obtained that exceeded the load capability of the cryostat, it would still be possible to reduce the specimen thickness and width if required, even after the specimens had been precracked. Thus, it would not be necessary to

fabricate new specimens to compensate for an exceptionally high level of toughness that is in excess of the value expected on the basis of available fracture toughness (K_{Ic}) data.

2. Specimen Precracking and Testing

The specimens were machined to the configuration shown in Figure 4. Each specimen was then elox machined to produce a part-through-crack starter in the gage area of the specimen. The elox starter notch was semi-elliptical in shape with an initial depth (a_o) of 0.02-in. and an initial length ($2c_o$) of 0.130 in. This notch was then extended in bending fatigue to a depth (a) of approximately 0.075 in. and a length ($2c$) of approximately 0.25 in. The actual values, which were determined by measurements of the specimen fracture faces after testing, are shown in Table 5. The maximum outer fiber stress during fatigue precracking was approximately 50 ksi; the cycling rate was approximately 1200 cps.

Specimen tests were conducted in liquid hydrogen at -423°F . A Baldwin tensile machine was used together with a Cryenco Cryostat. All specimens were loaded at uniform rate of 2500 lb/min (determined using a pacer) until failure occurred. The results obtained are shown in Table 5, together with measurements of the precrack dimensions and the fracture toughness (K_{Ic}) values. Figure 6 shows the fracture faces of the specimens after failure.

3. Fracture-Toughness Calculations and Discussion of Results

The plane-strain fracture-toughness values (K_{Ic}) were calculated using equation (1). The resulting data are shown in Table 5 and are summarized below.

TABLE 5

PLANE STRAIN FRACTURE TOUGHNESS - Ti-5 Al-2.5 Sn (ELI Grade) at -423°F⁽¹⁾

Specimen	Width, in.	Thickness, in.	Load, kips	Gross Stress, ksi	Crack, in.		Flaw Shape		K_{Ic} (ksi-in. ^{1/2})
					Length (2c)	Depth (a)	a/2c	Q	
1	1.14	0.202	36.5	158.5	0.3	0.08	0.27	1.33	75.7
2	1.14	0.198	35.6	157.5	0.26	0.085	0.33	1.51	72.8
3	1.14	0.201	33.8	147.5	0.29	0.095	0.33	1.57	71
4	1.14	0.196	33.7	151.0	0.31	0.085	0.27	1.37	73.4
5	1.14	0.200	41.2	181.0 ⁽²⁾	0.26	0.06	0.23	1.18	79.5
6	1.14	0.200	40.0	175.5 ⁽²⁾	0.24	0.07	0.29	1.38	77

(1) Material tensile properties at -423°F: ultimate strength, 186.8 ksi; 0.2% offset yield strength, 170.6 ksi; % elongation - 8.1

(2) Does not comply with ASTM recommendation that gross stress should not exceed 0.2% offset yield strength.

Specimen
Number

1

2

3

4

5

6

Magnification: 2X

Figure 6 - Fracture Faces of Part-Through-Crack Tensile Specimens Tested
in Liquid Hydrogen at -423°F , Ti-5 Al-2.5 Sn (ELI Grade) Material

Specimen No.	Gross Fracture Stress, ksi	K_{Ic} (ksi-in. ^{1/2})
1	158.5	75.7
2	157.5	72.8
3	147.5	71
4	151	73.4
5	181	79.5
6	175.5	77

As indicated by this data, unexpectedly high fracture-toughness values were obtained. Also, the gross fracture stress for specimens 5 and 6 exceeded the 0.2% offset yield strength. These toughness values were considered qualitative, although there is probably little significant difference between these and the K_{Ic} values for the remaining four specimens that are considered valid.

