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**JUNE 1975** 

TECHNICAL REPORT AFML-TR-75-97 FINAL REPORT FOR PERIOD APRIL 1973 - APRIL 1975

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Prepared for AIR FORCE MATERIALS LABORATORY Air Force Systems Command Wright-Patterson Air Force Base, Ohio 45433



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C. L. Harmsworth, Technical Manager for Engineering and Design Data Materials Engineering Branch Systems Support Division Air Force Materials Laboratory

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A. Olevitch, Chief Materials Engineering Branch Systems Support Division Air Force Materials Laboratory

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Columbus Laboratories		738106 (Tesk Number)
505 King Avenue, Columbus, Ohio	43201	
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Air Force Materials Laboratory		11. NUMBER OF PAGES
Wright Patterson Air Force Base	0610 45433	287
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This report was prepared by Battelle's Columbus Laboratories, Columbus, Ohio, under Contract F33615-73-C-5073. This contract was performed under Project No. 7381, "Materials Applications", Task No. 738106, "Engineering and Design Data". The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, by Mr. Clayton Harmsworth (AFML/MXE), technical manager.

This final report covers work conducted from April, 1973, to April, 1975. This report was submitted by the authors on April 30, 1975.

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#### INTRODUCTION

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The selection of materials to most effectively satisfy new environmental requirements and increased design load requirements for advanced Air Force weapons systems is of vital importance. A major difficulty that design engineers encounter, particularly for newly developed materials, materials processing, and product forms, is a lack of sufficient engineering data to effectively evaluate the relative potential of these developments for a particular application.

In recognition of this need, the Air Force has sponsored several programs at Eattelle's Columbus Laboratories to provide comparative engineering data for newly developed materials. The materials included in these evaluation programs were carefully selected to insure that they were either available or could become quickly available on request and that they would represent potentially attractive alloy projections for weapons system usage. The results of these programs have been published in six technical reports, AFML-TR-67-418, AFML-TR-68-211, AFML-TR-70-252, AFML-TR-71-249, AFML-TR-72-196, Volumes I and II, and AFML-TR-73-114.

This technical report is a result of the continuing effort to relieve the above situation and to stimulate interest in the use of newly developed alloys, or new processing techniques for older alloys, for advanced structures.

The materials evaluated under this program are as follows

7049-T7351 plate
 Inconel 617 annealed sheet
 7475-T7351 plate
 2419-T851 plate
 Ti-6A1-2Zr-2Sn-2Mo-2Cr duplex annealed forging
 Ti-6A1-2Cb-11a-1Mo annealed plate
 Ti-6A1-4V beta-annealed plate
 Ti-6A1-4V annealed castings
 Ti-6A1-4V isothermal forgings
 Incoloy 903 heat-treated sheet
 201.0 T7 castings.

The temper or heat-treat conditions selected for evaluation are described in each alloy section.

The program approach was, as on previous contracts, to search the published literature and to contact metal producers and aerospace companies for any pertinent data. If very little pertinent information was available, a complete material evaluation was conducted. On this program a complete evaluation was conducted for each material. Upon completion of each evaluation, a "data sheet" was issued to make the information immediately available to potential users rather than defer publication to the end of the contract term and this summary technical report. These data sheets are reproduced as Appendix III of this report.

Detailed information concerning the properties of interest, test techniques, and specimen types are contained in Appendices I and II of this report.

#### 7049-T7351 Aluminum Alloy Plate

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#### Material Description

Alloy 7049 was developed by Kaiser Aluminum and Chemical Corporation. The development aim was for an alloy with a strength level in the range of 7075-T6 and 7079-T6 coupled with a high resistance to stress corrosion cracking. Initial development and production was in the form of forgings and hand forgings. Further development has been in the form of extrusions and plate.

The material evaluated on this program was a 3-inch thick plate from Kaiser lot number 680201. The material had the following composition:

Chemical		
Composition	Percent	
Zinc	7.6	
Magnesium	2.5	
Copper	1.5	
Chromium	0.15	
Silicon	0.25 max	
Trop	0.35 max	
Titanium	0.10 max	
Manganese	0.20 max	
Aluminum	Balance	

#### Processing and Heat Treating

The specimen layout is shown in Flaure 1. Specimens were tested in the ascreceived T1751 compert

#### Test Results

<u>Tension</u>. Tests were conducted at room temperature, 250 F, 350 F, and 500 F on both longitudinal and long transverse specimens. Test results are given in Table I. Typical stress-strain curves at temperature are presented in Figures 2 and 3. Effect-of-temperature curves are presented in Figure 6.

<u>Compression</u>. Tests were conducted at room temperature, 250 F, 350 F, and 500 F on both longitudinal and long transverse specimens. Test results are given in Table II. Typical stress-strain and tangent-modulus curves at temperature are presented in Figures 4 and 5. Effect-of-temperature curves are shown in Figure 7.

Shear. Tests were conducted at room temperature only on pin-shear type longitudinal and long transverse specimens. Test results are given in Table III.





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52	5.8	534	548

Impact. Charpy V-notch test results for longitudinal and long transverse specimens are given in Table IV.

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<u>Fracture Toughness</u>. Results of slow-bend type tests in both the longitudinal (L-T) and long transverse (T-L) directions are given in Table V. Specimens were 1.00 inch thick by 2.00-inches wide with a span of 8 inches. The candidate K<sub>Q</sub> values shown in Table V are considered valid K<sub>Ic</sub> values by existing ASTM criteria.

<u>Fatigue</u>. Axial-load test results for long transverse specimens at a load ratio of R = 0.1 are given in Tables VI and VII. These tests were conducted at room temperature, 250 F, and 350 F for both unnotched and notched ( $K_t = 3.0$ ) specimens. These data are presented as S-N curves in Figures 8 and 9.

<u>Creep and Stress-Rupture</u>. Results of tests on long transverse specimens at 250 F, 350 F, and 500 F are given in Table VIII. Log-stress versus logtime curves are presented in Figure 10.

<u>Stress Corrosion</u>. Specimens were tested as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000-hour test duration.

<u>Thermal Expansion</u>. The coefficient of thermal expansion for this alloy is  $12.9 \times 10^{-5}$  in./in./F for 68 F to 212 F.

Density. The density of this material is 0.099 lb./in<sup>3</sup>.

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Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10 <sup>3</sup> ksi
		Longitudinal at R	oom Temperature		
1L-1	75.8	65.8	12.0	32.3	10.3
1L-2	75.4	67.3	13.5	37.8	10.1
1L-3	75.2	66.5	13.5	38.2	10.3
Average	75.5	66.5	13.0	36.1	10.2
	L	ong Transverse at	Room Temperature		
1T-1	73.1	63.4	10.5	24.4	10.4
1T-2	77.6	68.0	10.5	25.8	10.3
1T-3	73.0	62.8	11.0	26.5	10.4
Average	2 74.6	64.7	10.7	25.6	10.4
		<u>Longitudinal</u>	at 250 F		
1L-4	59.2	59.0	18.5	53.8	9.2
1L 5	59.3	58.7	18.0	50.9	9.5
1L-6	58.5	58.5	18.0	55.7	9.2
Average	59.0	58.7	18.2	53.5	9.3
		Long Transver	se at 250 F		
1T-4	60.2	58.6	15.5	44.3	9.6
1T-5	62.2	61.2	15.0	41.4	9.6
1 <b>T-6</b>	<u>60.0</u>	<u>58.6</u>	<u>16.0</u>	44.7	9.4
Average	e 60.8	59.5	15.5	43.4	9.5
		Longitudinal	at 350 F		
1L-7	45.7	45.4	20.0	64.5	7.7
1L-8	45.8	45.7	20.0	63.5	8.2
1L-9	<u>44.7</u>	44.3	20.5	<u>66.8</u>	<u>8,1</u>
Average	e 45.4	45.1	20.2	64.9	8.0
		Long Transver	se at 350 F		
1T-7	46.1	45.8	17.0	53.7	8.8
1T-8	48.4	47.2	17.0	54.3	7.9
1T-9	46.6	45.9	18.0	55.9	<u>8.5</u>
Average	e 47.0	46.3	17.3	54.6	8.4
		Longitudina1	<u>at 500 F</u>		
1L-10	14.9	14.7	32.0	85.8	5.4
1L-11	15.0	14.8	33.0	87.3	6.2
11-12	15.4	15.2	30.5	85.9	$\frac{0.3}{6}$
Average	e 15.1	14.9 Long Transver	8.15 ap at 500 F	80.3	0.0
		Long Transver	se at JUV F		
1 <b>T-1</b> 0	16.6	16.6	27.5	81.5	6,1
1T-11	17.3	17.2	30.0	84.0	5.3
17-12	17.8	17.7	29.0	84.0	5.8
Average	e 1/.2	17.2	28.8	83.2	5.7

## TABLE I. TENSILE TEST RESULTS FOR 7049-T7351 ALLOY PLATE

and a second second

Specimen Number	0.2 Yi	Percent Offset eld Strength, ksi	Compressive Modulus, 10 <sup>3</sup> ksi
	Longi	tudin at Room 1	emperature
211 212 213	Average	64.6 63.6 <u>64.0</u> 54.1	10.8 10.7 <u>10.9</u> 10.8
0 a <b>b</b>	Long	ransverse at Koom	Temperature
24 <b>1</b> 24 <b>-2</b> 2 <b>T</b> - <b>3</b>	Average	66.0 71.0 <u>70.7</u> 69.2	10.9 11.1 <u>10.6</u> 10.9
		Longitudinal at	<u>250 ¥</u>
21-4 21-5 21-6	Average	57.2 56.6 <u>56.7</u> 56.8	9.4 9.1 <u>9.8</u> 9.4
		Long Transverse a	<u>t 250 F</u>
2T -4 2T - 5 2T - 6	Average	60.4 56.7 <u>62.3</u> 59.8	9.7 9.9 <u>9.6</u> 9.7
		Longitudinal at	350 F
217 218 219	Average	44.1 44.5 <u>44.7</u> 44.4	8.0 8.2 <u>8.1</u> 8.1
	L	ong Transverse at	350 F
2T-7 2T-8 2T-9	Average	48.1 47.7 <u>46.8</u> 47.5	8.1 8.4 <u>8.4</u> 8.3
		Longitudinal at	500 F
24. 10 25-11 21-12	Average	16.1 16.6 <u>17.3</u> 16.7	7.1 6.8 <u>6.7</u> 6.9
	1	Long Transverse at	<u>500 F</u>
21-10 23-11 27-12	Average	15.8 17.6 <u>17.7</u> 17.0	6.9 7.5 <u>6.5</u> 7.0

TABLE CL. COMPRESSION TEST RESULTS FOR 7049-T7351 ALLOY PLATE

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TABLE III. PIN SHEAR TEST RESULTS FOR

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	7049-T7351 ALL ROOM TLMPERATU	.OY <b>PLATE AT</b> IRE
Specimen Number	U1 S	timate Shear trength, ksi
	Longitudinal	
4L-1		45.4
4L-2		42.4
4L-3		46.4
4L-4		50.2
	Average	46.1
	Long Transver	se
4T-1		48.3
4T-2		44.1
4 <b>T-3</b>		43.0
4T-4		46.3
	Average	45.4

# TABLE IV.IMPACT TEST RESULTS FOR7049-T7351ALLOY PLATEAT ROOM TEMPFRATURE

Specimen Number		Energy, ft/1b
	<u>Longitudinal</u>	
10L-1		8.0
10L-2		5.0
10L-3		5.0
10L-4		5.0
10L-5		6.0
10L-6		6.0
		<u> </u>
	Average	5.8
	Long Transverse	
10T-1		3.0
10T-2		4.0
10T-3		4.0
10T-4		3.0
10T-5		3.0
10T-6		3.0
		—
	Average	3.3

Specimen Number	W, inches	a, inches	B, inches	Р <sub>О</sub> , 15	Span, inches	$f(\frac{a}{w})$	KQ <sup>(a)</sup>
		Ī	ongitudina	1 (L-T)			
6L-1	2.00	0.934	1.00	5,000	8.0	2.403	34.0
6L-2	2.00	0.952	1.00	4,700	8.0	2.470	32.8
0L-3	2.00	0.964	1.00	4,750	8.0	2.517	33.8
9L-4 61 5	2.00	0.904	1.00	4,850	a.u	2.51/	34.5
6L-6	2.00	0.982	1.00	4,700 5,050	8.0	2.389	34.4
						Average	34.0
		L	ong Transve	erse (T-L)	Σ		
6T-1	2.00	0.886	1.00	4,550	8.0	2.237	28.8
6T-2	2.00	0.956	1.00	3,950	8.0	2.486	27.8
6 <b>T</b> -3	2.00	0.966	1.00	3,850	8.0	2.525	27.5
6T-4	2.00	0.980	1.00	3,810	8.0	2.581	27.8
6T-5	2.00	0.966	1.00	3,910	8.0	2.525	27.9
6T-6	2.00	0.952	1.00	4,080	8.0	2.471	28.5
						Average	28.1

TABLE V.RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTSFOR 7049-T7351 PLATE AT ROOM TEMPERATURE

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(a) These candidate  $K_{\rm Q}$  values are considered valid  $K_{\rm Ic}$  values by existing ASTM standards.

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Specimen Number	Maximum Stress, ksi	Lifetime, c <b>y</b> cles
	Room Temperature	
5-1	60	12,700
5-6	55	31,100
5-2	50	48,300
5-7	45	92,970
5-3	40	93,500
5-8	35	12,758,600 <sup>(a)</sup>
5-4	30	10,361,500 <sup>(a)</sup>
	<u>250 F</u>	
5-9	60	12,900
5-10	55	27,500
5-11	50	33,700
5-12	45	64,600
5-13	40	91,600
5 - 14	35	125,000
5-15	30	167,500
5-16	25	10,068,500 <sup>(a)</sup>
	<u>350 F</u>	
5-17	60	100
5-18	50	400
5-22	45	25,100
5-23	40	45,200
5-21	4Ŭ	64,300
5-19	35	174,700
5-20	30	3,529,000
5-24	25	7,954,100
5-25	20	16,836,600 <sup>(a)</sup>

### TABLE VI. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 7049-T7351 ALLOY PLATE (LONG TRANSVERSE, R = 0.1)

(a) Did not fail.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-31	45	3,700
5-32	40	5,200
5-33	35	11,600
5-34	30	18,900
5-35	25	32,700
5-37	20	177,100
5-36	15	2,965,700
5-38	10	2,784,200
5-46	10	11,989,200 <sup>(a)</sup>
	<u>250 F</u>	
5-39	40	5,000
5-40	35	8,800
5-41	30	17,800
5-42	25	39,600
5-43	20	79,500
5-44	15	835,400
5-45	10	1,630,400
5-46	10	10,300,000 <sup>(a)</sup>
	<u>350 F</u>	
5-48	40	3,300
5-49	35	6,700
5-50	30	15,600
5-51	25	31,400
5~52	20	96,200
5-53	15	399,000
5-54	10	10,990,000 <sup>(a)</sup>

TABLE VII. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ( $K_t = 3.0$ ) 7049-T7351 ALLOY PLATE (LONG TRANSVERSE, R = 0.1)

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SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR 7049-T7351 PLATE TABLE VIII.

Number         ksi         F         0.1         0.2         0           3-1         50         250         0.05         0.1         0         0           3-4         40         250         3.0         16         69         -         -         0           3-7         32         250         3.0         16         69         -         -         0           3-10         25         250         155         770         2770         -         -           3-10         25         250         155         770         2770         -         -           3-10         25         250         155         770         2770         -         -           3-10         25         250         155         770         2770         -         -           3-2         3-2         250         155         770         2770         -	nerimen	Stress	Temper- ature.	Hours to	o Indicí D	sted Creep ercent	Deform	atiun,	Initial Strain,	Rupture Time,	Elongation in 2 In.,	Reduction of Area,	Minimum Creep Rate,
3-1       50       250       0.05       0.1       0         3-4       40       250       3.0       16       69         3-7       32       250       20       140       -         3-10       25       250       20       140       -         3-10       25       250       155       770       2770         3-10       25       250       155       770       2770         3-10       25       250       155       770       2770         3-2       25       250       155       770       2770         3-11       2       350       0.5       1.8       116         3-11       5       350       15       75       280         3-3       1       5       350       50       50       5200         3-3       7       500       0.2       0.6       2       2       2	Number	ksi	íL.	0.1	0.2	0,5	1.0	2.0	percent	hours	percent	percent	percent
3-4       40       250       3.0       16       69         3-7       32       250       3.0       16       69         3-10       25       250       20       140       -         3-10       25       250       155       770       2770         3-10       25       250       155       770       2770         3-10       25       350       0.5       140       -         3-2       25       350       0.5       165       69         3-11       5       350       0.5       165       5200         3-3       7       500       0.2       0.6       2200         3-3       7       500       0.2       0.6       2200	3-1	05	2.50	0.05	0.1	0.3	0.6	1.3	0.770	3.6	19.0	42.5	1.5
3-7       32       250       20       140       -         3-10       25       250       155       770       2770         3-10       25       250       155       770       2770         3-10       25       250       155       770       2770         3-2       25       350       0.5       1.8       6         3-5       15       350       0.5       1.8       116         3-11       5       350       550       1650       5200         3-3       7       500       0.2       0.6       2200         3-3       7       500       0.2       0.6       2	3-4 - 4 -	0 <del>1</del>	250	3.0	16	69	140	215	0.504	288.9	17.4	48.9	0.0054
3-10     25     250     155     770     2770       3-2     25     350     155     770     2770       1     3-2     25     350     0.5     1.8     6       3-5     15     350     0.5     1.8     6       3-5     15     350     5.0     33     116       3-11     5     350     550     1650     5200       3-3     7     500     0.2     0.6     2	3-7	32	250	20	140	:	ł	ł	0.413	I48.0*	0.617	4	
3-2       25       350       0.5       1.8       6         3-5       15       350       0.5       1.8       6         11       3-8       12       350       5.0       33       116         3-11       5       350       550       15       75       280         3-11       5       350       550       1650       5200         3-3       7       500       0.2       0.6       2	3-10	25	250	155	770	2770,est	:	1	0.299	624.8*	0.478	1	c1000.0
3-2       25       350       0.5       1.8       6         3-5       15       350       5.0       33       116         3-5       15       350       5.0       33       116         3-8       12       350       15       75       280         3-11       5       350       15       75       280         3-11       5       350       550       1650       5200         3-3       7       500       0.2       0.6       2								·					
11     3-5     15     350     5.0     33     116       11     3-11     5     350     550     15     280       3-11     5     350     550     1650     5200       3-3     7     500     0.2     0.6     2	د . د	<u> 3</u> С	350	0.5	1.8	6.0	8,0	12.0	0.341	16.5	19.7	70.5	0.05
11     3-8     12     350     15     75     280       3-11     5     350     550     1650     5200       3-3     7     500     0.2     0.6     2	4 K - C	14	055			116	205	280	0.223	333.8	18.2	77.0	0.0034
3-11 5 350 550 1650 5200 3-3 7 500 0.2 0.6 2		12	350	15	75	280	525	815	0.178	1228.3	28.8	88.2	0.0014
3-3 7 500 0.2 0.6 2	3-11	141	350	550	1650	5200,est	:	:	0.045	1004.0*	ł	1	0.00045
3-3 7 500 0.2 0.6 2											·		
	Ċ	r	2002	0.2	0 Y	2.1	4.5	6.0	0.117	19.5	50.0	88.5	0.18
	י י י י	- <i>U</i>		5 6		32	68	118	0.127	281.9	35.6	71.6	0.011
1-0 V 500 12 30 80	2 0 1 1 1 1	4	2005 005	12	30	80	275	450	0.030	981.1	32.6	64.I	0.0029
3-12 2.5 500 50 295 2000	3-12	2.5	200	20	295	2000	4800,ec	it	0.042	931.5*	:	1	0.00018

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FIGURE 2. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)



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FIGURE 3. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONG TRANSVERSE)



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FIGURE 4. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)

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FIGURE 5. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONG TRANSVERSE)

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FIGURE 6. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE



FIGURE 7. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE



Lifetime, cycles

FIGURE 8. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7049-T7351 ALUMINUM ALLOY PLATE






Stress, ksi

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- Section

## Inconel 617 Alloy Sheet

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## Material Description

Inconel Alloy 617 is a solid-solution, nickel-chromium-cobaltmolybdenum alloy with a good combination of high-temperature strength and oxidation resistance. It has excellent resistance to a wide range of corrosive environments, and is readily formed and welded by conventional techniques.

The high nickel and chromium contents make the alloy resistant to a variety of both reducing and oxidizing media. The aluminum, in conjunction with the chromium, provides oxidation resistance at high temperatures. Solid-solution strengthening is provided by the cobalt and molybdenum.

The combination of high strength and oxidation resistance at elevated temperatures makes this alloy an attractive material for gas-turbine aircraft engines and other applications involving exposure to extreme temperatures.

The material used for this evaluation was a 0.047-inch-thick sheet from Huntington Alloys Heat XX00A7US with the following composition:

Chemical	•
Composition	Percent
Chromium	22.0
Cobalt	12.5
Molybdenum	9.0
Aluminum	1.0
Carbon	0.07
Nickel	54

#### Processing and Heat Treating

The specimen layout for this alloy is shown in Figure 11. Specimens were tested in the as-received cold-rolled and annealed condition.

#### Test Results

<u>Tension</u>. Test results for both longitudinal and transverse specimens at room temperature, 800 F, 1200 F, and 1600 F are given in Table IX. Typical stress-strain curves at temperature are shown in Figures 12 and 13. Effect-oftemperature curves are presented in Figure 16.

<u>Compression</u>. Results of tests in both the longitudinal and transverse directions at room temperature, 800 F, 1200 F, and 1600 F are given in Table X. Typical stress-strain and tangent-modulus curves at temperature are presented in Figures 14 and 15. Effect-of-temperature curves are shown in Figure 17.



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FIGURE 11. SPECIMEN LAYOUT FOR INCONEL 617 ALLOY SHEET

Shear. Test results for sheet-shear type specimens are given in Table XI. These tests were conducted at room temperature only on both longitudinal and transverse specimens.

<u>Fracture Toughness</u>. The specimens tested were 18 inches wide by 36 inches long with a center saw-cut flaw. Net section stress at fracture was greater than the tensile yield strength of the material, therefore the tests were not valid for K<sub>c</sub> determination.

<u>Fatigue</u>. Axial-load test results for transverse specimens at room temperature, 800 F, and 1200 F are given in Tables XII and XIII. These tests were conducted on both unnotched and notched ( $K_t = 3.0$ ) specimens at a load ratio of R = 0.1. S-N curves are presented in Figures 18 and 19.

<u>Creep and Stress-Rupture</u>. Tests were conducted at 800 F, 1200 F, and 1600 F on transverse specimens. Tabular test results are given in Table XIV. Log-stress versus log-time curves are presented in Figure 20.

<u>Stress Corrosion</u>. Tests on transverse specimens were conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the test duration.

<u>Thermal Fxpansion</u>. The coefficient of thermal expansion for this alloy in  $8.7 \times 10^{-8}$  in./in./F from room temperature to 1600 F.

Density. The density of this material is 0.302 lb/in.<sup>3</sup>.

	Ultimate	0.2 Percent	21 annah i an	Toredia			
Specimen Number	Tensile Strength, ksi	Strength, ksi	in 2 Inches, percent	Modulus, 10 <sup>3</sup> ksi			
	Longi	tudinal at Room Te	mperature				
1L-1	122.3	56.4	56.0	28.4			
1L-2	122.4	56.9	56.0	24.3			
11-3	$\frac{122.5}{122.4}$	20,2	24.2	28.4			
Avera	ge 122.4			27.0			
	Tran	sverse at Room Tem	perature				
1T - 1	122.9	55.9	56.0	30.9			
1 <b>T</b> -2	124.4	57.1	54.5	30.2			
1T-3	$\frac{123.5}{123.5}$	56.5	58.0	$\frac{30.4}{50.4}$			
Avera	ge 123.6	20.2	56.2	30.5			
		Longitudinal at 8	<u>00 F</u>				
1L-4	102.7	40.8	49.0	21.8			
1L-5	103.5	42.0	51.0	29.6			
1L-6	103.6	40.3	<u>50.0</u>	19.4			
Avera	ge 103.3	41.0	<b>50.</b> 0	23.6			
Transverse at 800 F							
1T-4	105.2	44.1	50.0	24.4			
1 <b>T-</b> 5	105.7	43.9	49.0	25.6			
1 <b>T</b> -6	106.2	42.3	53.0	24.4			
Avera	ge 105.7	43.4	50.7	24.8			
Longitudinal at 1200 F							
1L-7	83.4	37.6	48.0	21.1			
1L-8	82.6	38.3	49.0	25.3			
1L-9	85.8	38.6	33.0	23.0			
Avera;	ge 83.9	38.2	43.3	23.1			
		Transverse at 120	<u>0 F</u>				
1 <b>T</b> -7	95.9	39.1	44.0	28.3			
1T-8	96.3	39.4	43.0	29.1			
1 <b>T</b> -9	95.8	39.3	53.0	32,0			
Avera	ge 96.0	39.3	46.7	29.8			
Longitudinal at 1600 F							
1L-10	25.1	21.4	50.0	19.0			
1L-11	24.3	22.0	39.0	14.6			
1L-12	24.5	21.8	49.0	17.4			
Avera	ge 24.6	21.7	46.0	17.0			
		Transverse at 160	<u>OF</u>				
1T-10	25.3	24.3	50.0	13.3			
1T-11	23.7	21.6	70.0	20.0			
17-12	25.5	22.8	47.0	16.4			
Avera	ge 24.8	22 <b>.9</b>	55.7	16.6			

TABLE IX. TENSILE TEST RESULTS FOR INCONEL 617 ANNEALED SHEET

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Specimen Number	0 Of St:	.2 Percent ifset Yield rength, ksi	Compression Modulus, 10 <sup>3</sup> ksi
	Longitudi	nal at Room Temp	erature
2L-1		62.4	30.6
21-2		62.2	29.7
2L-3	Anonaga	$\frac{61.0}{61.0}$	$\frac{30.9}{30.4}$
	weige		JU.4
om 1	<u>transver</u>	40 f	22 7
21-1		62 2	33.1
2T-2 2T-3		61.8	33.5
	Average	61.5	33.7
	Long	itudinal at 800	F
2L-4		(a)	<b>25.</b> 7
2L-5		48.8	29.0
2L-6		<u>49.1</u>	$\frac{29.1}{29.1}$
	Average	48.9	27.9
	Tra	nsverse at 800 F	
2 <b>T</b> -4		51.2	29.6
2T-5		47.5	29.3
2 <b>T~6</b>	•	<u>50.9</u>	$\frac{30.3}{20.3}$
	Average	49.9	29.7
	Longi	tudinal at 1200	F
2L-7		41.1	21.5
2 <b>L-8</b>		40.9	24.3
2L-9		<u>40.9</u>	26.4
	Average	41.0	24.1
	Tran	sverse at 1200 F	
2 <b>T</b> -7		39.6	25.6
2 <b>T-8</b>		44.1	29.1
2T~9	Average	$\frac{41.2}{41.6}$	$\frac{27.9}{27.5}$
			27.3
A	Longi	tudinal at 1600	<u>F</u>
2L-10 21-11		30.2	19.3
21-11		30.8	22./ 19 A
<b>2 2 3 4</b>	Average	30.9	20.0
	Tran	sverse at 1600 F	
2 <b>T-1</b> 0		32.3	27.8
2 <b>T-11</b>		31.7	24.9
2T-12		30.7	20.0
	Average	31.6	24.2

# TABLE X. COMPRESSION TEST RESULTS FOR INCONEL 617 ANNEALED SHEET

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(a) Machine malfunction.

## TABLE XI. SHEAR TEST RESULTS FOR INCONEL 617 ANNEALED SHEET AT ROOM TEMPERATURE

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Specimen Number		Ultimate Shear Strength, ksi
	Longitudina1	
4L-1		(a)
4L-2		108.3
4L-3		104.7
4L-4		106.8
	Average	106.6
	Transverse	< C
4 <b>T</b> -1		104.7
4 <b>T</b> -2		107.5
4 <b>T-</b> 3		110.5
4 <b>T</b> -4		107.1
	Average	107.6

(a) Did not fail in shear.

Specimen Number	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature	
5-4	105.0	41,550
5-3	100.0	45,210
5-5	95.0	77,750
5-6	90.0	136,200
5-2	85.0	190,830
5-7	80.0	587,560
5-8	75.0	576,970
5-13	70.0	2,635,900
5-10	70.0	8,676,840
5-9	65.0	14,444,620 <sup>(a)</sup>
	800 F	
5-14	95.0	900
5-15	80.0	11,500
5-16	75.0	29,000
5-17	70.0	55,300
5-19	65.0	142,100
5-11	62.5	2,122,600
5-18	60.0	10,144,000 <sup>(a)</sup>
	1200 F	
5-20	80.0	5,800
5-22	75.0	18,400
5-23	72.5	38,300
5-21	70.0	2,501,100
5-24	65.0	4,245,000
5 - 25	60.0	10,244,900 <sup>(a)</sup>

## TABLE XII. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED ANNEALED INCONEL 617 SHEET (Transverse, R=0.1)

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(a) Did not fail.

