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ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS

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COLUMBUS LABORATORIES

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

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Mechanical Properties	Aluminum Alloys	7475
Fatigue Properties	Heat Resistant Alloys	2419
Creep Properties	Titanium Alloys	Ti-6Al-2Zr-2Mo-2Cr
Chemical Composition	7049	Ti-6Al-2Cb-1Ta-1Mo
Physical Properties	Inconel 617	Ti-6Al-4V

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The major objectives of this research program were to evaluate newly developed materials of interest to the Air Force for potential structural airframe usage, and to provide "data sheet" type presentations of engineering data for these materials. The effort covered in this report has concentrated on 7049-T7351 plate, Inconel 617 annealed sheet, 7475-T7351 plate, 2419-T851 plate, Ti-6Al-2Zr-2Sn-2Mo-2Cr duplex-annealed forging, Ti-6Al-2Cb-1Ta-1Mo annealed plate, Ti-6Al-4V beta-annealed plate, Ti-6Al-4V annealed castings, Ti-6Al-4V isothermal forgings, Incoloy 903 heat-treated sheet, and 201.0 T7 castings.

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19. Incoloy 903
201.0

20. The properties investigated include tension, compression, shear, bend, impact, fracture toughness, fatigue, creep and stress-rupture, and stress corrosion at selected temperatures.

FOREWORD

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

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 Battelle'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

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

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
Iron	0.35 max
Titanium	0.10 max
Manganese	0.20 max
Aluminum	Balance

Processing and Heat Treating

The specimen layout is shown in Figure 1. Specimens were tested in the as-received T7351 temper.

Test Results

Tension. 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.

Compression. 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.

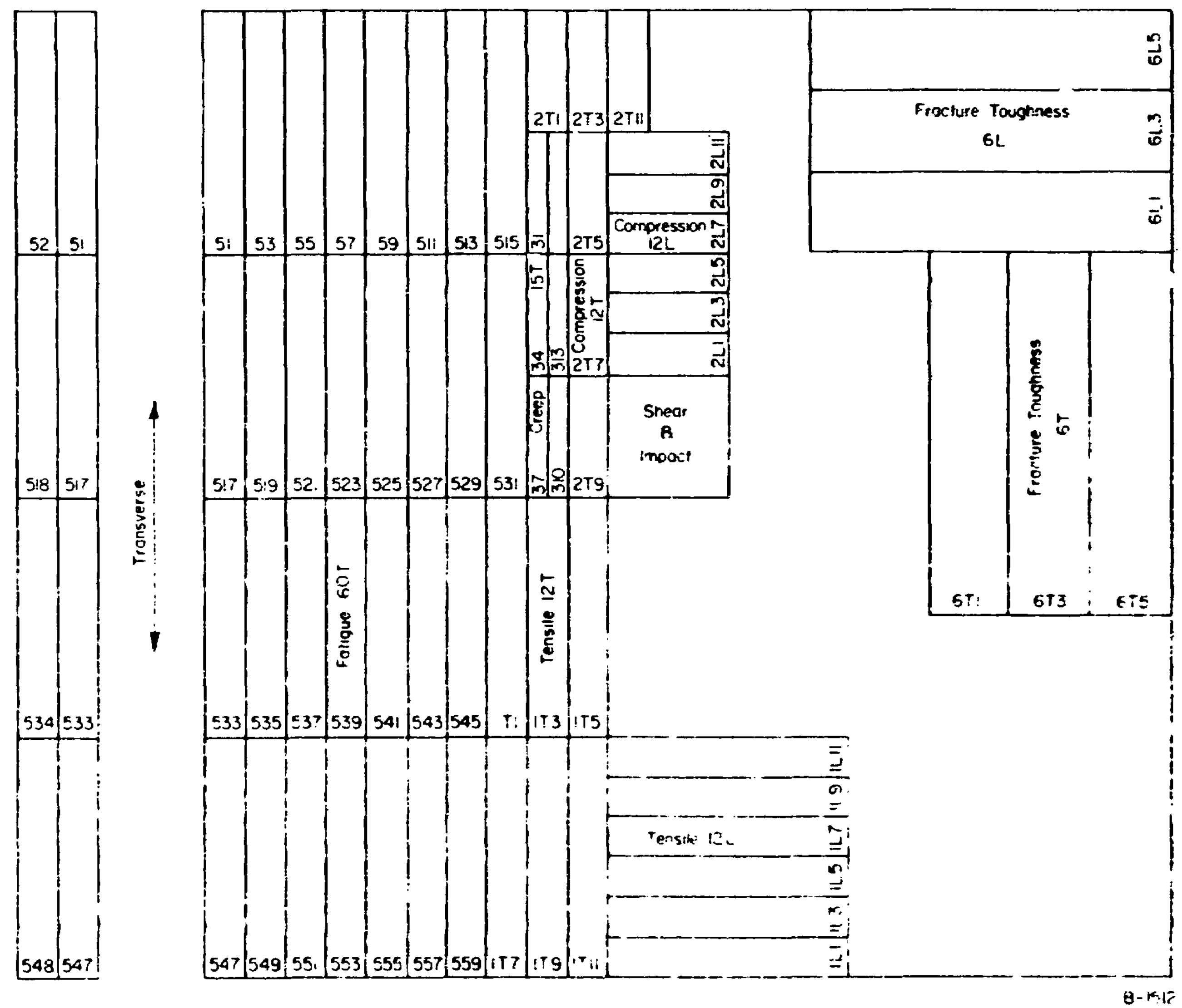

FIGURE 1. SPECIMEN LAYOUT FOR 7049-T7351 ALUMINUM ALLOY PLATE

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

Fracture Toughness. 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_Q values shown in Table V are considered valid K_{Ic} values by existing ASTM criteria.

Fatigue. 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.

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

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

Thermal Expansion. The coefficient of thermal expansion for this alloy is 12.9 x 10^{-6} in./in./F for 68 F to 212 F.

Density. The density of this material is 0.099 lb./in^3.

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

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^3 ksi
		Longitudinal at Room 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
		Long 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	74.6	64.7	10.7	25.6	10.4
		Longitudinal 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 Transverse 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
1T-6	60.0	58.6	16.0	44.7	9.4
Average	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	44.7	44.3	20.5	66.8	8.1
Average	45.4	45.1	20.2	64.9	8.0
		Long Transverse 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	8.5
Average	47.0	46.3	17.3	54.6	8.4
		Longitudinal at 500 F			
1L-10	14.9	14.7	32.0	85.8	5.4
1L-11	15.0	14.8	33.0	87.3	6.2
1L-12	15.4	15.2	30.5	85.9	6.3
Average	15.1	14.9	31.8	86.3	6.0
		Long Transverse at 500 F			
1T-10	16.6	16.6	27.5	81.5	6.1
1T-11	17.3	17.2	30.0	84.0	5.3
1T-12	17.8	17.7	29.0	84.0	5.8
Average	17.2	17.2	28.8	83.2	5.7

TABLE [illegible]. COMPRESSION TEST RESULTS FOR 7049-T7351 ALLOY PLATE

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^3 ksi
		Longitudinal at Room Temperature	
2L-1		64.6	10.8
2L-2		63.6	10.7
2L-3		64.0	10.9
	Average	54.1	10.8
		Long Transverse at Room Temperature	
2T-1		66.0	10.9
2T-2		71.0	11.1
2T-3		70.7	10.6
	Average	69.2	10.9
		Longitudinal at 250 F	
2L-4		57.2	9.4
2L-5		56.6	9.1
2L-6		56.7	9.8
	Average	56.8	9.4
		Long Transverse at 250 F	
2T-4		60.4	9.7
2T-5		56.7	9.9
2T-6		62.3	9.6
	Average	59.8	9.7
		Longitudinal at 350 F	
2L-7		44.1	8.0
2L-8		44.5	8.2
2L-9		44.7	8.1
	Average	44.4	8.1
		Long Transverse at 350 F	
2T-7		48.1	8.1
2T-8		47.7	8.4
2T-9		46.8	8.4
	Average	47.5	8.3
		Longitudinal at 500 F	
2L-10		16.1	7.1
2L-11		16.6	6.8
2L-12		17.3	6.7
	Average	16.7	6.9
		Long Transverse at 500 F	
2T-10		15.8	6.9
2T-11		17.6	7.5
2T-12		17.7	6.5
	Average	17.0	7.0

TABLE III. PIN SHEAR TEST RESULTS FOR 7049-T7351 ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number		Ultimate Shear Strength, ksi
	Longitudinal	
4L-1		45.4
4L-2		42.4
4L-3		46.4
4L-4		50.2
	Average	46.1
	Long Transverse	
4T-1		48.3
4T-2		44.1
4T-3		43.0
4T-4		46.3
	Average	45.4

TABLE IV. IMPACT TEST RESULTS FOR 7049-T7351 ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number		Energy, ft/lb
	Longitudinal	
10L-1		8.0
10L-2		5.0
10L-3		5.0
10L-4		5.0
10L-5		6.0
10L-6		6.0
	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

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

Specimen Number	W, inches	a, inches	B, inches	P_Q, lb	Span, inches	$f(\frac{a}{W})$	K_Q (a)
			Longitudinal (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
6L-3	2.00	0.964	1.00	4,750	8.0	2.517	33.8
6L-4	2.00	0.964	1.00	4,850	8.0	2.517	34.5
6L-5	2.00	0.982	1.00	4,700	8.0	2.589	34.4
6L-6	2.00	0.938	1.00	5,050	8.0	2.418	34.5
						Average	34.0
			Long Transverse (T-L)				
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
6T-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

(a) These candidate K_Q values are considered valid K_{Ic} values by existing ASTM standards.

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

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	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[a]
5-4	30	10,361,500[a]
	250 F	
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	10,068,600[a]
	350 F	
5-17	60	100
5-18	50	400
5-22	45	25,100
5-23	40	45,200
5-21	40	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[a]

(a) Did not fail.

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

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[a]
	250 F	
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[a]
	350 F	
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[a]

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

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hours	Elongation in 2 In., percent	Reduction of Area, percent	Minimum Creep Rate, percent
			0.1	0.2	0.5	1.0	2.0					
3-1	50	250	0.05	0.1	0.3	0.6	1.3	0.770	3.6	19.0	42.5	1.5
3-4	40	250	3.0	16	69	140	215	0.504	288.9	17.4	48.9	0.0054
3-7	32	250	20	140	--	--	--	0.413	148.0*	0.617	--	--
3-10	25	250	155	770	2770,est.	--	--	0.299	624.8*	0.478	--	0.00015
3-2	25	350	0.5	1.8	6.0	8.0	12.0	0.341	16.5	19.7	70.5	0.05
3-5	15	350	5.0	33	116	205	280	0.223	333.8	18.2	77.0	0.0034
3-8	12	350	15	75	280	525	815	0.178	1228.3	28.8	88.2	0.0014
3-11	5	350	550	1650	5200,est.	--	--	0.045	1004.0*	--	--	0.000085
3-3	7	500	0.2	0.6	2.1	4.5	8.0	0.117	19.5	50.0	88.5	0.18
3-6	5	500	2.5	7.5	32	68	118	0.127	281.9	35.6	71.6	0.011
3-9	4	500	12	30	80	275	450	0.030	981.1	32.6	64.1	0.0029
3-12	2.5	500	50	295	2000	4800,est.	--	0.042	931.5*	--	--	0.00018

* *Test discontinued.*

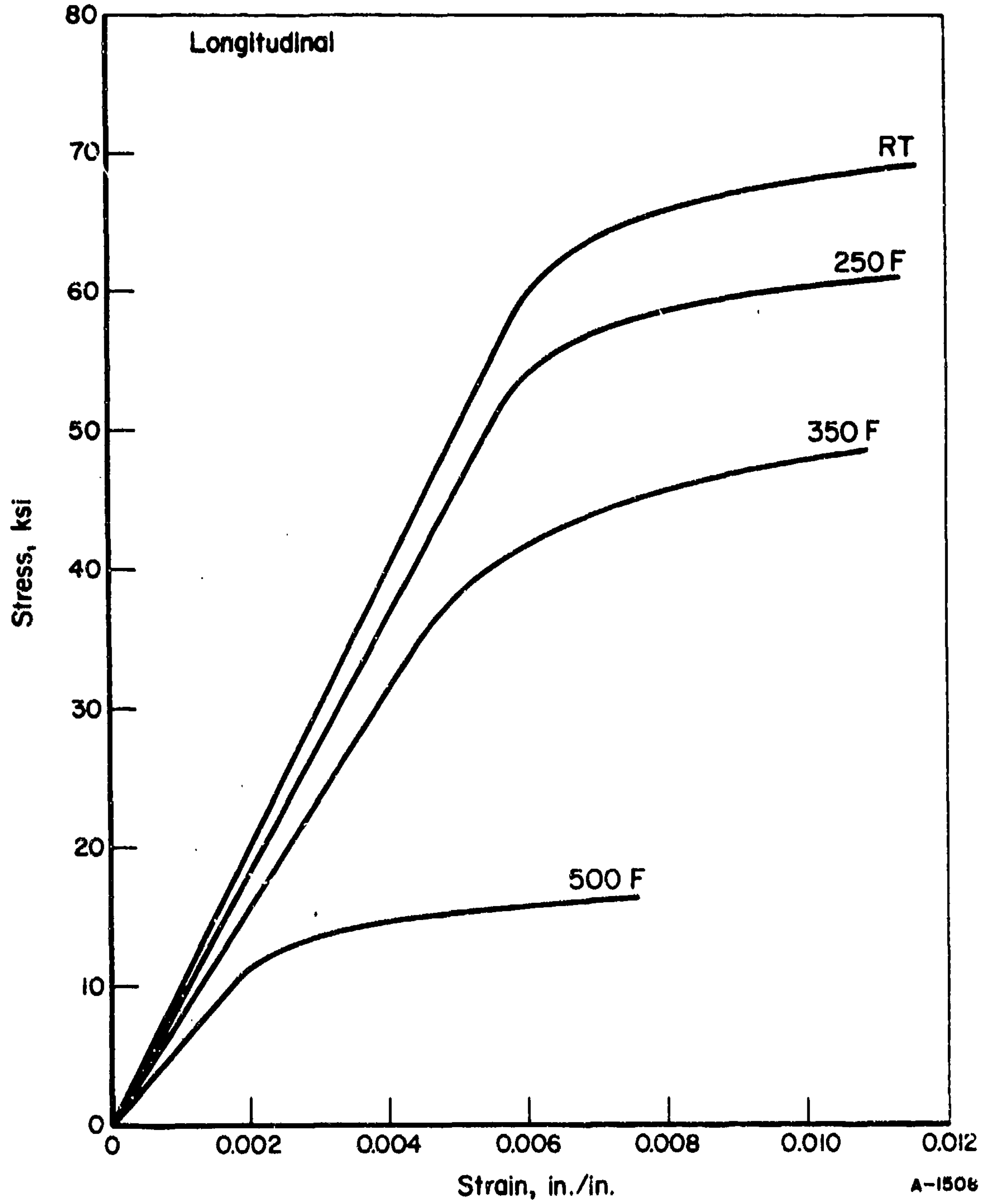

FIGURE 2. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)

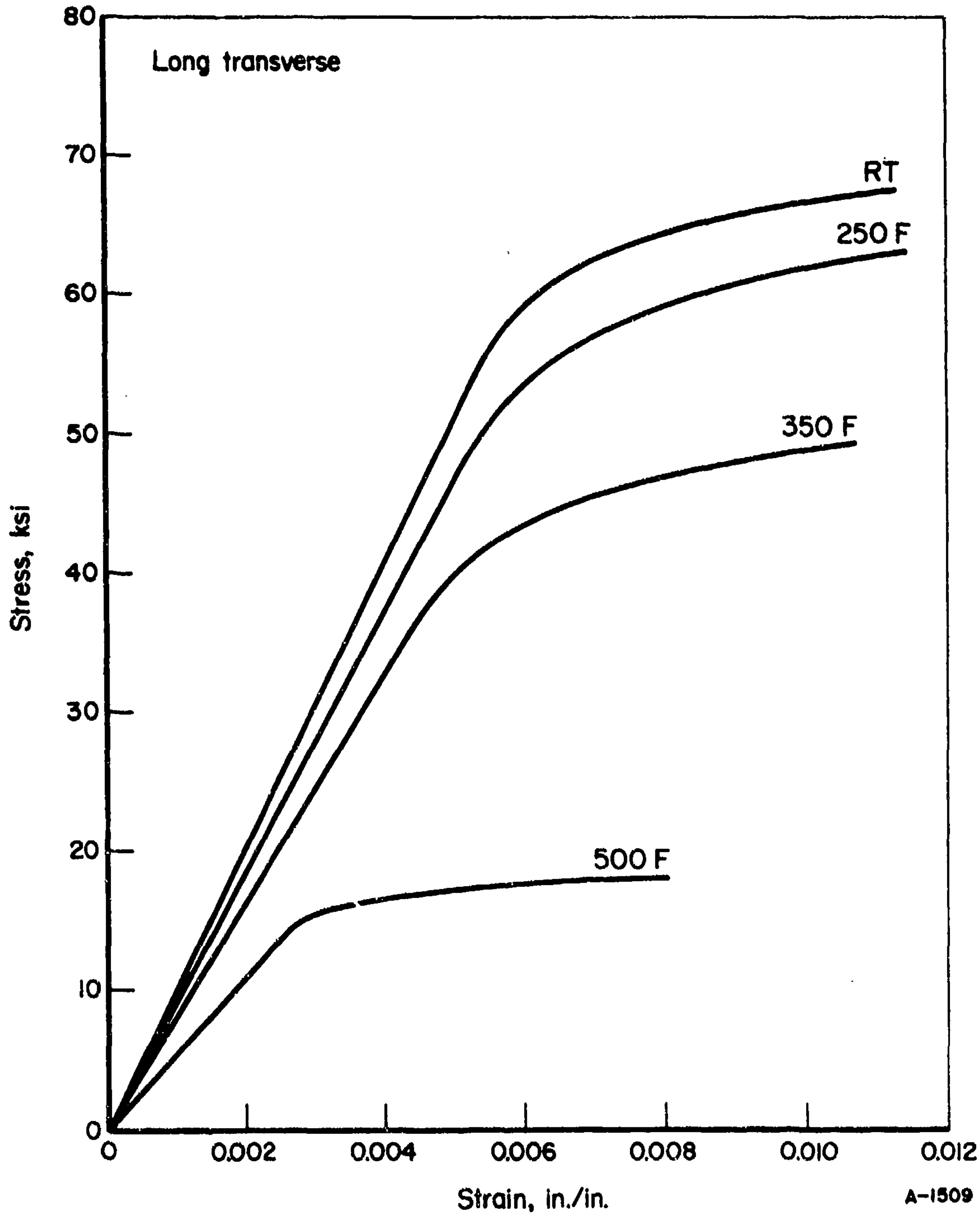

FIGURE 3. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONG TRANSVERSE)