The specimen fracture faces shown in Figure 6 are unusual in that they had a highly faceted condition, which has not been observed in other structural metals evaluated by Aerojet. As shown in Figure 7, this condition was also not observed on the fracture faces of test blanks of Ti-5 Al-2.5 Sn ELI plate (0.375 in. ground to 0.2 in. thick) which were elox machined and precracked to determine precracking parameters for the tensile specimens tested in this program. Although straight precracks parallel to the axis of the elox slot were obtained with the test blanks, the precracking fatigue extensions in the tensile specimens were slightly skewed relative to the elox slot and were not entirely perpendicular to the specimen surface. This effect may be due to the larger grain size in the Ti-5 Al-2.5 Sn (ELI grade) forging material compared with the plate material. The effect of this condition on the K_{Ic} values is not known.

The K_{Ic} values obtained in this program can be employed to calculate critical defect sizes under plane-strain conditions at -423°F. Such data are useful in assessing the adequacy of nondestructive inspection

Specimen
Number

1

2

3

Magnification: 2X

Figure 7 - Fracture Faces of Test Blanks of Ti-5 Al-2.5 Sn (ELI Grade)
Material Tested to Develop Precracking Parameters

techniques. Equation (1) is used for this purpose. Using the experimentally determined K_{Ic} value and an assumed applied stress level equivalent to the 0.2% yield strength, the critical normalized flaw depth (a/Q) is obtained. Various flaw depth/length ratios ($a/2c$) can then be assumed and Q can be determined from Figure 5. These data are then used to calculate the flaw depth (a) and length ($2c$) for each ratio of flaw depth to length. The results of such calculations for the Ti-5 Al-2.5 Sn (ELI grade) alloy at -423°F are shown in Table 6. A sample calculation for $a/2c = 0.3$ is shown below for a $K_{Ic} = 73.3$ (the average of specimens 1 to 4) and a 0.2% offset yield strength of 170.6 ksi.

$$\begin{aligned}(K_{Ic})^2 &= 1.21 \pi (a/Q) F^2 \\ (73.3)^2 &= 1.21 (3.14) \frac{a}{1.41} (170.6)^2 \\ \underline{a} &= \underline{0.069 \text{ in.}} \\ \underline{2c} &= \underline{0.23 \text{ in.}}\end{aligned}$$

Generally speaking, the most critical flaw shape relative to nondestructive testing is that for an $a/2c = 0.5$, since it represents the smallest surface flaw length for the flaw ratios normally encountered. On the basis of the data in Table 6, the critical flaw length for this flaw shape is 0.21 in., which should readily be detected by the most commonly nondestructive inspection techniques. These include dye penetrant and X-ray.

D. FATIGUE TESTING

1. Specimen Design

The specimens shown in Figure 2 were removed from the top section of the forging and represented material parallel to the radial direction. A total of 20 specimens were available for axial fatigue testing

TABLE 6
CRITICAL DEFECT SIZES - Ti-5 Al-2.5 Sn (ELI Grade) at -423°F⁽¹⁾

Surface Flaw Shape, (a/2c)	K_{Ic} (ksi-in. ^{1/2})	Applied Stress, ksi	Critical Surface Flaw Size, in.	
			Length (2c)	Depth (a)
0.1	73.3	170.6	0.43	0.043
0.3	73.3	170.6	0.23	0.069
0.5	73.3	170.6	0.21	0.107

(1) Material Tensile Properties at -423°F
 Ultimate strength, 186.6 ksi
 0.2% Offset yield strength, 170.6 ksi
 % Elongation, 8.1

in liquid hydrogen at -423°F . All tests were performed at the facilities of the Narmco R&D Division of Whittaker Corp., San Diego, as described below.

2. Test Equipment

a. Fixtures

Special test fixtures were designed to fit the specimens. Particular attention was paid to adequate gripping during reverse-stress loading. Also incorporated was an alignment sleeve that prevented any misalignment due to the tendency of the specimen to buckle under compressive loading. The fixtures were fabricated from steel and are shown in Figure 8.

b. Test Machine

A Budd 5000-lb direct-stress-fatigue test machine was used for all tests. This machine has an automatic electrohydraulic load-maintaining unit as shown in Figure 9.

A load cell (also shown in Figure 9) connected to a Budd strain instrument was added to the machine. This load-measuring system facilitated the initial loading of the specimen, and is more accurate than the load-lever-arm deflection measurement method normally used. In addition, it enabled periodic checking of the mean load while the test was in progress.