Room Temperature $5-32$ 70.012,860 $5-33$ 65.035,790 $5-34$ 60.068,710 $5-35$ 55.0124,500 $5-36$ 50.077,420 $5-37$ 45.076,750 $5-38$ 40.0534,190 $5-39$ 35.03,536,900 $5-40$ 30.010,000,000 (a) $\frac{800 \ F}{}$ $\frac{800 \ F}{}$ $5-56$ 65.01,100 $5-46$ 60.013,000 $5-44$ 40.06,212,300 $5-43$ 45.069,300 $5-44$ 40.06,212,300 (a) $5-45$ 35.013,022,100 (a) $5-47$ 60.03,000 $5-48$ 55.04,900 $5-49$ 50.08,200 $5-50$ 45.0121,500 $5-51$ 40.01,539,800 $5-52$ 35.0870,000 $5-53$ 30.011,249,200 (a)	Specimen Number	Maximum Stress, ksi	Lifetime, Cycles
5-32       70.0       12,860 $5-33$ 65.0       35,790 $5-34$ 60.0       68,710 $5-35$ 55.0       124,500 $5-36$ 50.0       77,420 $5-36$ 50.0       77,420 $5-36$ 50.0       76,750 $5-38$ 40.0       534,190 $5-39$ 35.0       3,536,900 $5-40$ 30.0       10,000,000 (a) $5-41$ 55.0       39,900 $5-42$ 50.0       70,200 $5-43$ 45.0       69,300 $5-44$ 40.0       6,212,300 $5-45$ 35.0       13,022,100 (a) $1200$ F       5 $5-47$ 60.0       3,000 $5-48$ 55.0       4,900 $5-50$ 45.0       121,500 $5-51$ 40.0       1,539,800		Room Temperature	
$5-33$ $65.0$ $35,790$ $5-34$ $60.0$ $68,710$ $5-35$ $55.0$ $124,500$ $5-36$ $50.0$ $77,420$ $5-37$ $45.0$ $76,750$ $5-38$ $40.0$ $534,190$ $5-39$ $35.0$ $3,536,900$ $5-40$ $30.0$ $10,000,000^{(a)}$ $800 F$ $800 F$ $1,100$ $5-46$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-46$ $60.0$ $13,000$ $5-46$ $60.0$ $70,200$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$	5-32	70.0	12,860
$5-34$ $60.0$ $68,710$ $5-35$ $55.0$ $124,500$ $5-36$ $50.0$ $77,420$ $5-37$ $45.0$ $76,750$ $5-38$ $40.0$ $534,190$ $5-39$ $35.0$ $3,536,900$ $5-40$ $30.0$ $10,000,000^{(a)}$ $800 F$ $800 F$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-33	65.0	35,790
$5-35$ $55.0$ $124,500$ $5-36$ $50.0$ $77,420$ $5-37$ $45.0$ $76,750$ $5-38$ $40.0$ $534,190$ $5-39$ $35.0$ $3,536,900$ $5-40$ $30.0$ $10,000,000^{(a)}$ $800 F$ $800 F$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-34	60.0	68,710
$5-36$ $50.0$ $77,420$ $5-37$ $45.0$ $76,750$ $5-38$ $40.0$ $534,190$ $5-39$ $35.0$ $3,536,900$ $5-40$ $30.0$ $10,000,000^{(a)}$ $\frac{800 \ F}{}$ $\frac{1000 \ F}{}$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $\frac{1200 \ F}{}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-35	55.0	124,500
$5-37$ $45.0$ $76,750$ $5-38$ $40.0$ $534,190$ $5-39$ $35.0$ $3,536,900$ $5-40$ $30.0$ $10,000,000^{(a)}$ $\frac{800 \ F}{}$ $5-56$ $65.0$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-36	50.0	77,420
$5-38$ $40.0$ $534,190$ $5-39$ $35.0$ $3,536,900$ $5-40$ $30.0$ $10,000,000^{(a)}$ $\frac{800 \ F}{}$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300^{(a)}$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-37	45.0	76,750
$5-39$ $35.0$ $3,536,900$ $5-40$ $30.0$ $10,000,000^{(a)}$ $\frac{800 \ F}{}$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-38	40.0	534,190
$5-40$ $30.0$ $10,000,000^{(a)}$ $\frac{800 \ F}{}$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-39	35.0	3,536,900
$\underline{800 \ F}$ $5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $5-45$ $55.0$ $4,900$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-40	30.0	10,000,000 <sup>(a)</sup>
$5-56$ $65.0$ $1,100$ $5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $\frac{1200 \text{ F}}{5-45}$ $55.0$ $4,900$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$		<u>800 F</u>	
$5-46$ $60.0$ $13,000$ $5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $1200 F$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-56	65.0	1,100
$5-41$ $55.0$ $39,900$ $5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-43$ $40.0$ $6,212,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $1200 \text{ F}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-46	60.0	13,000
$5-42$ $50.0$ $70,200$ $5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $1200 \text{ F}$ $1200 \text{ F}$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-41	55.0	39,900
$5-43$ $45.0$ $69,300$ $5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $\frac{1200 \text{ F}}{5-47}$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-42	50.0	70,200
$5-44$ $40.0$ $6,212,300$ $5-45$ $35.0$ $13,022,100^{(a)}$ $1200 F$ $1200 F$ $5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$	5-43	45.0	69,300
$5-45$ $35.0$ $13,022,100^{(a)}$ $1200 \text{ F}$ $5-47$ $5-47$ $60.0$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$	5-44	40.0	6,212,300
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	5-45	35.0	13,022,100 <sup>(a)</sup>
$5-47$ $60.0$ $3,000$ $5-48$ $55.0$ $4,900$ $5-49$ $50.0$ $8,200$ $5-50$ $45.0$ $121,500$ $5-51$ $40.0$ $1,539,800$ $5-52$ $35.0$ $870,000$ $5-53$ $30.0$ $11,249,200^{(a)}$		<u>1200 F</u>	
5-48       55.0       4,900         5-49       50.0       8,200         5-50       45.0       121,500         5-51       40.0       1,539,800         5-52       35.0       870,000         5-53       30.0       11,249,200 <sup>(a)</sup>	5-47	60.0	3,000
5-49       50.0       8,200         5-50       45.0       121,500         5-51       40.0       1,539,800         5-52       35.0       870,000         5-53       30.0       11,249,200 <sup>(a)</sup>	5-48	55.0	4,900
5-5045.0121,5005-5140.01,539,8005-5235.0870,0005-5330.011,249,200 (a)	5-49	50.0	8,200
5-5140.01,539,8005-5235.0870,0005-5330.011,249,200 (a)	5-50	45.0	121,500
5-5235.0870,0005-5330.011.249.200 (a)	5-51	40.0	1,539,800
5-53 30.0 11,249,200 <sup>(a)</sup>	5-52	35.0	870,000
	5-53	30.0	11,249,200 <sup>(a)</sup>

## TABLE XIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K<sub>t</sub>=3.0) ANNEALED INCONEL 617 SHEET (Transverse, R=0.1)

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(a) Did not fail.

TABLE XIV. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR ANNEALED INCONEL 617 SHEET

Specimen	Stress.	, Temper- ature.	Hour	s to Indi(	cated Creep percent	Deformat	tion,	Initial Strain,	Rupture Time,	Elongation in 2 Inches,	Minimum Creep Rate,
Number	ksi	F	0.1	0.2	0.5	1.0	2.0	percent	hours	percent	percent
3-1	121	800	1		ł	:	ł	8	On load	67.0	1
3-4	107	800	1	ł	ł	ł	ł	ł	ł	66.0	8 8
3-15	100	800	3300 <sup>(a)</sup>	7000 <sup>(a)</sup>	ł	1	1	45.010	1008.6 <sup>(b)</sup>	45.043	0.00002
3-12	90	800	ł	!	j I	ŧ	3 1	30.174	864.0 <sup>(b)</sup>	30.216	Nil
3-10	75	800		Nega	itive Creep	_		17.358	311.0 <sup>(b)</sup>	17,337	NII
3-6	50	800	ł	ł	3	1	ł	0.973	191.9 <sup>(b)</sup>	0.977	<b>NII</b>
<mark>27</mark>	75	1200	8 8	*	0.05	0.12	0.04	16.150	20.0	28.8	0.48
3-2	60	1200	0.10	0.3	1.5	7	15	I0.500	135.9	16.7	0.021
3~9	50	1200	0.12	0.35	2.7	120	435	2.907	738.3	6.5	0.0021
3-14	40	1200	525	850	$1800^{(a)}$	ł	1	0.305	961.0 <sup>(b)</sup>	0.549	0.00031
3-13	30	1200		Neg	itive Creep			0.142	331.3 <sup>(b)</sup>	0.114	ł
3-3	30	1600	ł	ł	ł	0.03	0.07	0.313	0,8	58.6	36.0
3-5	51	1600	0.2	0.4	1.0	2.2	4.8	0.095	56.5	48.4	0.41
3-6	10	1600	2.5	80	28	67	011	0.042	523.2	32.5	0.014
3-11	Ś	1600	325	965	3000 <sup>(a)</sup>	1	:	0.035	1008.3 <sup>(b)</sup>	0.252	0.00015
(a) Esti	mated.										

(b) Test discontinued.

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FIGURE 12. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED INCONEL 617 ALLOY SHEET (LONGITUDINAL)



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FIGURE 13. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED INCONEL 617 ALLOY SHEET (TRANSVERSE)

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FIGURE 14. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR ANNEALED INCONEL 617 ALLOY SHEET (LONGITUDINAL)



INCONEL 617 ALLOY SHEET (TRANSVERSE)

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FIGURE 17. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED INCONEL ALLOY 617 SHEET

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FIGURE 18. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED INCONEL ALLOY 617 SHEET



FIGURE 19. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (Kt-3.0) ANNEALED INCONEL ALLOY 617 SHEET





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### 7475-T7351 Aluminum Alloy Plate

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#### Material Description

Alloy 7475 was developed by the Alcoa Laboratories for sheet and plate applications that require high strength and superior fracture toughness. This product was previously designated "Alcoa 467 Process X7475 Alloy". The 467 Process is a proprietary process developed to enhance the toughness of a high-purity 7075 type alloy. It is still used in the production of 7475 sheet and plate.

Alloy 7475 is available as bare and alclad sheet and plate. The material used in this evaluation was 2-inch-thick bare plate from Alcoa lot number 109-141 produced within the following composition limits:

Chemical	
Composition	Percent
Silicon	0.10 max
Iron	0.12 max
Copper	1.2-1.9
Manganese	0.06 max
Magnesium	1.9-2.6
Chromium	0.18-0.25
Zinc	5.2-6.2
Titanium	0.6 max
Others	0.15 total
Aluminum	Balance .

#### Processing and Heat Treating

The specimen layout for this material is shown in Figure 21. The alloy was evaluated in the as-received -T7351 temper.

#### Test Results

<u>Tension</u>. Tests were conducted at room temperature, 250 F, 350 F, and 500 F on both longitudinal and transverse specimens. Test results are given in Table XV. Typical stress-strain curves at temperature are presented in Figures 22 and 23. Effect-of-temperature curves are shown in Figure 26.

<u>Compression</u>. Tests were conducted at room temperature, 250 F, 350 F, and 500 F. Tabular test results are given in Table XVI. Typical stress-strain and tangent-modulus curves at temperature are presented in Figures 24 and 25. Effect-of-temperature curves are shown in Figure 27.

Shear. Tests were conducted at room temperature only on pin-shear type longitudinal and transverse specimens. Test results are given in Table XVIII.





ũ	517	533	EX.
52	518	534	548

FIGURE 21. SPECIMEN LAYOUT FOR 7475-T7351 ALUMINUM ALLOY PLATE

Impact. Charpy V-notch test results for longitudinal and transverse specimens are given in Table XVIII.

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<u>Fracture Toughness</u>. Results of slow-bend type tests in both the longitudinal (L-T) and transverse (T-L) directions are given in Table XIX. Specimens were 1.00-inch thick by 2.00-inch wide with a span of 8 inches. The candidate  $K_0$  values shown in Table XIX are considered invalid  $K_{\rm Ic}$  values by existing ASTM criteria.

<u>Fatigue</u>. Axial-load test results for transverse specimens at a load ratio of R = 0.1 are given in Tables XX and XXI. These tests were conducted at room temperature, 250 F, and 350 F for both unnotched and notched ( $K_t = 3.0$ ) specimens. The data are presented as S-N curves in Figures 28 and 29.

<u>Creep and Stress-Rupture</u>. Test results for transverse specimens at 250 F, 350 F, and 500 F are given in Table XXII. Log-stress versus log-time curves are presented in Figure 30.

<u>Stress Corrosion</u>. Transverse specimens were tested as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000-hour test duration.

<u>Thermal Expansion</u>. The coefficient of thermal expansion for this alloy is  $12.9 \times 10^{-6}$  in./in./F from 70 F to 212 F.

Density. The density of this material is 0.101 lb/in.<sup>3</sup>.

Specimen Number	U Tensi	ltimate le Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongetion in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10 <sup>3</sup> ksi
		Long	Itudinal at Room	Temperature		
1L-1 1L-2 1L-3		71.8 72.3 <u>72.2</u>	63.0 62.9 <u>62,7</u>	18.5 18.5 <u>18.0</u>	47.9 48.4 <u>47.1</u>	10.7 10.3 <u>9.7</u>
	Average	72.1	62.9	18.3	47.8	10.2
	,	Tri	insverse at Room	Temperature		
1T-1 1T-2 1T-3	Average	73.2 73.5 <u>73.0</u> 73.2	62.5 62.5 <u>62.1</u> 62.4	14.0 16.0 <u>15.5</u> 15.2	34.9 36.6 <u>34.4</u> 35.3	9.7 9.8 <u>10.0</u> 9.8
			Longitudinal at	250 F		210
1L-4 1L-5 1L-6	Average	55.3 56.0 <u>55.4</u> 55.6	55.3 56.0 <u>55.3</u> 55.5	17.0 17.0 <u>18.0</u> 17.3	60.2 60.4 <u>60.8</u> 60.5	8.9 9.1 <u>9.1</u> 9.0
Transverse at 250 F						
1T-4 1T-5 1T-6	Áverage	57.8 55.9 <u>57.1</u> 56.9	55.8 54.9 <u>55.8</u> 55.5	17.0 17.0 <u>17.0</u> 17.0	52.4 53.0 <u>54.3</u> 53.2	9,2 10,1 <u>*9,4</u> 9,6
Longitudinal at 350 F						
1L-7 1L-8 1L-9	Average	44.7 44.2 <u>45.1</u> 44.7	44.4 44.3 <u>45.1</u> 44.6	20.0 25.0 <u>16.5</u> 20.5	70.0 73.4 <u>71.5</u> 71.6	7.7 7.8 <u>7.9</u> 7.8
	Transverse at 350 F					
1T-7 1T-8 1T-9	Average	45.1 45.7 <u>45.1</u> 45.3	44.7 45.5 <u>44.6</u> 44.9	33.5 23.5 <u>27.5</u> 28.2	72.1 67.0 <u>70.2</u> <b>69.8</b>	8.3 7.5 <u>7.6</u> 7.8
Longitudinal at 500 F						
1L-10 1L-11 1L-12	Average	16.8 18.0 22.3 19.0	16.5 17.8 <u>22.1</u> 18.8	39.5 40.0 <u>27.0</u> 35.5	91.9 91.8 <u>88.4</u> 70.7	7.1 6.7 <u>7.5</u> 7.1
			Transverse at	500 F		
1T-10 1T-11 1T-12	Average	17.4 17.6 <u>17.1</u> 17.4	17.2 17.3 <u>17.0</u> 17.2	40.5 43.5 <u>41.5</u> 41.8	92.2 92.5 <u>92.8</u> 92.5	7.0 6.8 <u>6.6</u> 6.8

## TABLE XV. TENSILE TEST RESULTS FOR 7475-T7351 ALLOY PLATE

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	C	.2 Percent	Compressive
Specimen	0	ffset Yield	Modulus,
Number	St	rength, ksi	10 <sup>3</sup> ksi
	Longitudina	1 at Room Temperature	
2L-1		60.1	10.5
2L-2		61.8	10.4
2L-3		61.1	10.9
	Average	61.0	10.6
	Transverse	at Room Temperature	
2 <b>T</b> -1		65.4	10.6
2T-2		65.7	10.4
2 <b>T</b> -3		65.5	10.4
	Average	65.5	10.5
	Long	Ltudinel at 250 F	
2L-4		54.4	9.6
2L-5		. 55.2	9.3
2L-6		55.0	9.4
	Average	54.9	9.4
	Tra	neverse et 250 F	
2 <b>2-</b> 4		57.3	10.0
2 <b>T</b> -5		57.5	9.9
2 <b>T-</b> 6		58,0	9.7
	Average	57,6	9.9
	Long	itudinal at 350 F	
2L-7		46.2	9.0
2L-8		46.2	8.9
2L-9		46.8	8.8
	Average	46.4	8.9
	Tra	nsverse at 350 F	
2 <b>T</b> -7		48.5	9.4
2 <b>T-</b> 8		48.2	9.9
2 <b>T</b> -9		48.6	9.6
	Average	48.4	9.6
	Long	itudinal at 500 F	
2L=10		17.7	8.2
2L-11		19.5	7.7
2L-12		<u>18.2</u>	7.6
	Average	18.5	7.8
	Tra	nsverse at 500 F	
2T-10		17.8	8.1
2T - 11		19.7	7.8
2 <b>T</b> -12		19.3	<u>7.1</u>
	Average	18,9	7.7

## TABLE XVI. COMPRESSION TEST RESULTS FOR 7475-T7351 ALLOY PLATE

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Specimen Number		Ultimate Shear Strength, ksi
	Longitudin	al
4L-1		45.0
4L-2		46.4
4L-3		44.8
4L-4		46.6
	Average	45.7
	Transvers	e .
4 <b>T</b> -1		43.8
4 <b>T</b> -2		46.3
4T-3		45.9
4 <b>T</b> -4		43.8
	Average	45.0

## TABLE XVII. PIN-SHEAR TEST RESULTS FOR 7475-T7351 ALLOY PLATE AT ROOM TEMPERATURE

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## TABLE XVIII.IMPACT TEST RESULTS FOR 7475-T7351ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number		Energy, ft/lb
	Longitudinal	
10 <b>L-1</b>		15.0
10L-2		21.0
10L-3		14.0
10L-4		15.5
10L-5		18.0
10L-6		19.0
	Average	17.1
	Transverse	
10T-1		7.0
10T-2		5.0
10T-3		5.0
10T-4		5.5
10T-5		8.0
10T-6		5.0
	Average	5.9

TABLE XIX.

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### X. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS FOR 7475-T7351 ALLOY PLATE

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Specimen Number	W, inches	B, inches	, a, Span, P <sub>O</sub> , P <sub>UAX</sub> , f hes inches inches 16 16		f ( <del>a</del> )	K <sub>Q</sub> <sup>(a)</sup>	R <sub>sb</sub> (b)		
			Long	itudinal	(L-T)				
6L-1 6L-2 6L-3 6L-4 6L-5 6L-6	2.00 2.00 2.00 2.00 2.00 2.00	1.00 1.00 1.00 1.00 1.00	1.182 1.061 1.064 0.981 1.069 1.057	8.0 8.0 8.0 8.0 8.0 8.0	7,000 7,200 6,900 7,600 6,800 6,700	8,000 8,200 7,720 9,000 7,950 7,710	3.655 2.947 2.962 2.585 2.987 2.927	72.4 60.0 57.8 55.5 57.5 55.4	2.29 1.78 1.67 1.66 1.76 1.66
			Tra	nsverse ('	<u>T-L)</u>				
6T-1 6T-2 6T-3 6T-4 6T-5 6T-6	2.00 2.00 2.00 2.00 2.00 2.00	1.00 1.00 1.00 1.00 1.00 1.00	1.068 1.043 1.134 1.022 1.078 1.182	8.0 8.0 8.0 8.0 8.0 8.0	6,100 6,300 6,550 6,550 6,350 6,000	6,720 6,550 6,820 6,700 6,550 6,450	2.982 2.859 3.347 2.761 3.033 3.655	51.4 50.9 62.0 51.2 54.5 62.0	1.49 1.38 1.75 1.35 1.48 1,85

(a) Candidate K<sub>Q</sub> values are invalid as K<sub>Ic</sub> values since they do not meet the standard of a, T, < 2.5  $(\frac{K_Q}{TYS})^2$ 

(b) R<sub>sb</sub> is a function of the maximum load that the specimen can sustain, its dimensions, and the yield strength of the material. As explained in ASTM E399-72, it is a useful comparative measure of toughness of materials where size may be less than sufficient for valid K<sub>IC</sub> determination.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-2	60.0	11,600
5-21	57.5	101,600
5-19	55.0	64,200
5-22	52,5	967,700
5-23	52,5	5,587,000
5-1	50,0	1,136,000
5-20	45,0	10,000,000 <sup>(a)</sup>
	<u>250 F</u>	
5-16	65.0	(b)
5-4	60.0	13,400
5-6	55,0	75,000
5-3	50.0	95,000
5-7	45.0	1,319,300
5-5	40.0	824,700
5-18	35.0	10,000,000 <sup>(a)</sup>
	350 F	
5-10	55.0	(b)
5-9	50.0	24,200
5-11	45.0	115,800
5-12	40.0	464,800
5-13	35.0	949,200
5-14	30.0	2,062,800
5-15	25.0	9,979,100

#### TABLE XX. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 7475-T7351 ALLOY PLATE

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(a) Did not fail.(b) Failed on loading.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-48	35	11,000
5-49	30	37,500
5-50	25	94,140
5-51	20	171,040
5-54	1.5	518,400
5-53	12,5	12,786,000 <sup>(a)</sup>
5-52	10	10,191,000 <sup>(a)</sup>
	<u>250 F</u>	
5-31	45	3,900
5-32	40	8,400
5-36	35	9,000
5-33	30	23,900
5-37	25	41,600
5-34	20	165,900
5-38	15	381,400
5-35	10	10,000,000 <sup>(a)</sup>
	<u>350 F</u>	
5-39	45	2,000
5-40	40	3,200
5-41	35	9,300
5-42	30	23,200
5-43	25	13,400
5-45	25	33,100
5-44	20	157,800
5-46	15	394,800
5-47	10	10,000,000 <sup>(a)</sup>

## TABLE XXI. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K<sub>t</sub>=3.0) 7475-T7351 ALLOY PLATE

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(a) Did not fail.

TABLE XXII. SUMMARY DATA ON CREEP AND RUFTURE PROPERTIES FOR 7475-T7351 ALUMINUM PLATE

Minimum Creep Rate,	percent	0.31	0.0029	1	0.00011	ł	0.0034	0.00078	0.00069	6.0	0.017	0.0019	0.00008	
Reduction of Area,	percent	56.7	62.8	ł	1 1	72.6	84.9	84.2	ł	90.6	93.5	88.2	1	
Elongation in 2 Inches,	percent	16.7	15.2	0.672	0.587	19.7	22.0	24.2	0.345	37.1	33,3	31.1	0.261	
Rupture Time,	hours	12.3	422.4 (b)	311.4 / 1	1004.2 <sup>\U)</sup>	11.8	209.1	930.5 , , ,	1821.8 <sup>(U)</sup>	0.8	61.0	1033, 8 / L /	1056.9(")	
Initial Strain,	percent	0.617	0.591	0,446	0,363	0.380	0.295	0.220	0.147	0.280	0.148	0.087	0.057	
ition,	2.0	6.0	350	1	8	ţ	190	830	ł	0.32	43	640	ł	
Deforma	1.0	3.0	250	i i	ł	7.8	160	660	:	0.17	30	410	:	
ced Creep percent	0.5	1.5	130		3550 <sup>(8)</sup>	ŝ	109	445 , 、	6200 <sup>(a)</sup>	0.09	19	190,	4450 <sup>(a)</sup>	
Indicat F	0.2	0.4	20	280	815	1.4	38	160	1800	0,04	8.0	45	1000	
Hours to	0.1	0.1	3.0	40	150	0.4	12	45	560	0,02	3.0	10	175	
Temper- ature,	EL	250	250	250	250	350	350	350	350	500	500	500	500	
Stress.	ksi	50	43	35	30	30	20	15	6	10		• •••	2.5	
Specimen	Number	3-2	3-4	3-7	3 <b>-</b> 8	3=11	0-6	44	3-12	35		3-6	3-10	

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(a) Estimate.

(b) Test discontinued.

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FIGURE 22. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)





FIGURE 23. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEAPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (TRANSVERSE)

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FIGURE 24. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)

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FIGURE 25. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (TRANSVERSE)



FIGURE 26. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7475-T7351 ALLOY PLATE



FIGURE 27. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7475-T7351 ALLOY PLATE

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FIG.RE 28. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7475-T7351 ALLOY PLATE







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∆ 05% creep O 0.2% creep

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X Rupture

#### 2419-T851\_Aluminum\_Place

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#### Material Description

Alloy 2419 is a recent development of the Aluminum Company of America. It is essentially a 2219 alloy with more closely controlled composition. Mechanical properties are the same as 2219 with improved fracture toughness. The alloy is readily weldable and is useful for applications at a wide range of temperatures from -452 F to about 600 F.

Composition limits for 2419 are as shown:

Chemical	
Composition	Percent
Silicon	0.15 max
Iron	0.18 max
Copper	5.8-6.8
Manganese	0.20-0.40
Magnasium	0.02 max
Zinc	0.10 max
Titanium	0.02-0.10
Others	each 0.05,
	total 0.15
Aluminum	Balance

The material used for this evaluation was a 2-inch-thick plate from Alcoa lot number 270-841.

#### Processing and Heat Treatment

The specimen layout for 2419 shown in Figure 31. The alloy was evaluated in the as-received -T851 temper.

#### Test Results

<u>Tension</u>. Tests were conducted at room temperature, 250 F, 350 F, and 500 F on both longitudinal and transverse specimens. Test results are given in Table XXIII. Typical stress-strain curves at temperature are presented in Figures 32 and 33. Effect-of-temperature curves are shown in Figure 36.

<u>Compression</u>. Tests were conducted at room temperature, 250 F, 350 F, and 500 F. Tabular test results are given in Table XXIV. Typical stress-strain and tangent-modulus curves at temperature are presented in Figures 34 and 35. Effect-of-temperature curves are shown in Figure 37.

Shear. Tests were conducted at room temperature only on pin-shear type longitudinal and transverse specimens. Test results are given in Table XXV.



<b>51</b> 9	613	971					4					B-15:2				
	ophess			Steui	et 116 Tough	Fractu	613	1								
	nocture To			5												
											671		671	674		
	<u> </u>									11 11		2 11	<b>9</b> 11	<b>E</b> 11	1 11	
	11	512 518 51	ราวราราร	זרו	20 60	boct						ensite 12 L				
	2TH	Compo			あ	Ē						4				
	213	215	npression IST	<u>8</u> 217		279			IT5						iTu	
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		21	<b> </b>			223	109	augito7	239						553	
		8				<u>S</u>			537						551	
<u></u>		53				59			535						549	
			1			517	<u> </u>		8						547	

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FIGURE 31. SPECIMEN LAYOUT FOR 2419-T851 ALUMINUM ALLOY PLATE

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<u>Impact</u>. Charpy V-notch test results for longitudinal and transverse specimens are given in Table XXVI.

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<u>Fracture Toughness</u>. Results of slow-bend type tests in both the longitudinal (L-T) and transverse (T-L) directions are given in Table XXVII. Specimens were 1.00-inch thick by 2.00-inch wide with a span of 8 inches. The candidate KQ values shown in Table XXVII are considered valid  $K_{\rm Ic}$  values by existing ASTM criteria.

<u>Fatigue</u>. Axial-load test results for transverse specimens at a load ratio of R = 0.1 are given in Tables XXVIII and XXIX. These tests were conducted at room temperature, 250 F, and 350 F for both unnotched and notched ( $K_t = 3.0$ ) specimens. The data are presented as S-N curves in Figures 38 and 39.

<u>Creep and Stress-Rupture</u>. Test results for transverse specimens at 250 F, 350 F, and 500 F are given in Table XXX. Log-stress versus log-time curves are presented in Figure 40.

<u>Stress Corrosion</u>. Transverse specimens were tested as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000-hour test duration.

<u>Thermal Expansion</u>. The coefficient of thermal expansion for this alloy is  $12.4 \times 10^{-6}$  in./in./F from 70 F to 212 F.

Density. The density of this material is 0.102 lb/in.<sup>3</sup>.