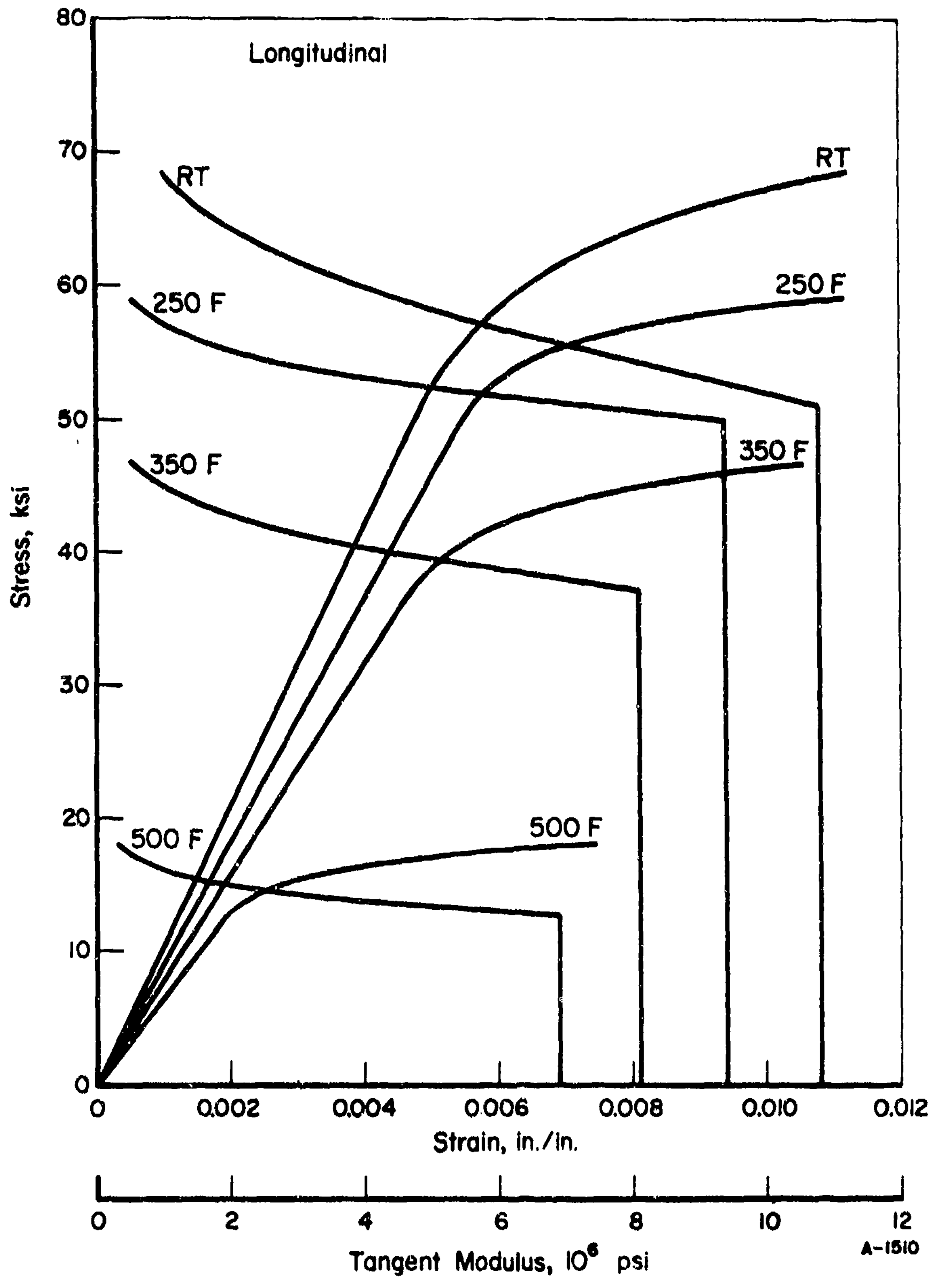

FIGURE 4. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)

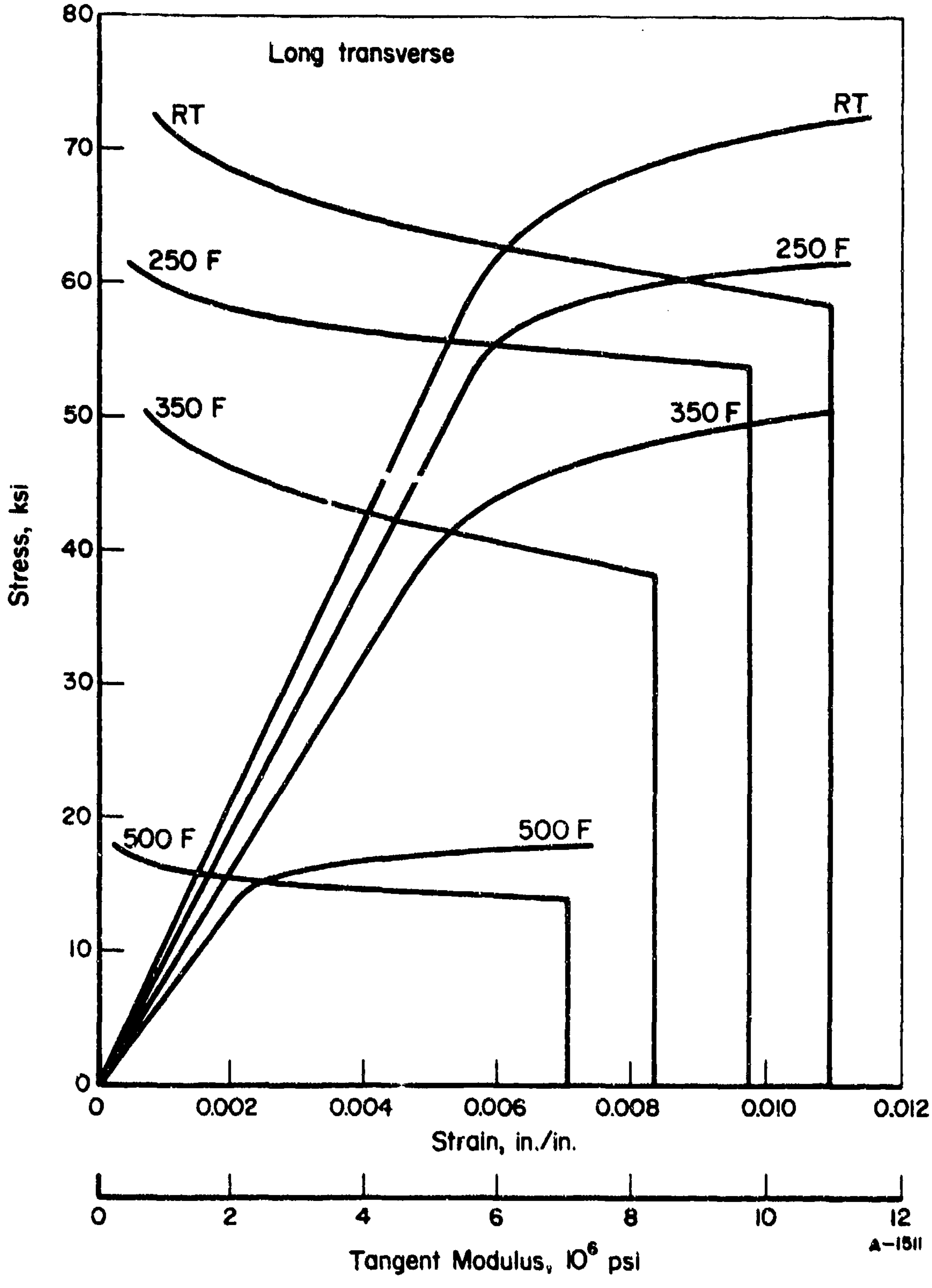

FIGURE 5. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONG TRANSVERSE)

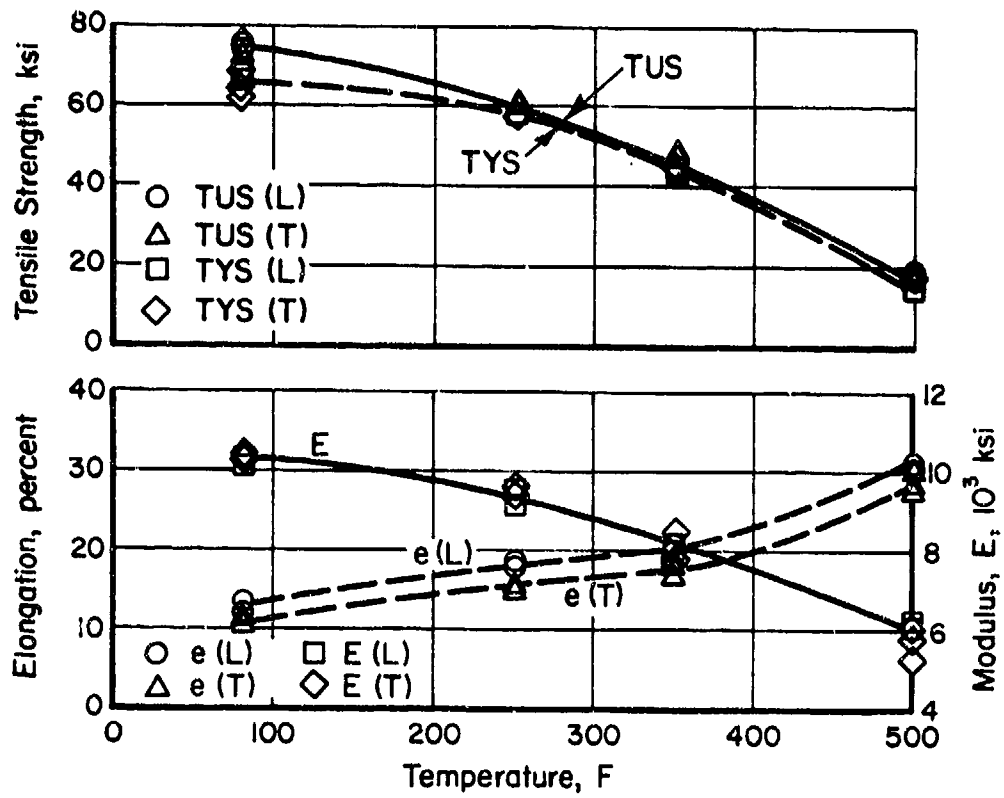

FIGURE 6. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE

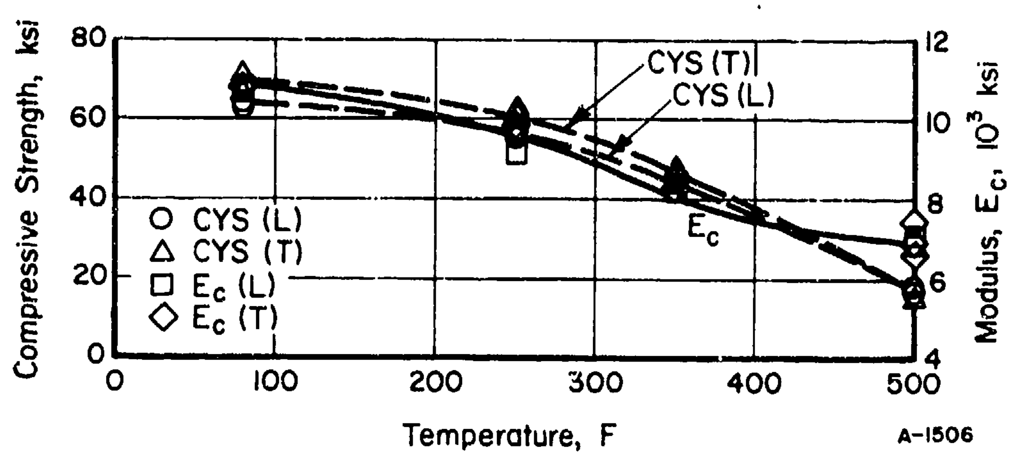

FIGURE 7. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE

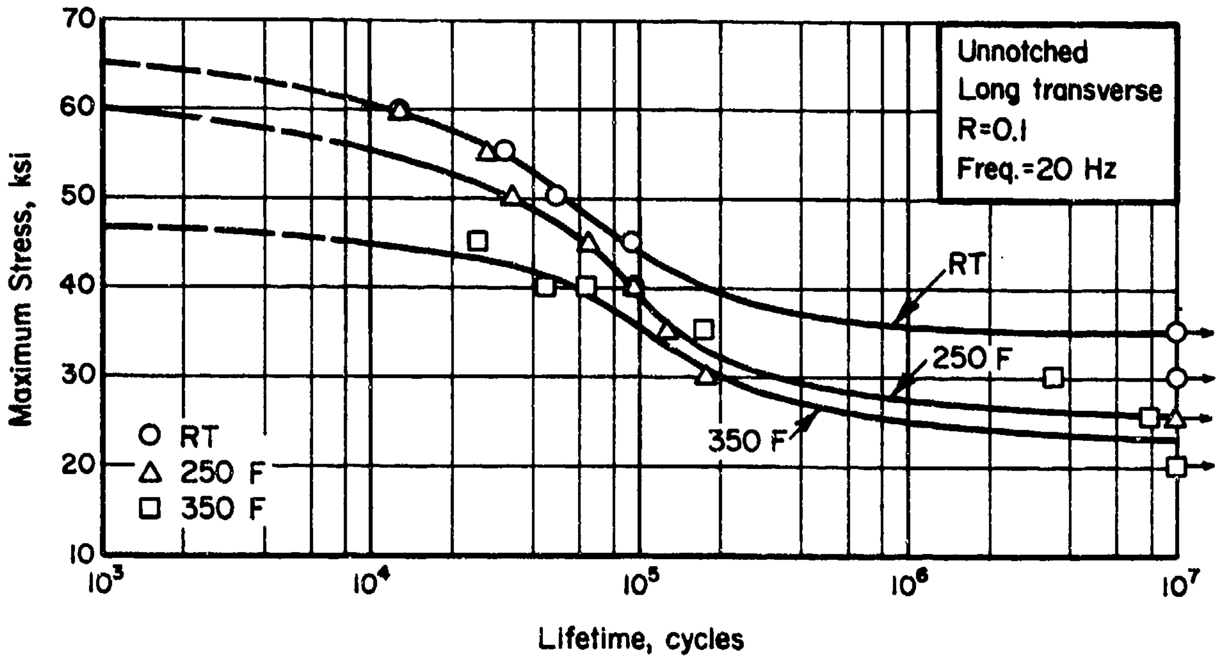

FIGURE 8. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7049-T7351 ALUMINUM ALLOY PLATE

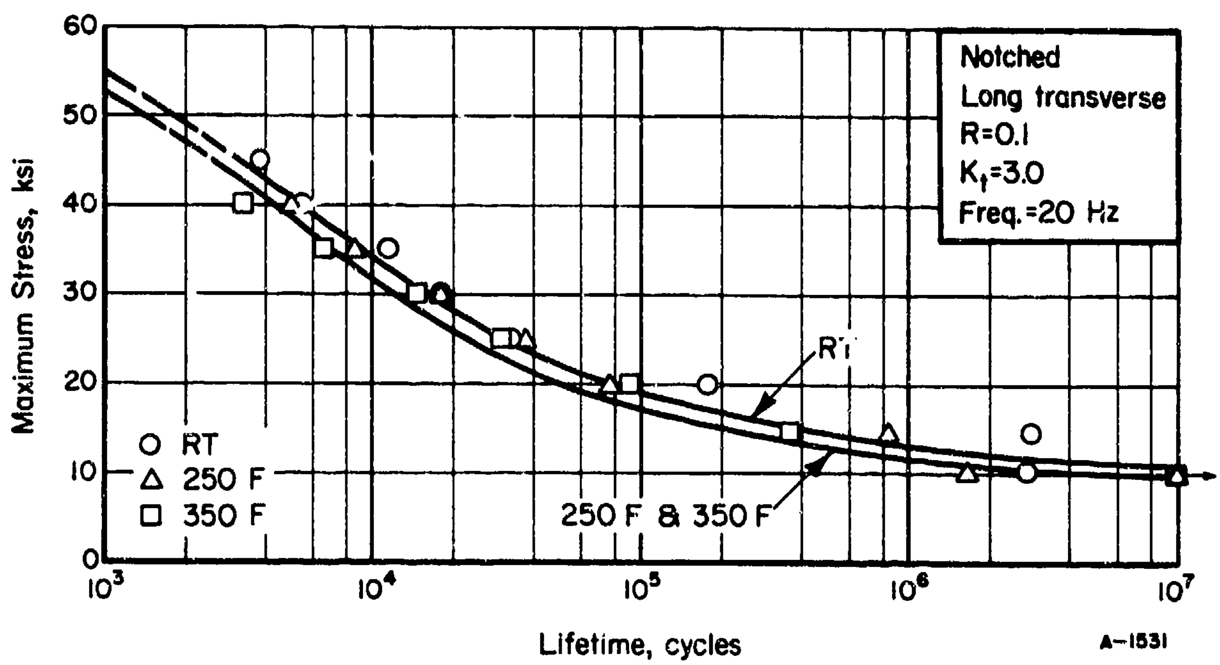

FIGURE 9. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) 7049-T7351 ALUMINUM ALLOY PLATE

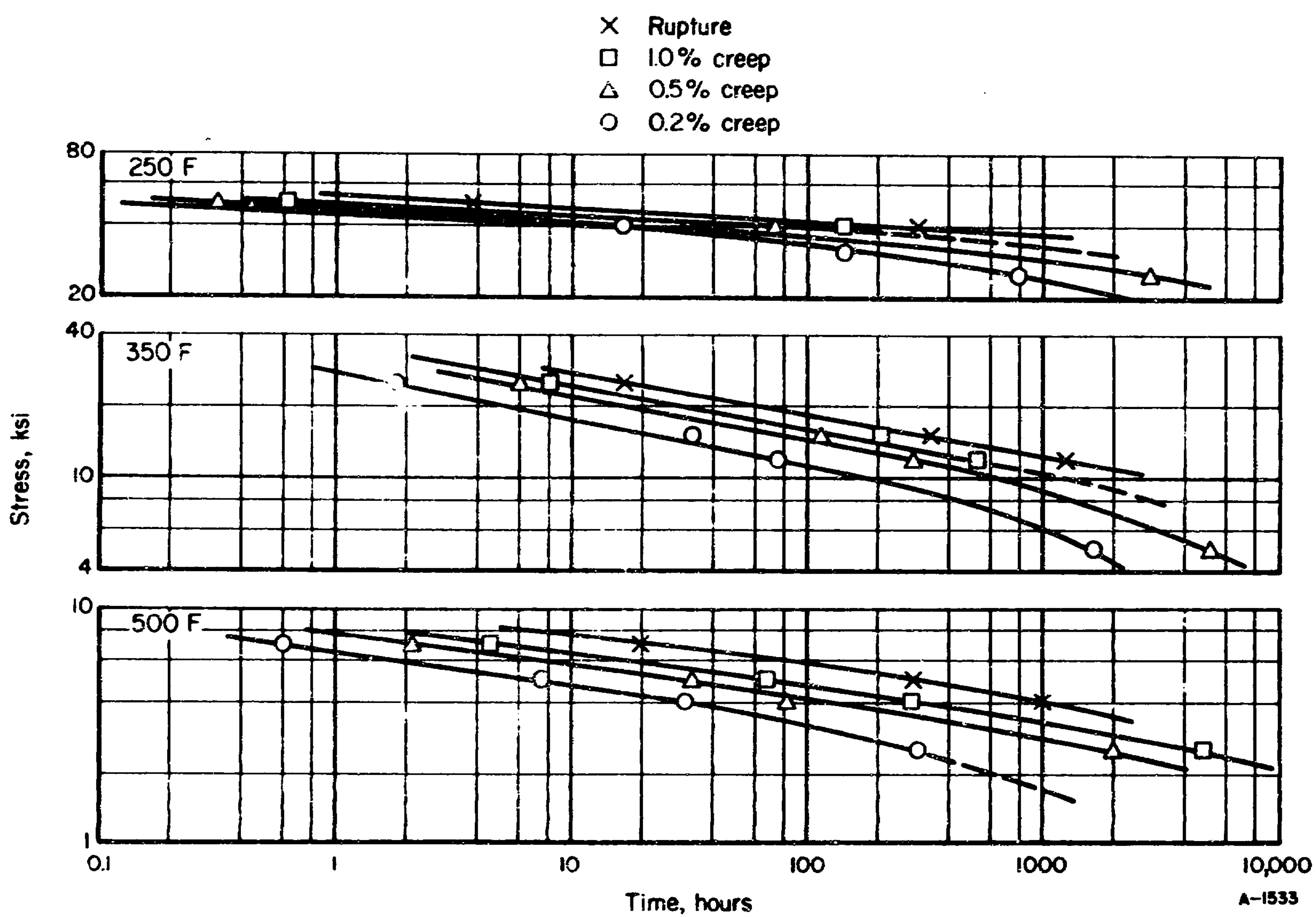

FIGURE 10. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7049-T7351 ALUMINUM ALLOY PLATE (LONG TRANSVERSE)

Inconel 617 Alloy Sheet

Material Description

Inconel Alloy 617 is a solid-solution, nickel-chromium-cobalt-molybdenum 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

Tension. 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-of-temperature curves are presented in Figure 16.

Compression. 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.