The test machine normally operates at a fixed frequency of 1500 cpm. For these tests, however, the machine was slowed to 1000 cpm by reducing the size of the motor pulley. This was done to increase the starting torque for the high loads expected during these tests.

An automatic shut-off was provided that stopped the machine at the moment of specimen failure.

Figure 8 - Test Fixtures Used for Fatigue Tests at -423°F Shown with Tested & Untested Specimens of Ti-5Al-25 Sn (ELI Grade)

NOTE:

Load cell is the white object above cryostat and is connected to Budd strain instrument on base of test machine. Not shown are the thermocouple leads and the L&N K-3 potentiometer, located in an adjoining room during test.

Figure 9 - Fatigue Test Machine with Cryostat Installed and LH₂ Transfer Line Connected

c. Cryostat

A specially constructed LH_2 cryostat (Figure 9) designed for use in conjunction with the Budd fatigue machine was used in all tests. It was of the double-wall-vacuum insulated type and had all the necessary fill and vent connections as well as provisions for instrumentation wiring.

Alignment pads were provided to ensure that the cryostat and load rod remained in axial alignment during the test. These pads were affixed directly to the load frame of the test machine as shown in Figure 9.

3. Instrumentation

Each specimen was instrumented with a copper-constantan thermocouple attached to the reduced area with glass tape. The thermocouples were monitored with a Leeds & Northrup K-3 potentiometer.

4. Loading Conditions

Three loading conditions were specified: zero mean stress, tension-tension at 0.95 load ratio (A), and tension-tension at 0.25 load ratio (A). Loads for each specimen were based on results of preceding tests.

5. Procedure

a. Tension-Tension Tests

The test specimen was assembled in the fixtures, a thermocouple was attached, and the entire assembly was installed in the cryostat. For tension-tension tests, the fixture alignment sleeve was not used.

The cryostat was installed in the test machine, sealed, and all LH_2 lines connected. The cryostat was then filled with liquid hydrogen to a level approximately 2 inches from the top, with approximately 12 inches of LH_2 over the specimen. The specimen was then loaded to the specified mean load and the machine was adjusted for the required cyclic load.

The load was monitored for a few minutes to check that thermal equilibrium had been reached, and the test machine was started. Experience had shown that an adequate level is maintained in the cryostat if it is topped off approximately every half hour. This was accomplished as required (during tests that lasted more than one half hour) without interrupting the test.

The thermocouple attached to the specimen was monitored periodically throughout the test to ensure that the test temperature remained at -423°F . This was primarily a precautionary measure, since maintaining the LH_2 at the proper level will assure the correct specimen temperature. The thermocouple also indicated that there was no measurable increase in temperature in the specimen due to loading, even at the higher load levels and 0.95 load ratio.

Each test was run until the specimen failed, or until a 1×10^6 cycles had been reached. The test machine automatically stopped at the instant of failure.

b. Zero-Mean-Stress Tests

The specimen and fixtures were assembled, the thermocouple was attached to the specimen, and the alignment sleeve was installed. The entire assembly was then installed in the cryostat.

The cryostat was filled with LH_2 before connecting the load rod, to prevent any loads being applied to the specimen due to thermal stresses. After thermal equilibrium had been reached, the load rod was connected. The machine was adjusted for zero mean stress and rechecked to ensure no loads due to residual thermal contraction.

The machine was then adjusted to provide the required cyclic load, and the test was started. The mean load was monitored throughout the test, as was the specimen temperature. For tests of long duration, the LH_2 was topped-off as required to maintain an adequate liquid level.

The test was continued until the specimen failed, or until 1×10^6 cycles had been reached.