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10 <sup>3</sup> ksi
	1	ongitudinal at R	oom Temperature		
1 <b>L-1</b>	66.6	52.2	11.0	24.0	10.0
1L-2	66.5	52.5	11.0	23.0	10.6
1 <b>L-3</b>	66.9	<u>52.5</u>	<u>11.0</u>	<u>23,7</u>	<u>10.7</u>
Avera	ige 66.7	52.4	11.0	23.6	10.4
		Transverse at Ro	om Temperature		
1 <b>T-1</b>	66.5	51.4	10.0	14.6	11.5
1 <b>T</b> -2	66.5	51.3	11.0	19.3	10.6
1T-3	66.3	50.9	11.0	$\frac{20.4}{10.1}$	<u>10.7</u>
Avet	lge 00.4	51.2	10.7	10.1	10.8
		Longitudine	1 at 250 F		
1L-4	55.2	46.9	13.0	36.5	10.9
1L-5	55.7	46.7	14.0	36.1	9.7
IL-6	<u>, , , , , , , , , , , , , , , , , , , </u>	40.8	18.0	$\frac{41.1}{37.0}$	$\frac{11.0}{10.5}$
Aver	<b>LÃE 2214</b>	40.0 Transvetse	13.0 At 250 F	37,9	10.5
1			10.0	a	0.6
17-4	JJ.4 5/ 9	43.0 /s 0	13.0	34.3	9.0
11-5	54.8	45.3	13.0	33 1	9.4
Aver	ige 54.9	45.4	13.2	33.9	9.5
		Longitudine	1 at 350 F		
1L-7	45.6	41.4	14.5	49.7	9.3
1L-8	45.8	41.5	14.5	46.0	8.9
1L-9	45,1	<u>41.2</u>	14.5	49.6	<u>9,1</u>
Aver	nge 45.5	41.4	14.5	48.4	9.1
		Transverse	at 350 F		
1 <b>T</b> -7	44.5	40.0	16.0	46.4	9.8
1 <b>T-8</b>	44.6	39.7	13.5	45.6	9.8
1T-9	44,2	39,5	$\frac{15.0}{14.9}$	40.7	8.8
AVET	<b>uga</b> 44,3	37.7	14.0	40.2	9.5
		Longitudini	al at 500 F		
1L-10	23.0	21.4	12.0	60.4	8.5
1L-11	20.6	20.0	12.0	45.3	6.1
1L~12	$\frac{23.0}{23.0}$	$\frac{21.3}{20.9}$	$\frac{12.0}{10.0}$	54.0	7.5
AVET	<b>-8</b> e 22,2	20. y	12.U	33.2	/.4
1	00 /	LIGNEVEIS		<u> </u>	A 3
1T=10 1m_11	22.4 23 A	4U./ 22 1	10 0	47.0 54 1	<b>7.</b> 3
17-11	23.4	44.L 99 9	18 0	53.0	7.J 8 8
Aver	age 23.1	21.7	18.0	51.6	9.1

# TABLE XXIII.TENSILE TEST RESULTS FOR 2419-T851ALUMINUM ALLOY PLATE

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Specimen Number	0 Of St	.2 Percent ifset Yield rength, ksi	Compressive Modulus, 10 <sup>3</sup> ksi
······································	Longi cudin	al at Room Temperature	
211		53.5	10.5
2L-2		53.0	11.2
2L-3		<u>53.3</u>	10.8
	Average	53.3	10.8
	Transvers	e at Room Temperature	
2 <b>T</b> -1		51.7	10.9
2 <b>T</b> -2		51.7	10.4
2 <b>T</b> -3	Augrage	<u>51.0</u> 51.7	$\frac{10.8}{10.7}$
	VAL OF	dendinal at 250 F	1011
0× 4	Long	10011111 40 130 F	10 3
21-4		40.2 47 4	10.5
216		47.7	10.4
24-0	Average	47.8	10.5
	Tra	nsverse at 250 F	
2T-4		47.0	10.2
2 <b>T</b> -5		46.9	10.2
2 <b>T</b> -6		<u>46.8</u>	<u>10.8</u>
	Average	46.9	10.4
	Long	<u>itudinal at 350 F</u>	
2L-7		41.8	10.0
2L-8		42.2	9.9
2L-9	Average	42.7	$\frac{10.0}{10.0}$
	Tr:	anguerge at 350 F	1010
0m 7		41 6	0.5
21-7 27-8		41.0	9.9
21-0 2 <b>T-9</b>		41.5	10.1
	Average	41.7	9.8
	Long	<u>zitudinal at 500 F</u>	
2L-10		25,3	8.8
2L-11		25.4	9.5
2L-12		25.8	<u>9.5</u>
	Average	25.5	9.3
	<u>Tra</u>	ansverse at 500 F	~ ~
2T-10		25.4	8.9
21-11 21-12		25.3	9.2
21-12	Average	25.5	9.0

### TABLE XXIV.COMPRESSION TEST RESULTS FOR 2419-T851 ALUMINUM ALLOY PLATE

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Specimen Number			Ultimate Shear Strength, ksi
	<u>Longitudinal</u>		
4L-1			38.5
4L-2			40.5
4L-3			38.9
4L-4			39.8
		Average	39.4
	Transverse		
4 <b>T</b> -1			39.3
4T-2			38.9
4 <b>T</b> -3			39.6
<b>4</b> T-4			40.1
		Average	39.5

# TABLE XXV. PIN SHEAR TEST RESULTS FOR 2419-T851 ALUMINUM ALLOY PLATE AT ROOM TEMPERATURE

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# TABLE XXVI. IMPACT TEST RESULTS FOR 2419-T851ALUMINUM ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number			Energy, ft/1b
	Longitudinal		
10L-1			6.0
10L-2			6.0
10L-3			5.0
10L-4			6.0
10L-5			5.0
10L-5			5,0
		Average	5.5
	Transverse		
10 <b>T-1</b>			4.0
10T-2			5.0
10T-3			4.0
10T-4			4.0
10T-5			5.0
10T-6			4.0
		Avenage	4.3

Specimen Number	W, inches	a, inches	B, inches	P <sub>Q</sub> . 15	Span, inches	f( <mark>å</mark> )	K <sub>Q</sub> (a)
		L	ongitudinal	(L-T)			
6L-1 6L-2 6L-3 6L-4 6L-5 6L-6	2.00 2.00 2.00 2.00 2.00 2.00	0.932 0.998 0.988 0.968 0.962 1.016	1.00 1.00 1.00 1.00 1.00	5,000 4,900 4,750 5,050 4,800 4,600	8.0 8.0 8.0 8.0 8.0 8.0	2.396 2.656 2.614 2.533 2.509 2.734	33.89 36.80 35.12 36.18 34.06 <u>35,58</u>
			Transverse	<u>(T-L)</u>		Average	35.30
6T-1 6T-2 6T-3 6T-4 6T-5 6T-6	2.00 2.00 2.00 2.00 2.00 2.00	0.972 0.944 0.988 0.994 0.961 0.974	1.00 1.00 1.00 1.00 1.00 1.00	4,200 4,400 4,200 4,000 4,450 3,900	8.0 8.0 8.0 8.0 8.0 8.0	2.549 2.440 2.614 2.639 2.505 2.556 Average	30.20 30.37 31.05 29.86 31.53 <u>28.20</u> 30.20

## TABLE XXVII. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS FOR 2419-T851 ALLOY PLATE AT ROOM TEMPERATURE

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(a) These candidate K<sub>Q</sub> values are considered valid K<sub>IC</sub> values by existing ASTM standards.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	60	12,200
5-6	55	14,100
5-8	52.5	24,500
5-2	50	33,400
5-4	45	29,700
5-9	45	121,100
5-3	40	207,500
5-7	35	14,128,800 <sup>(#)</sup>
5-5	30	10,000,000
	<u>250 F</u>	
5-12	60	6,700
5-13	55	17,200
5-11	50	36,200
5-14	45	97,500
5-10	40	326,200
5-15	37.5	749,700
5-16	35	3,536,800
5-17	32.5	2,461,400
5-18	32.5	2,453,800
5-19	30	6,881,000
	<u>350 F</u>	
5-55	50	100
5-57	50	150
5-56	40	120,200
5-58	35	186,200
5-59	30	2,365,400
5-60	27.5	5,921,900
5-61	25	10,000,000 (2)

# TABLE XXVIII. AXIAL LOAD FATIGUE TEST RESULTS FOR<br/>UNNOTCHED 2419-T851 ALLOY PLATE<br/>(TRANSVERSE, R = 0.1)

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(a) Did not fail.

Specimen Number	Maximum Stress, kui	Lifetime, cycles
	Room Temperature	
5-31	45	3,600
5-32	40	8,600
5-33	35	9,200
5-34	30	25,200
5-35	25	25,400
5-36	20	66,300
5-37	15	279,100
5-38	10	10,370,500 <sup>(A)</sup>
	<u>250 F</u>	
5-40	40	5,600
5-42	35	10,100
5-39	30	15,800
5-43	25	25,300
5-41	20	63,700
5-44	15	383,400
5-45	12.5	914,100
5-46	10	10,102,000 <sup>(a)</sup>
	<u>350 F</u>	
5-41	35	10,500
5-48	30	24,200
5-49	25	23,000
5-50	20	69,400
5-51	15	462,900
5-52	15	483,700
5-54	12.5	2,918,200
5-53	10	10,885,000

### TABLE XXIX. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ( $K_{L} = 3.0$ ) 2419-T851 ALLOY PLATE (TRANSVERSE, R = 0.1)

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(a) Did not fail.

TABLE XXX. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR 2419-T851 ALUMINUM ALLOY PLATE

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										Elongation		Mintaum
Spectmen	n Stress,	femper- ature,	Hours	te Indica P	sted Creep ercent	Deforma	tion,	Initial Strain,	Rupture Time,	fn 2 Inches,	Reduction of Area,	Creep Rate,
Number	ks í	<u>ند</u>	0.1	0.2	0.5	1.0	2.0	percent	hours	percent	percent	percent
3-7	50	256	:	1	:	0.07	0.16	2.234	0.4	11.5	26.1	8.4
3-10	45	250	0.3	0.06	0.4	2.0	-1	0.719	41.6	10.8	32.0	0.064
3-1	40	250	0.5	51	63	335	965	0.576	1243.7	5.4	10.6	0.0014
3-11	35	25 .	26	210	2100(5)	;	•	0.523	500.7 ( <sup>D)</sup>	0.778	;	0.00016
3-15	30	25ü	120	1970	:	1	ł	0.434	1319.7 <sup>(0)</sup>	0.611	;	0.00042
œ3-4	67	350	i i	0.01	0.03	0.06	0.14	0.835	0.4	13.1	40.8	12.0
S-5 1	35	350	0.05	0.1	0.9		6.5	0.496	11.3	11.5	46.5	0.26
3-3	30	350	0.6	3.5	20	61	126	0.385	172.6	6.2	1.91	0.013
3-6	25	350	5.2	37,25	250	680	1165	0.385	1313.3,	4.6	4.7	0.00005
3-9	<b>±</b>	350	200	30:00	;	•	1	0.250	1512.0 <sup>(D)</sup>	0.419	;	0.000025
3-16	22.6	500	*	8 1	:	:	ł	0.627	1.0	16.9	59.3	ł
3-12	20	505	0.05	0.11	0.45	1.1	2.2	0.387	3.2	۲.۲	31.1	0.87
3-13	14	503	7	t	37	65	06	0.177	94.9	3.1	4.6	0.01
3-8	<b>ا</b> د	500	20	<b>6</b> .5	269	510	:	0.181	698.1 /L	2.3	2.2	0.0015
3-14	¢	20 <u>0</u>	170	1:35	4500	:	ţ	0.031	1319.5 <sup>(U)</sup>	0.257	6	0.00009
3-2	5	50,1	>1000	4	:	t	1	0.100	600.8'")	0.173	ł	nf.l

(a) Estimated.

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(b) lest discontinued.



FIGURE 32. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (LONGITUDINAL)



FIGURE 33. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (TRANSVERSE)

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FIGURE 34. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (LONGITUDINAL)

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Stress, ksi

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FIGURE 35. TYPICAL COMPRESSIVE STRESS-STATE AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (TRANSVERSE)



FIGURE 36. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 2419-T851 ALLOY PLATE



FIGURE 37. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 2419-T851 ALLOY PLATE



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FIGURE 38. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 2419-T851 ALUMINUM ALLOY PLATE





Stress, ksi

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### Ti-6A1-2Zr-2Sn-2Mo-2Cr Alloy

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### Material Description

This alpha-beta alloy, designed for deep hardenability, is a recent development of RMI Company. Preliminary information shows the material also to have low density, high modulus, high toughness, and good producibility. Strength retention to 800 F is good.

The material used for this evaluation was a 4-inch x 6-inch forged billet from RMI ingot number 890180 which had the following composition:

Element	Percent
<b>A1</b>	5,8
Sn	2.1
Zr	1.8
Mo	2.0
Cr	1.9
Si	0.21
Fe	0.06
С	0.02
v	0.02
0,	0.11
N	0.01
Ti	Balance.

Additional information on this alloy is available from work performed by RMI Company under Contract F33615-72-C-1152.

#### Processing and Heat Treating

The billet was heat-treated to the duplex-annealed condition by RMI Company using the following procedure: 1745 F, 1 hour, air cool to 1560 F and water quench; plus 1000 F for 8 hours and air cool. Specimens received no further heat treatment before testing. The specimen layout is shown in Figure 41.

#### Test Results

<u>Tension</u>. Results of tests in both the longitudinal and long transverse directions at room temperature, 400 F, 600 F, and 800 F are given in Table XXXI. Typical stress-strain curves at temperature are shown in Figures 42 and 43. Effect-of-temperature curves are shown in Figure 46.

<u>Compression</u>. Results of tests in both the longitudinal and long transverse directions at room temperature, 400 F, 600 F, and 800 F are given in Table XXXII. Typical stress-strain and tangent-modulus curves are shown in Figures 44 and 45. Effect-of-temperature curves are presented in Figure 47.



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Shear. Pin shear test results for both the longitudinal and long transverse directions at room temperature are given in Table XXXIII. のないない。

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efit The second Indact. Results of Charpy V-notch tests at room temperature in both the longitudinal and long transverse directions are given in Table XXXIV.

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<u>Fracture Touchness</u>. Results of slow-bend type tests in both the longitudinal (L-T) and long transverse (T-L) directions are given in Table XXXV. Even though the candidate KQ values do not meet the rigorous a, T, < 2.5 (KQ/TYS)<sup>8</sup> criteria they are above 2.2 (KQ/TYS)<sup>8</sup> and should be considered good indicative K<sub>IC</sub> values.

Fatigue. Axial load fatigue tests were conducted at room temperature, 400 F, and 600 F for unnotched and notched long transverse specimens at a stress ratio of R = 0.1. Results are given in Tables XXXVI and XXXVII. S-N curves are presented in Figures 48 and 49.

specimens at 400 F, 600 F, and 800 F. Tabular test results are given in Table XXXVIII. Log-stress versus log-time curves are presented in Figure 50.

<u>Stress Corresion</u>. Specimens were tested as described in the experimental procedures section of this report. No fractures or cracks occurred in the 1000-hour test duration.

Thermal Expansion. The thermal expansion coefficient for this alloy is  $5.1 \times 10^{-5}$  in./in./F for 70 to 800 F.

Density. The density value is 0.162 lb./in.<sup>3</sup>.

## TABLE XXXI. TENSILE TEST RESULTS FOR DUPLEX ANNEALED T1-6A1-2Sn-2Zr-2Mo-2Cr FORGED BILLET

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Specimen Number	Ultimate Tensile Strength. ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10 <sup>9</sup> ksi
		ongitudinal at Re	om Tempersture		<u></u>
1L-1	152.8	141.4	17.5	38.9	15.2
1L-2	166.8	149.3	13.0	32.0	15.8
1L-3	155.7	140.8	15.5	37.0	15.9
Aver	age 158.4	143.9	15.3	36.0	15.6
	ł	ons Transverse at	Room Temperatur	<b>t</b> .	•
1 <b>T-1</b>	164.2	149.0	14.0	36.4	15.9
1T-2	163.8	148.6	14.5	37.7	15,9
1T-3	170.0	153.5	12.5	35.9	15.5
Aver	age 166.0	150.4	13.7	36.7	15.8
· .		Longitudinal	at 400 F	۰ ۱	* . . •
1L-4	135.9	111.4	15.0	45.1	13.7
11-5	131.8	107.9	18.0	51.8	15.9
1L-6	141.2	113.7	16.0	45.2	14.6
Aver	age 136.3	111.0	16.3	47.2	14.7
•		Long Transver	se at 400 F		
1 <b>T</b> -4	133.7	110.7	16.0	45.2	13.7
1T-5	151.5	120.7	12.0	54.1	14.0
1T-6	151.2	120.7	14.0	45.0	14.0
Aver	age 145.5	117.4	14.0	48.1	13.9
		Longitudinal	at 600 F		
1L-7	132.2	101.5	17.0	40.0	14.4
1L-8	138.4	101.5	16.0	34.9	14.5
1L-9	141.2	104.6	13.0	33.1	14.6
Aver	age 137.3	102.5	15.3	36.0	14.5
		Long Transver	se at 600 F		
1T-7	131.1	99.3	15.0	43.8	15.2
1T <b>-8</b>	131.9	100.5	17.0	44.8	14.6
1T-9	133.4	100.6	<u>16.0</u>	32.3	<u>14.7</u>
Avei	rage 132.1	100.6	16.0	40.3	14.8
		Longitudina1	<u>at 800 F</u>		
1L-10	132.3	96.9	18.0	50.3	13.6
1L-11	142.1	103.4	16.5	52.0	14.4
1L-12	<u>144.9</u>	105.7	15.0	<u>39,3</u>	12.3
Avei	rage 139.8	102.0	16.5	47.2	13.4
		Long Transver	se at 800 F		
1T-10	130.1	96.7	18.0	47.6	13.4
1T-11	136.7	103.6	19.0	53.2	13.4
11-12	131.8	96.2	18.0	45.5	13.5
Avei	cage 132.9	98.8	18.3	48.8	13.4

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 <sup>3</sup> ksi
ما	ngitudinal et Room Tempera	iture
2 <b>L-1</b>	148.6	16-4
21-2	151.5	16.2
2L-3	148.2	<u>15,6</u>
Averag	e 149.4	16.1
Lon	Transverse at Room Tempe	rature
27-1	155.7	16.5
2T-2	157.7	16.3
2 <b>T-3</b>	<u>150.5</u>	15.6
Averag	e 154,6	16.1
	Longitudinal at 400 F	
2L-4	119.2	15.0
215	119.0	14.3
2L-6	110.3	<u>14.8</u>
Averag	e 116.2	14.7
	Long Transverse at 400	F
2 <b>T</b> -4	129.1	15.2
2T-5	121.3	15.5
2T-6	e <u>116.1</u>	<u>15,2</u> 15,3
	tonnitudinal at 600 F	
<b>31 7</b>		14.4
21-7	108.2	14.0
219	102.7	14.0
Averag	e 106.4	14.3
	Long Transverse at 600	F
2 <b>T-7</b>	111.9	14.8
2 <b>T-8</b>	104.6	15.1
2 <b>T-9</b>	<u>105.9</u>	14.4
Averag	e 107.5	14.8
	Longitudinal at 800 F	
21-10	94.9	13.2
2L-11	101.0	13,6
2L-12 Averag	9/./	13.2
uverak		t → , c
10 <b>1</b> 0	Long transverse at 500	<u> </u>
28-10	100.0	11,0
21-11	102.1	12.9
Аунгли	102.1	13.4

# TABLE XXXII. COMPRESSION TEST RESULTS FOR DUPLEX ANNEALED Ti-6A1-2Sn-2Zr-2Mo-2Cr FORGED BILLET

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Specimën Number		U11 St	timate Shear rength, ksi
	Longitudinal		
4L-1			104.8
4L-2			100.2
4L-3			106.4
4L-4			49.7
		Average	102.8
	Long 'iransverse		
4T-1			104.1
4T-2		· .	104.1
4T-3			107.4
4T-4			104.8
		Average	105.1

TABLE XXXIII, PIN SHEAR TEST RESULTS FOR DUPLEX ANNEALED TI-6A1-2SB-2ZT-2ND-2CT FORGED BILLET AT ROOM TEMPERATURE

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### TABLE XXXIV. IMPACT TEST RESULTS FOR DUPLEX ANNEALED Ti-6A1-2Sn-2Zr-2Mo-2Cr FORGED BILLET AT ROOM TEMPERATURE

Specimen Number		Energy, foot-pound
	Longitudinal	
10L-1		11.5
10L-2		15.0
10L-3		15.0
10L-4		18.5
1015		14.5
	Average	14.9
يما	n <u>r lransverse</u>	
107-1		10.0
10T-2		15 1
10T-3		8 0
10T-4		17.0
10T-5		10.00
10T-6		$\Gamma_{1}$ o
	Avera date:	1

### TABLE XXXV. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGBNESS TESTS FOR DUPLEX\_ANNEALED TI-6A1-2Sn-2Zr-2Mo+2Cr FORGED BILLET

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pecimen Number	۷, inches	a, inches	T, inches	P. 1bs.	Span, inclus	f (g)	K <sub>Q</sub> (a)
	<u> </u>	Loi	ngitudinal	(L-T)			
6L-1	1.500	0.746	0.750	7,600	6.0	2.64	87.,4
6L-?	1,500	0.783	0.750	7,200	6.0	2,86	89,8
6L-3	1.500	0.723	0.750	7,950	6.0	2.52	87.1
614	1,500	0.763	0,750	7,350	6.0	2.74	87.7
		Lon	g Transvers	<u>e ((T-L)</u>		• •	
6T-1	1.500	0.770	0.750	7,650	6.0	2,78	92.7
67 . 7	1,500	0.777	0.750	7,550	6.0	2.82	92.9
61-3	1.500	9.770	0,750	8 025	6,0	2.78	97.2

(a) Candidate K<sub>Q</sub> values are invalid as K<sub>1</sub> values since they do not meet the rigorous standard of a, T,  $< 2.5 \left(\frac{K_Q}{TYS}\right)^2$ . However, they is exceed a 2.2  $\left(\frac{K_Q}{TYS}\right)^2$  and as such should be considered matrinally valid.

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Speciman Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-3	145	52,730
5-4	135	37,730
5-5	125	159,300
5-6	115	303,270
5-2	205	392,790
5-8	95	429,580
5-9	85	4,527,700
5-1	75	2,268,600
5-7	65	10,003,500 <sup>(a)</sup>
	400 F	
5-10	145	8,400
5-11	135	12,900
5-13	125	15,800
5-14	115	47,900
5-15	105	212,400
5-16	95	1,277,700
5-12	85	10,130,900(a)
	600 F	
5-24	135	( <b>b</b> )
5-23	125	15,400
5-18	115	14,700
5-19	105	218,300
5-20	95	836,60t
5-21	35	1,911,100
5-22	.5	ດໍ ເຮດ, ເປນ
5-25	• ()	13 808 600 11

# TABLE XXXVI. ANIAL LOAD FATUGUE TEST RESULTS FOR UNNOTCHED DUPLEX -ANNEALED T1-6A1-2Sn-2Zr-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE, R = 0.1)

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(a) bid not rail.

(b) shills on londing.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-32	95	3,600
5-31	85	8,600
5-33	75	11,400
5-34	65	23,400
5-35	55	89,100
5-37	50	89,900
5 <b>-38</b>	45	153,200
5-36	40	5,069,900
5-39	35	11,645,200 <sup>(a)</sup>
	400 F	
5-40	85	3,700
5-41	75	6,850
5-42	65	14,700
5-43	55	33,300
5-46	47.5	141,200
5-44	45	417,400
5-47	40	237,000
5-34	35	17,270,800 <sup>(a)</sup>
	600 F	
5-49	85	2,900
5-48	75	4,000
5-50	65	8,600
5-51	55	22,500
5-54	50	194,600
5-53	47.5	527.800
5-52	45	10,084,900 <sup>(a)</sup>
J <b>-</b> J <b>L</b>		,,

TABLE XXXVII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ( $K_{t} = 3.0$ ) DUPLEX-ANNEALED Ti-6A1-2Sn-2Zr-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE, R = 0.1)

(a) Did not fail.

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TABLE XXXVIII. SUPPARY DATA ON CREEP AND RUFURE PROPERTIES FOR DUPLEX ANNEALED TI-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET

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		Temper-	Hours	ro Indicare	ed Creep	Deformat	ion,	[nitial	Rupture	<b>Elongation</b>	Reduction	Minimum
norimon	Strees	ature.		ă	ercent .			Strain,	Time,	in 2 Inches,	of Area.	Creep Sate.
Number	ksi	ц	0.1	0,2	0.5	1.0	2.0	percent	hour	percent	percent	percent
							I			2 61	0 75	{
3-1	135.2	400	ł	1	:	ł	:	3.401	on Loading	0.01		
3_4.9	132	400	1	ł	!	:	ł	2.837	1009.0(0)	3.592	;	0.00010
	128	009	:	0.07	150	>1000	:	0.773	502.6(b)	3,365	:	• •
3-11	100	400	160	1500 <sup>(a)</sup>	ł	ł	;		1007.4(5)	0.950	1	0. JOOD 0
									on Londing	- 0	52.2	8 1
3-2	148	600	ł	ı	:	!	:	•		4 6	1	
3-5	131.6	600	ł	ł	4 1	1	;	:	On Loading	15.2	<b>J</b> , <b>L</b>	
3-100	1 28	600	ł	:	ł	;	;	2.564	1002.7(0)	2.99	:	0.0000
3-7	115	600	9.6	6.0	4 7	800	;	1.984	789.7(")	2.988	:	n. uuu24
3-10	00	600	13	65	800 <sup>(a)</sup>	1	ł	0.951	269.0 <sup>(0)</sup>	1.307	:	
3-12	80	600	30	375	3000 ( 4 )	1	1	0.340	634.0	0.570	:	0.0000
•		000				l t	1	1	On Loading	12.1	34.5	:
	151	800	:	4	:					-	16 0	0 0079
3-6	120	800	1	0.10	9.25		2	5.0/5	(q) , 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0	7.1		0.00067
3 <b>-</b> 8	85	800	2.0	12	180,3)	1200(3)	:	0.701	238.4 (b)	2.232	:	0000013
3-9	50	800	35	600	4700 <sup>(a)</sup>	:	;	0.280	840, 2	0.504	:	C/0000.0

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(a) Estimate.

(b) Test discontinued.

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FIGURE 42. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED TI-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET (LONGITUDINAL)



FIGURE 43. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED TI-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLLT (LONG TRANSVERSE)

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FIGURE 44. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED Ti-6A1-2Zr-2Su-2Mo-2Cr FORCED BILLET (LONGITUDINAL)



FIGURE 45. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED T1-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE)



FIGURE 46. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF DUPLEX ANNEALED T1-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET



FIGURE 47. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF DUPLEX ANNEALED Ti-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET



FIGURE 48. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED DUPLEX ANNEALED T1-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET



FIGURE 49. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_t = 3.0$ ) DUPLEX ANNEALED T1-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET

000 <u>8</u> Time, hours Q FIGURE 50. 800 F

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600 F

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Stress, ksi

#### Ti-6A1-7Cb-1Ta-1Mo Alloy Plate

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### Material Description

6A1-2Cb-1Ta-1Mo titanium alloy is a modification by RMI Company of the Ti-7A1-2Cb-1Ta composition. The modification was developed specifically for saltwater stress-corrosion resistance. The alloy is of medium strength and is forgeable and weldable. It is generally used in the annealed condition. Some increase in strength can be obtained by solution treating and aging, but at a sacrifice in ductility and toughness.

Ti-6A1-2Cb-1Ta-1Mo alloy is available as billet, bar, plate, sheet, and wire. It is normally processed in the beta phase region.

The material evaluated was a 13-inch-thick plate from RMI ingot number 294447 with the following composition:

Chemical Composition	Percent
Carbon	.02
Nitrogen	.006
Iron	.07
Aluminum	6.0
Columbium	1.9
Tantalum	.93
Molybdenum	.77
Oxygen	.08
Titanium	Balance.

#### Processing and Heat Treating

The material was evaluated in the as-received beta-processed and annealed (1825 F, 1 hour, air cooled) condition. The specimen layout is shown in Figure 51.

#### Test Results

<u>Tension</u>. Results of tests in the 'ongitudinal and transverse directions at room temperature, 400 F, 600 F, and 800 F are given in Table XXXIX. Typical stress-strain curves at temperature are shown in Figures 52 and 53. Effect-of-temperature curves are presented in Figure 56.

<u>Compression</u>. Results of tests in the longitudinal and transverse directions at room temperature, 400 F, 600 F, and 800 F are given in Table XL. Typical stress-strain and tangent-modulus curves are shown in Figures 54 and 55. Effect-of-temperature curves are presented in Figure 57.







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52	518	534	548

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Shear. Results of pin shear tests at room temperature for both the longitudinal and transverse directions are given in Table XLI.

Impact. Results of Charpy V-notch tests for longitudinal and transverse specimens at room temperature are given in Table XLII.

<u>Fracture Toughness</u>. Results of slow-bend type tests at room temperature for longitudinal (L-T) and transverse (T-L) specimens are given in Table XLIII. Candidate K<sub>Q</sub> values shown in the table are not valid K<sub>Ic</sub> values since they did not meet the standard of  $P_{max}/P_Q = 1.10$ . Therefore, as recommended in ASTM E399, R<sub>sb</sub> values have been calculated and are shown in the table.

<u>Fatigue</u>. Results of fatigue tests for unnotched and notched transverse specimens at room temperature, 400 F, and 600 F arc given in Tables XLIV and XLV. S-N curves are presented in Figures 58 and 59.

<u>Creep and Stress-Rupture</u>. Tests were conducted on transverse specimens at 400 F, 600 F, and 800 F. Tabular test results are given in Table XLVI. Log-stress versus log-time curves are presented in Figure 60.

<u>Stress Corrosion</u>. Specimens were tested as described in the experimental procedures section of this report. No failures or cracks occurred during the test duration.

<u>Thermal Expansion</u>. The coefficient of thermal expansion for this alloy is  $5.2 \times 10^{-6}$  in./in./F for room temperature to 800 F.

Density. The density of this material is 0.162 lb./in.<sup>3</sup>.