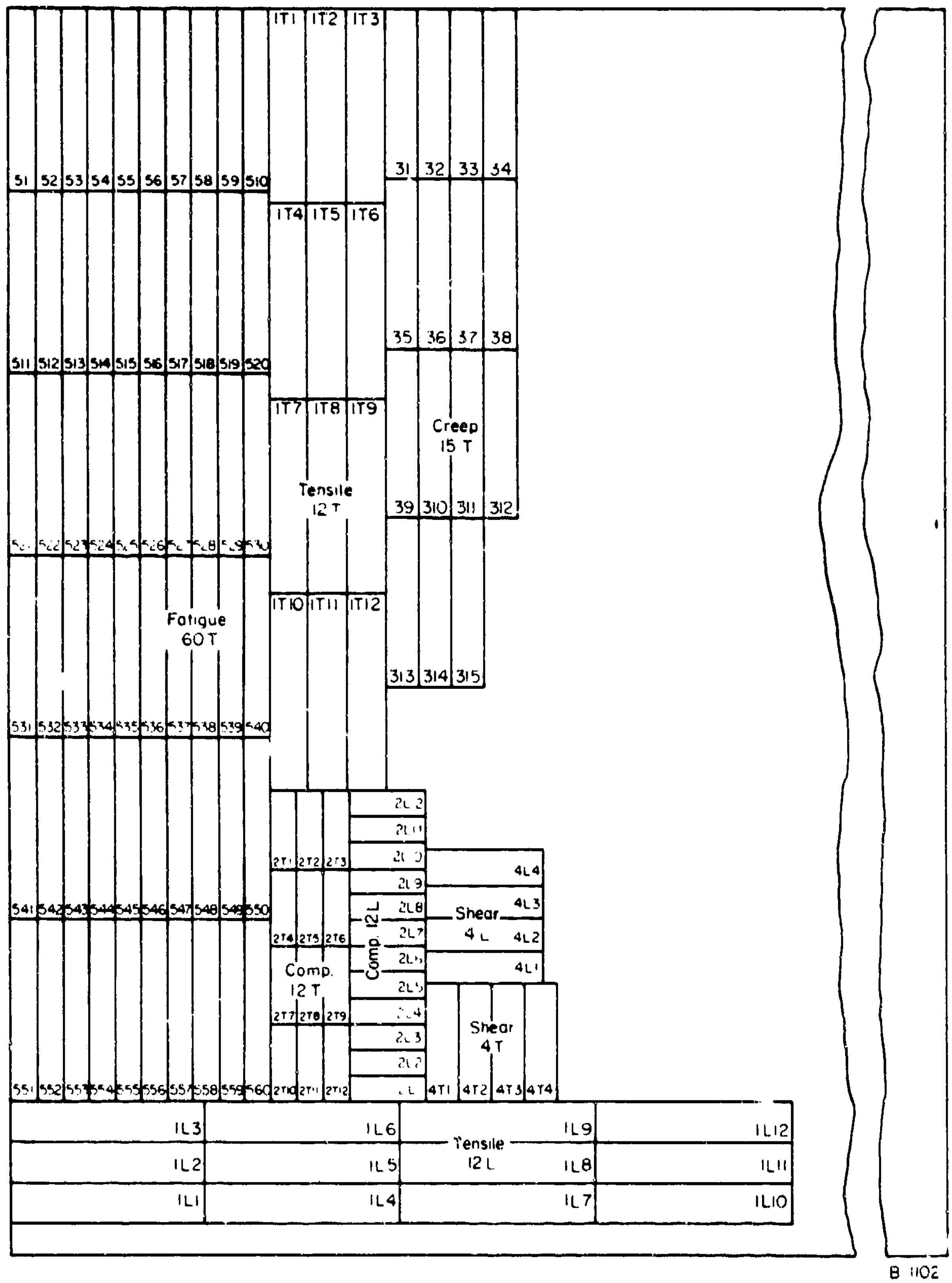

FIGURE 11. SPECIMEN LAYOUT FOR INCONEL 617 ALLOY SHEET

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.

Fracture Toughness. 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_c determination.

Fatigue. 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.

Creep and Stress-Rupture. 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.

Stress Corrosion. 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.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 8.7×10^{-6} in./in./F from room temperature to 1600 F.

Density. The density of this material is 0.302 lb/in.^{3}.

TABLE IX. TENSILE TEST RESULTS FOR INCONEL 617 ANNEALED SHEET

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, 10^3 ksi
		Longitudinal at Room Temperature		
1L-1	122.3	56.4	56.0	28.4
1L-2	122.4	56.9	56.0	24.3
1L-3	122.5	56.5	54.5	28.4
Average	122.4	56.6	55.5	27.0
		Transverse at Room Temperature		
1T-1	122.9	55.9	56.0	30.9
1T-2	124.4	57.1	54.5	30.2
1T-3	123.5	56.5	58.0	30.4
Average	123.6	56.5	56.2	30.5
		Longitudinal at 800 F		
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	50.0	19.4
Average	103.3	41.0	50.0	23.6
		Transverse at 800 F		
1T-4	105.2	44.1	50.0	24.4
1T-5	105.7	43.9	49.0	25.6
1T-6	106.2	42.3	53.0	24.4
Average	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
Average	83.9	38.2	43.3	23.1
		Transverse at 1200 F		
1T-7	95.9	39.1	44.0	28.3
1T-8	96.3	39.4	43.0	29.1
1T-9	95.8	39.3	53.0	32.0
Average	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
Average	24.6	21.7	46.0	17.0
		Transverse at 1600 F		
1T-10	25.3	24.3	50.0	13.3
1T-11	23.7	21.6	70.0	20.0
1T-12	25.5	22.8	47.0	16.4
Average	24.8	22.9	55.7	16.6

TABLE X. COMPRESSION TEST RESULTS FOR INCONEL 617 ANNEALED SHEET

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^3 ksi
	Longitudinal at Room Temperature		
2L-1		62.4	30.6
2L-2		62.2	29.7
2L-3		61.0	30.9
	Average	61.9	30.4
	Transverse at Room Temperature		
2T-1		60.5	33.7
2T-2		62.2	33.9
2T-3		61.8	33.5
	Average	61.5	33.7
	Longitudinal at 800 F		
2L-4		(a)	25.7
2L-5		48.8	29.0
2L-6		49.1	29.1
	Average	48.9	27.9
	Transverse at 800 F		
2T-4		51.2	29.6
2T-5		47.5	29.3
2T-6		50.9	30.3
	Average	49.9	29.7
	Longitudinal at 1200 F		
2L-7		41.1	21.5
2L-8		40.9	24.3
2L-9		40.9	26.4
	Average	41.0	24.1
	Transverse at 1200 F		
2T-7		39.6	25.6
2T-8		44.1	29.1
2T-9		41.2	27.9
	Average	41.6	27.5
	Longitudinal at 1600 F		
2L-10		30.2	19.3
2L-11		31.8	22.7
2L-12		30.8	18.0
	Average	30.9	20.0
	Transverse at 1600 F		
2T-10		32.3	27.8
2T-11		31.7	24.9
2T-12		30.7	20.0
	Average	31.6	24.2

(a) Machine malfunction.

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

Specimen Number		Ultimate Shear Strength, ksi
	Longitudinal	
4L-1		(a)
4L-2		108.3
4L-3		104.7
4L-4		106.8
	Average	106.6
	Transverse	
4T-1		104.7
4T-2		107.5
4T-3		110.5
4T-4		107.1
	Average	107.6

(a) Did not fail in shear.

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

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[(a)]
	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[(a)]
	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[(a)]

(a) Did not fail.

TABLE XIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t=3.0) ANNEALED INCONEL 617 SHEET (Transverse, R=0.1)

Specimen Number	Maximum Stress, ksi	Lifetime, Cycles
	Room Temperature	
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
5-37	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	
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]
	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]

(a) Did not fail.

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

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hours	Elongation in 2 Inches, percent	Minimum Creep Rate, percent
			0.1	0.2	0.5	1.0	2.0				
3-1	121	800	--	--	--	--	--	--	On load	67.0	--
3-4	107	800	--	--	--	--	--	--	--	66.0	--
3-15	100	800	3300(a)	7000(a)	--	--	--	45.010	1008.6(b)	45.043	0.00002
3-12	90	800	--	--	--	--	--	30.174	864.0(b)	30.216	Nil
3-10	75	800			Negative Creep			17.358	311.0(b)	17.337	Nil
3-6	50	800	--	--	--	--	--	0.973	191.9(b)	0.977	Nil
3-7	75	1200	--	--	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	10.500	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)	--	--	0.305	961.0(b)	0.549	0.00031
3-13	30	1200			Negative Creep			0.142	331.3(b)	0.114	--
3-3	30	1600	--	--	--	0.03	0.07	0.313	0.8	58.6	36.0
3-5	15	1600	0.2	0.4	1.0	2.2	4.8	0.095	56.5	48.4	0.41
3-8	10	1600	2.5	8	28	67	110	0.042	523.2	32.5	0.014
3-11	5	1600	325	965	3000(a)	--	--	0.035	1008.3(b)	0.252	0.00015

(a) Estimated.

(b) Test discontinued.

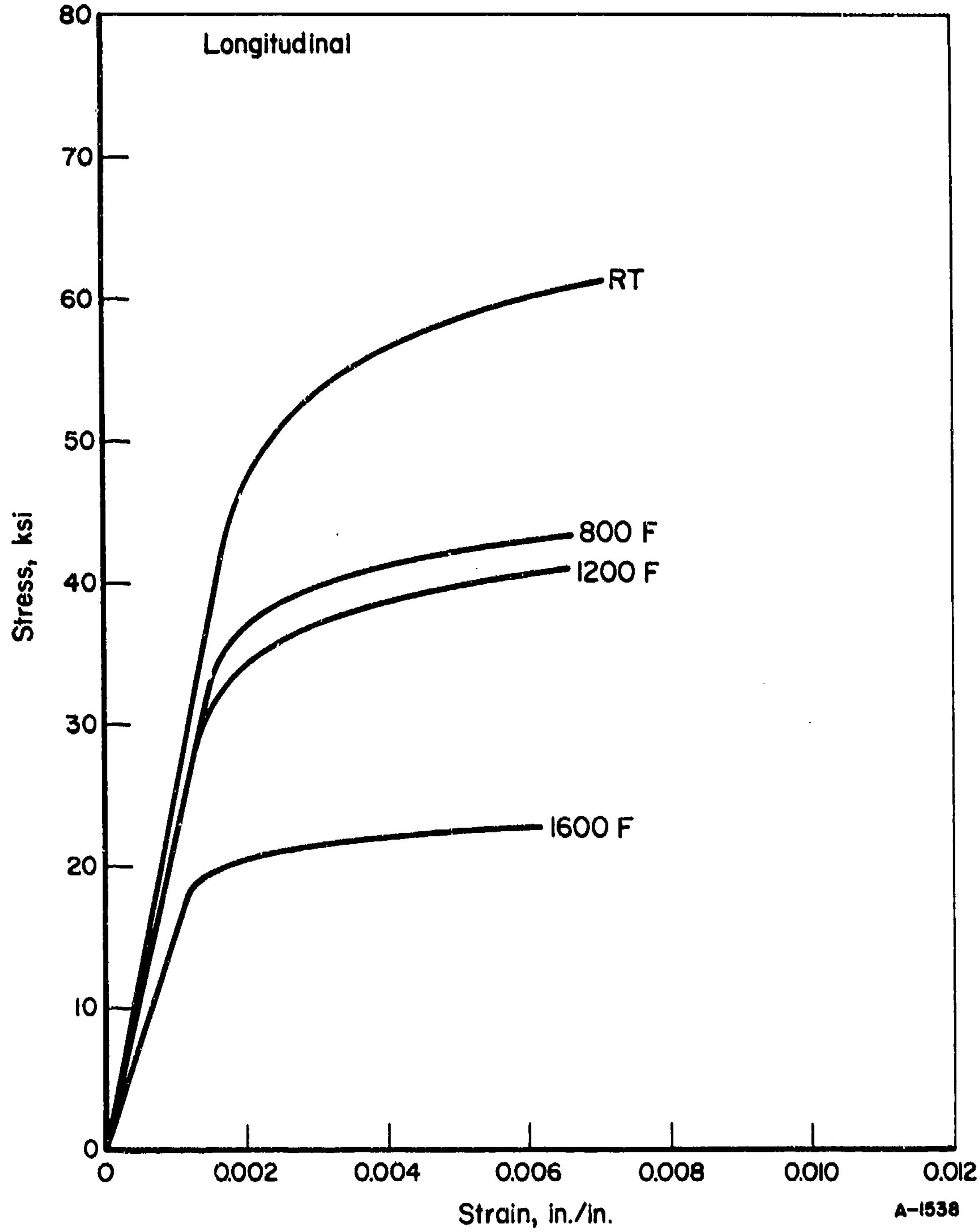

FIGURE 12. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED INCONEL 617 ALLOY SHEET (LONGITUDINAL)

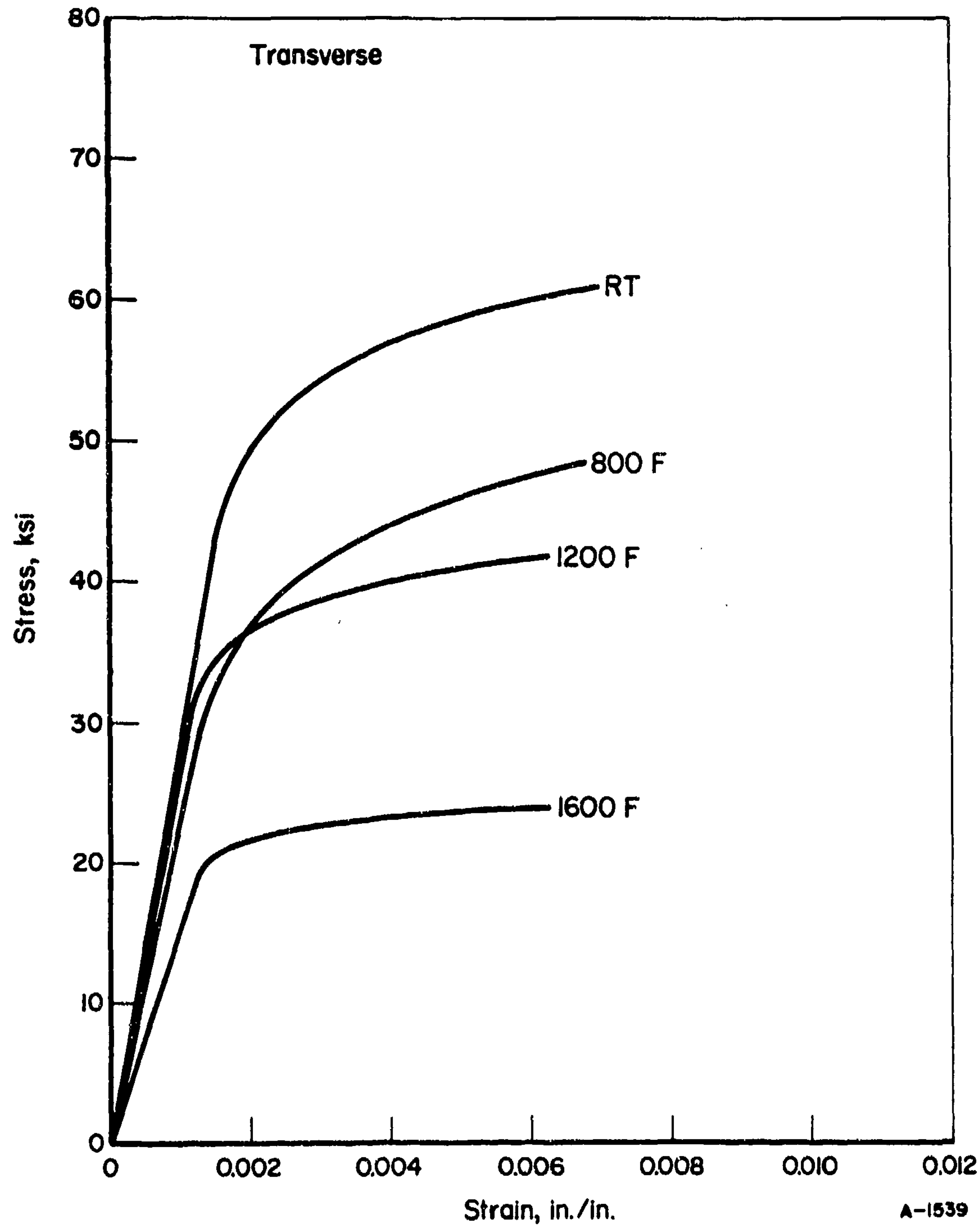

FIGURE 13. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED INCONEL 617 ALLOY SHEET (TRANSVERSE)

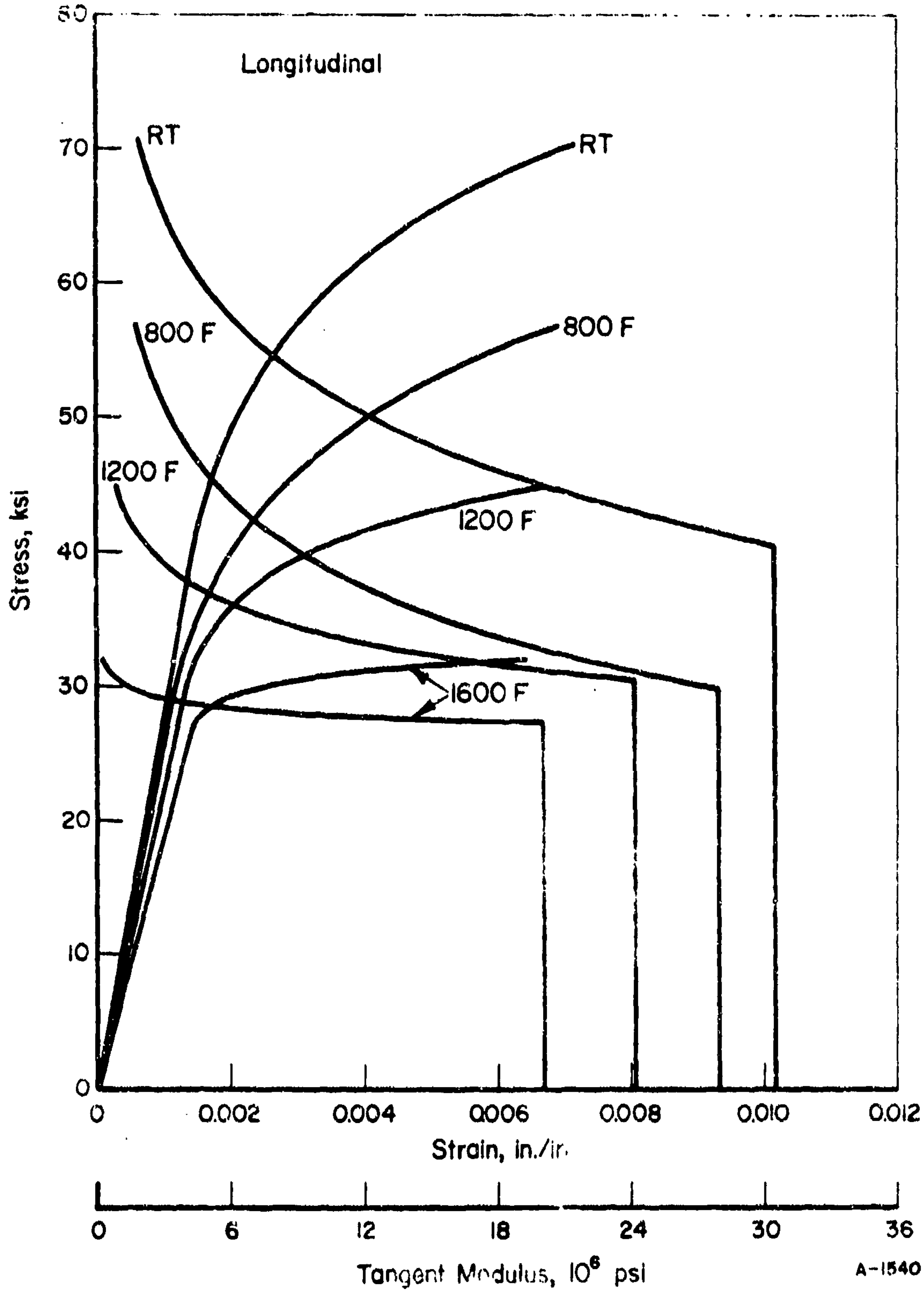

FIGURE 14. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR ANNEALED INCONEL 617 ALLOY SHEET (LONGITUDINAL)