6. Results

Results of these tests are shown in Table 7. Test data relative to maximum stress versus cycle life are shown in Figures 10, 11 and 12. On this basis, one million cycle endurance limits of 153, 91, and 76 ksi were obtained at load ratios of 0.20, 0.95 and α , respectively. Since load ratio, A , is the ratio of alternating to mean stress, the maximum stress figures above, were converted, as shown below:

$$\sigma_{\max} = \sigma_{\text{mean}} + \sigma_{\text{alt}} \quad \text{Equation (2)}$$

$$\text{Load Ratio } A = \sigma_{\text{alt}} / \sigma_{\text{mean}} \quad \text{Equation (3)}$$

therefore,
$$\sigma_{\max} = \sigma_{\text{mean}} + (A) \sigma_{\text{mean}}$$

$$\text{and } \sigma_{\text{mean}} = \sigma_{\max} / (1+A)$$

Solving for σ_{mean} and introducing the value into equation (3) results in the quantities required to establish the one-million-cycle operating limits for this material at -423°F in the form of the modified Goodman diagram shown in Figure 13.

TABLE 7

LH₂ AXIAL FATIGUE DATA, Ti-5 Al-2.5 Sn ELI FORGING

$\frac{\sigma_{Alt}}{\sigma_{Mean}} = A = 0.20$	<u>σ_{Mean}</u>	<u>σ_{Alt}</u>	<u>Life, kc</u>
	150	30	39.2
	125	25	1000.0
	130	26	115.0
	126	25.2	1000.0
	128	25.6	1000.0
	130	26	1000.0
	138	27.6	555.3
A = 0.95	60	58	114.5
	55	52	316.0
	50	47.5	185.4
	50	47.5	255.5
	50	47.5	341.3
	48.5	46	416.7
	46.2	44	1000.0
A = ∞	0	90	473.3
	0	80	283.8
	0	90	83.2
	0	80	590.7
	0	75	1000.0
	0	100	70.4

Figure 10 - LH₂ Ti-5 Al-2.5 Sn (ELI Grade) Axial Fatigue Data, $A = 0.20$

Figure 11 - LH₂ Ti-5 Al-2.5 Sn (ELI Grade) Axial Fatigue Data, $A = 0.95$

Figure 12 - LH₂ Ti-5 Al-2.5 Sn (ELI Grade) Axial Fatigue Data, $A = \infty$

Figure 13 - 10^6 Cycle Modified Goodman Diagram LH₂, Ti-5 Al-2.5 Sn (ELI Grade)

The data obtained in this program represented by points 1, 2, and 3 in Figure 13, fell between two existing liquid hydrogen axial fatigue data points reported in Reference 2. These two points were developed with 0.100-in.-thick low interstitial 5Al-2.5 Sn titanium sheet in axial fatigue at a load ratio of 0.98. The high stress point, 4, represented parent metal performance and the low stress point, 5, as-TIG-welded performance. Consequently, it can be seen that the fatigue performance of Ti-5 Al-2.5 Sn is strongly affected by grain size, which is indicated by the effect of welding on the sheet properties and by a comparison of the sheet properties with the forging properties. Although no grain size information was available for the sheet material, the forging stock was coarse grained. The metallographs of several failed fatigue specimens are shown in Figures 14 and 15. The coarseness of the grain affected the fatigue test results and contributed to the observed scatter in the data.

The lower location of the combined stress envelope, relative to the parent metal sheet data point, would result in heavier components if normal margins of safety were to be maintained. The resulting weight penalty is a strong incentive to develop forging techniques that would produce fine-grained material capable of operating at higher combined loads with greater reliability.

E. LIST OF REFERENCES

References used in this report were:

- (1) DMIC Review of Recent Developments in the Field of Mechanical Properties of Metals by J. E. Campbell, 23 November 1966; and
- (2) Cryogenic Materials Data Handbook, AFML-TDR-64-28, March 1966.

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100X

1% HF + H₂O₂

Figure 14 - Forged Ti-5Al-2.5 Sn (ELI) Showing Coarse Grain Size of Fatigue Specimen Tested at 50 ± 47.5 KSI for 185 kc at -423°F .

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100X

1% HF + H₂O₂

Figure 15 - Forged Ti 5Al-2.5 Sn (ELI), Coarse Grain Size of Fatigue Specimen Tested at 50 ± 47.5 KSI for 341 kc at -423°F .