# TABLE XXXIX. TENSILE TEST RESULTS FOR ANNEALEDTi-6A1-2Cb-1Ta-1Mo ALLOY PLATE

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Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in Two Inches, Percent	Reduction in Area, Percent	Tensile Modulus, 10 <sup>3</sup> ksi				
Longitudinal at Room Temperature									
1L-1 1L-2 1L-3 Average	116.5 117.7 <u>118.5</u> 117.6	103.1 101.1 <u>102.0</u> 102.1	19.0 18.0 <u>18.0</u> 18.3	33.7 35.3 <u>32.4</u> 33.8	16.9 17.1 <u>16.9</u> 17.0				
	-	<u>Transverse at Roc</u>	om <u>Temperature</u>						
1T-1 1T-2 1T-3 Average	119.6 119.7 <u>118.6</u> 119.3	103.5 104.5 <u>103.2</u> 103.7	18.0 17.0 <u>17.0</u> 17.3	32.9 32.4 <u>33.4</u> 32.9	17.3 17.0 <u>16.8</u> 17.0				
		Longitudinal	<u>at 400 F</u>						
1L-4 1L-5 1L-6 Average	88.1 87.5 <u>87.9</u> 87.8	64.1 63.8 <u>65.7</u> 64.5	18.0 19.0 <u>18.0</u> 18.3	43.4 40.8 <u>43.7</u> 42.6	16.0 16.0 <u>16.1</u> 16.0				
		<u>Transverse</u>	<u>at 400 F</u>						
1T-4 1T-5 ∴T-6 Average	89.3 89.6 <u>88.1</u> 89.0	66.6 66.0 <u>64.9</u> 65.8	17.0 17.0 <u>18.0</u> 17.3	42.1 42.0 <u>43.7</u> 42.6	17.3 17.5 <u>17.3</u> 17.4				
		Longitudinal	<u>l at 600 F</u>						
1L-7 1L-8 1L-9 Average	79.7 80.2 <u>80.7</u> 80.2	58.7 57.2 <u>58,1</u> 58.0	20.0 19.0 <u>20.0</u> 19.6	52.3 52.6 <u>50.3</u> 51.7	14.6 13.6 <u>13.9</u> 14.0				
		Transverse	<u>at 600 F</u>						
1T-7 1T-8 1T-9 Average	79.9 81.0 <u>80.5</u> 80.5	55.0 56.2 <u>57.1</u> 56.1	18.0 18.0 <u>18.0</u> 18.0	47.5 47.1 <u>47.1</u> 47.2	14.5 14.5 <u>15.3</u> 14.8				
Longitudinal at 800 F									
1L-10 1L-11 1L-12 Average	74.4 73.6 <u>74.0</u> 74.0	52.8 53.8 <u>50.7</u> 52.4	20.0 20.0 <u>19.0</u> 19.7	48.8 51.2 <u>50.9</u> 50.3	12.6 12.6 <u>13.1</u> 12.8				
		Transverse	<u>at 800 F</u>						
1T-10 1T-11 1T-12 Average	74.9 75.8 <u>74.9</u> 75.2	55.8 55.3 <u>55.0</u> 55.4	17.0 18.0 <u>17.0</u> 17.3	49.7 48.4 <u>48.8</u> 49.0	14.0 15.8 <u>13.5</u> 14.4				
	0.2 Percent	Compression							
-----------------	--------------------------	---------------------							
Specimen	Offset Yield	Modulus,							
Number	Strength, KB1	10- KB1							
Long	itudinal at Room Temj	perature							
2L-1	107.8	18.0							
2L-2	108.1	17.6							
2L-3	<u>108.9</u>	$\frac{17.1}{17.6}$							
Average	108.3	17.6							
Tra	nsverse at Room Tempe	erature							
2 <b>T</b> -1	112.4	17.3							
2 <b>T</b> -2	112.0	17.1							
2 <b>T</b> -3	$\frac{111.4}{2}$	$\frac{18.0}{12.0}$							
Average	111.9	17.5							
	Longitudinal_at 400	<u>0 F</u>							
2L-4	72.7	16.6							
2L-5	74.9	15.8							
21-0 Average	$\frac{75.0}{74.2}$	<u>15.3</u> 15.9							
NVELABE	74.2	12.7							
	Transverse at 400	<u> </u>							
2 <b>T</b> -4	76.8	16.1							
2 <b>T</b> -5	77.6	15.7							
21-6	77.9	15.1							
Average	77.4	15.6							
	Longitudinal at 600	<u>0 F</u>							
2L-7	60.8	15.3							
2L-8	61.1	14.8							
2L-9	60.5	14.8							
Average	00.0	13.0							
	<u>Transverse at 600</u>	F							
2 <b>T</b> -7	63.2	15.0							
2 <b>T-8</b>	63.7	15.3							
2T-9	$\frac{62.7}{62.2}$	$\frac{14.5}{14.5}$							
Average	03.2	14.9							
	Longitudinal at 80	<u>0 F</u>							
2L-10	55.2	13.6							
2L-11	54.6	13.6							
2L-12	55.9	$\frac{13.8}{12.7}$							
Average	33.4	13./							
	<u>Transverse at 800</u>	<u> </u>							
2 <b>T-1</b> 0	58.5	14.0							
2 <b>T-11</b>	58.0	14.1							
2T-12	<u>58.3</u>	13.0							
average	20,3	12.9							

# TABLE XL. COMPRESSION TEST RESULTS FOR ANNEALEDTi-6A1-2Cb-1Ta-1MoALLOYPLATE

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Specimen Number	Ultimate Shear Strength, ksi
	Longitudinal
4L-1	83.4
4L-2	85.0
4L-3	82.5
4L-4	<u>83,9</u>
Average	83.7
	<u>Transverse</u>
4 <b>T</b> -1	84.2
4T-2	82.5
4 <b>T</b> -3	84.4
4T-4	84.0
Average	83.8

#### TABLE XLI. PIN SHEAR TEST RESULTS FOR ANNEALED TI-6A1-2Cb-1Ta-1Mo ALLOY PLATE AT ROOM TEMPERATURE

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# TABLE XLII.IMPACT TEST RESULTS FOR ANNEALEDTi-6A1-2Cb-1Ta-1MoALLOYPLATEATATROOMTEMPERATURE

Specimen	Znergy,
Number	ft-1bs
Longitudina	1
10L-1	40
10L-2	38
10L-3	37
10L-4	40
10L-5	37
10L-6	39
Average	38.5
Transverse	<u>•</u>
10T-1	33
10T-2	33
107-3	33
10T-4	35
10T-5	33
10T-6	<u>36</u>
Average	33.8

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ipecimen Number	W, inches	T, inches	a, inches	Span, inches	P <sub>Q</sub> , 1bs	P <sub>max</sub> , 1bs	$f\left(\frac{a}{w}\right)$	KQ <sup>(a)</sup>	R <sub>sb</sub> (b)
			L	ongitudina	al (L-T)				
6L-1	2.00	1.00	1.063	8.0	11,750	15,750	2.957	98.2	2.09
6L-2	2.00	1.00	1.046	8.0	11,750	17,760	2.873	95,5	2.27
6L-3	2.00	1.00	1.000	8.0	12,000	16,750	2.664	90.4	1.97
6L-4	2.00	1.00	1.026	8.0	12,500	16,500	2.779	98.2	2.03
				Fransvers	e (T-L)				
6 <b>T-1</b>	2.00	1.00	0.988	8.0	13,000	16,250	2.614	96.1	1.85
6T-2	2.00	1.00	1.010	8.0	12,000	15,875	2.708	91.9	1.89
6T-3	2.00	1.00	1.004	8.0	12,750	16,000	2.682	96.7	1.88
6T-4	2.00	1.00	0.988	8.0	11,750	14,750	2.614	86.9	1.68

#### TABLE XLIII. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS FOR ANNEALED T1-6A1-2Cb-1Ta-1Mo ALLOY PLATE

(a) Candidate K<sub>Q</sub> values are invalid as K<sub>1</sub> values since they do not meet the standard of a, t,  $\sim 2.5 \ (K_Q/TYS)^i$  or the ratio of  $P_{max}/P_Q = 1.10$  or less.

(b)  $R_{sb}$  is a function of the maximum load that the specimen can sustain, its dimensions, and the yield strength of the material. As explained in ASTM E399-72, it is a use-ful comparative measure of toughness of materials where size may be less than sufficient for valid  $K_{lc}$  determination.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	110	27,100
5-2	105	34,700
5-3	100	37,900
5-5	95	780,900
5-6	90	1,091,500
5-7	85	1,346,900
5-4	80	2,965,900
5-8	75	2,952,000
5-9	70	4,271,300
5-10	65	10,016,500 <sup>(a)</sup>
	<u>400 F</u>	
5-23	90	17,400
5-22	85	114,800
5-21	80	78,700
5-20	75	127,800
5-19	70	662,700
5-24	65	3,877,800
5-25	60	4,683,300
5-26	55	11,934,000 <sup>(a)</sup>
	600 F	
5-12	80	140
5-14	75	214,600
5-13	70	241.700
5-16	65	1,235,800
5-17	60	2,658,100
5-18	55	9,435,800

#### TABLE XLIV. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED ANNEALED Ti-6A1-2Cb-1Ta-1Mo ALLOY PLATE (Transverse, R = 0.1)

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(a) Did not fail.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-31	85	4,100
5-32	75	7,200
5-33	65	18,300
5-34	60	27,700
5-35	55	60,000
5-36	45	99,600
5-37	35	3,715,300
5-38	30	5,065,600
5-44	25	10,000,000 <sup>(a)</sup>
	<u>400 F</u>	
5-39	75	4,100
5 -40	65	7,900
5-41	55	15,300
5 - 42	45	76,500
5-43	35	709,900
5-45	25	15,211,700 <sup>(a)</sup>
	<u>600 F</u>	
5 - 46	75	3,000
5 - 47	65	5,100
5-48	55	12,500
5 <b>- 49</b>	45	41,700
5-50	35	463,400
5-51	25	11,537,700 <sup>(a)</sup>

# TABLE XLV. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED(Kt = 3.0) ANNEALED Ti-6A1-2Cb-1Ta-1MoALLOY PLATE (Transverse, R = 0.1)

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(a) Did not fail.

TABLE XLVI, SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR TI-6A1-2Cb-1Ta-1Mo ALLOY PLATE

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3–3 95 3–4 90		0.1	Indicated 0.2	Creep De 0.5	1.0	percent 2.0	Strain, percent	Time, hours	in 2 In., percent	of Area, percent	Creep Rate, percent
3-4 90	¢00	1	1		8	8	:	On Loading	15.2	47.6	1
	400	:	;	ł	!	0.10	4.395	0.8,.	14.4	43.5	5.5
3-3-/ 85	400	;	ŀ	ł	0.10	45	2.361	782.3 <sup>(D)</sup>	4.380	;	0.00004
3-8 75	400	0.02	0.07	10	1 6	8	1.118	25.4 <sup>(D)</sup>	1.648	ł	:
3-11 70	400	0.06	<b>0.</b> 5	ł	:	ł	0.519	186.3 (0)	0.796	:	:
<b>G</b> 3-12 65	400	0.60	>5000	1	2	:	0.530	573.3 <sup>(0)</sup>	0.663	ł	nfl
3-1 82.7	600	:	:	;		1	:	On Loading	16.7	55.5	;
3-13 79	600	1	0.05	1300,	10,000 <sup>(a)</sup>	1	5.042	1002.4 ( <sup>b</sup> )	5.521	ł	0.00005
3-6 75	600	0,05	1.1	5000 <sup>(a)</sup>	•	;	2.160	$961.0^{(0)}$	2.417	ł	0.000006
3-9 70	600	1675 <sup>(a)</sup>	8300 <sup>(a)</sup>	:	ł	ł	1.470	1009.7	1.562	:	0.000015
3-2 75.5	800	ł	:	:	;	ł	;	On Loading	16.7	57.0	ł
3-14 72	800	0.2	1	11	58	210,21	3.470	834.1	14.4	31.0	0.0060
3-5 65	800	٢	45	425	1400	3400 <sup>(a)</sup>	1.341	983.9(0)	2.141	:	0.00050
3-10 55	800	06	550	4600 <sup>(8)</sup>	1	ł	0.595	914.1 <sup>(0)</sup>	0.822	1	0.000072

(a) Estimate.

(b) Test discontinued.

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FIGURE 52. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPER-ATURE FOR ANNEALED Ti-6A1-2Cb-1Ta-1Mo ALLOY PLATE (Longitudina1)

160 Transverse 140 120 RT 100 Stress, ksi 80 400 F 600 F 800 F 60 40 20 Ö 0.006 0.010 0.002 0.004 0.008 0.012 0 A-1556 Strain, in./in.

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FIGURE 53. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED TI-6A1-2Cb-1Ta-1Mo ALLOY PLATE (Transverse)

160 Longitudinal 140 RT RT 120 100 Stress, ksi 400 F 400 F 80 600 F 600 F '800 F 60 8001 40 20 0.002 0.004 0.008 0.010 0.012 0.006 0 Strain, in./in.

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FIGURE 54. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MOUDLUS CURVES AT TEMPERATURE FOR ANNEALED Ti-6A1-2Cb-1Ta-1Mo ALLOY PLATE (Longitudinal)

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Tangent Modulus, 10<sup>6</sup> psi

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FIGURE 55. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR ANNEALED T1-6A1-2Cb-1Ta-1Mo ALLOY PLATE (TRANSVERSE)



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FIGURE 56. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED T1-6A1-2Cb-1Ta-1Mo ALLOY PLATE



FIGURE 57. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED TI-6A1-2Cb-1Ta-1MO ALLOY PLATE

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FIGURE 58. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED T1-6A1-2Cb-1Ta-1Mo ALLOY PLATE







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#### Ti-6A1-4V Alloy Plate

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#### Material Description

Ti-6Al-4V is one of the most used titanium alloys and thus needs no descriptive words. It is used in great quantities and in various product forms for aerospace and other applications. The 0.57-inch-thick plate used for this evaluation was GFM from material produced for Boeing to their low oxygen specification.

#### Processing and Heat Treating

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The specimen layout is shown in Figure 61. The material was tested in the as-received, beta-annealed condition.

#### Test Results

Tension. Results of tests in both the longitudinal and transverse directions at room temperature, 400 F, 600 F, and 800 F are given in Table XLVII. Typical stress-strain curves at temperature are shown in Figures 62 and 63. Effect-of-temperature curves are presented in Figure 66.

<u>Compression</u>. Results of tests in both the longitudinal and transverse directions at room temperature, 400 F, 600 F, and 800 F are given in Table XLVIII. Typical stress-strain and tangent-modulus curves at temperature are shown in Figures 64 and 65. Effect-of-temperature curves are presented in Figure 67.

Shear. Pin shear test results at room temperature are given in Table XLIX for longitudinal and transverse specimens.

Impact. Charpy V-notch test results for longitudinal and transverse spec. mens at room temperature are given in Table L.

<u>Fracture Toughness</u>. Results of compact-tension type tests are given in Table LI. Due to the thickness of the plate (0.57 inch) the size requirements of ASTM E399 could not be met; however,  $R_{sc}$  values were calculated from the test results and are presented in Table LI.

<u>Fatigue</u>. Test results for transverse specimens in both the unnotched and notched conditions at room temperature, 400 F, and 600 F are given in Tables LII and LIII. S-N curves are presented in Figures 68 and 69.



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FIGURE 61. SPECIMEN LAYOUT FOR TI-6A1-4V ALLOY PLATE

<u>Creep and Stress Rupture</u>. Results of tests on transverse specimens at 400 F, 600 F, and 800 F are given in Table LIV. Log-stress versus log-time curves are shown in Figure 70. Downloaded from http://www.everyspec.com

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<u>Stress Corrosion</u>. Tests were conducted as described in the experimental procedures section of this report. No failures or cracks occurred in the test duration.

<u>Thermal Expansion</u>. The coefficient of thermal expansion for this alloy is  $5.0 \times 10^{-8}$  in./in./F for 70 F to 1200 F.

Density. The density for this material is 0.160 lb./in.<sup>3</sup>.

pecimen Number	i Tensi	lltimate le Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	T <b>ensi</b> le Modulus, 10 <sup>3</sup> ksi
		Longit	udinal at Room T	emperature		
1L-1 1L-2		138.0 134.3	130.7	12.0	<b>14.6</b> 23.4	17.6
1L-3	Average	<u>134.9</u> 135.8	$\frac{126.4}{127.7}$	$\frac{12.5}{12.2}$	<u>24.8</u> 20.9	$\frac{17.5}{17.5}$
	-	Trans	verse at Room Te	mperature		
<b>1T</b> -1		136.5	126.8	12.0	27.3	16.8
1 <b>.T-2</b>		136.0	125.6	12.5	29.3	16.9
1 <b>T</b> -3		<u>135.5</u>	<u>127.7</u>	<u>11.5</u>	25.6	<u>17.1</u>
	Average	136.0	126.7	12.0	27.4	16.9
			Longitudinal at	<u>400 F</u>		
1L-4		103.2	87.6	16.0	34.3	16.3
1L-5		102.8	84.8	16.0	32.5	16.0
17-0	Average	103.3	86.1	$\frac{16.0}{16.0}$	$\frac{36.4}{34.4}$	$\frac{16.0}{16.1}$
			Trapsverse at 4	00 F		
1 <b>T-</b> 4		102.8	84.9	16.0	34.6	16.0
1T-5		103.9	86.0	17.0	31.1	16.4
1T-6	Average	$\frac{104.4}{103.7}$	<u>85.9</u> 85.6	$\frac{14.0}{15.7}$	$\frac{30.9}{32.2}$	$\frac{17.1}{16.5}$
	-		Longitudinal at	600 F		
1L-7		92.7	72.7	16.0	33.4	16.4
1L-8		92.7	72.3	14.0	36.2	16.0
1L-9		<u>92.2</u>	71.4	<u>15.0</u>	<u>35.8</u>	<u>15.2</u>
	Average	92.5	72.1	15.0	35.1	15.9
			Transverse at 6	<u>500 F</u>		
1T-7		92.8	71.2	15.0	35.8	15.3
1T-8		92.2	70.7	14.0	34.4	15.3
1T <del>-</del> 9	Average	$\frac{93.3}{97.7}$	$\frac{72.7}{71.5}$	$\frac{14.0}{14.3}$	$\frac{32.7}{34.3}$	$\frac{15.4}{15.3}$
	uver age	74.1	Longitudinal at	800 F		13.3
11 10		02 1	<u>46 0</u>	24.0	40 0	13 /
11-10		82.3	64.6	24.0	40.2	13.4
1L-12		83.7	65.9	20.0	51.1	13.0
	Average	83.0	65.5	20.7	48.8	13.2
			Transverse at a	300 F		
1 <b>T-</b> 10		82.4	64.4	18.0	45.5	14.7
1T-11		82.6	63.7	18.0	43.6	14.1
11-12	Average	82.2	<u>04.2</u> 64.1	19.0	<u>43.8</u> 45.0	$\frac{13.0}{12.0}$
	verage.	04.3	0++ L	10.3	4J.U	13.2

### TABLE XLVII. TENSILE TEST RESULTS FOR BETA-ANNEALED Ti-6A1-4V ALLOY PLATE

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Specimen Number	0. Of: Str	2 Percent fset Yield ength, ksi	Compressive Modulus, 10 <sup>3</sup> ksi
	Longitudi	nal at Room Temper	rature
2L-1		132.0	17.0
2L-2		132.3	16.6
26-3	Average	<u>132.4</u>	$\frac{17.8}{17.7}$
	Transver	se at Room Temper	ature
2 <b>T</b> -1		134.1	17.2
2T-2		134.5	17.9
2 <b>T</b> -3		<u>135.7</u>	$\frac{17.4}{17.4}$
	Average	134.8	17.5
	Lon	gitudinal at 400	<u>E</u>
2L-4		88.8	15.8
21-3		90.0	10.1
21-0	Average	89.5	15.8
	Tr	ansverse at 400 F	
2T-4		92.3	16.1
2T-5		90.7	15.0
2T-6		<u>91.3</u>	<u>15.2</u>
	Average	91.4	15.4
	Lor	gitudinal at 600	F
2L-7		73.3	14.7
2L-8		72.9	14.5
2L-9		<u>74.4</u>	$\frac{15.1}{15.1}$
	Average	73.5	14.8
	Tr	ansverse at 600 F	
2 <b>T</b> -7		76.7	14.7
2T-8		76.2	15.7
21-9	Average	<u>76.9</u> 76.6	<u>15.0</u> 15.1
	Lor	gitudinal at 800	F
2110		67.8	- 14 0
21-11		68.6	13.6
2L-12		68.4	14.3
	Average	68.3	14.0
	<u></u>	ansverse at 800 F	
2 <b>T-</b> 10		70.6	13.9
2 <b>T</b> -11		69.6	14.2
2 <b>T</b> -12		69.4	<u>13.8</u>
	Average	69.9	14.0

#### TABLE XLVIII. COMPRESSION TEST RESULTS FOR BETA-ANNEALED T1-6A1-4V ALLOY PLATE

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### TABLE XLVIX. PIN SHEAR TEST RESULTS FOR BETA-ANNEALED T1-6A1-4V ALLOY PLATE AT ROOM TEMPERATURE

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Specimen Number	Ult St:	imate Shear rength, ksi
]	Longitudinal	
4L-1		89.4
4L-2		89.0
4L-3		92.3
4L-4		<u>91.7</u>
	Average	90.6
	Transverse	
4 <b>T-</b> 1		89.4
4 <b>T-2</b>		91.0
4 <b>T-</b> 3		89.6
4 <b>T-</b> 4		89.4
	Average	89.9

# TABLE L. IMPACT TEST RESULTS FOR BETA-<br/>ANNEALED Ti-6A1-4V ALLOY PLATE<br/>AT ROOM TEMPERATURE

Specimen Number		Energy, ft./lbs.
	Longitudinal	
101-1		23.5
10L-2		23.0
10L-3		24.0
10L-4		24.0
10L-5		23.0
10L-6		24.0
	Average	23.6
	Transverse	
10T-1		21.0
10T-2		24.0
10T-3		24.0
10T-4		24.0
10T-5		23.0
10T-6		23.0
	Average	23.2

Specimen Number	W, inches	B, inches	a, inches	P <sub>Q</sub> 1bs.	P <sub>max</sub> ; lbs.	f (🔹)	Kq <sup>(a)</sup>	R <sub>sc</sub> (b)
			Longitud	inal (L-T	2			
6L-1	3.0	0.561	1.62	10,375	11,000	10.842	115.7	1.235
6L-2	3.0	0.560	1.62	10,600	11,500	10.842	118.5	1.294
6L-3	3.0	0.560	1.62	10,650	11,550	10.842	119.1	1.299
6L-4	3.0	0.560	1.60	10,600	11,750	10.607	115.9	1.281
6L-5	3.0	0.561	1.70	9,750	10,250	11.929	119.7	1.317
6L-6	3.0	0,560	1.66	10,250	10,450	11.342	119.9	1.254
			Transve	erse (T-L)				
6 <b>T-1</b>	3.0	0.561	1.61	10,250	11,000	10.724	113.1	1.216
6T-2	3.0	0.560	1.60	9,600	10,000	10.607	104.9	1.109
6T-3	3.0	0.560	1.60	10,750	11,325	10.607	117.6	1,235
6 <b>T</b> -4	3.0	0.561	1.60	10,875	11,300	10.607	118.7	1.230
6 <b>T-5</b>	3.0	0.561	1.62	10,625	11,025	10.842	118.5	1.238
6T-6	3.0	0.560	1.64	10,625	11,250	11.049	121.0	1.30

# TABLE LI.RESULTS OF COMPACT TENSION TYPE FRACTURE TOUGHNESSTESTS ON BETA-ANNEALED Ti-6A1-4VALLOY PLATE

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(a) Candidate K<sub>Q</sub> values are invalid as K<sub>IC</sub> values. Tests do meet the  $P_{max}/P_Q$  requirement but do not meet the size requirement.

(b) R<sub>sc</sub> is a function of the maximum load that the specimen can sustain, its dimensions, and the yield strength of the material. As explained in ASTM E399-72, it is a useful comparative measure of toughness of materials where size may be less than sufficient for valid K<sub>Ic</sub> determination.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
· · ·	Room Temperature	
5-2	120	19,300
5-5	115	32,100
5-3	110	234,200
5-4	105	417,800
5-1	100	1,237,900
5-6	95	2,064,600
5-7	90	10,814,900 <sup>(a)</sup>
	<u>400 F</u>	
5-8	110	15
5-22	100	11,400
5-9	90	32,700
5-11	85	57,000
5-10	80	2,699,800
5-23	80	6,519,100
5-12	75	530,600 <sup>(b)</sup>
5-14	70	L1. <b>792,</b> 700 <sup>(a)</sup>
	<u>600 F</u>	
5-16	90	7,600
5-17	85	27,200
5-15	80	605,400
5-18	75	2,508,800
5-19	70	1,235,800 <sup>(b)</sup>
5-20	70	1,261,900 <sup>(b)</sup>
5-21	70	10,328,700

TABLE LII. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED BETA ANNEALED TI-6A1-4V PLATE (TRANSVERSE, R = 0.1)

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(a) Did not fail.

(b) Failed at thermccouple weld.

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-31	120	1,600
5-32	110	1,900
5-33	100	2,900
5-34	85	7,400
5-35	75	10,000
5-36	60	63,700
5-37	50	225,300
5-38	40	576,400
5-39	30	16,935,000 <sup>(a)</sup>
	<u>400 F</u>	
5-42	60	15,400
5-45	55	19,100
5-41	50	34,900
5-43	45	258,400
5-40	40	280,100
5-44	35	11,161,100 <sup>(a)</sup>
	<u>600 F</u>	
5-46	60	9,600
5-48	55	12,900
5-47	50	31,100
5-50	45	388,000
5-49	40	6,739,500
5-51	37.5	3,488,800
5-52	35	10,064,700 <sup>(a)</sup>

## TABLE LIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ( $K_{t}$ = 3.0) BETA ANNEALED Ti-6A1-4V PLATE (TRANSVERSE, R = 0.1)

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(a) Did not fail.

TABLE LIV. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR BETA ANNEALED TI-6A1-4V PLATE

Minimum	Creep Rate,	percent	8	0.00002	níl	1	ł	0.000004		ł	060000.0	0,000042	1.1	0.05	0.0084	0.0010	0.000053
Reduction	of Area,	percent	34.5	;	ł	1	;	ł		39.5	1	ł	41.2	33.6	27.9	ł	•
Elengation	In 2 Inches,	percent	14.6	5.323	3.240	1.958	1.192	0.765		13.1	5.450	2.587	15.4	18.5	18.5	1.012	0.300
Rupture	Time,	hours	On loading	515.3(8)	$553.0^{(n)}_{(2)}$	258.8	454.5 <sup>(a)</sup>	1004.5'3)		On loading	1127.4 <sup>(8)</sup>	384.0	4.8	136.2	1031.7/2	284.0	1005.5'='
Initial	Strain,	percent	:	3.005	1.807	1.154	0.738	0.585		:	5.031	2.384	5.208	2,808	0.954	0.407	0.165
fon,		2.0	•	0.4	>1000	;	;	1		1	:	ŧ	ד. ני	:6	175	:	:
p Deformat		1.0	:	:	0.12	>1000	;	ł		;	:	1	0.6	4	58	650 <sup>6</sup>	1
cated Creel	percent	0.5		;	:	0.1	>1000	1			$2100^{(c)}$	6300 <sup>151</sup>	0.2	6-1 	77	145,27	8006,
s to Indic		0.2		!	ł	:	20.0	6000 <sup>1 C)</sup>		!	25	750	9.07	0.2	2.4	18,5,	2225 <sup>' CJ</sup>
Hour		0.1	:	ł	:	!	1	0.15		ł	0.05	0.1	0.01	0.1	0.6	4.0	4 <b>0</b> 0
Temper-	ature.	Ē	400	400	400	4:00	400	400		600	00ÿ	00ª	80G	200	800	800	3C0
	Stress,	ksi	104	100	95 <sup>(b)</sup>	90	85	80		¢3.5	06	55	Å5	80 8	70	55	25
	Specimen	Number	3-1	3-6	3-4	3-9	3-12	3-14	1	° j−2	3-7	3-5	3-10	3-3	3-3	3-11	3-13

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(a) Test discontinued.

(b) Failed on loading to 102,000 psi.

(c) Estimate.

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FIGURE 62. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR BETA-ANNEALED TI-6A1-4V ALLOY PLATE (LONGITUDINAL)





FIGURE 63. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR BETA-ANNEALED T1-6A1-4V ALLOY PLATE (TRANSVERSE)

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FIGURE 64. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR BETA-ANNEALED T1-6A1-4V ALLOY PLATE (LONGITUDINAL)

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FIGURE 65. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR BFTA-ANNEALED T1-6A1-4V ALLOY PLATE (TRANSVERSE)



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FIGURE 66. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF BETA-ANNEALED TI-6A1-4V ALLOY PLATE



FIGURE 67. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF BETA-ANNEALED TI-6A1-4V ALLOY PLATE



FIGURE 68. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED BETA-ANNEALED TI-6A1-4V ALLOY PLATE



FIGURE 69. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K<sub>t</sub> = 3.0) BETA-ANNEALED Ti-6A1-4V ALLOY PLATE



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- 10% creep

- 0.5% creep 0.2% creep

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#### Ti-6A1-4V Alloy Castings

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#### Material Description

Ti-6Al-4V castings have been utilized in airframe construction for a number of years, primarily in simple shapes and in unstressed or low stress areas. Recently, more complex shapes have been used as confidence in casting properties has increased. One of the primary reasons is that parts can be cast to a finished or near-finished shape instead of being machined to size from a large forging or thick plate.