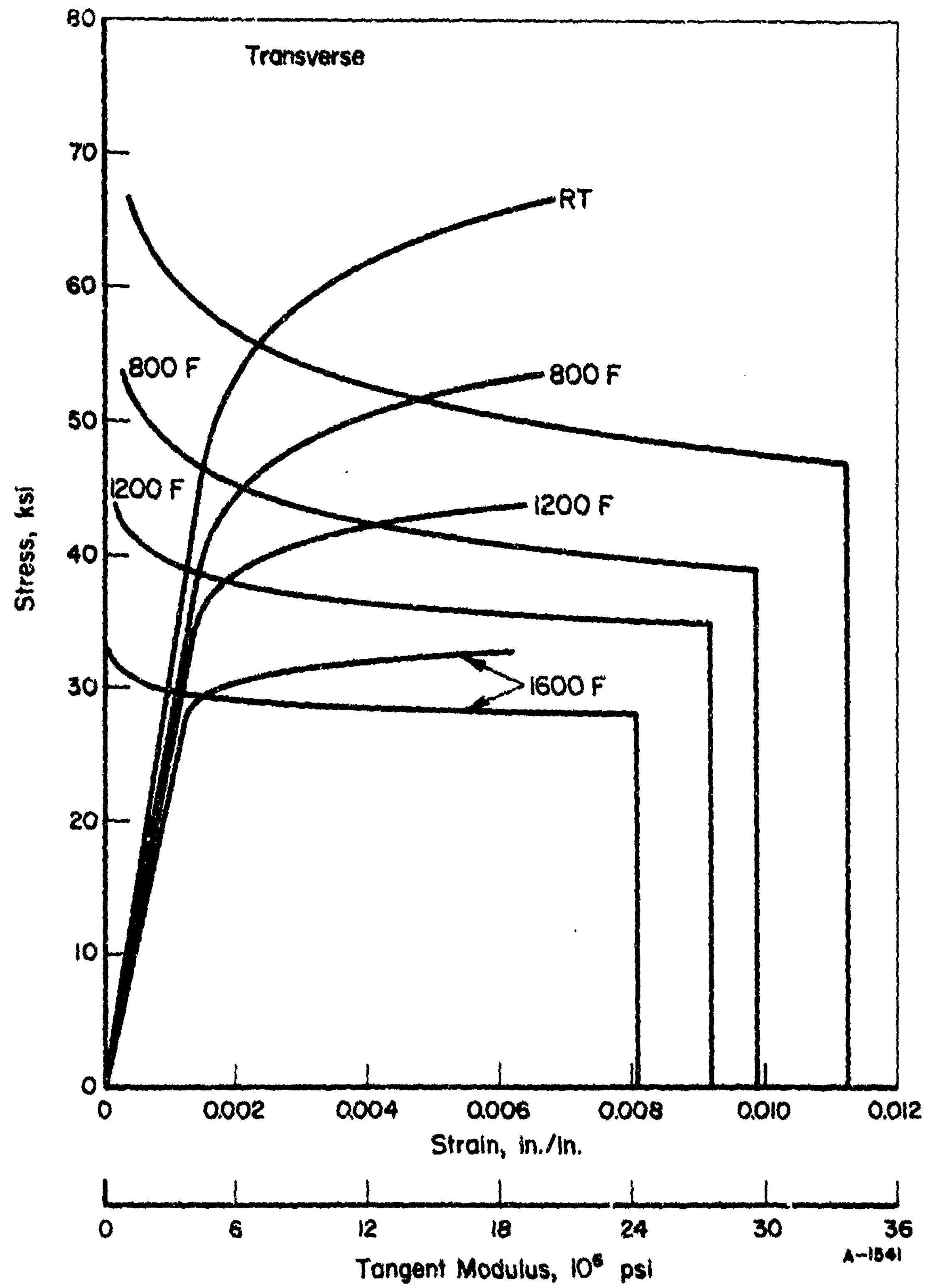

FIGURE 15. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR ANNEALED INCONEL 617 ALLOY SHEET (TRANSVERSE)

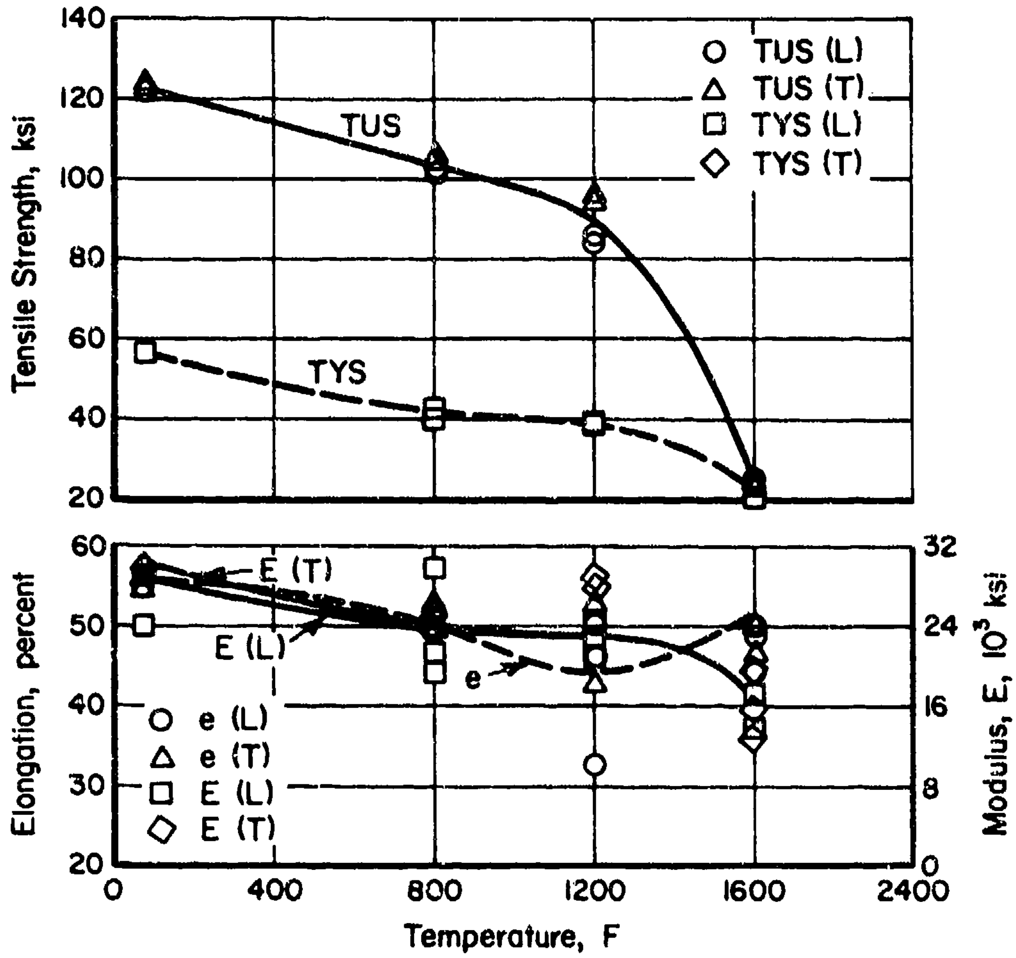

FIGURE 16. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED INCONEL ALLOY 617 SHEET

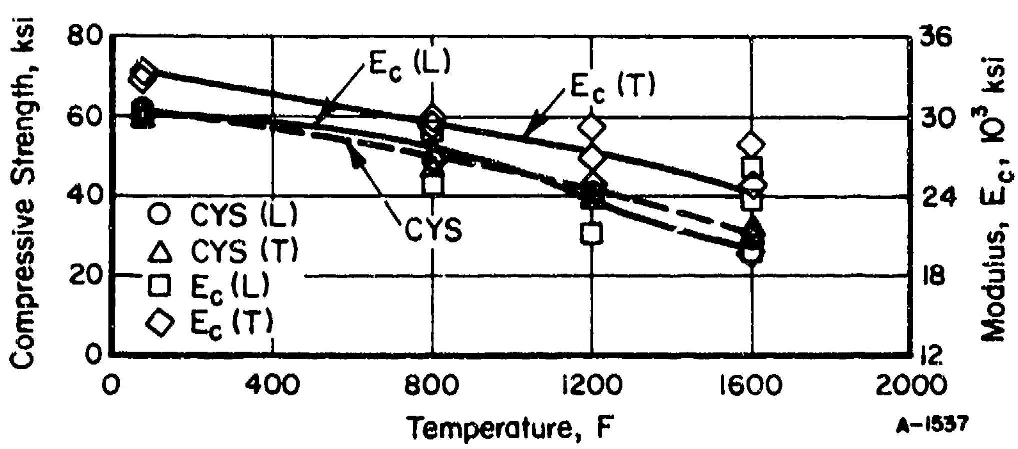

FIGURE 17. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED INCONEL ALLOY 617 SHEET

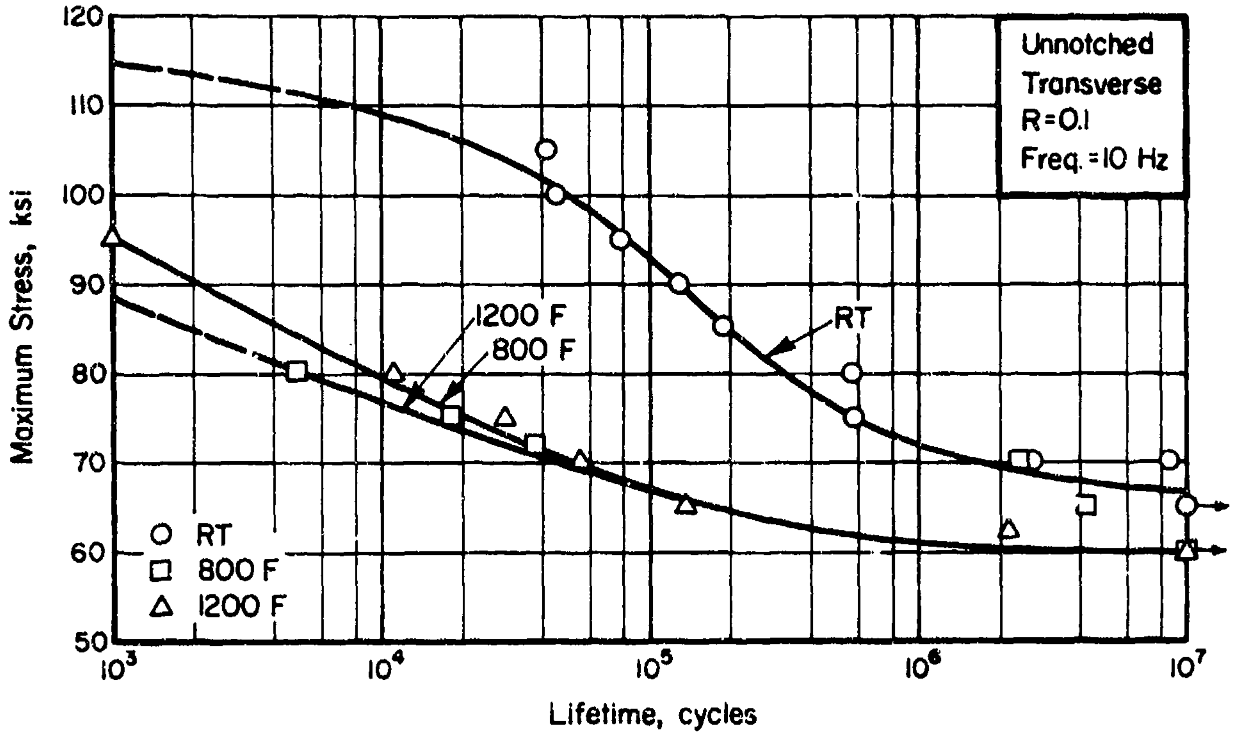

FIGURE 18. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED INCONEL ALLOY 617 SHEET

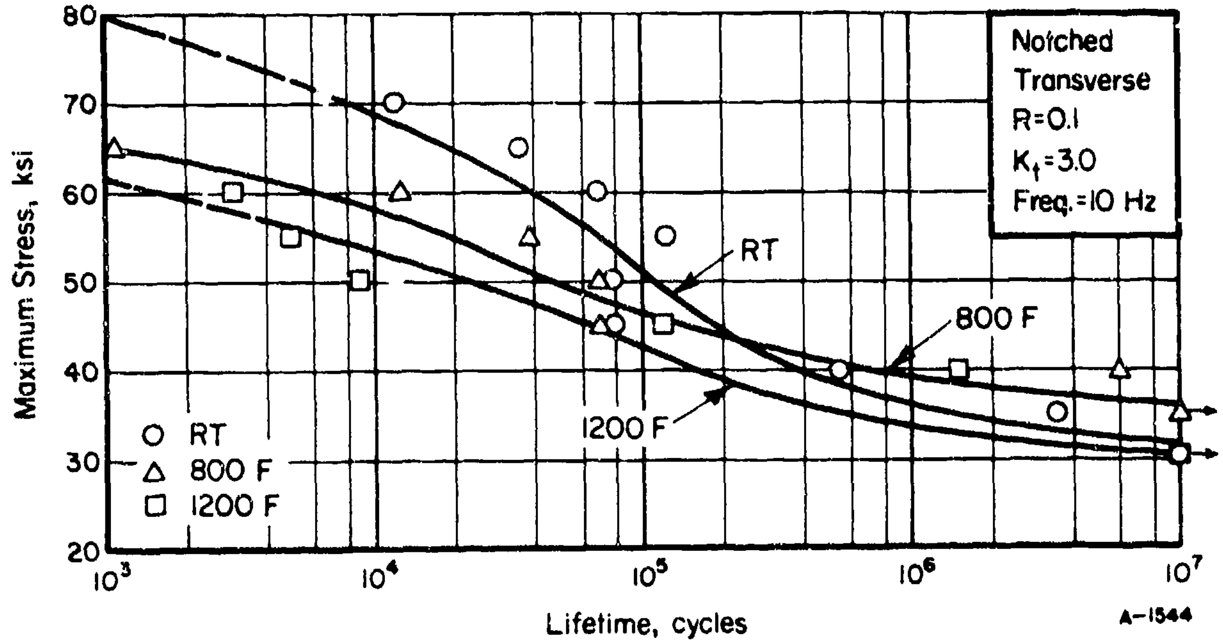

FIGURE 19. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t=3.0) ANNEALED INCONEL ALLOY 617 SHEET

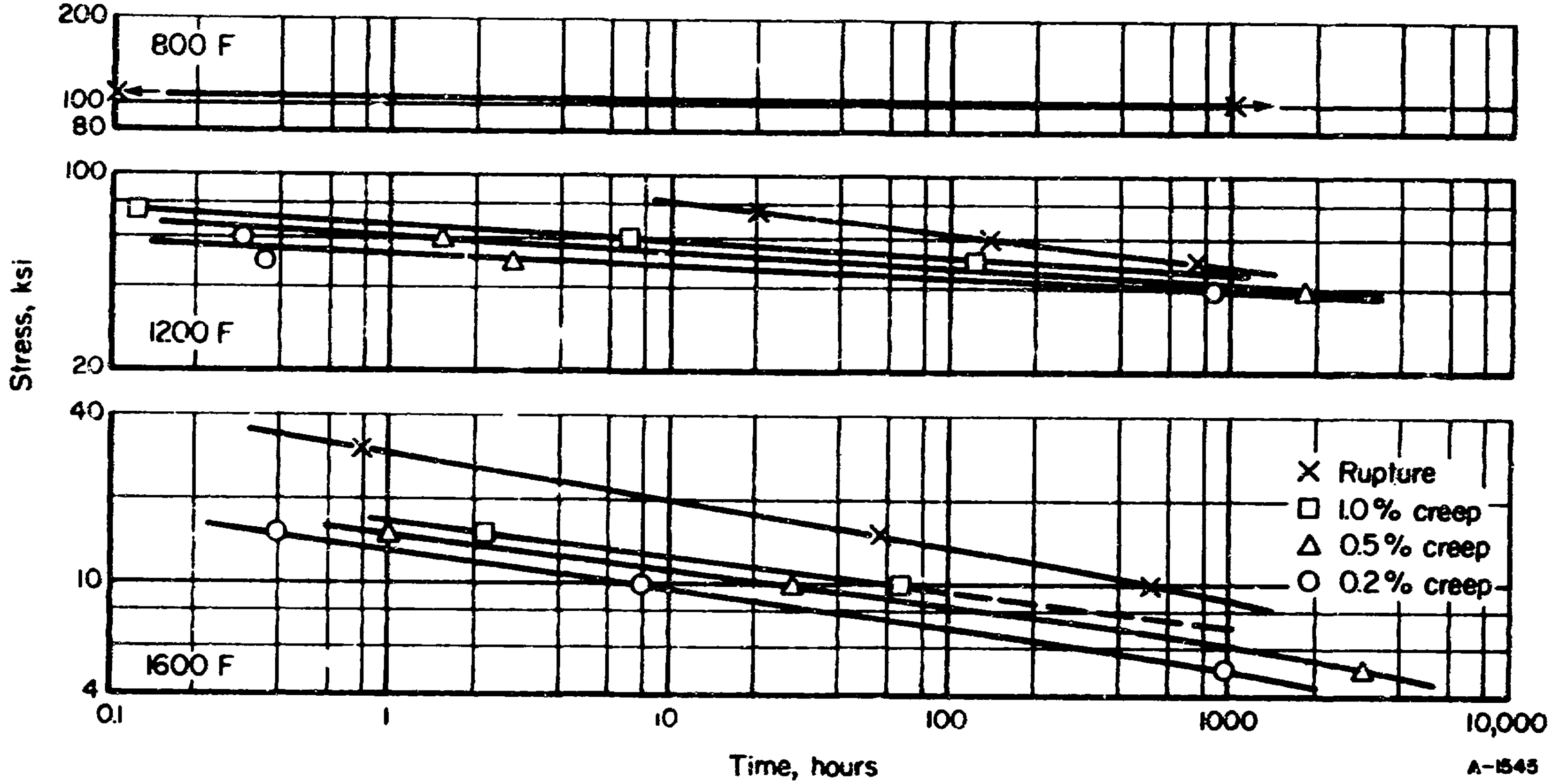

FIGURE 20. STRESS-RUPTURE AND PLASTIC-DEFORMATION CURVES FOR ANNEALED INCONEL 617 ALLOY SHEET (TRANSVERSE)

7475-T7351 Aluminum Alloy Plate

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

Tension. 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.

Compression. 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.

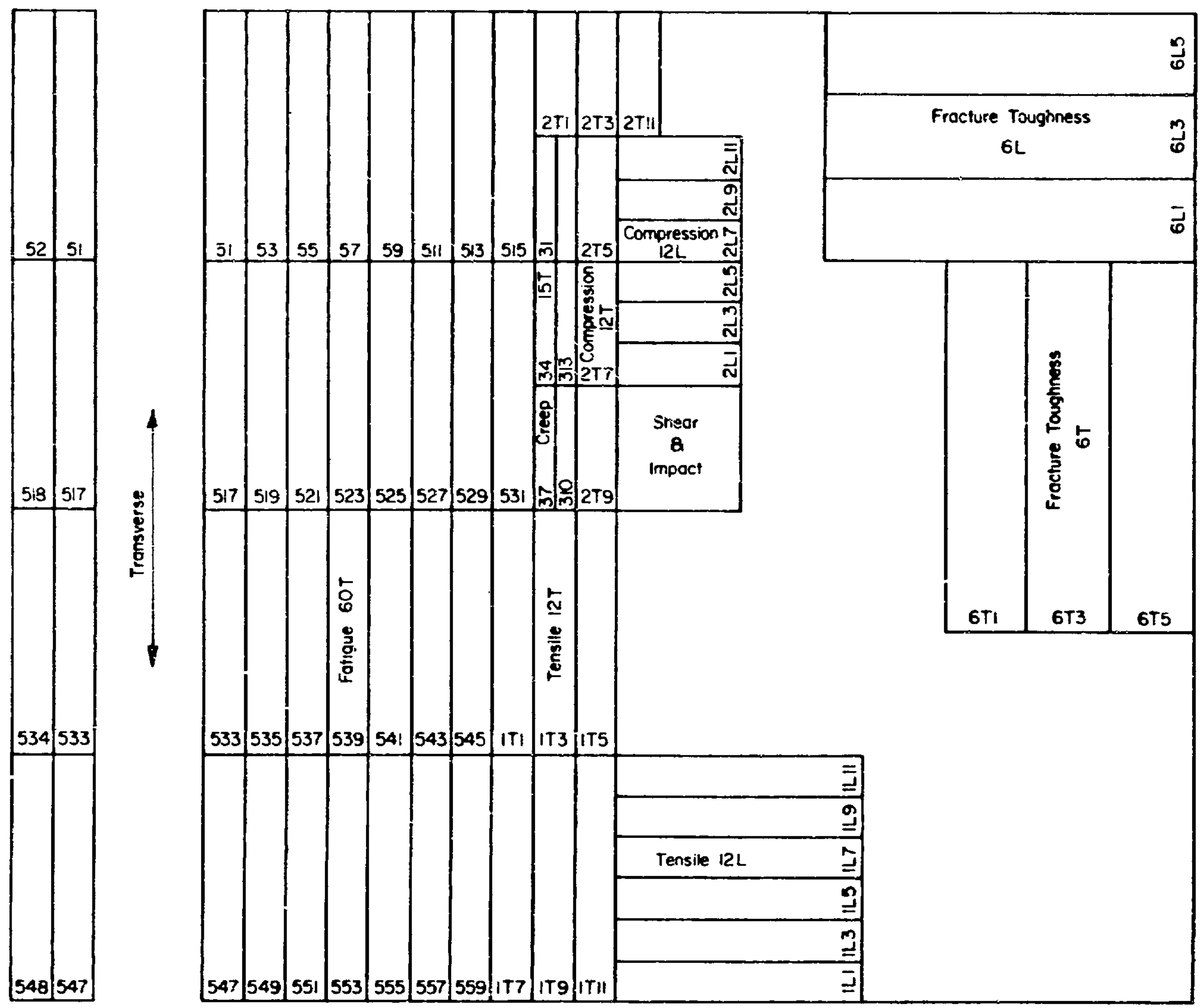

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FIGURE 21. SPECIMEN LAYOUT FOR 7475-T7351 ALUMINUM ALLOY PLATE

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

Fracture Toughness. 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_Q values shown in Table XIX are considered invalid K_{Ic} values by existing ASTM criteria.

Fatigue. 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.

Creep and Stress-Rupture. 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.

Stress Corrosion. 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.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 12.9 x 10^{-6} in./in./F from 70 F to 212 F.

Density. The density of this material is 0.101 lb/in.^{3}.

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

Specimen Number		Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^3 ksi
			Longitudinal at Room Temperature			
1L-1		71.8	63.0	18.5	47.9	10.7
1L-2		72.3	62.9	18.5	48.4	10.3
1L-3		72.2	62.7	18.0	47.1	9.7
	Average	72.1	62.9	18.3	47.8	10.2
			Transverse at Room Temperature			
1T-1		73.2	62.5	14.0	34.9	9.7
1T-2		73.5	62.5	16.0	36.6	9.8
1T-3		73.0	62.1	15.5	34.4	10.0
	Average	73.2	62.4	15.2	35.3	9.8
			Longitudinal at 250 F			
1L-4		55.3	55.3	17.0	60.2	8.9
1L-5		56.0	56.0	17.0	60.4	9.1
1L-6		55.4	55.3	18.0	60.8	9.1
	Average	55.6	55.5	17.3	60.5	9.0
			Transverse at 250 F			
1T-4		57.8	55.8	17.0	52.4	9.2
1T-5		55.9	54.9	17.0	53.0	10.1
1T-6		57.1	55.8	17.0	54.3	9.4
	Average	56.9	55.5	17.0	53.2	9.6
			Longitudinal at 350 F			
1L-7		44.7	44.4	20.0	70.0	7.7
1L-8		44.3	44.3	25.0	73.4	7.8
1L-9		45.1	45.1	16.5	71.5	7.9
	Average	44.7	44.6	20.5	71.6	7.8
			Transverse at 350 F			
1T-7		45.1	44.7	33.5	72.1	8.3
1T-8		45.7	45.5	23.5	67.0	7.5
1T-9		45.1	44.6	27.5	70.2	7.6
	Average	45.3	44.9	28.2	69.8	7.8
			Longitudinal at 500 F			
1L-10		16.8	16.5	39.5	91.9	7.1
1L-11		18.0	17.8	40.0	91.8	6.7
1L-12		22.3	22.1	27.0	88.4	7.5
	Average	19.0	18.8	35.5	70.7	7.1
			Transverse at 500 F			
1T-10		17.4	17.2	40.5	92.2	7.0
1T-11		17.6	17.3	43.5	92.5	6.8
1T-12		17.1	17.0	41.5	92.8	6.6
	Average	17.4	17.2	41.8	92.5	6.8

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

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^3 ksi
	Longitudinal 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		
2T-1		65.4	10.6
2T-2		65.7	10.4
2T-3		65.5	10.4
	Average	65.5	10.5
	Longitudinal 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
	Transverse at 250 F		
2T-4		57.3	10.0
2T-5		57.5	9.9
2T-6		58.0	9.7
	Average	57.6	9.9
	Longitudinal 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
	Transverse at 350 F		
2T-7		48.5	9.4
2T-8		48.2	9.9
2T-9		48.6	9.6
	Average	48.4	9.6
	Longitudinal at 500 F		
2L-10		17.7	8.2
2L-11		19.5	7.7
2L-12		18.2	7.6
	Average	18.5	7.8
	Transverse at 500 F		
2T-10		17.8	8.1
2T-11		19.7	7.8
2T-12		19.3	7.1
	Average	18.9	7.7

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

Specimen Number		Ultimate Shear Strength, ksi
	Longitudinal	
4L-1		45.0
4L-2		46.4
4L-3		44.8
4L-4		46.6
	Average	45.7
	Transverse	
4T-1		43.8
4T-2		46.3
4T-3		45.9
4T-4		43.8
	Average	45.0

TABLE XVIII. IMPACT TEST RESULTS FOR 7475-T7351 ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number		Energy, ft/lb
	Longitudinal	
10L-1		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. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS FOR 7475-T7351 ALLOY PLATE

Specimen Number	W, inches	B, inches	a, inches	Span, inches	P_Q, lb	P_{max}, lb	$f(\frac{a}{W})$	K_Q (a)	R_{sb} (b)
				Longitudinal (L-T)					
6L-1	2.00	1.00	1.182	8.0	7,000	8,000	3.655	72.4	2.29
6L-2	2.00	1.00	1.061	8.0	7,200	8,200	2.947	60.0	1.78
6L-3	2.00	1.00	1.064	8.0	6,900	7,720	2.962	57.8	1.67
6L-4	2.00	1.00	0.981	8.0	7,600	9,000	2.585	55.5	1.66
6L-5	2.00	1.00	1.069	8.0	6,800	7,950	2.987	57.5	1.76
6L-6	2.00	1.00	1.057	8.0	6,700	7,710	2.927	55.4	1.66
				Transverse (T-L)					
6T-1	2.00	1.00	1.068	8.0	6,100	6,720	2.982	51.4	1.49
6T-2	2.00	1.00	1.043	8.0	6,300	6,550	2.859	50.9	1.38
6T-3	2.00	1.00	1.134	8.0	6,550	6,820	3.347	62.0	1.75
6T-4	2.00	1.00	1.022	8.0	6,550	6,700	2.761	51.2	1.35
6T-5	2.00	1.00	1.078	8.0	6,350	6,550	3.033	54.5	1.48
6T-6	2.00	1.00	1.182	8.0	6,000	6,450	3.655	62.0	1.85

(a) Candidate K_Q values are invalid as K_{Ic} values since they do not meet the standard of a, T, $< 2.5 \left(\frac{K_Q}{TYS}\right)^2$

(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 useful comparative measure of toughness of materials where size may be less than sufficient for valid K_{Ic} determination.

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

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[(a)]
	250 F	
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[(a)]
	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

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

TABLE XXI. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t=3.0) 7475-T7351 ALLOY PLATE

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	15	518,400
5-53	12.5	12,786,000[(a)]
5-52	10	10,191,000[(a)]
	250 F	
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[(a)]
	350 F	
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[(a)]

(a) Did not fail.

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

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent: 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hours	Elongation in 2 Inches, percent	Reduction of Area, percent	Minimum Creep Rate, percent
3-2	50	250	0.1	0.4	1.5	3.0	6.0	0.617	12.3	16.7	56.7	0.31
3-4	43	250	3.0	20	130	250	350	0.591	422.4	15.2	62.8	0.0029
3-7	35	250	40	280	--	--	--	0.446	311.4 (b)	0.672	--	--
3-8	30	250	150	815	3550 (a)	--	--	0.363	1004.2 (b)	0.587	--	0.00011
3-11	30	350	0.4	1.4	5	7.8	--	0.380	11.8	19.7	72.6	--
3-9	20	350	12	38	109	160	190	0.295	209.1	22.0	84.9	0.0034
3-1	15	350	45	160	445	660	830	0.220	930.5	24.2	84.2	0.00078
3-12	9	350	560	1800	6200 (a)	--	--	0.147	1821.8 (b)	0.345	--	0.00069
3-5	10	500	0.02	0.04	0.09	0.17	0.32	0.280	0.8	37.1	90.6	6.0
3-3	7	500	3.0	8.0	19	30	43	0.148	61.0	33.3	93.5	0.017
3-6	5	500	10	45	190	410	640	0.087	1033.8	31.1	88.2	0.0019
3-10	2.5	500	175	1000	4450 (a)	--	--	0.057	1056.9 (b)	0.261	--	0.00008

(a) Estimate.

(b) Test discontinued.

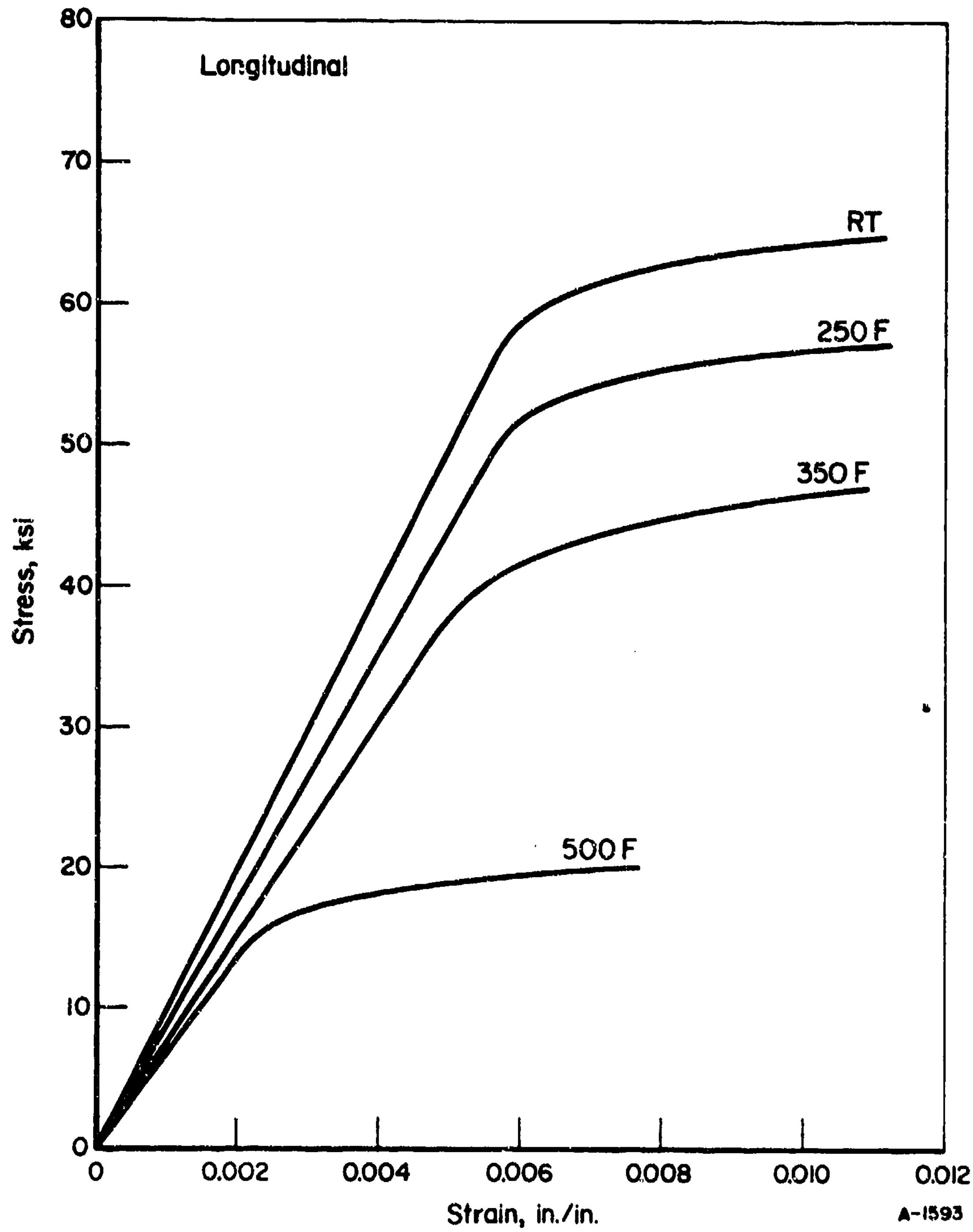


FIGURE 22. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)

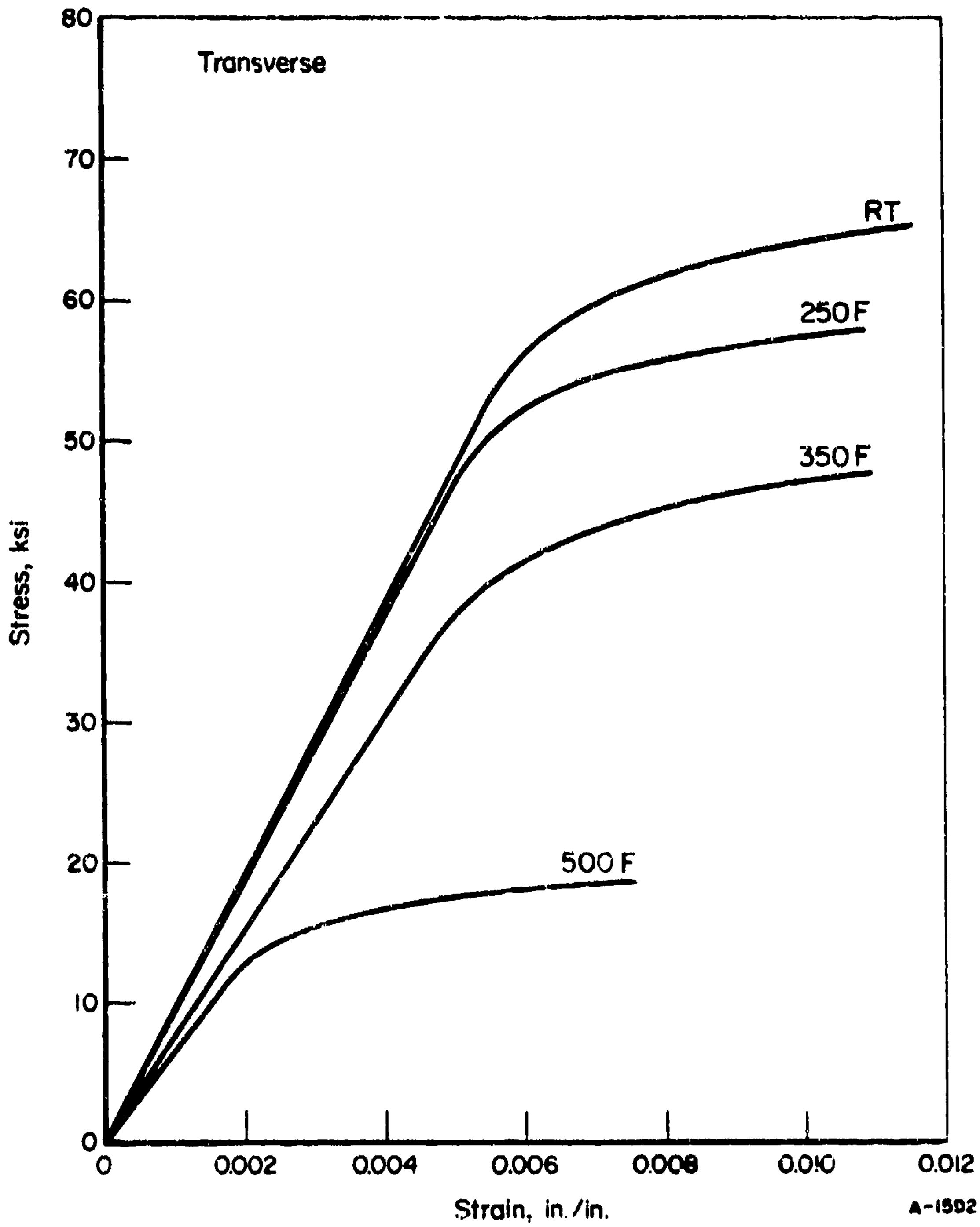


FIGURE 23. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (TRANSVERSE)

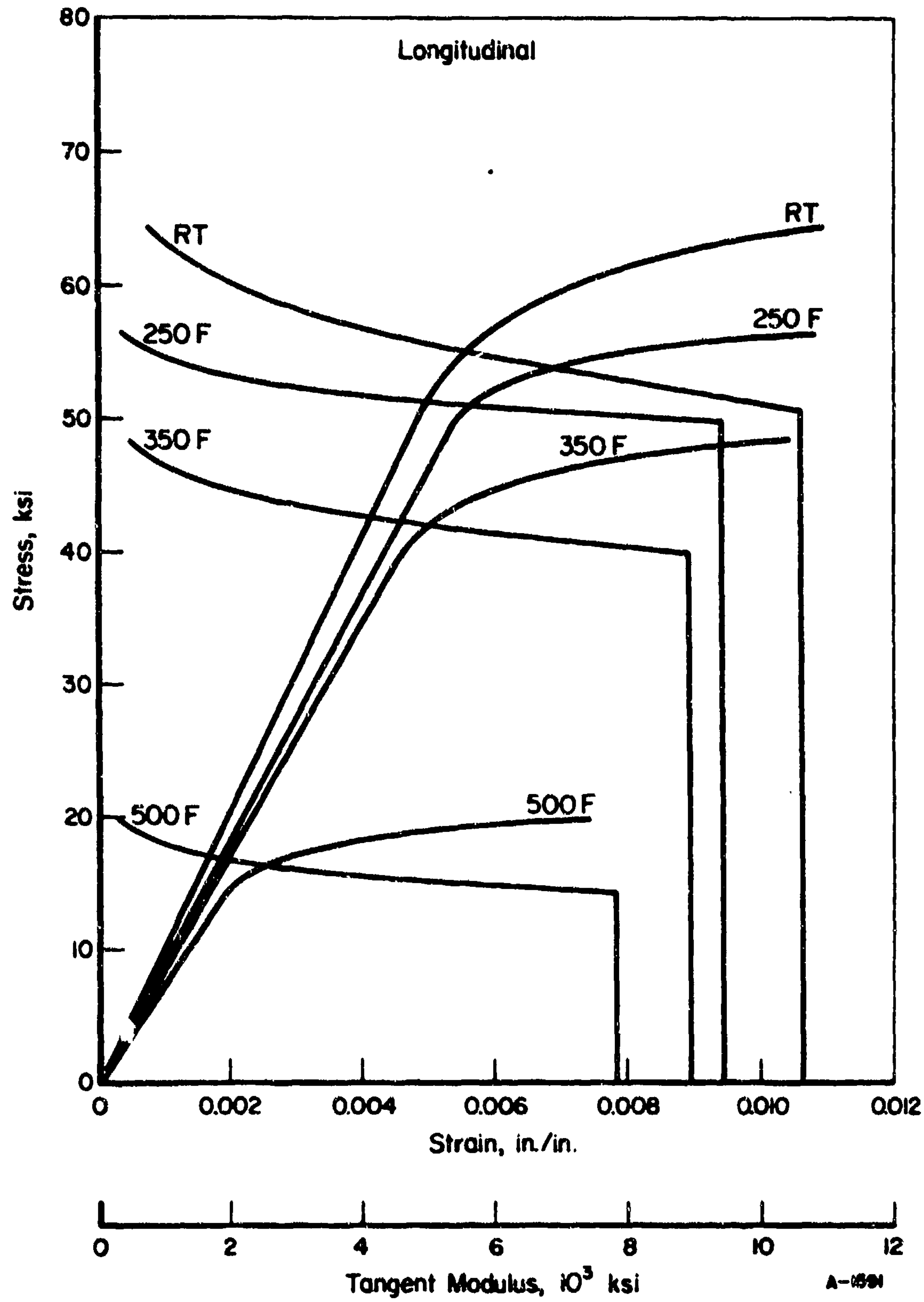


FIGURE 24. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (LONGITUDINAL)