The material used for this evaluation was cast, wedge shaped, plates approximately 5 inches by  $6\frac{1}{2}$  inches and tapering from about 1 inch to  $\frac{1}{2}$  inch. The material was from TiTech International casting heat number 6-4 2119 and had the following composition:

Percent
0.28
.18
.0027
.015
5.90
3.90
.10
Balance .

#### Processing and Heat Treating

The specimens were all machined in one direction from the cast plates described above and no specimen layout is shown. The material was received in the annealed condition and no further heat treating was done.

#### Test Results

<u>Tension</u>. Results of tests at room temperature, 400 F, 600 F, and 800 F are given in Table LV. Typical stress-strain curves at temperature are shown in Figure 71. Effect-of-temperature curves are presented in Figure 73.

<u>Compression</u>. Results of tests at room temperature, 400 F, 600 F, and 800 F are given in Table LVI. Typical stress-strain and tangent-modulus curves are shown in Figure 72. Effect of temperature curves are shown in Figure 74. Shear. Results of pin shear tests at room temperature are given in Table LVII.

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<u>Impact</u>. Charpy V-notch test results at room temperature are given in Table LVIII.

<u>Fracture Toughness</u>. In view of the invalid results obtained from Ti-6Al-4V beta-annealed (preceding section of this report) with approximately the same thickness of material, it was believed that the casting data would also be invalid. However, compact tension type tests were attempted.  $K_Q$ values from the first three specimens were in the same range as the betaannealed alloy test results, therefore no further tests were conducted.

<u>Fatigue</u>. Test results for unnotched and notched specimens at room temperature, 400 F, and 600 F are given in Tables LIX and LX. S-N curves are presented in Figures 75 and 76.

<u>Creep and Stress Rupture</u>. Tests were conducted at 400 F, 600 F, and 800 F. Tabular test results are given in Table LXI. Log-stress versus logtime curves are presented in Figure 77.

<u>Stress Corrosion</u>. Tests were conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the test duration.

<u>Thermal Expansion and Density</u>. Values for these properties are the same as for wrought Ti-6A1-4V.

Specimen Orientation



Cast Wedge

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 1-inch, percent	Reduction in Area, percent	Tensile Modulus, 10 <sup>3</sup> ksi
		Room Temperatu	re		
1L-1	136.9	130.0	6.5	10.1	17.4
1L-2	137.9	130.1	6.5	13.5	17.6
1L-3	138.5	131.0	6.5	9.9	16.5
Avera	ige 137.8	130.4	6.5	11.2	17.2
		<u>400 F</u>			
1L-4	99.0	86.9	8.0	15.3	17.2
1L-5	102.5	89.3	12.5	20.4	16.3
1L-6	1.00.9	88.4	10.0	21.2	16.8
Avera	ige 100.8	88.2	10.2	19.0	16.8
		<u>600 F</u>			
1L-7	83.5	68.9	11.5	25.5	16.2
1L-8	83.9	69.9	10.5	22.0	14.8
1L-9	86.9	70.6	14.0	25.4	14.7
Aver	sge 84.8	69.8	12.0	24.3	15.2
		<u>800_F</u>			
1L-10	75.6	62.7	10.5	27.4	14.9
1L-11	78.5	63.9	13.0	30.4	16.1
1L-12	78.4	64.9	12.5	27.3	14.4
Aver	age 77.5	63.8	12.0	28.4	15.1

TABLE LV. TENSILE TEST RESULTS FOR ANNEALED T1-6A1-4V CASTINGS

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<u>R</u>	oom Temperature					
	136.9	16.3				
	138.1	16.4				
	137.4	16.8				
verage	137.5	16.5				
	<u>400 F</u>					
	90.9	16.1				
	93.3	15.7				
	94.6	15.0				
verage	92.9	15.6				
	<u>600 F</u>					
	73.7	14.1				
	74.4	15.3				
	75.7	15.3				
verage	74.6	14.9				
<u>800 F</u>						
	65.8	13.5				
	69.8	12.7				
	66.9	14.3				
verage	67.5	13.5				
	verage verage verage	$\frac{400 \text{ F}}{138.1}$ $\frac{400 \text{ F}}{90.9}$ $90.9$ $93.3$ $94.6$ $92.9$ $\frac{600 \text{ F}}{73.7}$ $74.4$ $\frac{75.7}{74.4}$ $\frac{75.7}{74.6}$ $\frac{800 \text{ F}}{65.8}$ $69.8$ $69.8$ $66.9$ $67.5$				

# TABLE LVI.COMPRESSION TEST RESULTS FOR<br/>ANNEALED Ti-6A1-4V CASTINGS

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# TABLE LVII.PIN SHEAR TEST RESULTS FOR<br/>ANNEALED Ti-6A1-4V CASTINGS<br/>AT ROOM TEMPERATURE

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Specimen Number	Ultimate Shea Strength, ks			
4L-1	92.7			
4L-2	94.7			
4L-3	92.3			
41-4	<u>91.5</u>			
	Average 92.8			

#### TABLE LVIIL IMPACT TEST RESULTS FOR ANNEALED TI-6A1-4V CASTING AT ROOM TEMPERATURE

Specimen Number		Energy, ft/1b	
	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,		
10L-1		16.5	
10L-2		15.0	
10L-3		15.0	
10L-4		16.0	
10L-5		18.5	
10L-6		16.0	
	Average	16.2	

TABLE LIX.

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AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED ANNEALED Ti-6A1-4V CASTINGS (R = 0.1)

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Specimen Number	Maximum Stress, ksi	Lifetime, cycles
-	Room Temperature	,
5-1	100	54,200
5-2	80	70,800
5-3	70	102,700
5-4	60	209,000
5-5	55	22,800
5-6	50	2,276,500
5-7	47.5	471,500
5-8	42.5	_ 10,061,700 <sup>(a)</sup>
	<u>400 F</u>	
5-12	90	5,200
5-11	80	35,200
5-9	70	162,200
5-10	60	297,200
5-13	50	114,600
5-14	45	989,300
5-15	42.5	1,603,200
5-16	40	8,332,800
	<u>600 E</u>	
<b>5-</b> 17	90	6,500
5-18	80	24,700
5-19	70	42,700
5-20	60	216,700
5-21	50	2,835,700
5-22	45	863,600
5-23	40	4,184,700
5-24	40	4,443,100
5-25	35	$10,263,900^{(a)}$

(a) Did not fail.
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Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	1
5-31	80	10,100
5-32	70	17,700
5-33	60	85,500
5-34	50	256,500
5-35	45	1,307,700
5-36	42.5	439,000
5-37	40	10,068,000
	<u>400 F</u>	
5-41	70	7,800
5-38	60	20,100
5-39	50	66,700
5-40	45	267,000
5-42	40	2,841,300
5-43	37.5	5,823,600
5-44	35	2,806,200
5-45	32.5	509,900
5-46	30	2,261,000
5-55	30	3,765,700
	<u>600 F</u>	
5~51	70	5,500
5-48	60	11,800
5-47	50	42,600
5-49	40	234,000
5~50	35	8,419,300
5-52	35	250,700
5-53	30	2,009,000
5-54	25	14,433,000

TABLE LX. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ( $K_{c} = 3.0$ ) ANNEALED T1-6A1-4V CASTINGS (R = 0.1)

(a) Did not fail.

TABLE LXI. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR ANNEALED T1-6A1-4V CASTINGS

Sherimen		Temper-	Hours	to Indica	sted Creep ercent	Deforme	tíon,	Initial Strain.	Rupture Time.	Elongation in 2 fn	Reduction of Area.	Minimum Creen Rate.
Number	ks f	<b>i</b>	1.0	0.2	0.5	1.0	2.0	percent	hours	percent	percent	percent
3~5	98.7	400	:		:	:	1	ł	On loading	8.5	22.2	:
3-6	95	400	ł	:	:	:	<b>6.1</b>	1.746	0.1	6.9	13.3	:
3-8	06	400	:	•	0.01	0.13	0.8	0.950	1.8,.	5.4	11.0	1.2
3-13	85	400	1	ł	0.15	3.3	>1000	0.854	623.8 <sup>(U)</sup>	1.964	8	0,00003
3-9	80	400	0.05	0.08	10	>1000	:	0.592	502.7 <sup>(0)</sup>	1,141	:	
3-11	75	400	0.60	>5000	:	:	1	0.554	839.8 <sup>(D)</sup>	0.696	в в	0,000001
1	1								•	1		
	85	600	ł	:	1-2-	1	1	1	On loading	8.5	26.3	•
3-4	80	600	0.08	260	4500 (4)	:	1 1	2.673	1000.1	2,918	1	0.00007
3-7	75	600	500	2600 <sup>(a)</sup>	:	;		1,241	1104.2 <sup>(D)</sup>	1.377	•	0.000046
3-1	80	800	:	ł	:	ł	ł	ł	On loading	10.1	31.9	:
3-10	70	800	1.2	3.7	16	53	160	1.519	647.8	11.5	22.5	600.0
3-3	60	800	1.0	15	75,27	310	006	0.581	1077.4 (0)	2.823	:	0.0014
3-12	40	800	40	200	1100(2)	:	:	0.307	288, 3 ( <sup>b</sup> )	0.535	:	0.00035
3-14	30	800	50	575	7000 <sup>(2)</sup>	t 1	:	0.292	695.7 <sup>(D)</sup>	0.500	:	0.00005

(a) Estimate.

(b) Test discontinued.

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FIGURE 71. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED TI-6A1-4V CASTINGS



FIGURE 72. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR ANNEALED TI-6A1-4V CASTINGS



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FIGURE 73. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED TI-6A1-4V ALLOY CASTINGS



FIGURE 74. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED TI-6A1-4V ALLOY CASTINGS



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FIGURE 75. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED T1-6A1-4V ALLOY CASTINGS



FIGURE 76. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_t = 3.0$ ) ANNEALED TI-6A1-4V ALLOY CASTINGS





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### Ti-6A1-4V Isothermal Forging

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#### Material Description

Application of the isothermal forging concept to titanium alloys has been investigated on a laboratory scale for many years. The material evaluated on this program came from an Air Force sponsored program (F33615-71-C-1264) at the Ladish Company. The specific goal was to develop isothermal forging technology as a process that will yield titanium airframe parts having surfaces which are "net", or which require no post-forging machining. The results of this program have been published in AFML-TR-74-123 from which additional information regarding this material may be obtained.

#### Processing and Heat Treating

The stabilizer rib from which the specimens were machined was of varying thickness and complex shape so no specimen layout is shown. All specimens were sectioned from the forging in the transverse direction. Specimens were tested in the as-received (annealed) condition.

### Test Results

<u>Tension</u>. Results of transverse tests at room temperature, 400 F, 600 F, and 800 F are given in Table LXII. Typical stress-strain curves at temperature are shown in Figure 78. Effect-of-temperature curves are presented in Figure 80.

<u>Compression</u>. Results of transverse compression tests at room temperature, 400 F, 600 F, and 800 F are given in Table LXIII. Typical stressstrain and tangent-modulus curves at temperature are presented in Figure 79. Effect-of-temperature curves are shown in Figure 81.

Shear. Results of pin shear tests at room temperature are given in Table LXIV.

Impact. Charpy V~notch test results at room temperature are given in Table LXV.

<u>Fracture Toughness</u>. Only one specimen (compact tension) of sufficient, dimensions was available from the forging due to the varying thickness. This specimen produced a valid test result of  $K_{T_c} = 59$  ksi /in.

<u>Fatigue</u>. Axial load fatigue test results for unnotched and notched transverse specimens at room temperature, 400 F, and 600 F are given in Tables LXVI and LXVII. S-N curves are shown in Figures 82 and 83.

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<u>Creep and Stress Rupture</u>. Tests were conducted on transverse specimens at 400 F, 600 F, and 800 F. Tabular test results are given in Table LXVIII. Log-stress versur log-time curves are presented in Figure 84.

<u>Stress Corrosion</u>. Tests were conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the test duration.

Thermal Expansion and Density. These values are the same as for wrought Ti-6A-4V.



Sketch of Forging

# TABLE LXII.TENSILE TEST RESULTS FOR Ti-6A1-4VISOTHERMAL FORGINGS (TRANSVERSE)

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Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 1 Inch, percent	Reduction in Area, percent	Tensile Modulus, 10 <sup>3</sup> psi
		Room Temperat	ure		J.
1T-1 1T-2 1T-3	142.5 144.0 <u>145.2</u> Average 143.9	134.1 138.0 <u>130.8</u> 136.3	17.0 17.0 <u>17.0</u> 17.0	46.6 45.3 <u>45.2</u> 45.7	16.2 16.6 <u>16.4</u> 16.4
		400 F			
1T-4 1T-5 1T-6	110.7 111.3 <u>109.6</u> Average 110.5	102.1 104.6 <u>100.0</u> 102.2	17.5 18.0 <u>17.0</u> 17.5	47.8 50.0 <u>45.3</u> 47.7	15.1 15.9 <u>14.7</u> 15.2
		600 F			
1T_7 1T_8 1T_9	98.7 100.1 <u>101.6</u> Average 99.8	92.7 92.7 94.7 93.4	18.5 18.0 <u>19.0</u> 18.5	55.8 54.8 <u>51.7</u> 54.1	14.7 14.9 <u>13.9</u> 14.5
		800 F			
1 <b>T-10</b> 1 <b>T-11</b> 1 <b>T-12</b>	87.0 85.7 <u>89.6</u> Average 87.4	75.6 79.1 80.3 78.3	20.5 21.0 <u>23.0</u> 21.5	64.8 62.1 <u>60.0</u> 62.3	12.5 13.2 13.0 12.9

Specimen Number	0 01 St	.2 Percent Efset Yield rength, ksi	Compression Modulus, 10 <sup>3</sup> ksi
	Ro	om Temperature	
2 <b>T-1</b> 2 <b>T-2</b> 2T <b>-3</b>	Average	136.2 135.7 <u>136.0</u> 135.9	16.5 16.9 <u>16.0</u> 16.5
		<u>400 F</u>	
2T-4 2T-5 2T-6	Average	100.2 102.1 <u>101.9</u> 101.4	15.9 15.5 <u>14.9</u> 15.4
		<u>600 F</u>	
2T-7 2T-8 2T-9	Average	94.5 93.2 <u>92.0</u> 93.2	13.9 14.2 <u>13.7</u> 13.9
		800 F	
2T-10 2T-11 2T-12	Average	81.9 79.6 <u>77.4</u> 79.6	13.2 12.6 <u>13.0</u> 12.9

# TABLE LXIII.COMPRESSION TEST RESULTS FOR Ti-6A1-4VISOTHERMAL FORGINGS (TRANSVERSE)

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Specimen Number	Ultimate She Strength, ks
4-1	99.4
4-2	98.3
4-3	97.3
4-4	93.7
	Average 97.2

# TABLE LXIV.TRANSVERSE SHEAR TEST RESULTS FOR Ti-6A1-4VISOTHERMAL FORGINGS AT ROOM TEMPERATURE

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# TABLE LXV.CHARPY V-NOTCH TEST RESULTS FOR<br/>Ti-6A1-4V ISOTHERMAL FORGINGS<br/>(TRANSVERSE)

Specimen Number	Energy, ft./1b.
10T-1	16.5
101-2	17.5
10T-3	16.5
10T-4	17.0
	Average 16.9

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
• <u>1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 199</u>	Room Temperature	
5-1	130	48,640
5-2	120	539,620
5-3	110	746,390
5-4	110	895,770
5-5	100	1,329,130
5-6	95	1,133,900
5-7	90	1,624,500
5-8	80	3,368,800
5-9	70	10,099, <u>2</u> 50 <sup>(a)</sup>
	<u>400_F</u>	
5-11	110	16,180
5-12	105	26,260
5-20	100	605,000
5-13	95	1,609,000
5-21	90	325,8u0 <sup>(b)</sup>
5-19	90	1,765,000
5-14	90	2,530,760
5-22	80	597,200 <sup>(b)</sup>
5-10	80	10,100,000 <sup>(a)</sup>
	<u>600 F</u>	
5-15	90	50,100 <sup>(b)</sup>
5-18	90	184,140
5-22	85	316,400
5-17	80	5,119,160
5-23	75	5,620,200
5-16	70	10,124,000 <sup>(a)</sup>

# TABLE LXVI.AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHEDTi-6A1-4V ISOTHERMAL FORGINGS (TRANSVERSE, R=0.1)

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(a) Did not fail.

(b) Failed in grip.

Specimen Number	t Maximum Stress, ksi	Lifetime, cycles
	R om Temperature	
5-31	60	14,090
5-34	55	55,950
5-33	50	146,910
5-35	45	103,370
5-32	40	173,520
5-36	35	386,740
5-37	30	13,894,000 <sup>(a)</sup>
	<u>400 F</u>	
5-38	60	15,800
5-44	55	38,000
5-41	50	181,500
5-42	40	823,600
5-39	30	6,592,500
5-40	30	6,339,100
5-43	25	14,831,000 <sup>(a)</sup>
	<u>600 F</u>	
5-45	60	13,300
5-51	55	23,900
5-46	50	34,600
5-48	45	54,300
5-52	42.5	174,900
5-47	40	1,282,800
5-50	40	983,900
5-49	35	11,353,000 <sup>(a)</sup>

### TABLE LXVII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ( $K_{t} = 3.0$ ) T1-6A1-4V ISOTHERMAL FORGINGS (TRANSVERSE, R = 0.1)

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(a) Did not fail.

TABLE LXVIII. SUMMARY DATE ON CREEP AND RUPTURE PROPERTIES FOR TI-6A1-4V ISOTHERMAL FORGING

Minimum Creep Rate,	percent	ł	0.00034	0.00040	0.000013	;	0.00054	:	ŧċ	0.000063	1.2	0.15	0.046	0.0035	0.00015	0.000075
Reduction of Area,	percent	61.7	:	:	ţ	70.2	:	;	:	:	75.2	78.0	80.0	1	1	:
Elongation in 2 Inches,	percent	19.2	7.650 8/	5.520	1.031	20.0	8.082	3.360	1.207	0.639	30.0	0.04	44.6	0.984	0.457	0.388
Rupture Time,	hours	On loading	791.6(1)	666.7( <sup>a</sup> )	1103.2'*'	On loading	933.4(8)	116.3(5)	43.4( <sup>a</sup> )	1102.8'*	12.9	100.2	360.7	66.1(*)	257.6(=)	500.6
Initial Strain,	percent	ł	3.827	2.662	0.834	ł	4.788	1.931	0.573	0.430	1.465	0.981	0.781	0.400	0.219	0.165
aticn,	0 ;;	:	0.05	10	;	4	36	500 <sup>(b)</sup>	ι •	1	0.7	2.6	<b>1</b> 9	:	:	:
p Deform	1.0	:	:	0.1	ł	ł	3.2	19,1,	6006	1	0.25	0.8	4.4	$200^{(b)}$	ł	ł
ted Cree ercent	0.5	:	:	ł	:	ł	1.0	4	20,1	6000 <sup>1 0</sup> )	0.1	0.2	1.0	45,2,	2000(5)	¢100,017
to Indica P	0.2	:	;		1500 <sup>( b /</sup>	:	0.01	<b>1.</b> 0	5.0	1000	:	0.1	0.3	2.0	137	350
Hours	0.1	ł	:	ł	25	:	1	0.10	1.5	170	ł	!	0.07	0.4	14	30
Temper- sture,	F	400	400	400	400	600	600	600	600	600	800	800	800	300	800	800
Stress.	ksi	112.5	109	105	95	105.3	100	6	80	70	85	75	65	40	20	15
Spectmen	Number	3-1	3 <b>-</b> 8	3-3	3-15	3-2	3-4	11-E 14	0 3-13	3-14	3-6	3-5	3-7	3-9	3-10	3-12

(a) Test discontinued.

(b) Estimated.

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160 Transverse 140 RT 120 400 F 100 600 F Stress, ksi 800 F 80 60 40 20 0 0.002 0.004 0.008 0.0Ю 0.006 0.012 0 Strain, in./in. A- 1605

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FIGURE 78. TYPICAL TENSILE STRESS\_STRAIN CURVES AT TEMPERATURE FOR T1-6A1-4V ISOTHERMAL FORGINGS (TRANSVERSE)



FIGURE 79. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR TI-6A1-4V ISOTHERMAL FORGINGS







FIGURE 81. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF T1-6A1-4V ISOTHERMAL FORGINCS



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FIGURE 83. ANIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_{t} = 3.0$ ) TI-6A1-4V ISOTHERMAL FORGINGS



Rupture 1.0% creep 0.5% creep 0.2% creep x 🗆 🖄 O

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STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR "1-64,-4V ISOTHERMAL FORGINGS (TRANSVERSE) FIGURE 84. нул ;;

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### Incoloy 903 Alloy Sheet

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### Material Description

Incoloy Alloy 903 is a precipitation-hardenable nickel…iron-cobalt alloy whose outstanding characteristics are a constant low coefficient of thermal expansion, a constant modulus of elasticity, and high strength. Because the alloy contains no chromium, oxidation resistance may become a consideration for some high temperature applications.

The material used for this evaluation was a 0.063-inch-thick sheet from Huntington Alloys Heat Number HH25A9UK with the following composition:

Chemical Composition	Percent
Carbon	0.03
Manganese	0.16
Iron	40.92
Sulfur	0.004
Silicon	0.07
Nickel	38.08
Aluminum	0.88
Titanium	1.61
Cobalt	15.22
Columbium plus	
Tantalum	3.01

### Processing and Heat Treating

The specimen layout for Incoloy 903 is shown in Figure 85. The sheet was received in the annealed condition (1700 F) and was heat treated as follows: 1325 F, 8 hours, furnace cool at 100 F per hour to 1150, hold for 8 hours, air cool.

### Test Results

Tension. Test results for longitudinal and transverse specimens at room temperature, 800 F, 1000 F, and 1200 F are given in Table LXIX. Typical stress-strain curves at temperature are shown in Figures 86 and 87. Effectof-temperature curves are shown in Figure 90.

<u>Compression</u>. Test results for both the longitudinal and transverse directions at room temperature, 800 F, 1000 F, and 1200 F are given in Table LXX. Typical stress-strain and tangent-modulus curves are shown in Figures 88 and 89. Effect-of-temperature curves are presented in Figure 91.



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FIGURE 85. SPECIMEN LAYOUT FOR INCOLOY 903 SHEET

Shear. Test results for sheet-shear type specimens at room temperature in both the longitudinal and transverse directions are given in Table LXXI.

Fracture Toughness. Plane-stress center-notched type tests were conducted at room temperature. Results are presented in Table LXXII.

<u>Fatigue</u>. Test results for transverse unnotched and notched specimens at room temperature, 800 F, and 1000 F are given in Tables LXXIII and LXXIV. S-N curves are shown in Figures 92 and 93.

<u>Creep and Stress Rupture</u>. Tests were conducted at 1000 F, 1200 F, and 1400 F for transverse specimens. Test results are given in Table LXXV. Logstress versus log-time curves are presented in Figure 94. The material tested was in the recrystallized condition; hence, the creep and stress rupture properties exhibited are not indicative of the material's capability. Incoloy 903 in the nonrecrystallized condition would be expected to display superior creep and stress rupture properties.

<u>Stress Corrosion</u>. No failures or cracks occurred when specimens were tested as described in the experimental procedures section of this report.

<u>Thermal Expansion</u>. The coefficient of thermal expansion for this alloy is  $5.6 \times 10^{-5}$  in./in./F (RT to 1200 F)

Density. The density of this alloy is 0.294 lb/in.<sup>3</sup>.

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Specimen Number	Ulti St	mate Tensile rength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, 10 <sup>3</sup> ksi		
		Longitudin	nal_at_Room_Tempera	ature			
1L-1		193.5	156.1	14.5	23.2		
1L-2		191.2	156.0	13.5	26.3		
1L-3		<u>190,8</u>	<u>154.3</u>	13.0	24.6		
•	Average	191.9	155.5	13.7	24.7		
		Transver	rse at Room Temper.	ature			
1T-1		194.4	168.5	16.0	27.7		
1T-2		191.9	161.4	17.0	25.5		
1T-3		<u>192.7</u>	<u>165.2</u>	<u>15.0</u>	24.2		
	Average	193.0	165.0	16.0	25.8		
		Long	gitudinal at 800 F				
1L-4		169.7	144.0	17.0	22.8		
1L-5		171.6	139.6	18.0	21.0		
1L-6		<u>170.9</u>	<u>139.0</u>	<u>17.6</u>	<u>21.0</u>		
	Average	170.7	140.8	17.3	21.6		
		Trai	nsverse at 800 F				
1T-4		170.0	142.0	16.5	22.2		
1T-5		168.4	145.6	15.5	23.0		
1T-6		<u>171.9</u>	<u>140.2</u>	15.5	21.4		
	Average	170.1	142.6	15.8	22.2		
		Long	itudinal at 1000 F				
1L-7		167.2	138.5	16.5	22.1		
1L-8		168.0	134.6	17.0	24.2		
1L-9		164.6	131.4	18.0	<u>21.4</u>		
	Average	166.6	134.8	17.2	22.2		
		Trai	nsverse at 1000 F				
1T-7	•	164.6	137.2	16.5	22.1		
1T-8		160.8	134.6	13.5	23.2		
1T-9		165.2	135.6	14.0	21.7		
	Average	163.5	135.6	14.7	22.3		
		Long	itudinal at 1200 F				
1L-10		132.0	116.0	18.0	21.4		
1L-11		131.6	118.5	14.5	22.1		
1L-12		128.2	115.6	17.0	20.7		
	Average	130.6	116.7	16.5	21.4		
		Tra	nsverse at 1200 F				
1T <b>-</b> 10		131.9	120.3	17.5	20.1		
1T <b>-</b> 11		129.6	121.3	17.0	22.6		
1T-12		<u>133.4</u>	<u>119.7</u>	<u>17.5</u>	20.7		
	Average	131.6	120.4	17.3	21.1		

# TABLE LXIX.TENSILE TEST RESULTS FOR HEAT-<br/>TREATED INCOLOY 903 SHEET

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Specimen Number	0. Ofi Str	2 Percent fset Yield ength, ksi	Compression Modulus, 10 <sup>3</sup> ksi
Lon	gitudinal	at Room Temp	erature
2L-1 2L-2 2L-3	A	168.7 168.0 <u>164.2</u>	24.5 25.2 <u>26.0</u>
Tr	ansverse	at Room Tempe	zJ.z
شت 2T-1		176.2	26.0
2T-2 2T-3	Average	174.6 <u>171.9</u> 174.2	24.0 22.9 24.3
	Longit	udinal at 800	F
2L-4 2L-5 2L-6	Average	152.6 152.0 <u>153.7</u> 152.2	22.4 24.3 <u>21.7</u> 22.8
	Trans	verse at 800	F
2T-4 2T-5 2T-6	Average	160.0 159.0 <u>163.7</u> 160.9	25.0 22.2 <u>23.8</u> 23.7
	Longitu	dinal at 1000	F
2L-7 2L-8 2L-9	Average	138.7 142.6 <u>143.0</u> 141.4	21.6 24.0 <u>23.5</u> 23.0
	Transv	erse at 1000	F
2 <b>T-7</b> 2 <b>T-8</b> 2 <b>T-9</b>	Average	144.7 144.5 <u>147.8</u> 145.6	23.7 21.9 <u>24.1</u> 23.2
	Longitu	<u>dinal at 1200</u>	F
2L-10 2L-11 2L-12	Àverage	122.7 125.0 <u>119.7</u> 122.5	21.1 22.1 <u>20.9</u> 21.4
	Transv	erse at 1200	<u>F</u>
2T-10 2T-11 2T-12	Average	130.2 124.8 <u>120.4</u> 125.1	23.1 22.0 <u>21.5</u> 22.2

## TABLE LXX.COMPRESSION TEST RESULTS FOR HEAT-<br/>TREATED INCOLOY 903 SHEET

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Specimen Number	Ult: Str	imate Shear ength, ksi
	Longitudinal	
4L-1		124.4
4L-2		119.6
4L-3		127.8
	Average	123.9
	Transverse	
4T-1		127.3
4 <b>T</b> -2		127.4
4 <b>T-3</b>		125.6
	Average	127.8

# TABLE LXXI.SHEAR TEST RESULTS FOR HEAT-TREATED<br/>INCOLOY 903 SHEET AT ROOM TEMPERATURE

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TABLE LXXI.FRACTURE TOUGHNESS TEST RESULTS (T-L) FOR HEAT-<br/>TREATED INCOLOY 903 SHEET AT ROOM TEMPERATURE

Specimen Number	Thickness, B, inch	Width, w, inch	Maximum Stress, ksi	Initial Precrack, inches	Apparent SIF, Kapp, 1 ksi-in. <sup>2</sup>	Net Section Stress, ksi
6-1	.0635	18.0	100.6	3.70	243	126.6
6-2	.0635	18.0	100.8	3.64	241	126.4
6-3	.0635	18.0	102.1	3.63	244	127.5
6-4	.0635	18.0	104.6	3.64	250	131.1

5-7	100	528,790
5~8	90	4,683,200
5-9	80	10,000,000 <sup>(a)</sup>
	<u>800 F</u>	
5-10	140	1,230
5-11	130	10,200
5-12	120	84,900
5-13	115	57,200
5-14	110	120,800
5-15	100	198,700
5-16	95	500,700
5-20	90	417,200
5-19	80	987,600
5-48	70	11,402,000 <sup>(a)</sup>
	<u>1000 F</u>	
5-21	130	14,100
5-22	120	15,200
5-23	110	84,900
5-24	100	57,900
5-25	90	101,400
5-26	80	987,100
5-27	70	8,200,700

#### TABLE LXXIII. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE, R = 0.1)

Lifetime,

cycles

100

3,000

12,800

92,100

198,200

462,100

10,000,000<sup>(a)</sup>

Maximum

Stress, ksi

Room Temperature

160

150

140

130

120

110

100

Specimen

Number

5-1

5-2

5-3

5-4

5-5

5-6

5-7

(a) Did not fail.

5-28

152

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-30	120	3,300
5-32	100	10,200
5-31	90	15,600
5-32	80	99,200
5-33	70	120,600
5-34	60	784,200
5-35	55	1,101,600
5-36	50	4,296,700
5-37	45	10,000,000 <sup>(a)</sup>
	<u>800 F</u>	
5-39	100	500
5-40	90	1,200
5-38	80	52,000
5-41	70	17,100
5-42	60	342,100
5-44	50	848,600
5-43	40	10,000,000 <sup>(a)</sup>
	<u>1000 F</u>	
5-45	90	9,600
5-46	80	12,200
5-47	70	184,000
5-48	60	177,000
5-49	55	432,700
5-50	50	1,409,700
5-51	45	7,216,000
5-52	40	$11,250,000^{(a)}$

# TABLE LXXIV.AXIAL LOAD FATIGUE TEST RESULTS FOR<br/>NOTCHED (K\_ = 3.0) HEAT-TREATED<br/>INCOLOY 903 SHEET (TRANSVERSE, R = 0.1)

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(a) Did not fail.

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TABLE LXXV, SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR HEAT-TREATED INCOLOY 903 SHEET

nar fmen	Stress	Temper- ature.	Ho	urs to Deform	Indica ation.	ated Cre percent	e b	Initial Strain,	Rupture Time,	Elongation in 2 Inches,	Minimum Creep Rate,
Number	ksi	ís.	0.1	0.2	0.5	1.0	2.0	percent	hours	percent	percent
								700 00	1.10		
3-1	66	1000	:	:	!	8	:	CU2.U2	21.4		
, 	50	1000	;	1	:	ł	ł	2.863	49.2	4.6	( <b>e</b> )
4 c 1 c		1000	;	•	ł	0.2	:	0.907	196.3/_	2.8	(9)
	0 <del>1</del>	0001		i			:	0.053	1510.7 <sup>(c)</sup>	-0.102	( <b>e</b> )
3-4	50	1000	•			I		•			
								010 0	6 7	9 -	(a)
3-6	<b>60</b>	1200	!	1	:	1	t 1	610.0	(P)		
3-5	50	1200	:	1	ł	1	1	0.397	68.0 <sup>(c)</sup>	0	
3-8	40	1200	A I	:	4 1	;	ł	0.132	1080.7	0.149	110
•		0071		01	20	28	1	0.400	38.9	8.8	0.013
7-5	40	1400	t			•				16.2	0 0000
3-9	20	1400	20	55	150	150	290	0.144	4.00.0	C • 01	0.0044
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(a) Negative creep occurred.

(b) Failed through pin hole.

(c) Test discontinued.



FIGURE 86. TYPICAL TENSILE STRESS\_STRAIN CURVES AT TEMPERATURE FOR HEAT\_TREATED INCOLOY 903 SHEET (LONGITUDINAL)



FIGURE 87. TYPICAL TENSILE STRFSS-STRAIN CURVES AT TEMPERATURE FOR HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE)



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FIGURE 88. TYPICAL COMPRESSIVE STRESS\_STRAIN AND TANGENT\_ MODULUS CURVES AT TEMPERATURE FOR HEAT\_TREATED INCOLOY 903 SHEET (LONGITUDINAL)

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FIGURE 89. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE)



FIGURE 90. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHEET



FIGURE 91. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHFET



FIGURE 92. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED HEAT-TREATED INCOLOY 903 SHEET



FIGURE 93. AXIMU LOAD FATIGUE BEHAVIOR OF NOTCHED  $M_{t} = 3.0$  HEAT-TREATED INCOLOY 903 SHEET





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#### 201.0 T7 Aluminum Castings

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#### Material Description

201 is a recently developed heat-treatable, high strength aluminum casting alloy which contains copper, silver, magnesium, and titanium. Premium quality castings made from this alloy have exhibited improved mechanical properties when compared to premium quality castings of other conventional aluminum alloys. The alloy can be cast by sand, permanent mold, or investment casting techniques.

The castings used for this evaluation were actual production parts used in airframe construction.

#### Processing and Heat Treating

The alloy was tested in the as-received -T7 condition.

#### Test Results

Tension. Results of tensile tests at room temperature, 300 F, 400 F, and 500 F are given in Table LXXVI. Typical stress-strain curves at temperature are shown in Figure 95. Effect-of-temperature curves are shown in Figure 97.

Compression. Test results at room temperature, 300 F, 400 F, and 500 F are given in Table LXXVII. Typical stress-strain and tangent-modulus curves are shown in Figure 96. Effect-of-temperature curves are shown in Figure 98.

Shear. Pin shear test results at room temperature are given in Table LXXVIII.

Impact. Charpy V-notch test results at room temperature are given in Table LXXIX.

Fracture Toughness. The maximum thickness of the casting (about 1/2-inch) was not sufficient for fracture tests.

<u>Fatigue</u>. Axial load test results for unnotched and notched specimens at room temperature, 300 F, and 400 F are given in Tables LXXX and LXXXI. S-N curves are presented in Figures 99 and 100.

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Creep and Stress Rupture. Tests were conducted at 300 F, 400 F, and 500 F. Tabular test results are given in Table LXXXII. Log-stress versus log-time curves are presented in Figure 101.

<u>Stress Corrosion</u>. Tests were conducted as described in the experimental procedure section of this report. No failures or cracks occurred in the test duration.

<u>Thermal Expansion</u>. The coefficient of thermal expansion is  $13.2 \times 10^{-6}$  in./in./F.

Density. The density of this alloy is 0.101 1b./in.<sup>3</sup>.

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Specimer Number	1	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, 10 <sup>3</sup> ksi
			Room Temperature	<u>)</u>	
1-1 1-2 1-3	Average	66.1 67.1 68.0 67.1	60.4 59.7 <u>59.8</u> 60.0	4.5 5.0 <u>4.5</u> 4.7	10.1 11.0 <u>10.3</u> 10.5
			<u>300 F</u>		
1-4 1-5 1-6	4 Average	56.5 57.0 57.0 56.8	49.4 49.1 <u>48.8</u> 49.4	6.0 8.5 7.0 7.2	9.3 9.4 <u>10.0</u> 9.6
			400 F		
1-7 1-8 1-9	Average	48.7 49.4 <u>47.2</u> 48.4	46.7 46.7 <u>45.2</u> 46.2	9.5 9.0 <u>10.0</u> 9.5	9.1 8.6 <u>8.7</u> 8.8
			500 F		
1-10 1-11 1-12	Average	29.2 29.2 <u>31.0</u> 29.8	28.0 27.6 29.4 28.3	14.0 15.0 <u>14.5</u> 14.5	7.5 8.5 <u>7.9</u> 8.0

# TABLE LXXVI. TENSION TEST RESULTS FOR 201-T7 ALUMINUM ALLOY CASTING

Specimer Number	n :	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10 <sup>3</sup> ksi
	Ro	om Temperature	
2-1 2-2 2-3	Average	62.0 61.6 <u>59.0</u> 60.9	$   \begin{array}{r}     11.1 \\     11.2 \\     \underline{10.9} \\     11.1   \end{array} $
2-4 2-5 2-6	Average	300 F 55.8 52.0 53.0 53.6	9.8 10.1 <u>10.0</u> 9.9
2-7 2-8 2-9	Average	400 F 52.0 46.0 46.6 48.2	9.6 9.9 <u>9.7</u> 9.7
2-10 2-11 2-12	Average	500 F 33.1 29.7 30.0 30.9	9.1 8.9 <u>8.9</u> 9.0

# TABLE LXXVII. COMPRESSION TEST RESULTS FOR 201-T7 ALUMINUM ALLOY CASTINGS

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# TABLE LXXVIII. SHEAR TEST RESULTS FOR 201-T7 ALUMINUM ALLOY CASTINGS AT ROOM TEMPERATURE

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Specimen Number	U	ltimate Shear Strength, ksi
4-1		39.3
4-2		39.0
4-3		39.8
4-4		39.3
	Average	39.3

## TABLE LXXIX. IMPACT TEST RESULTS FOR 201-T7 ALUMINUM ALLOY CASTINGS AT ROOM TEMPERATURE

Specimen Number		Energy, ft./lbs.
10-1		7.0
10-2		5.0
10-3		4.0
10-4		4.0
10-5		5.0
10-6		5.0
	Average	5.0

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Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-2	60.0	9,500
5-3	55.0	21,300
5-1	50.0	30,200
5 -4	45.0	70,600
5-3	42.5	2,581,900
5-5	40.0	50,400
5-7	37.5	53,300
5-6	35.0	3,858,400
5-9	30.0	11,340,800 <sup>(a)</sup>
	<u>300 F</u>	
5-10	60.0	8,400
5-11	55.0	17,400
5-12	50.0	42,200
5-13	45.0	124,100
5-15	42.5	223,900
5-14	40.0	109,300
5-16	37.5	2,384,200
5-17	35.0	204,300
5-18	30.0	238,300(0)
5-19	25.0	11,538,190(4)
	<u>400 F</u>	·
5-20	6 <b>0.</b> U	100
5-24	50.0	28,100
5-22	45.0	33,700
5-25	42.5	97,800
5-21	40.0	177,900
5-26	37.5	212,300
5-23	35.0	2,851,600
5-27	30.0	236,800
5-28	25.0	14,461,900

# 201-T7 ALUMINUM ALLOY CASTINGS

(a) Did not fail.

(b) Failed at Radius.

# TABLE LXXXI. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ( $K_{\pm} = 3.0$ ) 201-T7 ALIMINIM ALLOY CASTINGS

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Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-31	40.0	7,500
5-32	30.0	21,600
5-34	25 <b>.0</b>	44,700
5-36	22,5	107,400
5-33	20.0	247,500
5-35	17.5	2,646,500
5-37	15.0	14,621,000 <sup>(a)</sup>
	300 F	
5 -44	40.0	6,400
5-45	30.0	26,600
5-47	25.0	48,300
5-46	20.0	91,800
5-49	17.5	1,061,800
5-50	15.0	8,524,200
5-51	12.5	11,392,300 <sup>(a)</sup>
	400 F	
5-38	40.0	6,100
5-39	30.0	15,400
5-41	25.0	43,800
5-40	20.0	128,400
5-42	17.5	243,600
5-43	15.0	509,000
5-52	12.5	4,744,700
5-53	10.0	$13.384.100^{(a)}$

(a) Did not fail.

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.) Test discontinued.

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Minimum Creep Rate	percent	0.037 0.0004 0.00007	0.055 0.0023	0.00028	0.25	0.0027 0.00032 0.00008
Reduction of Area,	percent	22.4 26.4 	41.1 10.1 3.9	1	27.0	54.5
Elongation in 2 in.,	percent	8.9 7.4 1.315 0.770	12.6 5.9 3.7	• ) 0.655	8.2	14.1 0.397 0.255
Rupture Time,	hours	0.1 77.8 1363.2 <sup>(b</sup> 1325.4 <sup>(b</sup>	0.02 34.8 333.7	1033.1 <sup>(b</sup>	6.7	416.6 527.3 <sup>(t</sup> 984.5 <sup>(t</sup>
Initial Strain,	percent	2.710 0.674 0.507 0.574	2.655 0.541 0.367	0.274	0.274	0.141 0.118 0.056
-	2.0	1811	 29 325	ł	5.4	352
Deformation	1.0		 17 275	3165 <sup>(a)</sup>	3.5	277 
cated Creep percent	0.5		5 180	1475 (a)	1.6	160 1200 (a) 
s to Indí	0.2	 0.50 80 1375	 1.0 62	410	0.6	52 310 1000
Hour	0.1			125	0.2	12 105 200
Temper- ature.	E	300	00 <b>: :</b>	` <b>:</b>	500	: : 200
Stress	ksi.	60 60 60 60 60 60	50 35 35	25	20	10 6.5 4.5
·····	aper tues		3-10 1-12 3-9	<u> </u>	3-7	3-1 3-5 3-11

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TABLE LYCALL. SUPPARY CREE? AND RUPTURE DATA FOR 201-T7 ALUMINUM ALLOY CASTINGS



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FIGURE 95. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 201-T7 ALUMINUM ALLOY CASTINGS

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FIGURE 96. TYPICAL COMPRESSIVE SIRESS-STRAIN AND TANGENT-MODULUS CORVES AT FEMPERATURE FOR TOI-17 ALEMENTM ALLOY CASTINGS



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FIGURE 100. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_t = 3.0$ ) 201-T7 ALUMINUM ALLOY CASTINGS

STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR 201-T7 ALLAINUM ALLOY CASTINGS FIGURE 101.



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#### DISCUSSION OF PROGRAM RESULTS

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The tendency in an evaluation program of this type is to compare the materials property information obtained with similar data on materials already in use. Whether such a comparison should be the deciding factor for interest in a accor alloy is open to question. Many criteria, such as forming characteristics; exidation resistance, weldability, etc., can be of particular importance in a particular application so that strength properties may become secondary. However, since first comparisons are usually made on the basis of mechanical strength (tensile ultimate and tensile yield), the materials evaluated on this program are compared to each other and to similar alloys. Figures 102 and 103 are effect-of-temperature curves concerned with these properties.

This data sheet effort was concerned primarily with aluminum and titanium alloys. As can be seen from Figures 102 and 103, the aluminum alloys were similar in strength, as were the titanium alloys. The two heat-resistant alloys, Inconel 617 and the higher strength Incoloy 903, show good strength properties with extremely good strength retention at elevated temperatures. The development aim for these alloys seems to have been achieved.

As mentioned above, the aluminum alloys and the titanium alloys, as a group, show similar strength properties. Table LXXXIII presents the room temperature fatigue strength at  $10^7$  cycles for these materials. It is interesting to note that, although there is some variation in the unnotched fatigue strength, the notched (K<sub>t</sub> = 3.0) fatigue properties (of prime importance in structural design) are very similar. In fact, the two cast alloys show higher notched fatigue properties than their wrought alloy counterparts.

Alloy	Fatigue Strength at Unnotched	10 <sup>7</sup> cycles, ksi Notched
. 049	35	11
7475	48	13
2419	36	11
201	30	16
Ti-6-4 Cast	44	41
Ti-6-4 Forged	75	31
Ti-6-4 Beta Annealed	92	35
Ti-6-2-1-1	68	28
T1-6-2-2-2-2	76	40

TABLE LXXXIII. FATIGUE STRENGTHS AT ROOM TEMPERATURE FOR PROGRAM ALLOYS







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#### CONCLUSIONS

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The objective of this program was the generation of useful engineering data for newly developed materials. During the contract term, the following materials were evaluated

- (1) 7049-T7351 plate
- (2) Inconel 617 annealed sheet
- (3) 7475-T7351 plate
- (4) 2419-T851 plate
- (5) Ti-6A1-2Zr-2Sn-2Mo-2Cr duplex-annealed forging
- (6) Ti-6A1-2Cb-1Ta-1Mo annealed plate
- (7) Ti-6A1-4V beta-annealed plate
- (8) Ti-6Al-4V annealed castings
- (9) Ti-6A1-4V isothermal forgings
- (10) Incoloy 903 heat-treated sheet
- (11) 201.0 T7 castings.

A data sheet was issued for each material. As a summary, each of the data sheets is reproduced in Appendix III.

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APPENDIX 1

EXPERIMENTAL PROCEDURE

#### APPENDIX I

#### EXPERIMENTAL PROCEDURE

### Mechanical Properties

The various mechanical properties of interest for each of the materials are as follows:

(1) Tension

- (a) Tensile ultimate strength, TUS
- (b) Tensile yield strength, TYS
- (c) Elongation, e,
- (d) Reduction in area, RA
- (e) Modulus of elasticity, E.

(2) Compression

- (a) Compressive yield strength, CYS
- (b) Modulus of elasticity, E.
- (3) Creep and stress-rupture
  - (a) Stress for 0.2 or 0.5 percent deformation in 100 hours and 1000 hours
  - (b) Stress for rupture in 100 hours and 1000 hours.
- (4) Shear
  - (a) Shear ultimate strength, SUS
- (5) Axial fatigue\*
  - (a) Unnotched, R = 0.1, lifetime:  $10^3$  through  $10^7$  cycles

<sup>\* &</sup>quot;R" represents the algebraic ratio of the minimum stress to the maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "K<sub>t</sub>" represents the Neuber-Peterson theoretical stress concentration factor.

- (b) Notched ( $K_t = 3.0$ ), R = 0.1, lifetime:  $10^3$  through  $10^7$  cycles.
- (6) Fracture toughness,  $K_{Ic}$  or  $K_{c}$
- (7) Strels corrosion
  - (a) 80 percent TYS for 1000 hours maximum, 3-1/2 percent NaCl solution.
- (8) Thermal expansion.

(9) Bend

- (a) Minimum radius.
- (10) Impact
  - (a) Charpy V-notch.
- (11) Density.

#### Specimen Identification

A simple system of numbers and letters was used for specimen identification. Coding consisted of a number indicating the type of test and also indicating a comparable area on the sheet, plate, or forging. For certain test types, the number was followed by a letter signifying specimen orientation (L for longitudinal, T for transverse, ST for short transverse). The test types where the letter did not appear were creep, fatigue, and bend since, in these cases, only one specimen orientation was used. The next number in the coding specifies the location from which the specimen blank was taken from the original material configuration. Coding was as follows:

Assigned Number	Test Type		
1	Tension		
2	Compression		
3	Creep and stress-rupture		
4	Shear		
5	Fatigue		
6	Fracture toughness		

<u>Number</u>	Test Type	
7	Stress corrosion	
8	Thermal expansion	
9	Bend	
10	Impact	
11	Linsity	

As an example, a specimen numbered 2-T5 is a compression specimen, transverse orientation, cut from Location 5. Also, a specimen numbered 5-12 is a fatigue specimen cut from Location 12.

#### Test Description

#### Tension

Procedures used for tension testing are those recommended in ASTM methods E8-69 and E21-70 as well as in Federal Test Method standard No. 151 Six specimens (three longitudinal and three transverse) were tested at each temperature to determine ultimate tensile strength, 0.2 percent offset yield strength, elongation, and reduction in area. The modulus of elasticity was obtained from load-strain curves plotted by an autographic recorder during each test.

All tensile tests were carried out in Baldwin Universal testing machines. These machines are calibrated at frequent intervals in accordance with ASTM method E4-72 to assure loading accuracy within 0.2 percent. The machines are equipped with integra! automatic strain pacers and autographic strain recorders.

Specimens tested at elevated temperatures were heated in standard wire-wound resistance-type furnaces. Each furnace was equipped with a Foxboro controller capable of maintaining the test temperature to within 5 F of the control temperature over a 2-inch gage length. Chromel-Alumel thermocouples attached to the specimen gage section were used to monitor temperatures. Each specimen was soaked at temperature at least 20 minutes before being tested.

An averaging-type linear differential transformer extensometer was used to measure strain. For clevated temperature testing, the extensometer was equipped with extensions to bring the transformer unit out of the furnace. The extensometer conformed to ASTM E83-67 Classification B1 having a sensitivity of 0.0001 inch/inch. The strain rate in the elastic region was maintained at 0.005 inch/inch/minute. After yielding occurred, the head speed was increased to 0.1 inch/inch/minute unt+1 fracture.

#### ompression

Procedures for conducting compression tests are outlined in ASTM Method E9-70 along with temperature control provisions of E-21-70. All sneet and thin plate tests were carried out in Baldwin Universal testing machines using a North American type compression fixture as shown in Reference 2. Specimen heating was accomplished by a forced-air furnace for temperatures up to 1000 F. Specimen temperature was maintained by means of a Wheelco pyrometer. Three Chromel-Aluael thermocouples attached to the fixture were used to monitor temperatures to within 3 F of the test temperature. For higher temperatures, wire-wound furnaces were used with controls as described in the tensile test section.

The extensioneter used for the compression tests was quite similar to that used in the tensile testing. The extension arms were fastened to the specimen at small notches spanning a 2-inch gage length. The output from the microformer was fed into a load-strain recorder to provide autographic load-strain curves. During testing the strain rate was adjusted to 0.005 inch/inch/minute.

For bar and forging material, cylindrical specimens similar to those described in ASTM E9-70 were used with appropriate temperature control and strain measurement as described above.

Six specimens (three longitudinal and three transverse) were tested at each temperature.

#### Shear

Single-shear sheet-type specimens were used for sheet and thin-plate material; for bar and forgings, a double-shear pin-type was used. Shear testing was performed at room temperature only. A minimum of six specimens (three longitudinal and three transverse) were used to determine ultimate shea: strength.

#### Bend

The procedures for conducting bend tests are described in Report MAR-192-M. The specimens were placed in a rigid three-point loading fixture and bending tups of various sizes were used to determine the minimum bend radius at room temperature.

#### Creep and Stress Rupture

Standard dead-weight type creep testing frames were used for the creep and stress-rupture tests. These machines are calibrated to operate well within the accuracy requirements of ASTM method E139-70. Specimens similar to those used for tension tests were used for the creep and stress-rupture studies. A platinum strip "slide rule" extensometer is attached tor measuring creep strain and three Chromel-Alumel thermocouples are attached to the gage section for temperature measurements. Extensometer measurements were made visually through windows in the furnace by means of a filar micrometer microscope in which the smallest division equals 0.00005 inch.

The furnace was of conventional Chromel A wire-wound design with taps along the side to allow for correcting small temperature differences. Furnace temperature was maintained to within  $\pm 2$  F by Foxboro controllers in response to signals from the centrally located thermocouple. The temperature of a specimen under test was stabilized for at least 1/2 hour prior to loading.

For each temperature condition creep and stress-rupture data were obtained to 100 and 1000 hours using as many specimens as necessary to obtain precise information. The percent creep deformation obtained was dependent on the material under test. In most instances stress-time curves were defined for 0.2 and 0.5 percent elongation.

#### Stress Corrosion

Seven specimens of each alloy were tested for susceptibility to stresscorrosion cracking by alternate immersion in 3-1/2 percent sodium chloride solution at room temperature.

Specimens were prepared for testing by degreasing with acetone. Where a surface film remained from heat treating, it was abraded off one side and the adjacent long edge of five of the specimens, and left intact on the other two.

Each specimen was placed in a four-point loading fixture and deflected to a stress corresponding to 80 percent of the tensile yield strength of the particular material The specimen was electrically insulated from the fixture by means of glass or sapphire rods. Deflection for a given maximum fiber stress was calculated by the following expression:

$$y = \frac{\sigma (3\ell^2 - 4a^2)}{12dE}$$

where

- y = deflection
- c = maximum fiber stress
- l = distance between outer load points
- a = distance between outer and inner load points
- d = specimen thickness
- E = modulus of specimen material.

Each stressed specimen was suspended on an alternate immersion unit. This unit alternately immersed specimens in the 3.5 percent sodium chloride solution for ten minutes and held them above the solution to dry for 50 minutes. Tests were continued to the first sign of cracking or for 1000 hours, whichever occurred first. のないたので、「「「「」」のないで、

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Specimens were given frequent low-power microscopic examinations to detect cracks. At the first sign of cracking the specimen was removed. At the conclusion of the test, selected samples were sectioned and examined metallographically for any indication of cracking. Representative samples in which cracks were found were also given a metallographic examination to establish the type and extent of the cracks.

#### Thermal Expansion

Linear-thermal-expansion measurements were performed in a recording dilatometer with specimens protected by a vacuum of about  $2 \times 10^{-5}$  mm of mercury. In this apparatus a sheet-type specimen is supported between two graphite structures inside a tantalum-tube heater element. On heating, the differential movement of the two structures caused by specimen expansion results in the displacement of the core of a linear-variable differential transformer. The output of the transformer is recorded continuously as a function of specimen temperature. The entire assembly is enclosed in a vacuum chamber.

The furnace is controlled to heat at the desired rate, usually 5 F per minute. Errors associated with measurements in this apparatus are estimated not to exceed + 2 percent. This is based on calibration with materials of known thermal-expansion characteristics.

#### Fatigue

Fatigue tests were conducted using MTS electrohydraulic-servocontrolled testing machines. The frequency of cycling of these machines is variable to beyond 2,000 cpm depending on specimen rigidity. These machines operate with closed-loop deflection, strain or load control. Under load control used in this program, cyclic loads were automatically maintained (regardless of the required amount of ram travel) by means of load-cell feedback signals. The calibration and alignment of each machine are checked periodically. In each case, the dynamic load-control accuracy is better than  $\pm 3$  percent of the test load.

For elevated temperature studies, an induction heating coil controlled by a Level Induction Heater was used. A thermocouple placed on the center of the specimen controlled temperature to  $\pm 5$  degrees.

After machining and heat treating (when required), the edges of all sheet and plate specimens were polished according to Battelle-Columbus' standard practice prior to testing. The unnotched specimens were held against a rotating drum covered with emery paper and polished using a kerosene lubricant. Successively finer grits of emery paper were used, as required, to produce a surface of about 10 RMS. Unnotched round specimens were polished in the Battelle-Columbus polishing apparatus. This machine utilizes a rotating belt sander driven rectilinearly along the specimen test section while the specimen is being rotated. The belt speed and specimen speed are adjusted so that polishing marks on the specimen are in the longitudinal direction. The surface finish is about the same as that on the flat specimens. The notched flat specimens were held in a fixture and polished with a slurry of oil and alundum grit applied liberally to a rotating wire. Notched round specimens are polished in the same manner, except that the specimen is rotated.

A shadowgraph optical comparator was used for measuring the test sections of all polished specimens and for inspection of the root radius in the case of the notched specimens.

The stress ratio for all specimens was R = 0.1. Stresses for notched  $(K_t = 3.0)$  and unnotched specimens were selected so that S-N curves were defined between 10<sup>3</sup> and 10<sup>7</sup> cycles using approximately 10 specimens for each set of fatigue conditions.

#### Fracture Toughness

Three types of fracture toughness tests were used. For heavy section materials, the chevron-notched, slow bend test specimen or the compact tension specimen of ASTM Method E-399 was selected. For thinner section sheet materials, center through-cracked tension panels were used as test specimens. All specimens were precracked in fatigue and subsequently fractured in a servocontrolled electrohydraulic testing system of appropriate load capacity.

The slow-bend type specimens were precracked and tested under 3-point loading. The pop-in load for materials susceptible to brittle fracture was determined from the load-compliance curve. When pop-in was not detectable, the curves were analyzed using the 5 percent secant offset mothod of the ASTM procedure.

The thin sheet center through-crack tension panels were initially sawcut and then precracked in constant amplitude fatigue loading. In order to maintain a flat fatigue crack and not plastically strain the uncracked section, the maximum stresses were adjusted to keep the applied stress-intensity factor less than one-third or one-quarter of that anticipated at fracture. This usually involved stepping down the stresses as the cracking proceeded. The crack was extended to approximately one-quarter of the panel width. Buckling guides were attached and a clip-type compliance gage was mounted in the central notch. The panels were fractured in a rising load test at a stress rate in the range

which corresponds nominally to the gross strain rate of standard tensile testing.

# APPENDIX II

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# SPECIMEN DRAWINGS



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FIGURE 108. SHEET CREEP - AND STRESS-RUPTURE SPECIMEN



FIGURE 109. ROUND CREEP - AND STRESS-RUPTURE SPECIMEN





FIGURE 112. UNNOTCHED SHEET FATIGUE SPECIMEN



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FIGURE 113. NOTCHED SHEET FATIGUE SPECIMEN



FIGURE 114. UNNOTCHED ROUND FATIGUE SPECIMEN



FIGURE 115. NOTCHED ROUND FATIGUE SPECIMEN A-1226



# APPENDIX III

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# DATA SHEETS

# MECHANICAL-PROPERTY DATA 7049-T7351 ALUMINUM ALLOY

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Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

# BATTELLE

Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

## 7049-T7351 Aluminum Plate

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# Material Description

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Alloy 7049 was developed by Kaiser Aluminum and Chemical Corporation to have a strength level in the range of 7075-T6 and 7079-T6 coupled with a high resistance to stress corrosion cracking. Initial development and production was in the form of forgings and hand forgings. Further development has been in plates and extrusions.

The material evaluated was a 3-inch-thick plate supplied by Kaiser with the following composition:

Percent
7.6
2.5
1.5
0.15
0.25 max
0.35 max
0.10 max
0.20 max
Balance

# Processing and Heat Treating

Specimens were tested in the as-received -T7351 temper.