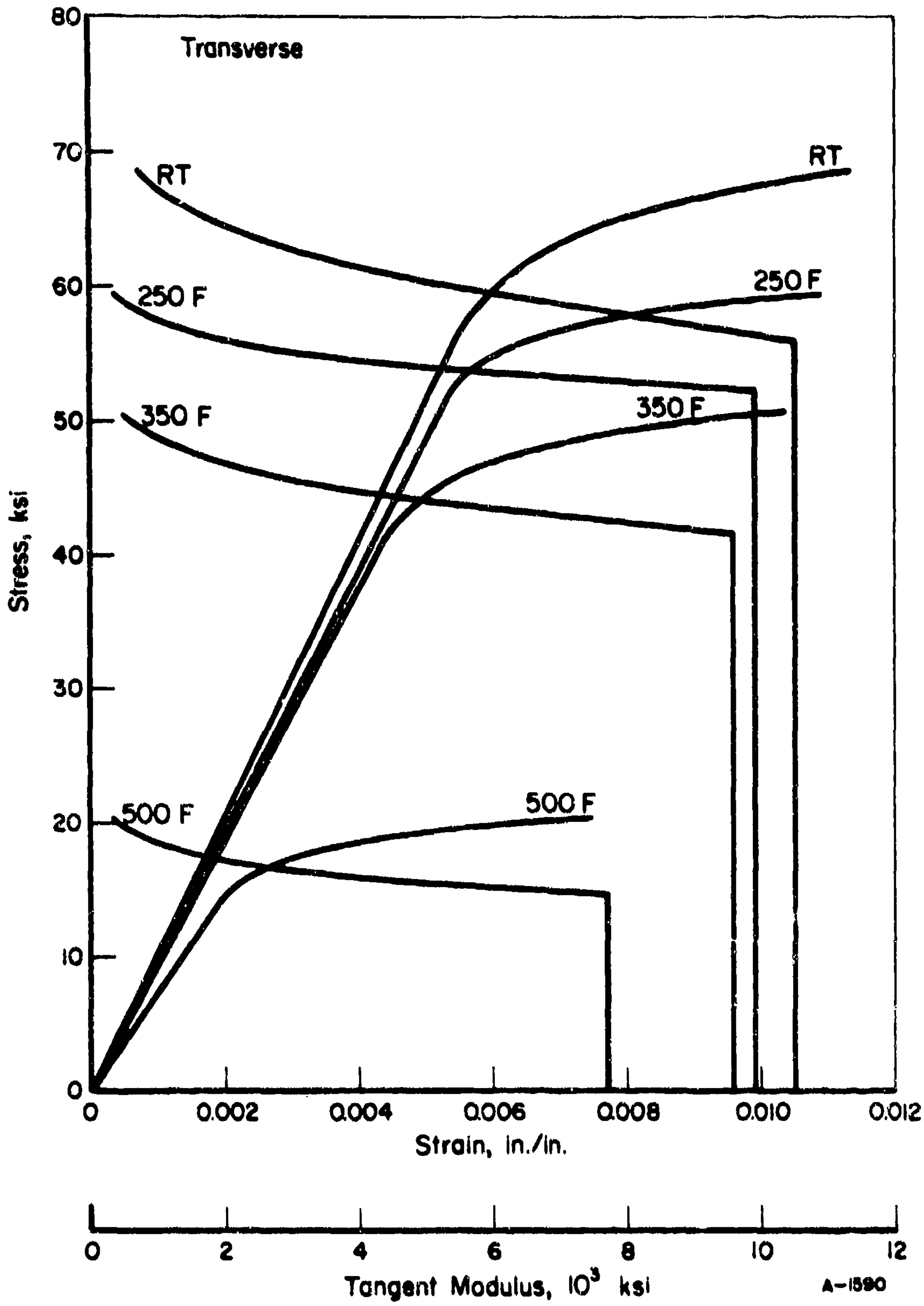


FIGURE 25. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7475-T7351 ALUMINUM ALLOY PLATE (TRANSVERSE)

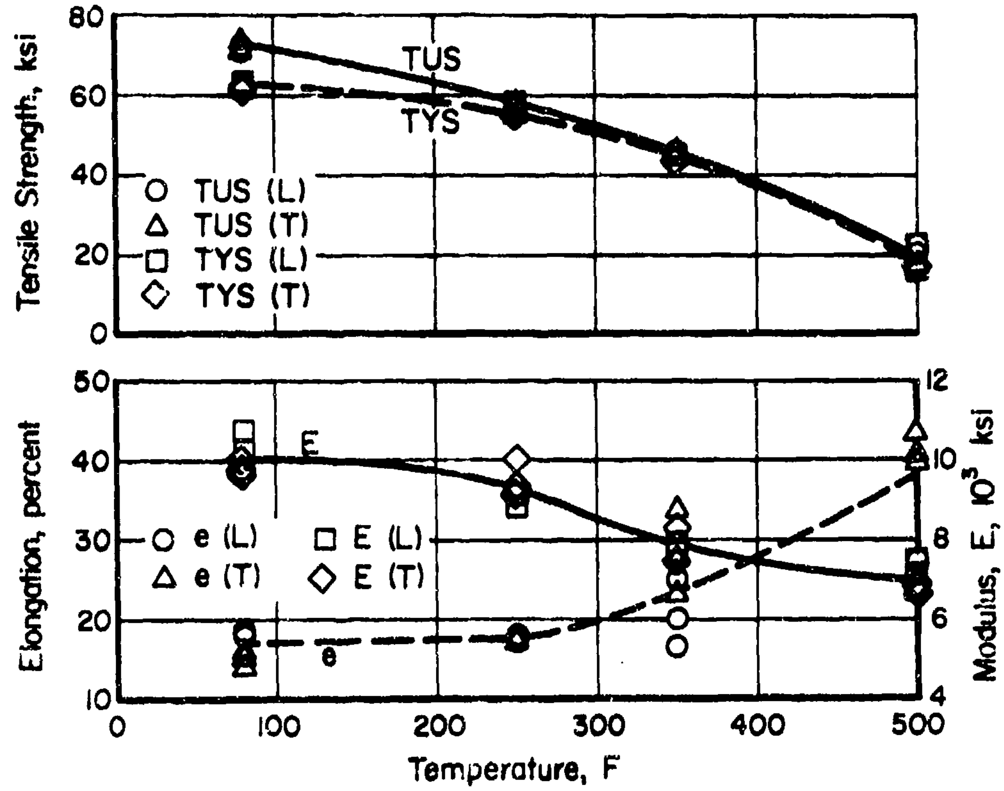


FIGURE 26. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7475-T7351 ALLOY PLATE

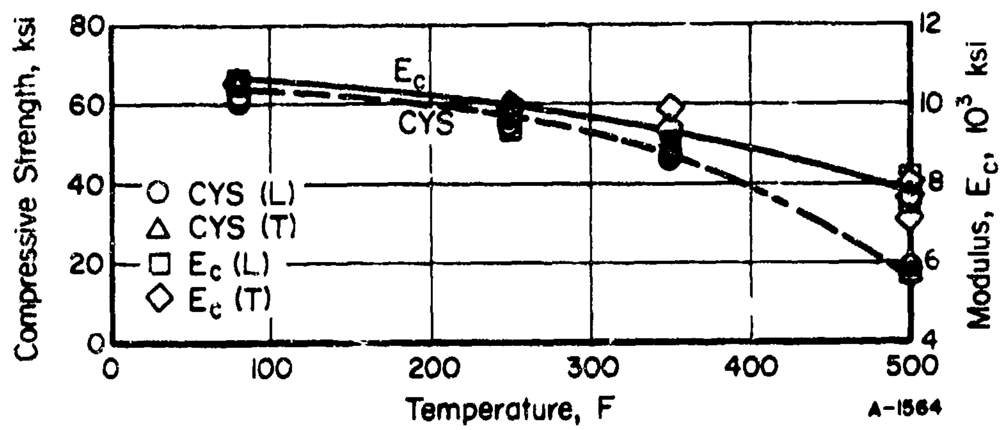


FIGURE 27. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7475-T7351 ALLOY PLATE

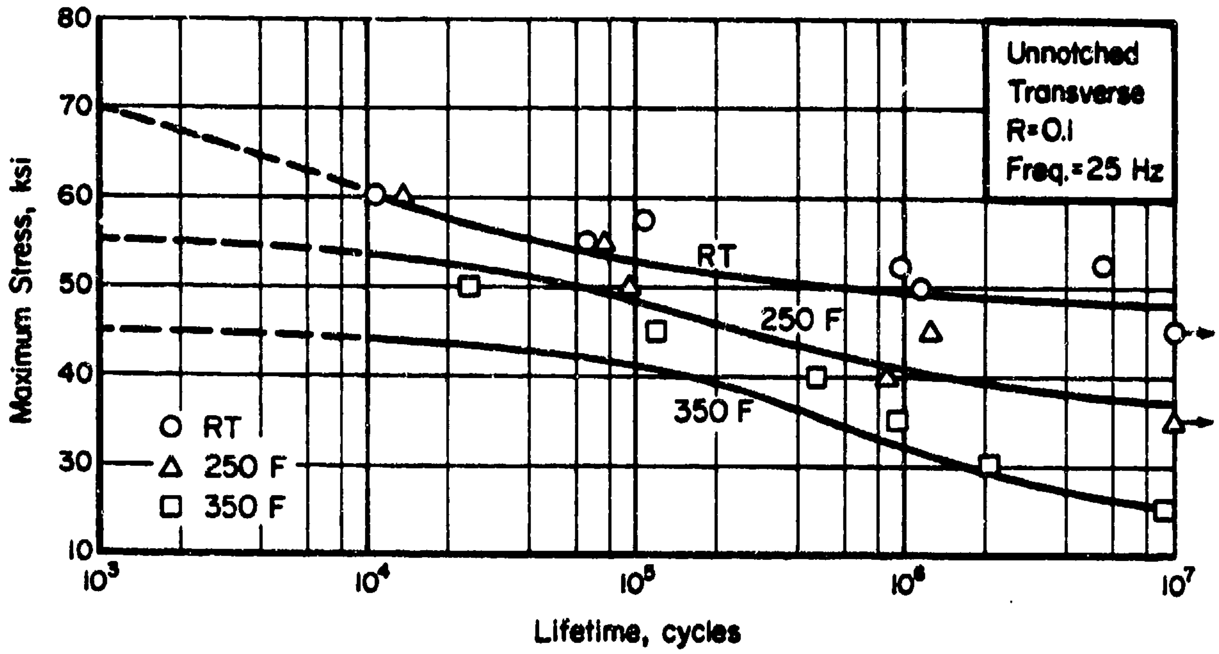


FIG.JRE 28. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7475-T7351 ALLOY PLATE

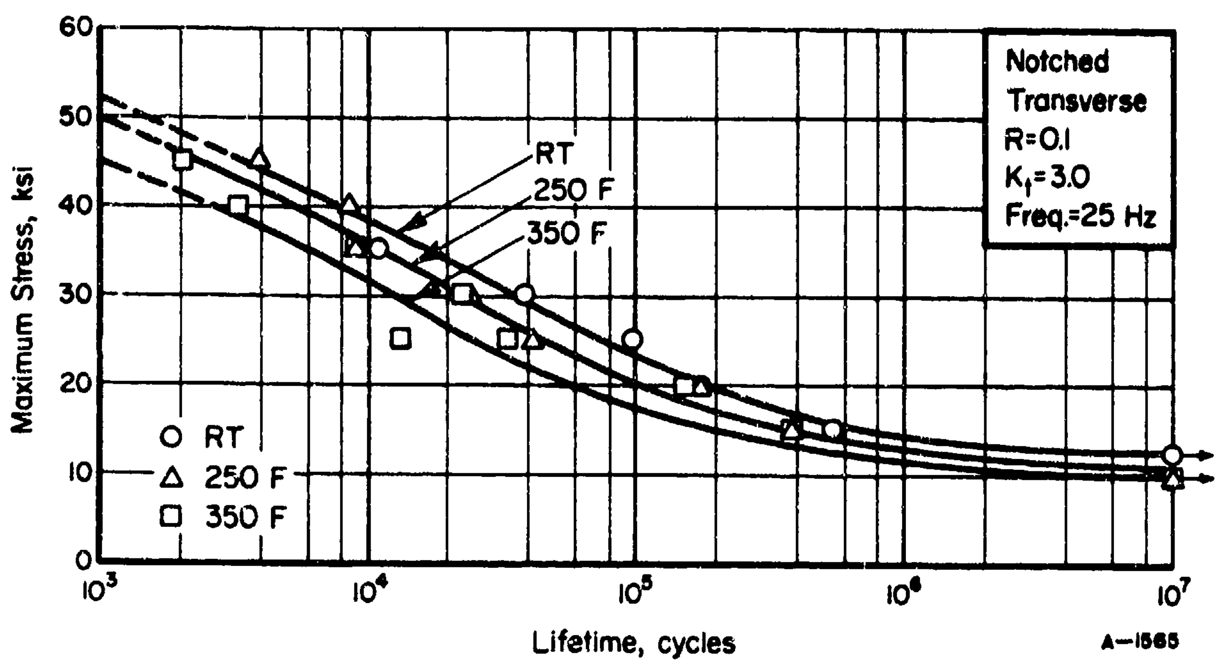


FIGURE 29. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) 7475-T7351 ALLOY PLATE

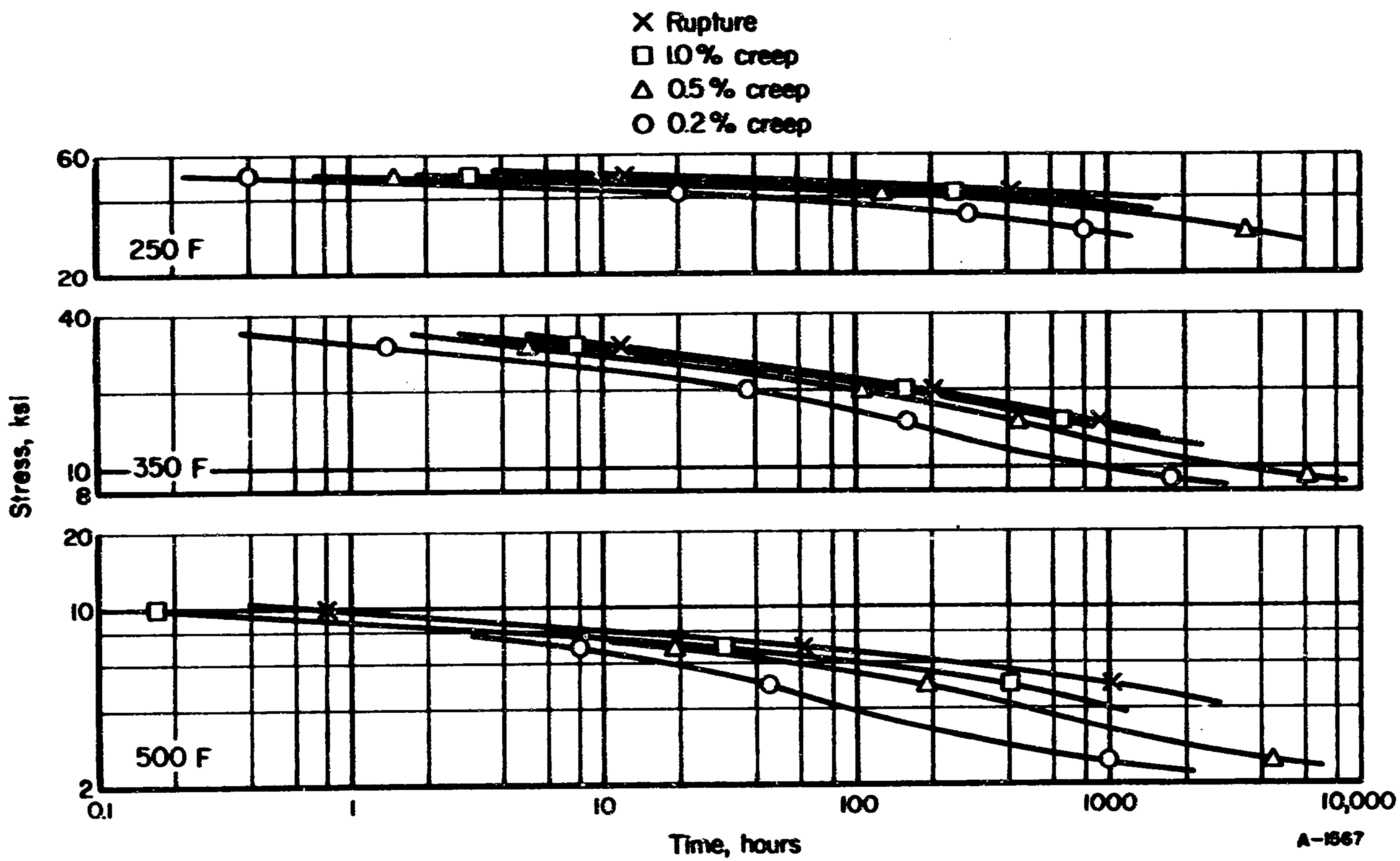


FIGURE 30. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7475-T7351 ALUMINUM ALLOY PLATE (TRANSVERSE)

2419-T851 Aluminum Plate

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
Magnesium	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

Tension. 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.

Compression. 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.