7049-T7351 Alloy Data<sup>(a)</sup>

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Thickness:	3-inch	plate
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Property	Temperature, F			
	RT	250	350	500
Tension				
TUS (longitudinal), ksi	75.5	59.0	45.4	15.1
TUS (transverse), ksi	74.6	60.8	47.0	17.3
TYS (longitudinal), ksi	66.5	58.7	45.1	14.9
TYS (transverse), ksi	64.7	59.5	46.3	17.2
e (longitudinal), percent in 2 in.	13.0	18.2	20.2	31.9
e (transverse), percent in 2 in.	10.7	15.5	17.3	28.8
RA (longitudinal), recent	36.1	53.5	64.9	86.3
RA (transverse), percent	25.6	43.4	54.6	83.2
E (longitudinal), lo ksi	10.2	9.3	8.0	6.C
e (transverse), 10 ksi	10.4	4.5	8.4	·./
Compression				
CYS (longitudinal), ksi	64.1	56.8	44.4	10.7
CYS (transverse), ksi	69.2	59.8	47.5	17.0
E <sub>c</sub> (longitudinal), 10 ksl	10.8	9.4	8.1	6.9
E <sub>c</sub> (transverse), 10° ksi	10.9	9.7	8.3	7.0
Shear <sup>(b)</sup>				
SUS (longitudinal), kai	46.1	н <sup>(с)</sup>	<u>ا</u> ر	1
SUS (transverse), ksi	45.4	ť	1.	l
Impact <sup>(d)</sup>				
V-notch Charpy, It.16.				
(longitudinal)	5.8	ľ	[·	1.
(transverse)	3.3	ſ.	1.	ſ.
Fracture Toughness (e)				
K <sub>r</sub> (L-T), ksi (in.	34.0	ť	l.	į
K <sub>Ic</sub> (T-L), ksi (in.	28,1	ť	ť	١.
Axial Fatigue (transverse) (f)				
Unnotched $R = 0.1$				
$10^{\circ}$ cycles, ksi	65	60	47	1.
10 <sup>°</sup> cycles, ksi	14	39	36	1.
10 <sup>7</sup> cycles, ksi	35	26	23	ť
Notched, $K_{L} = 3.0, R = 0.1$				
10° cycles, ksi	55	53	53	U
10 <sup>k</sup> cycles, ksi	i u	17	17	ť.
10 <sup>7</sup> cycles, ksi	11	10	10	ſ.

Property	Temperature, F			
	RT	250	350	500
Creep (transverse)				
0.27 plastic deformation, 100 hr. ksi 0.27 plastic deformation, 1000 hr. ksi	NA <sup>(c)</sup> NA	3.2 2 '4	11	3 2
<u>Stress Rupture (transverse)</u>				
Rupture, 100 hr, ksi Rupture, 1000 hr, ksi	NA NA	42 37	18 12	6 '+
Stress Corrosion (transverse)	No Cracks			
80. TYS, 1000 hr maximum				
Coefficient of Thermal Expansion				

#### 7049-17351 Alloy Data (Continued)

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12.9 x 10<sup>-1</sup> in./in./F (70 to 212 F)

#### Density

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0.099 lb./in.

- (a) Values are average of triplicate tests conducted at sattelle under the subject contract unless otherwise indicated. Fatigue, creep, and stressrupture values are from curves generated using the results of a greater number of tests.
- (b) Double-shear pin-type specimen; average of 4 tests.
- (c) U, unavailable; NA, not applicable.
- (d) Average of 6L and 6T tests.
- (c) Specimens were slow-bend type 1-inch thick x 2-inches wide with a span of 8 inches.  $K_{Le}$  values are valid by existing ASTM criteria.
- (f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . " $K_t$ " represents the Neuber-Peterson theoretical stress concentration factor.
- (y) Room-temperature three-point bend test. Alternate immersion in 3 1/2 NaCl



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FIGURE 1. "LEFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE



<sup>1</sup> FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE

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FIGURE 3. ANIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7049-77351 ALUMINUM ALLOY PLATE



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_t = 3.0$ ) 7049-T7351 ALUMINUM ALLOY PLATE


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# MECHANICAL-PROPERTY DATA INCONEL 617 ALLOY

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ANNEALED SHEET

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Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

### BATTELLE

Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### Inconel 617 Alloy

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Material Description

Inconel Alloy 617 is a solid-solution, nickel-chromium-cobaltmolybdenum alloy with an exceptional combination of high-temperature strength and oxidation resistance. It has excellent resistance to a wide range of corrosive environments, and is readily formed and welded by conventional techniques.

The high nickel and chromium contents make the alloy resistant to a variety of both reducing and oxidizing media. The aluminum, in conjunction with the chromium, provides oxidation resistance at high temperatures. Solidsolution strengthening is provided by the cobalt and molybdenum.

The combination of high strength and oxidation resistance at elevated temperatures makes this alloy an attractive material for gas-turbine aircraft engines and other applications involving exposure to extreme temperatures.

The material used for this evaluation was 0.047-inch-thick sheet from Heat XX00A7US with the following composition:

Chemical	-
Composition	<u>Percent</u>
Chromium	22.0
Cobalt	12.5
Molybdenum	9.0
Aluminum	1.0
Carbon	0.07
Nickel	54.0

#### Frocessing and Heat Treating

Specimens were tested in the as-received cold-rolled and annealed condition.

# INCONEL ALLOY 617 DATA<sup>(a)</sup>

Thick mess: 0.047 winch nominal Condition: Cold-rolled and annualed

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	Temperature, F					
Properties	·.·	RT	800	1200	1600	
Tension						
TUS (longitudinal), ksi		122.4	103,3	83.9	24.6	
TUS (transverse), ksi		123.6	105.7	96.0	24.8	
TYS (longitudinal), ksi	÷.,	56,6	41.0	38.2	21.7	
TYS (transverse), ksi	1.0	56.5	43.4	39.3	22.9	
e (longitudinal), percent in 2-in.	•	55.5	50.0	43.3	46.0	
e (transverse), percent in 2-in.		56.2	50.7	46.7	55.0	
E (lorgitudinal), 10 <sup>3</sup> ksi		27.0	23.6	23.1	17.0	
E (transverse), 10 <sup>3</sup> ksi		30.5	24.8	29.8	16.6	
Compression						
(VS (longitudinal) kei		61 9	48 9	41.0	30.9	
(VS (transverse) kei		61 5	49.9	41.6	31.6	
$E_{\rm c}$ (longitudinal) 103 kei		30 4	27.9	24.1	20.0	
$E_{c}$ (transverse), 10 <sup>3</sup> ksi		33.7	29.7	27.5	24.2	
Shear <sup>(b)</sup>						
		106 6	,, (c)	**	17	
SUS (fongitudinal), Ksi SUS (transverse), ksi		107.6	U	บ บ	U	
Bend (transverse)			-	-		
Minimum Radius		0Т	U	U	U	
Fracture Toughness				,		
K <sub>c</sub> , T-L, ksi√In.		(d)	U	U	U	
<u>Axial Fatigue (transverse)</u> (e)						
Unnotched, $R = 0.1$						
10 <sup>3</sup> cycles, ksi		115	95	88	U	
10 <sup>5</sup> cycles, ksi		93	67	67	U	
10 <sup>7</sup> cycles, ksi		67	60	60	U	
Notched, $K = 3.0$ R = 0.1					-	
103 overlage ket		80	65	61	U	
10 <sup>5</sup> cycles, ksi		52	46	43	Ū	
10 <sup>7</sup> cycles, ksi		32	36	31	ü	
TO CYCICO, NOL				~~	· · · · ·	

			Temperat	ure.F	
Properties		RT	800	1200	1600
(reep (transverse)	н 11				
0.2 plustic deformation, 100 nr. ksi 0.2 plastic deformation, 1000 hr, ksi	•	NA NA	(f) (f)	43 39	7
Rupture (transverse)	·		••	·	,
Rupture, 100 hr. ksi Rupture, 1000 hr. ksi		NA NA	103 102	62 48	14 9
Stress Corrosion (transverse) <sup>(g)</sup>			· ·		
80 1.5, 1000 fr maximum		no cracks	U	Ů	U
Contretent of Themal Expansion				к 1	
7.6 x $10^{-6}$ in./in./F (Rf to 500 F) 8.0 x $10^{-9}$ in./in./F (RT to 1200 F)					

#### INCONEL ALLOY 617 DATA (Continued)

8.7 x 10<sup>-6</sup> in./in./1 (RT to 1600 F)

#### Density

0.302 16/in.<sup>3</sup>

- (a) Values are average of triplicate tests conducted at Batcelie under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.
- (b) Sheet shear type specimen: average of four tests in each direction.
- (c) U, unavailable; NA, not applicable.
- Specimens were 10-inches wide by 36-inches long with a saw-cut flaw in the (d) center. Net stress at fracture was greater than the tensile yield strength of the material, therefore, the test was not valid for  $K_{\rm e}$ .
- (e)  $^{\prime\prime}R^{\prime\prime}$  represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "K<sub>t</sub>" represents the Neuber-Peterson theoretical stress concentration factor.
- (t) No appreciable deformation.

<sup>(</sup>c) Room-temperature three-point bend test, Alternate immersion in 3-1/2° NaCL.



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED INCOMEL ALLOY 617 SHEET



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED INCONEL ALLOY 617 SHEET



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FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED INCONEL ALLOY 617 SHEET

# MECHANICAL-PROPERTY DATA 7475 ALUMINUM ALLOY

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-T7351 PLATE

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Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

BATTELLE Columbus Laboratories Columbus, Ohio 43201

F 33615 73-C-5073

#### 7475 Aluminum Alloy

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### Material Description

Alloy 7475 was developed by the Alcoa Laboratories for sheet and plate applications that require high strength and superior fracture toughness. This product was previously designated "Alcoa 467 Process X7475 Alloy". The 467 Process is a proprietary process developed to enhance the toughness of a high-purity 7075 type alloy. It is still used in the production of 7475 sheet and plate.

Alloy 7475 is available as bare and alclad sheet and plate. The material used in this evaluation was 2 inch thick i re plate produced within the following corposition limits:

Composition	Percent
Silicon	0.10 max
Iron	0.12 max
Copper	1.2-1.9
Manganese	0.06 max
Magnesium	1.9-2.6
Chromium	0.18-0.25
Zinc	5.2-6 2
Titanium	0.6 max
Others	0.15 total
Aluminum	Balance

#### Processing and Heat Treating

The alloy was evaluated in the as-received -T7351 temper.

# 7475-T7351 ALLOY DATA<sup>(a)</sup>

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Thic	kness:	2 i	.nches
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	Temperature, F				
Properties	RT	250	350	500	
Tension					
TUS (longitudinal), ksi	72.1	55.6	44.7	19.0	
TUS (transverse), ksi	73.2	56.9	45.3	17.4	
TYS (longitudinal), ksi	62.9	55.5	44.6	18.8	
TYS (transverse), ksi	62.4	55.5	44.9	17.2	
e (longitudinal), percent in 2 in.	18.3	17.3	20.5	35.5	
e (transverse), percent in 2 in.	15.2	17.0	28.2	44.8	
RA (longitudinal), percent	47.8	60.5	71.6	90.7	
RA (transverse), percent	35.3	52.2	69.8	92.5	
E (longitudinal), 10 <sup>°</sup> ksi	10.2	9.0	7.8	7.1	
E (transverse), 10 <sup>3</sup> ksi	9.8	9.6	7.8	6.8	
Compression					
CYS (longitudinal), ksi	61.0	54.9	46.4	18.5	
CYS (transverse), ksi	65.5	57.6	48.4	18.9	
E <sub>c</sub> (longitudinal), 10 <sup>3</sup> ksi	10.6	9.4	8.9	7.8	
E <sub>c</sub> (transverse), 10 <sup>3</sup> ksi	10.5	9.9	9.6	7.7	
Shear (b)					
SUS (longitudinal), ksi	45.7	נ <sup>(</sup> כ)	U	Ľ	
SUS (transverse), ksi	45.0	v	Ŭ	Ů	
Impact <sup>(d)</sup>					
V-notch Charpy, ft/1b					
(longitudinal)	17.1	tt	U	יו	
(transverse)	5.9	U	Ŭ	Ū	
Fracture Toughness					
K <sub>Ic</sub> , ksi/in.	(e)	U	U	Ľ	
$\frac{Axial Fatigue (transverse)}{Unnotched, R = 0.1}$ (f)					
	63	55	45	1;	
$10^{\circ}$ cycles, ksi	53	48	45	U U	
10 <sup>7</sup> cycles, ksi	48	37	27	t.	
Notched, $K_{r} = 3.0$ , $R = 0.1$					
$10^{9}$ evelop by	C 1)	5.0			
$10$ Cycles, KS1 $10^5$ cycles, ks1	54	50	45	U	
10 Cycles, Ksi	24	20	17	U U	
10 cycles, ksi	13	11	10	U	

		Temperature, F			
Properties	RT	250	350	500	
Creep (transverse)					
0.2% plastic deformation, 100 hr, ksi	NA	38	17	4	
0.2% plastic deformation, 1000 hr, ksi	NΛ	29	10	2.5	
Rupture (transverse)					
Rupture, 100 hr, ksi	NA.	46	22	7	
Rupture, 1000 hr, ksi	NA	41	15	5	
Stress Corrosion (transverse) <sup>(g)</sup> 80% TYS, 1000 hr maximum	no crac	ks			
Coefficient of Thermal Expansion 12.9 x 10 in./in./F (68 - 212 F)	·				
$\frac{D_{cnsity}}{0.101} \text{ lb/in.}$					

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- (a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.
- (b) Pin-shear tests. Average of four tests in each direction.
- (c) U, unavailable; NA, not applicable.

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- (d) Average of six tests in each direction.
- (e) Specimens were slow-bend type 1-inch thick x 2-inches wide with an 8-inch span. Average K<sub>0</sub> obtained was 59.8 for L-T specimens and 55.3 for T-L specimens. These values are considered indicative of the material toughness, but do not meet the rigorous size standard of ASTM E399-72 and, therefore, are not valid K<sub>1c</sub> values.
- (f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "K<sub>t</sub>" represents the Neuber-Peterson theoretical stress concentration factor.
- (g) Room-temperature three-point bend test. Alternate invuersion in  $3\frac{1}{2}$  NaCl.



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FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7475-T7351 ALLOY PLATE



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7475-T7351 ALLOY PLATE



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FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7475-T7351 ALLOY PLATE



FIGURE 4. AXIAL TOAD FAFIGUE BEHAVIOR OF NOTCHED  $(K_1 = 3, 0)$  7475-77351 ALLOY PLATE



IGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7475-17351 ALLOY PLATE (TRANSVERSE)

# MECHANICAL-PROPERTY DATA 2419 ALUMINUM ALLOY

http://www.everyspec.com

Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Issued by

**T851** 

Prepared by

#### BATTELLE

Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### 2419 Arominum Alloy

#### Material Description

Alloy 2419 is a recent development of the Aluminum Company of America. It is essentially a 2219 alloy with more closely controlled composition. Mechanical properties are the same as 2219 with improved tracture toughness. The alloy is readily weldable and is useful for applications at a wide range of temperatures from (452 F to about 600 F.

Composition limits for 2419 are as shown:

Chemical Composition Silicon Iron Copper Manganese Magnesium Zinc Titanium Others Aluminum

#### Percent

0.15 max. 0.18 max. 5.8 to 6.8 0.20 to 0.40 0.02 max. 0.10 max. 0.02 to 0.10 each 0.05, to al 0.15 Balance

The material used for this evaluation was a 2-inch-thick plate from Alcoa lot number 270-841.

Processing and Heat Treatment

The alloy was evaluated in the overaged and stress-relieved -T851 temper.

## 2419-T851 Alloy Data

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Condition: -T851 Thickness: 2-inch plate

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	Temperature, F				
Properties	RT	250	350	500	
Tension				· · · ·	
muc (lensteudinel) het	4 ( <b>7</b>	65 /			
TUS (longitudinal), KS1	00.7		40,0 47,0	. 22.2	
IUS (transverse), KS1	00.4 60 /	24.9 55 6	44,0	29.1	
TYS (long) cudinal), KS1	52.4	40.8	41.4	20.9	
TYS (transverse), ksi	52.1	45.0	39.7	21.7	
e (longitudinal), percent in 2 in.	11.0	15.0	14.5	10.0	
e (transverse), percent in 2 in.	10.7	13.2	14.8	18.0	
RA (longitudinal), percent	23.6	37.9	48.4	53.2	
RA (transverse), percent	18.1	33.9	46.2	51.6	
E (longitudinal), 10 <sup>°</sup> ksi	10,4	10.4	9.1	7,4	
E (transverse), 10' ksi	10.8	9.5	9.5	9.1	
Compression					
CYS (longitudinal), ksi	53.3	47.8	42.2	25.5	
CYS (transverse), ksi	51.7	46.9	41.7	25.5	
E. (longitudinai), i0 ksi	10.8	10.5	10.0	9.3	
$E_c$ (transverse), 10 <sup>°</sup> ksi	10.7	10.4	9.8	9,0	
Shear					
SUS (longitudinal), ksi	39.4	U	ţr	v	
SUS (transverse), ksi	39.5	1)	U	ť	
Impact					
V-notch Charpy, ft-1b					
(longitudinal)	5.5	U	. U	ť	
(transverse)	4.3	U.	V	l;	
Fracture Toughness					
$K_{T,n}$ (L-T), ksi/in,	35.3	U	U	U	
$K_{Ic}$ (T-L), kst/in.	30.2	U	U	U	
Axial Fatigue (transverse) (f)					
Unnotched, $R = 0.1$					
10 <sup>°°</sup> cycles, ksi	. 66	55	+5	ł	
10 cycles, ksi	42	42	39	ľ.	
10 <sup>7</sup> cvcles, ksi	36	30	26	î.	
Notched, $K_{+} = 3.0$ , $R = 0.1$					
10° cviles, ksi	50	48	., 5	ι.	
10 cvcler, ksi	19	17	17	i	
10 eveles kai	11	10	10	ł.	
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#### 2419-T851 Alloy Data (Continued)

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		Temperature, F				
Properties		RT	250	350	500	
<u>Creep (transverse)</u>	•			,	1	
0.2% plastic deformation, 100 hr, ksi 0.2% plastic deformation, 1000 hr, ksi		NA NA	36 32	23 18	9.4 6.2	
Stress Rupture (transverse)						
Rupture, 100 hr, ksi Rupture, 1000 hr, ksi		NA NA	44 41	31 26	14 9.4	
Stress Corrosion (transverse) <sup>(g)</sup>		۰.				
80% TYS, 1000 hr maximum	No	cracks			•	

#### Coefficient of Thermal Expansion

 $12.4 \times 10^{-6}$  in./in./F (70 to 212 F)

#### Density

0.102 lb/in.<sup>3</sup>

- (a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stressrupture values are from curves generated using the results of a greater number of tests.
- (b) Double-shear pin-type specimen; average of 4 tests in each direction.
- (c) U, unavailable; NA, not applicable.
- (d) Average of 6 tests in each direction.
- (e) Specimens were slow-bend type 1-inch thick by 2-inches wide with a span of 8 inches. K<sub>IC</sub> values are valid by existing ASTM criteria.
- (f) "R" represents the albebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "Kt" represents the Neuber-Peterson theoretical stress concentration factor.
- (g) Room-temperature three-point bend test. Alternate immersion in  $3\frac{1}{2}\%$  NaCl.



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 2419-T851 ALLOY PLATE



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 2419-T851 ALLOY PLATE



 $\begin{array}{c|c} \Delta & 250 \text{ F} \\ \hline \hline & 350 \text{ F} \\ \hline & 10^4 \\ \hline & 10^5 \\ \hline & 10^6 \\ \hline \\ & \text{Lifetime, cycles} \end{array}$ 

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FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_t = 3.0$ ) 2419-T851 ALUMINUM ALLOY PLATE



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FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 2419-T851 ALUMINUM ALLOY PLATE

# MECHANICAL-PROPERTY DATA Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY

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### DUPLEX ANNEALED FORGED BILLET

issued by

Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

### BATTELLE Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073 220

#### Ti-6A1-2Zr-2Sn-2Mo-2Cr Alloy

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#### Material Description

This alpha-beta alloy, designed for deep hardenability, is a recent development of RMI Company. Preliminary information shows the material also to have low density, high modulus, high toughness, and good producibility. Strength retention to 800 F is good.

The material used for this evaluation was a 4-inch x 6-inch forged billet from RMI ingot number 890180 which had the following chemistry:

Element	Percent
A1	5.8
Sn	2.1
Zr	1.8
Mo	2.0
Cr	1.9
Si	0.21
Fe	0.06
С	0.02
v	0.02
Ti	Balance

Additional information on this alloy is available from work performed by RMI Company under Air Force Contract F33615-72-C-1152.

#### Processing and Heat Treating

The billet was heat-treated to the duplex-annealed condition by RMI Company using the following procedure: 1745 F, 1 hour, air cool to 1560 F and water quench; plus 1000 F for 8 hours and air cool. Specimens received no further heat-treatment before testing.

# Ti-6A1-2Zr-2Sn-2No-2Cr ALLOY DATA (a)

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Condition: duplex annealed Thickness: 4 inch x 6 inch forged billet

	Temperature, F				
Properties	RT	400	600	800	
tension					
TUS (longitudinal), ksi	158.4	Lah.3	137.3	139.4	
TUS (transverse), ksi	166.0	145.5	132.1	132.9	
TYS (longitudinal), ksi	143.9	111.0	102.5	102.0	
TYS (transverse), ksi	150.4	11.4	100.6	98.8	
e (longitudinal), percent in 2 in.	15.3	16.3	15.3	16.5	
e (transverse), percent in 2 in.	13.7	14.0	16.0	18.3	
RA (longitudinal), percent	36.0	47.4	36.0	47.2	
RA (transverse), percent	36.7	48.1	40.3	48.8	
E (longitudinal), 10 ksi	15.6	14.7	14.5	13.4	
4 (transverso), 10° ksi	15.8	13.9	14.8	13.4	
Compression					
CYS (longitudinal), ksi	149.4	116.2	106.4	91.9	
CYS (transverse), ksi	154.6	122.2	107.5	102.1	
E <sub>c</sub> (longitudinal), 10° ksi	16.1	17	14.3	13.1	
E <sub>e</sub> (transverse), 10° ksi	16.1	15.3	14.8	13.4	
Shear <sup>(b)</sup>					
SUS (longitudinal), ksi	102.5	ر ب <sub>ا</sub> د)	C	Ľ	
SUS (transverse), kal	105.4	t	l.	Ľ	
lmpact (d)					
V-notch Charpy, ft. 1bs.					
(longitudinal)	14.9	ť	1.	Ľ	
(transverse)	14.9	ť	i.	v	
Erastura Taughnees (e)					
$K_{1.1}$ , L-T. edge, ksi/in.	45.1	Ľ	ť	r	
Kra, L-T, center, ksi/in.	51.8	U	r	i.	
K <sub>lc</sub> , ST-L, center, ksi/in.	62.0	L1	U	Ľ	
Axial Fatigue (transverse) (f)					
Unnotched, K=U.1	177	1//	2.37	• •	
$10^{\circ}$ cycles, ksi	164	144	134	ι π	
$10^{\circ}$ cycles, ksi	130	76	76	U: 11	
io cycles, ksi	/()	/()	70	Ċ.	
Notched, $K_t=3.0$ , $R=0.1$					
10° cycles, ksi	110	100	92	ť	
10° cycles, ksi	50	46	46	U	
10' cycles, ksi	40	40	40	U	

#### Ti-6A1-2Zr-2Sn-2Mo-2Cr ALLOY DATA

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(Continued)

	Temporature, F				
Properties	RT	400	600	800	
Creep (Lransverse)					
0.2" plastic deformation, 100 hr., ksi	NA	107	96	70	
0.2% plastic deformation, 1000 hr., ksi	NA	102	70	44	
Stress-Bupture (transverse)					
Rupture, 100 hr., ksi	NA	133.5	1.29	121	
Rupture, 1000 hr., ksi	3A	133	128.5	118	
Stress Correction $(transverse)^{(g)}$	no cracks	\$			

 $\frac{\text{Coefficient of Thermal Expansion}}{5.1 \times 10^{-1} \text{ in./in./F} (68 to 800 \text{ F})}$ 

Density 0.165 10./in.

- (a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatikue, creep, and stressrupture values are from curves generated using the results of a greater number of tests.
- (b) Souble-shear pin-type specimen; average of 4 test: in each direction.
- (c) 0, unavailable: NA, net applicable.
- (d) Average of 6 tests in each direction.
- (c) Values shown are from valid tests at RMI Company. Battelle tests were considered marginally valid and are not reported, even though they generally agreed with the RMI results.
- (f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R=S_{min}/S_{max}$ . "Kt" represents the Nouber-Peterson theoretical stress concentration factor.
- (g) Room-temperature three-paint bond test. Alternate immersion in 3-172 NaCL.



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF DUPLEX ANNEALED Ti-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF DUPLEX ANNEALED Ti-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET

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FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_t = 3.0$ ) DUPLEX ANNEALED Ti-6A1-2Zr-2Sn-2No-2Cr FORGED BILLET

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FIGURE 5. STRESS RUPTURE AND PLASTIC DEFORM-ATION CURVES FOR TI-6A1-2Zr-2Sn-2Mo-2Cr FORGED BILLET (TRANSVERSE)

# MECHANICAL-PROPERTY DATA 6AI-2Cb-ITa-IMo TITANIUM ALLOY

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ANNEALED PLATE

Issued by Air Force Materials Laboratory Air Force Systems Command

Wright-Patterson Air Force Base, Ohio

Prepared by

### BATTELLE

Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### Ti-6A1-2Cb-1Ta-1Mo Alloy

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#### Material Description

6A1-2Cb-1Ta-1Mo titanium alloy is a modification by RMI Company of the Ti-7A1-2Cb-1Ta composition. The modification was developed specifically for saltwater stress-corrosion resistance. The alloy is of medium strength and is forg-able and weldable. It is generally used in the annealed condition. Some increase in strength can be obtained by solution treating and aging, but at a sacrifice in ductility and toughness.

Ti-6Al-2Cb-1Ta-1Mo is available as billet, bar, plate, sheet, and wire. It is normally processed in the beta phase region.

The material evaluated was a  $l_2^1$ -inch-thick plate from RMI ingot number 294447 with the following composition:

Chemical			
Composition	Percent		
Carbon	.02		
Nitrogen	.006		
Iron	.07		
Aluminum	6.0		
Columbium	1.9		
Tantalum	.93		
Molybdenum	.77		
Oxygen	.080		
Titanium	Balance		

#### Processing and Heat Treating

The material was evaluated in the as-received, beta processed and annealed (1825 F, 1 hour, air cooled) condition.

## Ti-6A1-2Cb-1Ta-1Mo Alloy Data<sup>(a)</sup>

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Condition: Annealed Thickness:  $\begin{bmatrix} 1_2 \\ - \end{bmatrix}$  inch plate

Properties		Tempera	ature. F	
	RT	400	600	800
Tension			· · · · · · · · · · · · · · · · · · ·	<u> </u>
TUS (longitudinal), ksi	117.6	87.8	80.2	74.0
TUS (transverse), ksi	119.3	89.0	80.5	75.2
TYS (longitudinal), ksi	102.1	64.5	58.0	52.4
TYS (transverse), ksi	103.7	65.8	56.1	55.4
e (longitudinal), percent in 2 in.	18.3	18.3	19.6	19.7
e (transverse), percent in 2 in.	17.3	17.3	18.0	17.3
RA (longitudinal), percent	33.8	42.6	51.7	50.3
RA (transverse), porcent	32.9	42.6	47.2	49.0
E (longitudinal), 10 <sup>°</sup> ksi	17.0	16.0	14.0	12.8
E (transverse), 10 <sup>3</sup> ksi	17.0	17.4	14.8	14.4
Compression		· 1	3	· .
CYS (longitudinal), ksi	1.00.3.	74.2	60.8	55.2
CYS (transverse), ksi	111.9	77.4	63.2	58.3
E_ (longitudinal), 10 <sup>°</sup> ksi	17.6	15.9	15.0	13.7
$E_{c}$ (transverse), $10^{2}$ ksi	17.5	15.6	14.9	13.9
Shear <sup>(b)</sup>				
SUS (longitudinal) kei	83.7	11(c)		11
SUS (transverse), ksi	83.8	U	U	ັບ
Impact <sup>(d)</sup>				
V-notch Charpy, ft/1b				
(longitudinal)	38.5	U	ប	U
(transverse)	33.8	U	U	U
Fracture Toughness				
K <sub>lc</sub> , ksi√in.	(e)	U	U	U
<u>Axial Fatigue (transverse)</u> (f)				
Unnotched, $R = 0.1$				
$10^{\circ}$ cycles, ksi	115	90	80	U
10 <sup>b</sup> cycles, ksi	97	78	74	Ũ
10 <sup>°</sup> cycles, ksi	68	57	54	Ū.

Properties	Temperature, F			
	RT .	400	600	800
Notched, $K_{2} = 3.0$ , $K = 0.1$				
10° cycles, ksi	90	83	80	U
10 <sup>b</sup> cycles, ksi	49	45	40	U,
10 cycles, ksi	28	26	25	U
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi 0.2% plastic deformation, 1000 hr, ksi	NA <sup>(0.)</sup> NA	67 66	73 72	<b>61</b> 52
Stress Rupture (transverse)		с. С	іс.	• . • .
Rupture, 100 hr, ksi	NA	88	.81	~ 73
Rupture, 1000 hr, ksi	NA	Ø7	<b>a</b> U	. 12
Stress Corrosion <sup>(g)</sup>				
80% TYS, 1000 hr maximum	No cracks	а 1		
Coefficient of Thermal Expansion			-	

Ti-6Al-2Cb-lTe-180 Alloy Data (continued)

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5.2 x 10 in./in./F(RT to 1200 F)

Density

0.162 lb/in."

- (a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.
- (b) Double-shear pin-type specimen; average of four tests.
- (c) U, unavailable; NA, not applicable.
- (d) Average of six tests in each direction.
- (e) Specimens were slow-bend type 1-inch thick x 2-inches wide with a span of 8 inches. Tests did not meet the size standard of ASTM E399-72. From this specification, the specimen strength ratios  $(R_{sb})$  were calculated. These averaged 2.18 for L-T specimens and 1.82 for T-L specimens.
- (1) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle, that is,  $R + S_{min}/S_{max}$ . "K<sub>c</sub>" represents the Neuber-Peterson theoretical stress concentration factor.
- (g) Room temperature three-point bend test. Alternate immersion in  $3\frac{1}{2}$  NaCl.



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FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED Ti-6A1-2Cb-1Ta-1Mo ALLOY PLATE



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED TI-6A1-2Cb-1Ta-1Mo ALLOY PLATE



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FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_{t} = 3.0$ ) ANNEALED Ti-6A1-2Cb-1Ta-1% ALLOY PLATE



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FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED Ti-6A1-2Cb-1Ta-1Mo ALLOY PLATE
## MECHANICAL-PROPERTY DATA Ti-6Al-4V ALLOY

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BETA-ANNEALED PLATE

Issued by

Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

BATTELLE Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### Ti-6A1-4V Alloy

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#### Material Description

Ti-6A1-4V is one of the most used titanium alloy and thus needs no descriptive words. It is used in great quantities and in various product forms for aerospace and other applications. The 0.57-inch-thick plate used for this evaluation was GFM from material produced for Boeing to their low oxygen specification.

#### Processing and Heat Treating

The material was tested in the as-received, beta-annealed condition.

### Ti-6A1-4V ALLOY DATA<sup>(a)</sup>

Condition: Beta annealed Thickness: 0.57 plate

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	Temperature, F					
Properti <b>es</b>	RT	400	600	800		
Tension						
TUS (longitudinal), ksi	135.8	103.3	92.5	83.0		
TUS (transverse), ksi	136.0	103.7	92,7	82.5		
TYS (longitudinal), ksi	127.7	86.1	72.1	65.6		
TYS (transverse), ksi	126.7	85.6	71.5	64.1		
e (longitudinal), percent in 2 in.	12.2	16.0	15.0	20.7		
e (transverse), percent in 2 in.	12.0	15.7	14.3	18.3		
RA (longitudinal), percent	20.9	34.4	35.1	48.8		
RA (transverse), percent	27.4	32.2	34.3	45.0		
E (longitudinal), 10 <sup>3</sup> ksi	17.5	16.1	15.9	13.2		
E (transverse), 10 <sup>3</sup> ksi	16.9	16.5	15.3	13.9		
Compression						
CYS (longitudinal), ksi	132.4	89.5	73.5	68.3		
CYS (transverse), ksi	134.8	91.4	76.6	69.9		
E <sub>c</sub> (longitudinal), 10 <sup>°</sup> ksi	17.1	15.8	14.8	14.0		
E <sub>c</sub> (transverse), 10 <sup>3</sup> ksi	17.5	15.4	15.1	14.0		
Shear <sup>(b)</sup>						
SUS (longitudinal), ksi	90.6	U <sup>(C)</sup>	U	U		
SUS (transverse), ksi	89.9	U	U	U		
Impact <sup>(d)</sup>						
V-notch Charpy, ft.1bs.						
(longitudinal)	23.6	U	ឋ	ប		
(transverse)	23.2	U	U	U		
Fracture Toughness	(e)					
Axial Fatigue (transverse) <sup>(f)</sup>						
Unnotched, $R = 0.1$						
10 <sup>°</sup> cycles, ksi	126	102	92	U		
10' cycles, ksi	112	85	78	U		
10° cycles, ksi	92	77	70	U		
Notched, $K_t = 3.0$ , $R = 0.1$						
10° cycles, ksi	110	92	80	U		
10° cycles, ksi	53	44	43	U		
l0' cycles, ksi	35	35	35	U		

		Tempera	ture, F	
Properties	RT	400	600	800
Green (transverse)				
0.2% plastic deformation. 100 hr., ksi	NA	82	88	46
0.2% plastic deformation, 1000 hr., ksi	NA	81	84	30
Stress Rupture (transverse)				
Rupture, 100 hr., ksi	NA	102.5	92	82
Rupture, 1000 hr., ksi	NA	102	91.5	70
Stress Corrosion (transverse) <sup>(g)</sup> 80% TYS, 1000 hr., maximum	no crack	s		
<u>Coefficient of Thermal Expansion</u> 5.0 x 10 <sup></sup> in./in./F (RT to 800 F)				
Density 0.160 lb./in. <sup>3</sup>				

Ti-6Al-4V ALLOY DATA (Continued)

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- (a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stressrupture values are from curves generated using the results of a greater number of tests.
- (b) Double-shear pin-type specimen; average of 4 tests in each direction.
- (c) U, unavailable; NA, not applicable.
- (d) Average of 6 tests in each direction.
- (e) Specimens were compact tension type. Tests did meet the P /P requirement but not the size requirement of E399-72. Specimen strength ratios (R ) were calculated and are 1.28 for L-T specimens; 1.22 for I-L specimens.
- (f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "K<sub>t</sub>" represents the Neuber-Peterson Theoretical stress concentration factor.
- (g) Room-temperature three-point bend test. Alternate immersion in 31% NaCl.



FIGURE 1. UFFECT OF TEMPERATCRE OF THE TENSILE PROPERTIES OF BELA-ANNEALED TI-GAL- C. MLOY PLATE



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF BETA-ANNUALED FI-GAU-4V ALLOY PLATE

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10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、10月1日に、1

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FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED BETA-ANNEALED Ti-6A1-4V ALLOY PLATE



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_t = 3.0$ ) BETA-ANNEALED T1-6A1-4V ALLOY PLATE



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FIGURE 5. STRESS-RUPTURE A PAIRIC DEFORMATION CURVES FOR BETA-ANNEALED TI-0A1-4V ALLOY PLATE (TRANSVERSE)

## MECHANICAL-PROPERTY DATA Ti-6Al-4V ALLOY

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ISOTHERMAL FORGING

Issued by

Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

BATTELLE Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### Ti-6A1-4V Isothermal Forging

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#### Material Description

Application of the isothermal forging concept to titanium alloys has been investigated on a laboratory scale for many years. The material evaluated on this program came from an Air Force sponsored program (F33615-71-C-1264) at the Ladish Company. The specific goal was to develop isothermal forging technology as a process that will yield titanium airframe parts having surfaces which are "net", or which require no past-forging machining. The results of this program have been published in AFML-TR-74-123 from which additional information regarding this material may be obtained.

#### Processing and Heat Treating

The stabilizer rib from which the specimens were machined was of varying thickness and complex shape. All specimens were sectioned from the forging in the transverse direction. Specimens were tested in the as-received (annealed) condition.

### Ti-6Al-4V Alloy Data<sup>(a)</sup>

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Condition: Isothermally Forged and Annealed Thickness: Various 「「「「」」

語文

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RT	400	600	<u> </u>
	the second s		000
143.9	110.5	99.8	87.4
136.3	102.2	93.4	78,3
17.0	17.5	18.5	21.5
45.7	47.7	54.1	62.3
16.4	15.2	14.5	12.9
135.9	101.4	93.2	79.6
16.5	15.4	13.9	12.9
97.2	U <sup>(e)</sup>	Ū	U
( 4 )			
16.9 <sup>(a)</sup>	U	ឋ	U
(e)			
59.0	U	U	U
135	110	95	U
128	105	89	U
/5	80	73	U
65	45	6 E '	.,
0J // 6	0) 50	00 62	U 17
40	20	45	и 11
	$   \begin{array}{r}     143.9 \\     136.3 \\     17.0 \\     45.7 \\     16.4 \\     135.9 \\     16.5 \\     97.2 \\     16.9^{(d)} \\     59.0^{(e)} \\     135 \\     128 \\     75 \\     65 \\     46 \\     31 \\   \end{array} $	$143.9$ $110.5$ $136.3$ $102.2$ $17.0$ $17.5$ $45.7$ $47.7$ $16.4$ $15.2$ $135.9$ $101.4$ $16.5$ $15.4$ $97.2$ $U^{(u)}$ $16.9^{(d)}$ $U$ $59.0^{(e)}$ $U$ $135$ $110$ $128$ $105$ $75$ $80$ $65$ $65$ $46$ $50$ $31$ $28$	$143.9$ $110.5$ $99.8$ $136.3$ $102.2$ $93.4$ $17.0$ $17.5$ $18.5$ $45.7$ $47.7$ $54.1$ $16.4$ $15.2$ $14.5$ $135.9$ $101.4$ $93.2$ $16.5$ $15.4$ $13.9$ $97.2$ $U^{(u)}$ $U$ $16.9^{(d)}$ $U$ $U$ $135$ $110$ $95$ $128$ $105$ $89$ $75$ $80$ $73$ $65$ $65$ $65$ $46$ $50$ $43$ $31$ $28$ $35$

#### Ti-6A1-4V Alloy Data (Continued)

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		erature, F		
Properties	RT	400	600	800
Creep (Transverse)			ъ	
0.2% plastic deformation. 100 hr. ksi	NA	98	.74	21
0.2% plastic deformation, 1000 hr, ksi	NA	96	70	11
Stress Rupture (transverse)		2		
Rupture, 100 hr, ksi	NA	112	102	101
Rupture, 1000 hr, ksi	NA	111	101	57
Stress Corrosion (transverse) <sup>(g)</sup> 80% TYS, 1000 hr, maximum	•			,
Coefficient of Thermal Expansion 5.0 x 10° in./in./F (RT to 800 F)	•			
Density 0.160 lb./in. <sup>3</sup>				

- (a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stressrupture values are from curves generated using the results of a greater number of tests.
- (b) Double-shear pin-type specimen; average of 4 tests.
- (c) U, unavailable; NA, not applicable.
- (d) Average of 6 tests.

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- (e) Compact tension type specimen.
- (f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "K<sub>t</sub>" represents the Neuber-Peterson theoretical stress concentration factor.
- (g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.



CURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF T1-6A1-4V ISOTHERMAL FORGINGS



FIGURE 2. EFFECT OF TURPERATURE ON THE COMPRESSIVE PROPERTIES OF TI-6A1-4V ISOTHERMAL FORGINGS





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TION CURVES FOR T1-6A1-4V ISOTHERMAL FORGINGS

## MECHANICAL-PROPERTY DATA Ti-6Al-4V ALLOY

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ANNEALED CASTINGS

Issued by

Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

BATTELLE Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### Ti-6A1-4V Alloy Castings

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#### Material Description

Ti-6Al-4V castings have been utilized in airframe construction for a number of years, primarily in simple shapes and in unstressed or low stress areas. Recently, more complex shapes have been used as confidence in casting properties has increased. One of the primary reasons is that parts can be cast to a finished or near-finished shape instead of being machined to size from a large forging or thick plate.

The material used for this evaluation was cast, wedge shaped, plates approximately 5 inches by 6 1/2 inches and tapering from about 1 inch to 1/2 inch. The material was from TiTech International casting Heat Number 6-4 2119 and had the following composition:

Chemical Composition	Percent
Carbon	.028
Oxygen	.18
Hydrogen	.0027
Nitrogen	.015
Aluminum	5.90
Vanadium	3 , 90
Iron	.10
Titanium	Balance

#### Processing and Heat Treating

The specimens were all machined in one direction from the cast plates described above. The material was received in the annealed condition and no further heat treating was done.

### Ti-6Al-4V Alloy Casting Data<sup>(a)</sup>

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#### Condition: Annealed Thickness: 0.5 to 1 inch

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Properties         RT         400         600         80           Tension         TUS (longitudinal), ksi         137.8         100.8         84.8         77           TYS (longitudinal), ksi         130.4         88.2         69.8         63           e (longitudinal), percent in 1 in.         6.5         10.2         12.0         12           RA (longitudinal), percent         11.2         19.0         24.3         28           E (longitudinal), lo <sup>3</sup> ksi         17.2         16.8         15.2         15           Compression         CYS (longitudinal), ksi         137.5         92.9         74.6         67           E <sub>c</sub> (longitudinal), lo <sup>3</sup> ksi         16.5         15.6         14.9         13           Shear         SUS (longitudinal), ksi         92.8 <sup>(b)</sup> U <sup>(c)</sup> U         U           Impact         V-notch Charpy, ft.lbs.         16.2 <sup>(d)</sup> U         U		Temperature, F				
TensionTUS (longitudinal), ksi137.8100.884.877TYS (longitudinal), ksi130.488.269.863e (longitudinal), percent in 1 in.6.510.212.012RA (longitudinal), percent11.219.024.328E (longitudinal), 10 <sup>3</sup> ksi17.216.815.215Compression CYS (longitudinal), ksi137.592.974.667E_c (longitudinal), 10 <sup>3</sup> ksi16.515.614.913Shear SUS (longitudinal), ksi92.8UUUImpact V-notch Charpy, ft.lbs. (longitudinal)16.2UUU	Properties	RT	400	600	800	
TUS (longitudinal), ksi137.8100.884.877TYS (longitudinal), ksi130.488.269.863e (longitudinal), percent in 1 in.6.510.212.012RA (longitudinal), percent11.219.024.328E (longitudinal), 10 <sup>3</sup> ksi17.216.815.215CompressionCYS (longitudinal), ksi137.592.974.667E_c (longitudinal), 10 <sup>3</sup> ksi16.515.614.913Shear SUS (longitudinal), ksi92.8 $\upsilon$ $\upsilon$ $\upsilon$ Impact V-notch Charpy, ft.lbs. (longitudinal)16.2 $\upsilon$ $\upsilon$ $\upsilon$						
TYS (longitudinal), ksi130.488.269.863e (longitudinal), percent in 1 in.6.510.212.012RA (longitudinal), percent11.219.024.328E (longitudinal), 10 <sup>3</sup> ksi17.216.815.215Compression CYS (longitudinal), ksi137.592.974.667E_c (longitudinal), 10 <sup>3</sup> ksi16.515.614.913Shear SUS (longitudinal), ksi92.8 $\psi(c)$ $\psi(c)$ $\psi(c)$ Impact V-notch Charpy, ft.lbs. (longitudinal)16.2 $\psi(c)$ $\psi(c)$ $\psi(c)$	ongitudinal), ksi	137.8	100.8	84.8	77.5	
e       (longitudinal), percent in 1 in.       6.5       10.2       12.0       12         RA       (longitudinal), percent       11.2       19.0       24.3       28         E       (longitudinal), 10 <sup>3</sup> ksi       17.2       16.8       15.2       15         Compression       CYS (longitudinal), ksi       137.5       92.9       74.6       67         E       (longitudinal), 10 <sup>3</sup> ksi       16.5       15.6       14.9       13         Shear       SUS (longitudinal), ksi       92.8 <sup>(b)</sup> U <sup>(c)</sup> U       U         Impact       V-notch Charpy, ft.1bs.       16.2 <sup>(d)</sup> U       U       U	ongitudinal), ksi	130.4	88.2	69.8	63.8	
RA (longitudinal), percent       11.2       19.0       24.3       28         E (longitudinal), $10^3$ ksi       17.2       16.8       15.2       15         Compression       CYS (longitudinal), ksi       137.5       92.9       74.6       67         E_c (longitudinal), $10^3$ ksi       16.5       15.6       14.9       13         Shear       SUS (longitudinal), ksi       92.8 <sup>(b)</sup> U <sup>(c)</sup> U       U         Impact       V-notch Charpy, ft.1bs.       16.2 <sup>(d)</sup> U       U       U	ongitudinal), percent in 1 in.	6.5	10.2	12.0	12.0	
E       (longitudinal), $10^3$ ksi       17.2       16.8       15.2       15         Compression CYS (longitudinal), ksi       '137.5       92.9       74.6       67         E_c       (longitudinal), $10^3$ ksi       16.5       15.6       14.9       13         Shear SUS (longitudinal), ksi       92.8 <sup>(b)</sup> U <sup>(c)</sup> U       U         Impact (longitudinal)       16.2 <sup>(d)</sup> U       U       U	ongitudinal), percent	11.2	19.0	24.3	28.4	
$\begin{array}{c} \underline{Compression} \\ CYS (longitudinal), ksi \\ E_{c} (longitudinal), 10^{3} ksi \\ \underline{Shear} \\ SUS (longitudinal), ksi \\ \underline{SUS} (longitudinal), ksi \\ \underline{SUS} (longitudinal), ksi \\ \underline{V-notch} Charpy, ft.lbs. \\ (longitudinal) \\ \underline{Inpact} \\ \underline{V-notch} Charpy, ft.lbs. \\ (longitudinal) \\ \underline{I6.2^{(d)}} \\ U \\ \underline{U} \\ U \\ \underline{U} \\ U \\ \underline{U} $	ongitudinal), 10 <sup>3</sup> ksi	17.2	16.8	15.2	15.1	
CYS (longitudinal), ksi       137.5       92.9       74.6       67 $E_c$ (longitudinal), 10 <sup>3</sup> ksi       16.5       15.6       14.9       13         Shear       SUS (longitudinal), ksi       92.8 <sup>(b)</sup> U <sup>(c)</sup> U       U         Impact       V-notch Charpy, ft.1bs.       16.2 <sup>(d)</sup> U       U       U	ion					
$E_c$ (longitudinal), 10 <sup>3</sup> ksi16.515.614.913Shear SUS (longitudinal), ksi92.8(b) $U^{(c)}$ UUImpact V-notch Charpy, ft.lbs. (longitudinal)16.2(d)UUU	ongitudinal), ksi	137.5	92.9	74.6	67.5	
Shear SUS (longitudinal), ksi92.8(b)U(c)UUImpact V-notch Charpy, ft.lbs. (longitudinal)16.2(d)UUU	ongitudinal), 10 <sup>3</sup> ksi	16.5	15.6	14.9	13.5	
Impact V-notch Charpy, ft.1bs. (longitudinal) 16.2 <sup>(d)</sup> U U U	ongitudinal), ksi	92.8 <sup>(b)</sup>	U(c)	U	IJ	
V-notch Charpy, ft.1bs. (longitudinal) 16.2 <sup>(d)</sup> U U U						
(longitudinal) 16.2 <sup>(u)</sup> U U U	n Charpy, ft.1bs.	(4)				
	gitudinal)	16.2	U	U	U	
Fracture Toughness (c) U U	Toughness	(c)	U	U	U	
Axial Fatigue (longitudinal) $(f)$	tigue $(1 \text{ ongitudinal})^{(f)}$					
$10^3$ cycles kst 130 130 84 II	cvcles kst	130	130	84	11	
$10^5$ cycles, ksi 70 63 60 11	cycles, ksi	70	63	60	11	
$10^7$ cycles, ksi 44 39 37 II	cvcles, ksi	44	39	37	11	
				2,	Ū	
Notched, $K_{\star} = 3.0, R = 0.1$	d, $K_{\perp} = 3.0$ , $R = 0.1$					
10 <sup>3</sup> cycles, ksi 90 82 76 U	cycles, ksi	90	82	76	U	
10 <sup>5</sup> cycles, ksi 58 49 44 U	cycles, ksi	58	49	44	U	
10" cycles, ksi 41 29 27 U	cycles, ksi	41	29	27	U	

	Temperature, F				
Properties	RT	400	600	800	
Creep (longitudinal)					
0.2% plastic deformation, 100 hr, ksi	NA	77	81	45	
0.2% plastic deformation, 1000 hr, ksi	NA	76	77	25	
Stress Rupture (longitudinal)					
Rupture, 100 hr, ksi	NA	88	82	72	
Rupture, 1000 hr, ksi	NA	. 87	81	6 <b>9</b>	
Stress Corrosion (longitudinal) (g)					
80% TYS, 1000 hr, maximum	no cracks				
Coefficient of Thermal Expansion 5.0 x $10^{-6}$ in./in./F (RT to 800 F)					
<u>Density</u> 0.160 lb./in. <sup>3</sup>					
<ul> <li>(a) Values are average of triplicate tes subject contract unless otherwise in rupture values are from curves gener</li> </ul>	ts conducted dicated. Fat	at Battel igue, cre	lle under eep, and s of a gr	the stress eater	

#### Ti-6Al-4V Alloy Casting Data (Continued)

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- (b) Double-shear pin-type specimen; average of 4 tests.
- (c) U, unavailable; NA, not applicable.
- (d) Average of 6 tests.

number of tests.

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- (e) Material thickness was not sufficient for valid test results.
- (f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "K<sub>t</sub>" represents the Neuber-Peterson theoretical stress concentration factor.
- (g) Room-temperature three-point bend test. Alternate immersion in 3½% NaCl.



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED TI-6A1-4V CASTINGS



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSION PROP-ERTIES OF ANNEALED TI-6A1-4V CASTINGS

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FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED T1-6A1-4V CASTINGS



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ( $K_c = 3.0$ ) ANNEALED TI-6A1-4V CASTINGS



FIGURE 5. SITURESS SUPPORE AND PLASTIC DEFORMA-FION CURVES FOR ANNEALED TI-0A1-4V CASIINGS

# MECHANICAL-PROPERTY DATA INCOLOY 903 ALLOY

#### HEAT TREATED SHEET

Issued by

Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

#### BATTELLE

Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### Incoloy 903 Alloy

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#### Material Description

Incoloy alloy 903 is a precipitation-hardenable nickel-iron-cobalt alloy whose outstanding characteristics are a constant low coefficient of thermal expansion, a constant modulus of elasticity, and high strength. Because the alloy contains no chromium, oxidation resistance may become a consideration for some high temperature applications.

The material used for this evaluation was a .0635-inch-thick sheet from Huntington Alloys Heat No. HH25A9UK with the following composition:

Chemical Composition	Percent
Carbon	0.03
Manganese	0.16
Iron	40.92
Sulfur	0.004
Silicon	0.07
Nickel	38.08
Aluminum	0.88
Titanium	1.61
Cobalt	15.22
Columbium plus	
Tantalum	3.01 .

#### Processing and Heat Treating

The sheet was received in the annealed condition and was heat treated as follows: 1325 F, 8 hours, furnace cool at 100 F per hour to 1150, held for 8 hours, air cool.

### Incoloy 903 Alloy Data<sup>(a)</sup>

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#### Condition: Heat Treated Thickness: .0635 inch

	Temperature, F				
Properties	Rſ	800	1000	1200	
Tension					
TUS (longitudinal), ksi	191.9	170.7	166.6	130.6	
TUS (transverse), ksi	193.0	170.1	163.5	131.6	
TYS (longitudinal), ksi	155.5	140.8	134.8	116.7	
TYS (transverse), ksi	165.0	142.6	135.6	120.4	
e (longitudinal), percent in 2 in.	13.7	17.3	17.2	16.5	
e (transverse), percent in 2 in.	16.0	15.8	14.7	17.3	
E (longitudinal), 10 <sup>3</sup> ksi	24.7	21.6	22.6	21.4	
E (transverse), 10 <sup>3</sup> ksi	25.8	22.2	22.3	21.1	
Compression					
CYS (longitudinal), ksi	167.0	152.2	141.4	122.5	
CYS (transverse), ksi	174.2	160,9	145.6	125.1	
E_ (longitudinal), 10 <sup>3</sup> ksi	25.2	22.8	23.0	21.4	
E <sup>C</sup> (transverse), 10 <sup>3</sup> ksi	24.3	23.7	23.2	22.2	
Shear <sup>(b)</sup>					
SUS (longitudinal), ksi	123.9	υ <sup>(c)</sup>	U	IJ	
SUS (transverse), ksi	127.8	U	U	U	
Fracture Toughness	(h)				
K <sub>c</sub> (T-L) ksi/in.	244.5				
$\frac{Axia1 \ Fatigue \ (Transverse)}{Unnotched, R = 0.1}^{(e)}$					
10 <sup>3</sup> cycles, ksi	154	140	131	U	
10 <sup>5</sup> cycles, ksi	125	112	98	U	
10 <sup>7</sup> cycles, ksi	84	73	67	Ŭ	
Notched, $K_{\rm r} = 3.0$ , $R = 0.1$		-	- •	-	
10 <sup>3</sup> cycles, ksi	120	100	100	U	
10 <sup>F</sup> cycles, ksi	73	64	64	Ū	
10 <sup>7</sup> cycles, ksi	46	44	44	Ū	

#### Incoloy 903 Alloy Data (Continued)

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		Temperature, F			
		RT	800	1000	1200
Cree 0.	<u>p (transverse)</u> 2% plastic deformation, 100 hr, ksi		(no c	reep)	15
0.	2% plastic deformation, 1000 hr, ksi				14
Stre	ss Rupture (transverse)				
Ru	pture, 100 hr, kal	NA	48	50	31
Ru	pture, 1000 hr, ksi	NA	35	44	15
Stra	es Corrosion (transverse) (f)				
80	7. TYS. 1000 hr. maximum	no cracks			
Coef	ficient of Thermal Expansion				
٦.	0 x 10 - 1n./1n./F				
Dens	ity				,
0.	294 1b./in. <sup>3</sup>				
	x				
(a)	Values are average of triplicate to	sts conductual	Lub Rabbal	le under	the
(a)	subject contract unless otherwise in	ndicated. Fa	tigue. cre	ep. and s	tress-
	rupture values are from curves genes	rated using t	he results	of a gre	ater
	number of tests.	-		-	
(ኬ)	Sheet-shear type appriment average (	of 3 tests in	each dire	ection	
(")	Sheet sheat type speciment, average				
(c)	U, unavailable; NA, not applicable.				
(a)	Specimens were 18 x 36 with a center	r flaw. valu	le 18 avera	ige of 4 t	ests.
(e)	"R" represents the algebraic value	of minimum st	ress to ma	ximum str	ess in
	one cycle; that is, $R = S_{min}/S_{max}$ .	"K <sub>+</sub> " represe	ents the Ne	uber-Pete	rson
	theoretical stress concentration fa	ctor.			
	· · · · · ·				
(f)	Room-temperature three-point bend to	est. Alterna	te immersi	log in $3\frac{1}{2}$ %	NaCl.



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHEET



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHEET

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## MECHANICAL-PROPERTY DATA 201.0 ALUMINUM ALLOY

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-T7 CASTING

Issued by

Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

Prepared by

#### BATTELLE

Columbus Laboratories Columbus, Ohio 43201

F33615-73-C-5073

#### 201-T7 Aluminum Castings

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#### Material Description

201 is a recently developed heat-treatable, high strength aluminum casting alloy which contains copper, silver, magnesium, and titanium. Promium quality castings made from this alloy have exhibited improved mechanical strength properties when compared to castings of other conventional aluminum alloys. The alloy can be cast by sand, permanent mold, or investment casting techniques.

The castings used for this evaluation were actual production parts used in airframe construction.

#### Processing and Heat Treating

The alloy was tested in the as-received -T7 condition.

## 201-T7 Alloy Data<sup>(a)</sup>

Condition: -T7 Thickness: Various

	Temperature, F				
Properties	RT	300	400	500	
Tension					
TUS (longitudinal), ksi	67.1	56.8	48.4	29.8	
TYS (longitudinal), ksi	60.0	49.4	46.2	28.3	
e (longitudinal), percent in 2 in.	4.7	7.2	9.5	14.5	
E (longitudinal), 10 <sup>3</sup> ksi	10.5	9.6	8.8	8.0	
Compression					
CYS (longitudinal), ksi	60.9	53.6	48.2	30.9	
E <sub>c</sub> (longitudinal), 10 <sup>3</sup> ksi	11.1	9.9	9.7	9.0	
Shear	(1.)	(-)			
SUS (longitudinal), ksi	39.3	U <sup>(c)</sup>	U	U	
Impact					
V-notch Charpy, ft.1bs.	(d)				
(longitudinal)	5.0	U	U	U	
Axial Fatigue (transverse) (e)					
Unnotched, $R = 0.1$					
10 <sup>3</sup> cycles, ksi	62	62	62	U	
10 <sup>5</sup> cycles, ksi	37	36	35	U	
10 <sup>7</sup> cycles, ksi	31	27	25		
Notched, $K_{r} = 3.0, R = 0.1$					
10 <sup>3</sup> cycles, ksi	54	54	50	U	
10 <sup>5</sup> cycles, ksi	22	21	19	υ	
10 <sup>7</sup> cycles, ksi	16	14	12	U	

201-T7 Alloy	Data	(Continued)	
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Properties	Temperature, F			
	RT	300	400	500
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	U	43	34	8
0.2% plastic deformation, 1000 hr, ksi	U	41	19	4.5
Stress Rupture (transverse)				
Rupture, 100 hr. ksi	U	50	39	13
Rupture, 1000 hr, ksi	ប	47	32	3.5
Stress Corrosion (transverse)(f)		·		
80% TYS, 1000 hr, maximum	no cracks			

- (a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress rupture values are from curves generated using the results of a greater number of tests.
- (b) Double-shear pin-type specimen; average of 4 tests.
- (c) U, unavailable; NA, not applicable.

(d) Average of 6 tests.

- (e) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is,  $R = S_{min}/S_{max}$ . "K<sub>t</sub>" represents the Neuber-Peterson theoretical stress concentration factor.
- (f) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.









FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 201-T7 ALUMIDUM ALLOY CASTINGS



FIGURE 3. ANIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 201-17 ALUMINUM ALLOY CASTING