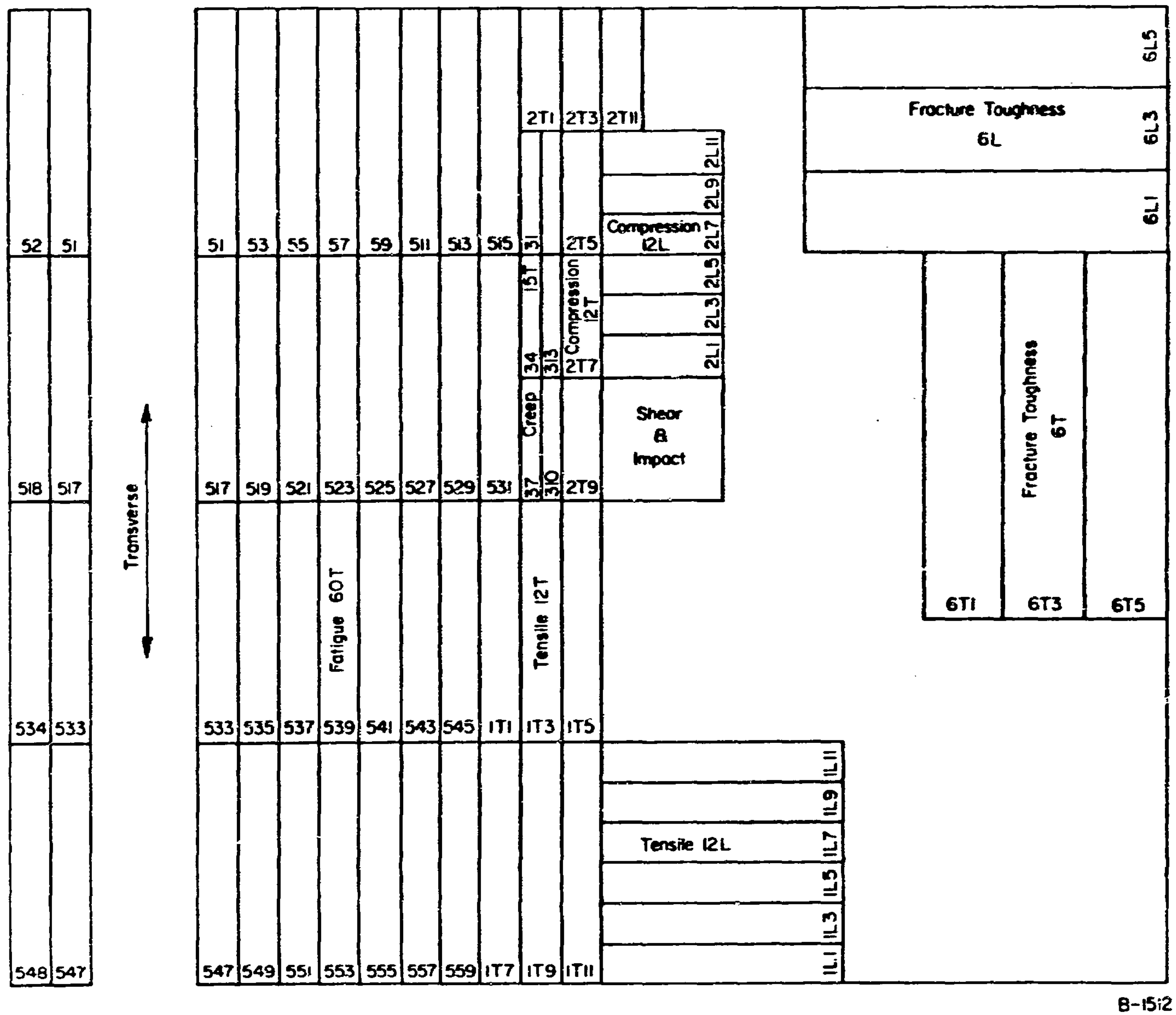


FIGURE 31. SPECIMEN LAYOUT FOR 2419-T851 ALUMINUM ALLOY PLATE

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

Fracture Toughness. 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 K_Q values shown in Table XXVII are considered valid K_{Ic} values by existing ASTM criteria.

Fatigue. 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.

Creep and Stress-Rupture. 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.

Stress Corrosion. 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.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 12.4 x 10^{-6} in./in./F from 70 F to 212 F.

Density. The density of this material is 0.102 $lb/in.^3$.

TABLE XXIII. TENSILE TEST RESULTS FOR 2419-T851 ALUMINUM ALLOY PLATE

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^3 ksi
		Longitudinal at Room Temperature			
1L-1	66.6	52.2	11.0	24.0	10.0
1L-2	66.5	52.5	11.0	23.0	10.6
1L-3	66.9	52.5	11.0	23.7	10.7
Average	66.7	52.4	11.0	23.6	10.4
		Transverse at Room Temperature			
1T-1	66.5	51.4	10.0	14.6	11.5
1T-2	66.5	51.3	11.0	19.3	10.6
1T-3	66.3	50.9	11.0	20.4	10.7
Average	66.4	51.2	10.7	18.1	10.8
		Longitudinal 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
1L-6	55.2	46.8	18.0	41.1	11.0
Average	55.4	46.8	15.0	37.9	10.5
		Transverse at 250 F			
1T-4	55.4	45.6	13.0	34.5	9.6
1T-5	54.8	45.9	13.5	34.1	9.6
1T-6	54.6	45.3	13.0	33.1	9.4
Average	54.9	45.6	13.2	33.9	9.5
		Longitudinal 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	41.2	14.5	49.6	9.1
Average	45.5	41.4	14.5	48.4	9.1
		Transverse at 350 F			
1T-7	44.5	40.0	16.0	46.4	9.8
1T-8	44.6	39.7	13.5	45.6	9.8
1T-9	44.2	39.5	15.0	46.7	8.8
Average	44.5	39.7	14.8	46.2	9.5
		Longitudinal 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	23.0	21.3	12.0	54.0	7.5
Average	22.2	20.9	12.0	53.2	7.4
		Transverse at 500 F			
1T-10	22.4	20.7	17.0	47.8	9.3
1T-11	23.4	22.1	19.0	54.1	9.3
1T-12	23.5	22.2	18.0	53.0	8.8
Average	23.1	21.7	18.0	51.6	9.1

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

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^3 ksi
	Longitudinal at Room Temperature		
2L-1		53.5	10.5
2L-2		53.0	11.2
2L-3		53.3	10.8
	Average	53.3	10.8
	Transverse at Room Temperature		
2T-1		51.7	10.9
2T-2		51.7	10.4
2T-3		51.6	10.8
	Average	51.7	10.7
	Longitudinal at 250 F		
2L-4		48.2	10.3
2L-5		47.4	10.8
2L-6		47.7	10.4
	Average	47.8	10.5
	Transverse at 250 F		
2T-4		47.0	10.2
2T-5		46.9	10.2
2T-6		46.8	10.8
	Average	46.9	10.4
	Longitudinal at 350 F		
2L-7		41.8	10.0
2L-8		42.2	9.9
2L-9		42.7	10.0
	Average	42.2	10.0
	Transverse at 350 F		
2T-7		41.6	9.5
2T-8		42.0	9.9
2T-9		41.5	10.1
	Average	41.7	9.8
	Longitudinal at 500 F		
2L-10		25.3	8.8
2L-11		25.4	9.5
2L-12		25.8	9.5
	Average	25.5	9.3
	Transverse at 500 F		
2T-10		25.4	8.9
2T-11		25.7	9.0
2T-12		25.3	9.2
	Average	25.5	9.0

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

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

TABLE XXVI. IMPACT TEST RESULTS FOR 2419-T851 ALUMINUM ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number		Energy, ft/lb
	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	
10T-1		4.0
10T-2		5.0
10T-3		4.0
10T-4		4.0
10T-5		5.0
10T-6		4.0
	Average	4.3

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

Specimen Number	W, inches	a, inches	B, inches	P_Q, lb	Span, inches	$f(\frac{a}{W})$	K_Q (a)
			Longitudinal (L-T)				
6L-1	2.00	0.932	1.00	5,000	8.0	2.396	33.89
6L-2	2.00	0.998	1.00	4,900	8.0	2.656	36.80
6L-3	2.00	0.988	1.00	4,750	8.0	2.614	35.12
6L-4	2.00	0.968	1.00	5,050	8.0	2.533	36.18
6L-5	2.00	0.962	1.00	4,800	8.0	2.509	34.06
6L-6	2.00	1.016	1.00	4,600	8.0	2.734	35.58
						Average	35.30
			Transverse (T-L)				
6T-1	2.00	0.972	1.00	4,200	8.0	2.549	30.20
6T-2	2.00	0.944	1.00	4,400	8.0	2.440	30.37
6T-3	2.00	0.988	1.00	4,200	8.0	2.614	31.05
6T-4	2.00	0.994	1.00	4,000	8.0	2.639	29.86
6T-5	2.00	0.961	1.00	4,450	8.0	2.505	31.53
6T-6	2.00	0.974	1.00	3,900	8.0	2.556	28.20
						Average	30.20

(a) These candidate K_Q values are considered valid K_{Ic} values by existing ASTM standards.

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

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[a]
5-5	30	10,000,000[a]
	250 F	
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
	350 F	
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[a]

(a) Did not fail.

TABLE XXIX. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) 2419-T851 ALLOY PLATE (TRANSVERSE, R = 0.1)

Specimen Number	Maximum Stress, ksi	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(a)
	250 F	
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(a)
	350 F	
5-47	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

(a) Did not fail.

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

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent: 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hours	Elongation in 2 Inches, percent	Reduction of Area, percent	Minimum Creep Rate, percent
3-7	50	250	--	--	--	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	15	0.719	41.6	10.8	32.0	0.064
3-1	40	250	0.5	16	63	335	965	0.576	1243.7	5.4	10.6	0.0014
3-11	35	250	20	210	2100[a]	--	--	0.523	500.7[b]	0.778	--	0.00016
3-15	30	250	120	1970	--	--	--	0.434	1319.7[b]	0.611	--	0.000042
3-4	40	350	--	0.01	0.03	0.06	0.14	0.835	0.4	13.1	40.8	12.0
3-5	35	350	0.05	0.1	0.9	2.7	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	16.1	0.013
3-6	25	350	5.2	37	250	680	1165	0.385	1313.3	4.6	4.7	0.00005
3-9	16	350	200	3000[a]	--	--	--	0.250	1512.0[b]	0.419	--	0.000025
3-16	22.6	500	--	--	--	--	--	0.627	1.0	16.9	59.3	--
3-12	20	500	0.05	0.11	0.45	1.1	2.2	0.387	3.2	7.7	31.1	0.87
3-13	14	500	2	6	37	65	90	0.177	94.9	3.1	4.8	0.01
3-8	10	500	20	65	260	510	--	0.181	698.1	2.3	2.2	0.0015
3-14	6	500	170	1135	4500[a]	--	--	0.031	1319.5[b]	0.257	--	0.00009
3-2	5	500	>1000	--	--	--	--	0.100	600.8[b]	0.173	--	nil

(a) Estimated.

(b) Test discontinued.

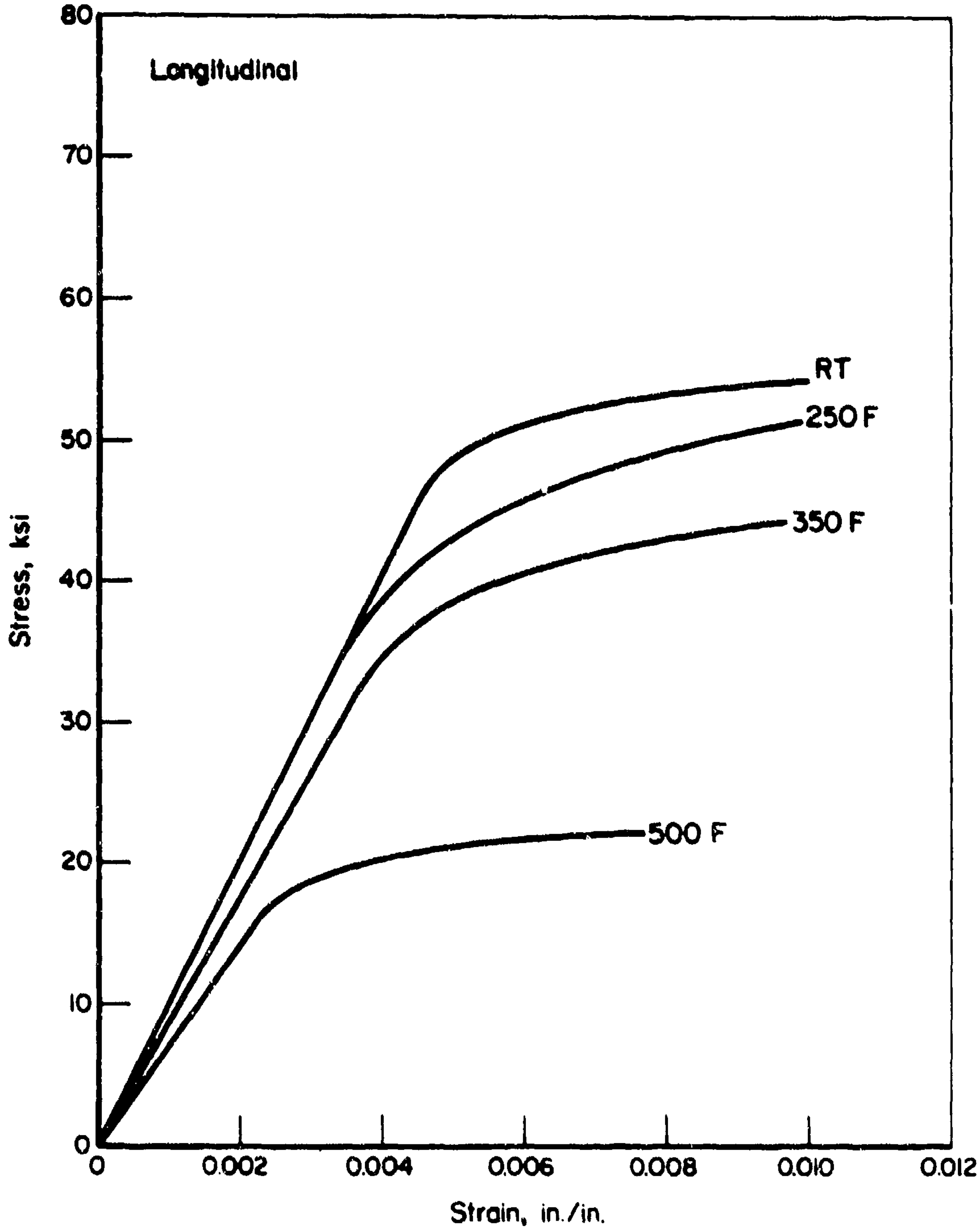


FIGURE 32. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (LONGITUDINAL)

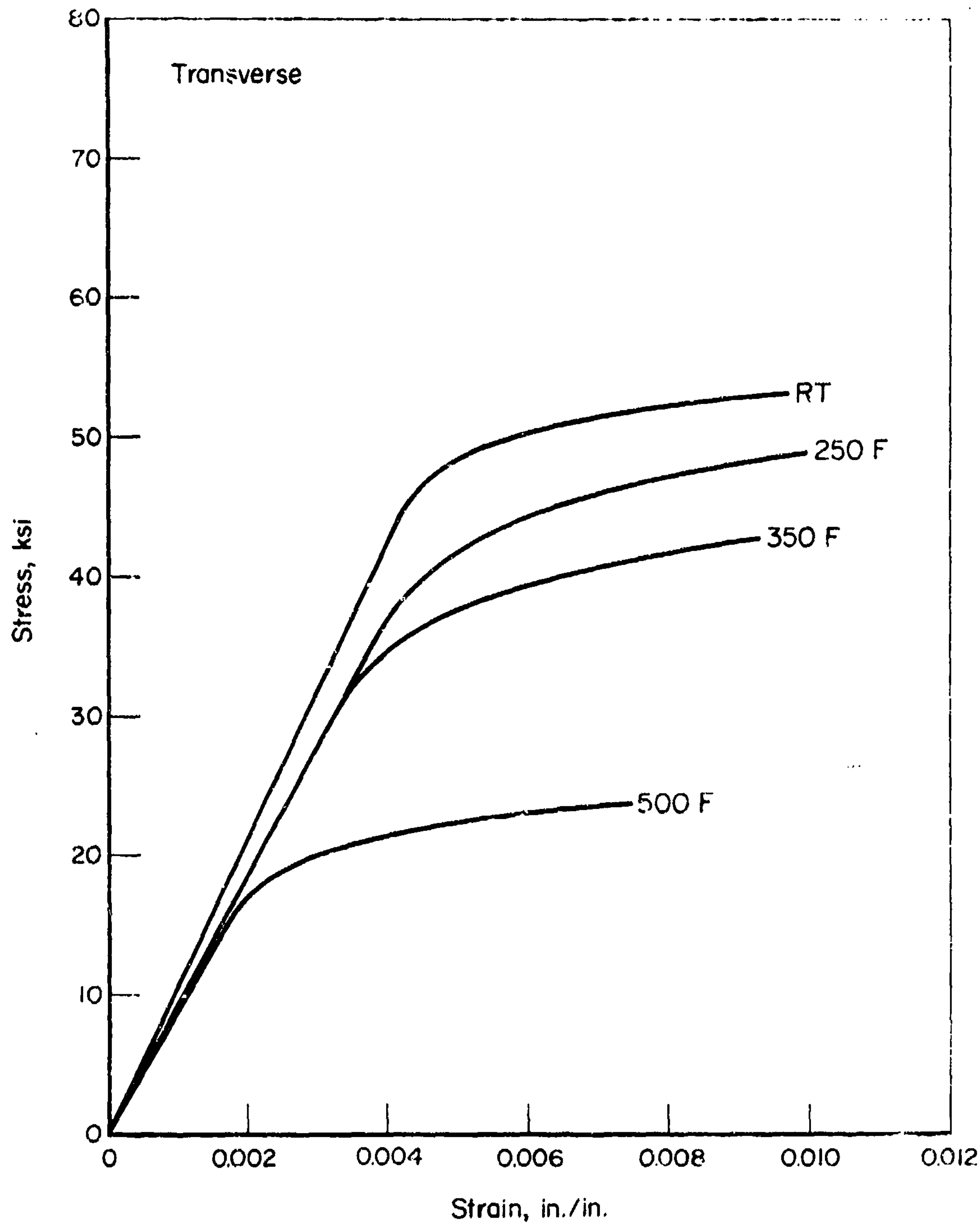


FIGURE 33. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (TRANSVERSE)

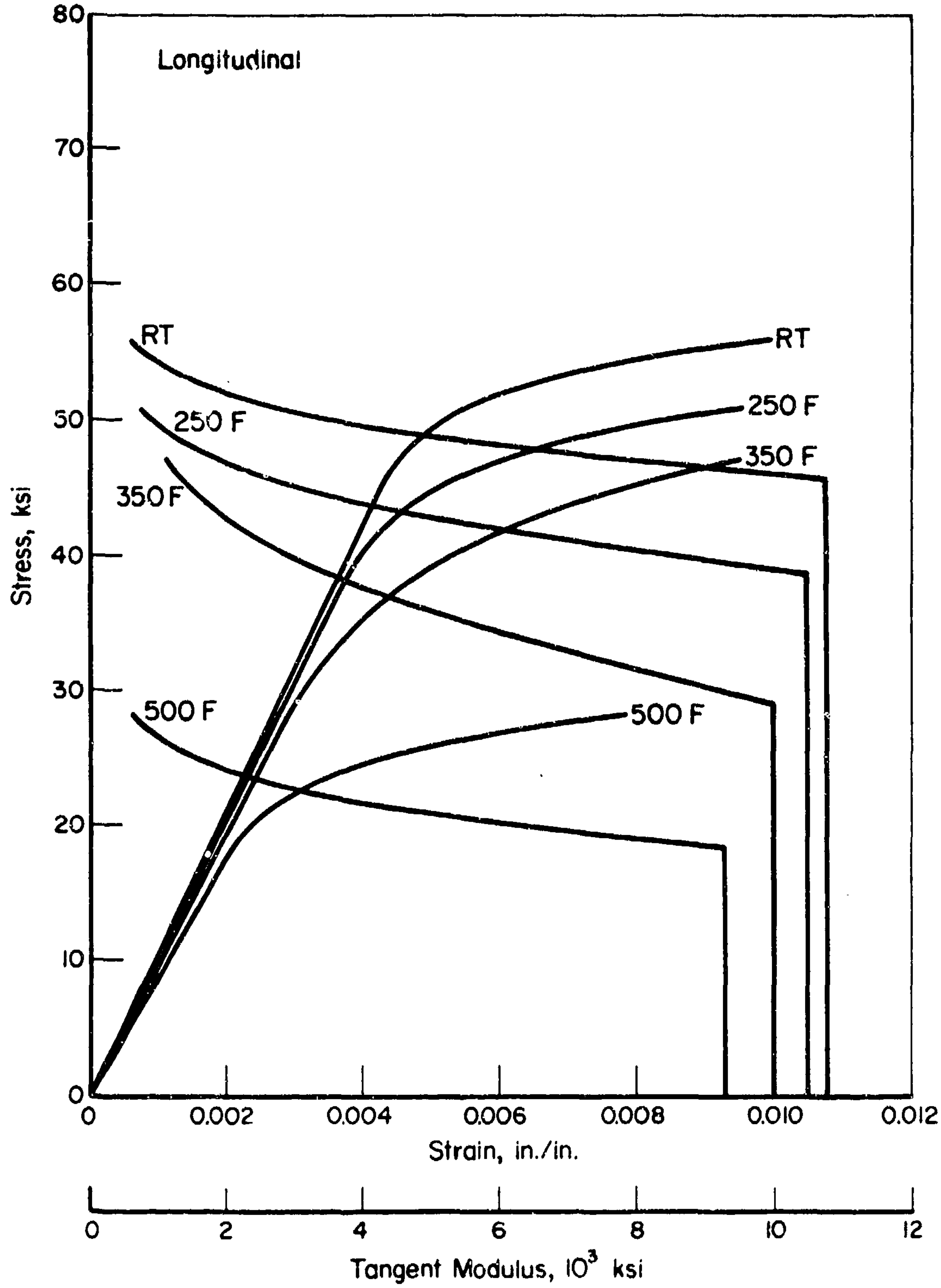


FIGURE 34. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (LONGITUDINAL)

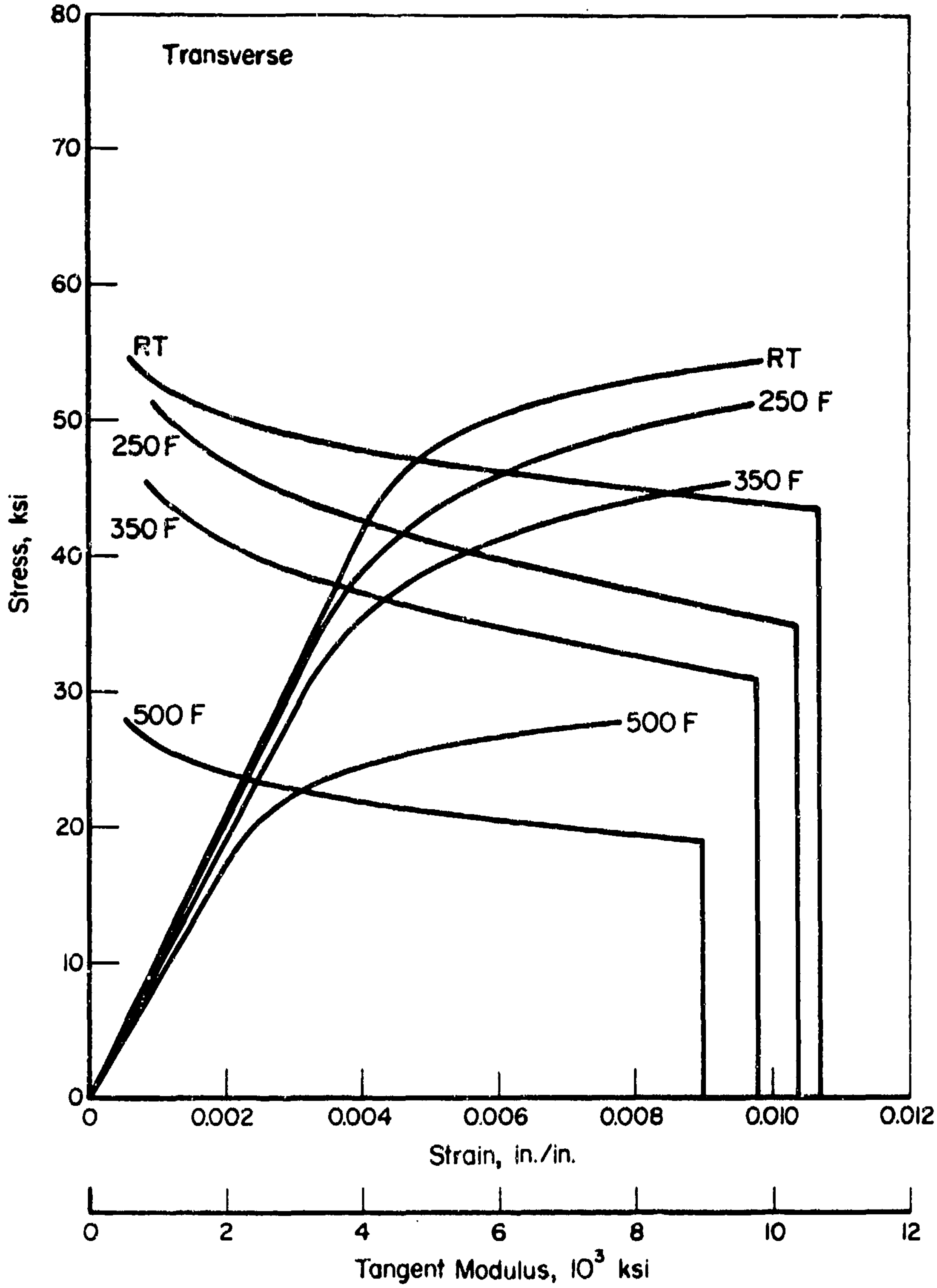


FIGURE 35. TYPICAL COMPRESSIVE STRESS-STATE AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 2419-T851 ALUMINUM ALLOY PLATE (TRANSVERSE)

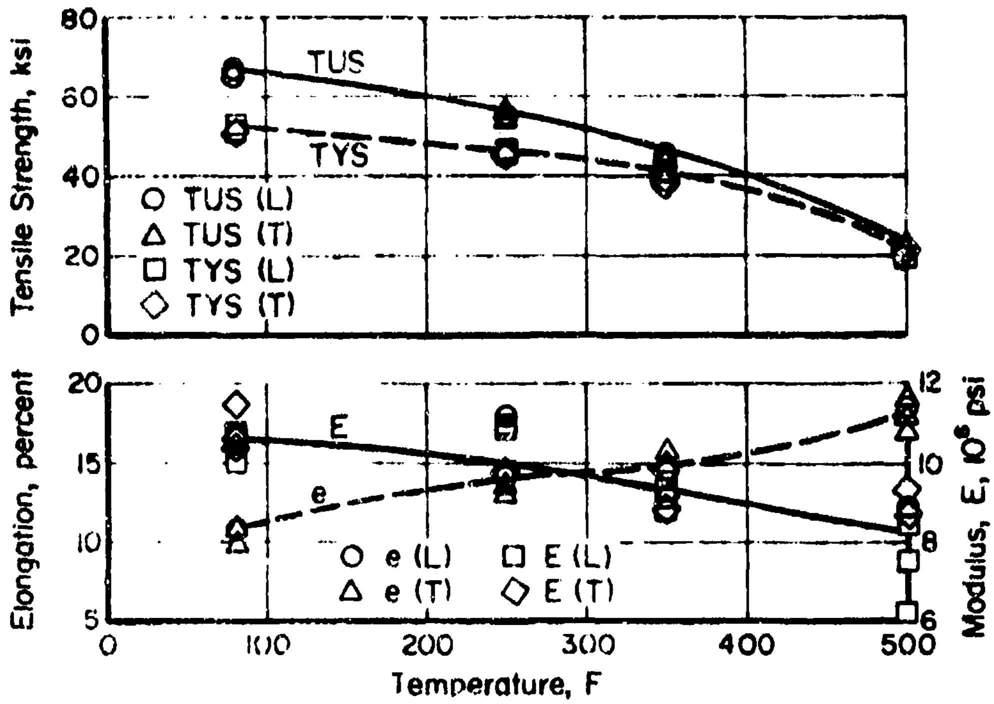


FIGURE 36. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 2419-T851 ALLOY PLATE

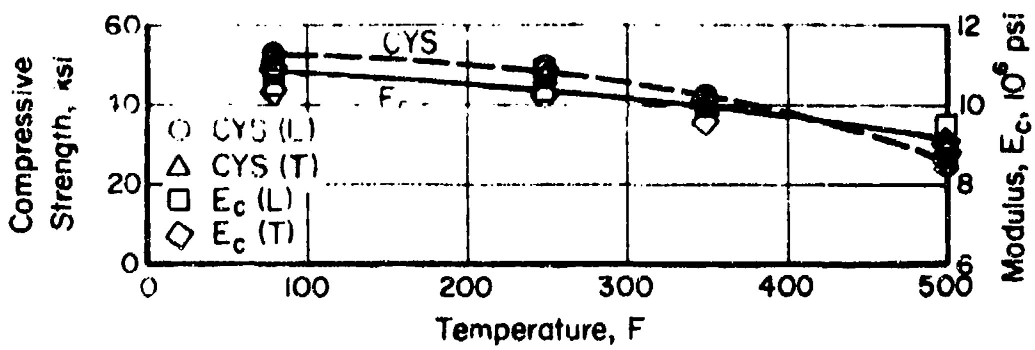


FIGURE 37. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 2419-T851 ALLOY PLATE

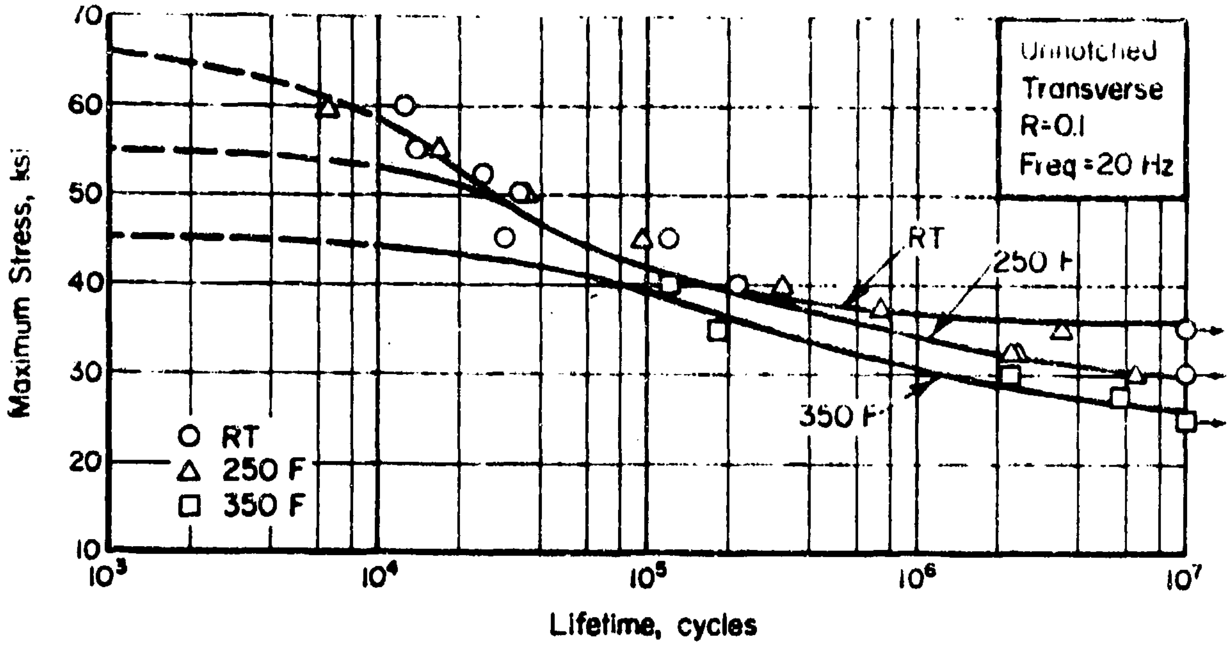


FIGURE 38. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 2419-T851 ALUMINUM ALLOY PLATE

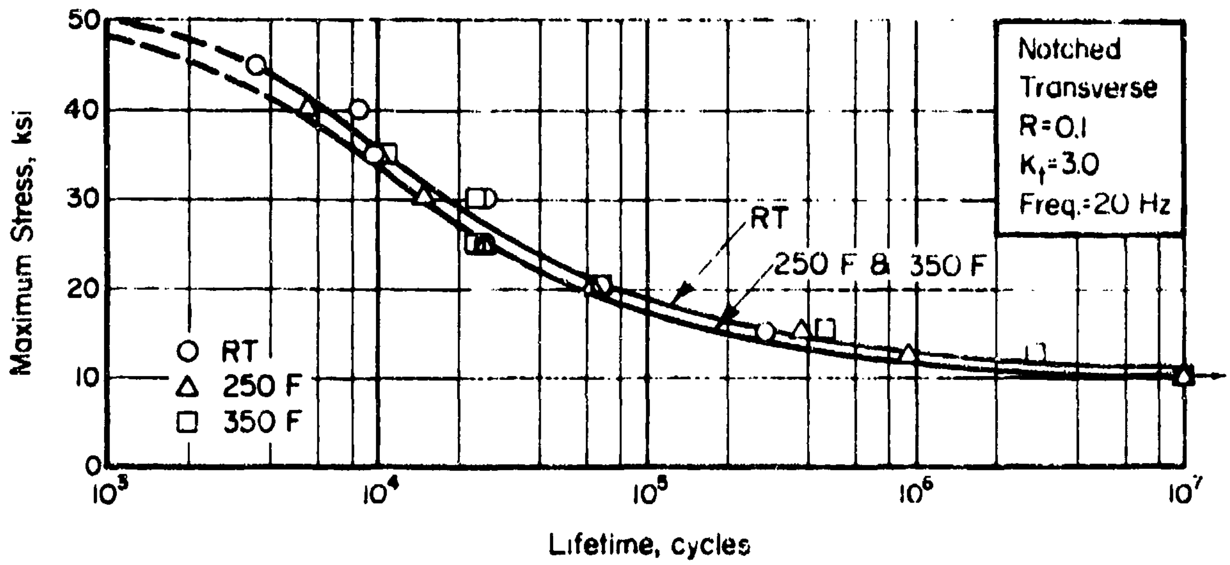


FIGURE 39. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) 2419-T851 ALUMINUM ALLOY PLATE

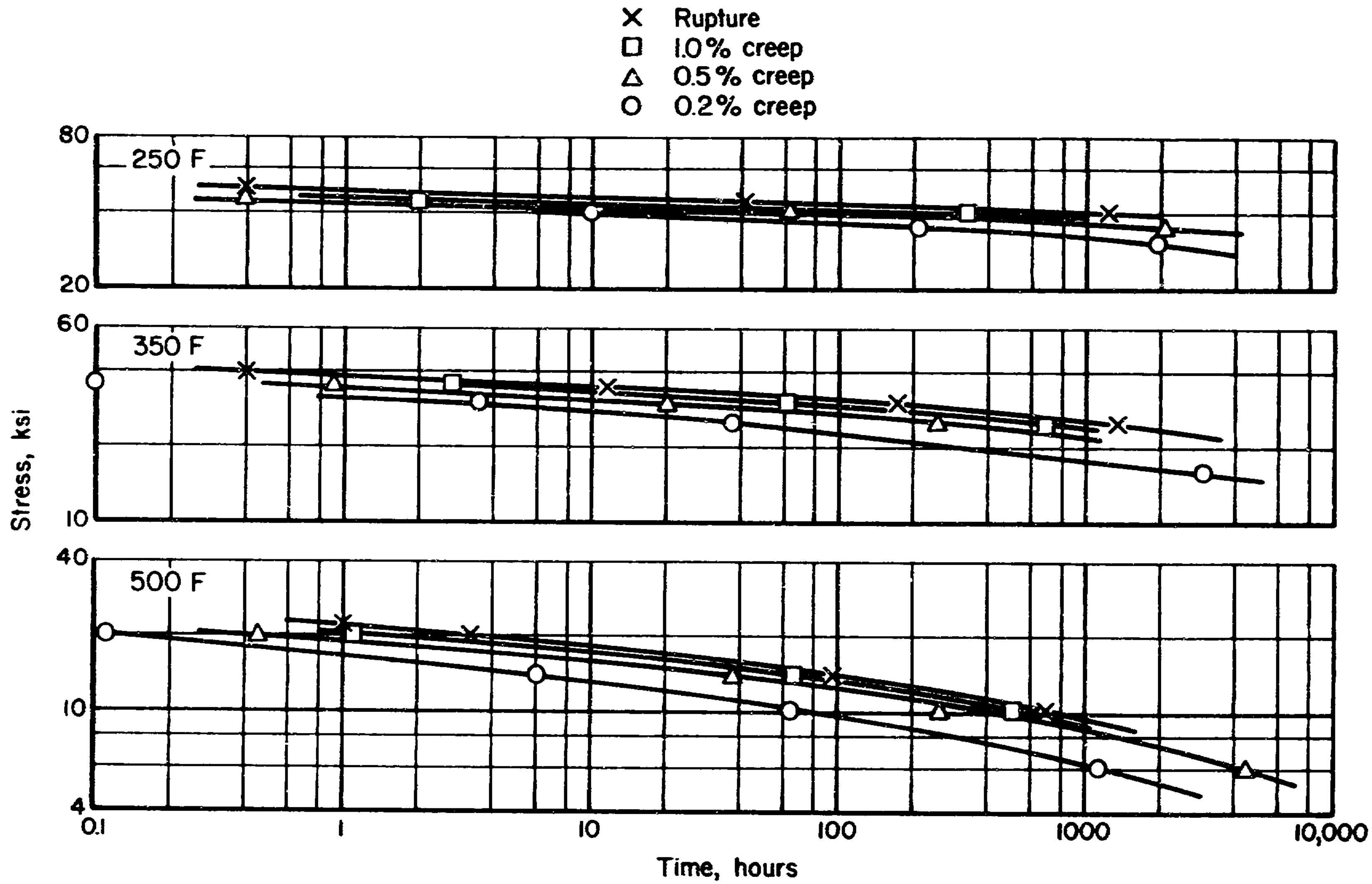


FIGURE 40. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR 2419-T7351 ALUMINUM ALLOY (TRANSVERSE)

Ti-6Al-2Zr-2Sn-2Mo-2Cr Alloy

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
Al	5.8
Sn	2.1
Zr	1.8
Mo	2.0
Cr	1.9
Si	0.21
Fe	0.06
C	0.02
V	0.02
O_2	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

Tension. 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.

Compression. 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.

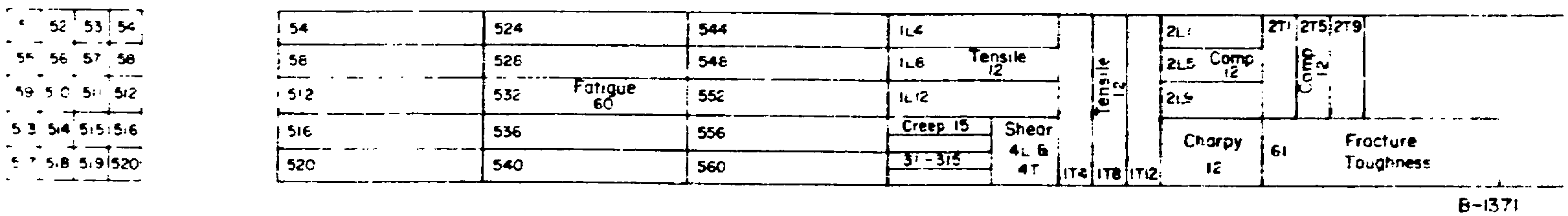


FIGURE 41. SPECIMEN LAYOUT FOR Ti-6Al-2Sn-2Zr-2Mo-2Cr FORGED BILLET

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

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

Fracture Toughness. 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 K_Q values do not meet the rigorous a, T, $< 2.5 (K_Q/TYS)^2$ criteria they are above $2.2 (K_Q/TYS)^2$ and should be considered good indicative K_{Ic} 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.

Creep and Stress Rupture. Tests were conducted on long transverse 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.

Stress Corrosion. 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 5.1×10^{-6} in./in./F for 70 to 800 F.

Density. The density value is 0.162 lb./in.^{3}.

TABLE XXXI. TENSILE TEST RESULTS FOR DUPLEX ANNEALED Ti-6Al-2Sn-2Zr-2Mo-2Cr FORGED BILLET

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^3 ksi
Longitudinal at Room Temperature					
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
Average	158.4	143.9	15.3	36.0	15.6
Long Transverse at Room Temperature					
1T-1	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
Average	166.0	150.4	13.7	36.7	15.8
Longitudinal at 400 F					
1L-4	135.9	111.4	15.0	45.1	13.7
1L-5	131.8	107.9	18.0	51.8	15.9
1L-6	141.2	113.7	16.0	45.2	14.6
Average	136.3	111.0	16.3	47.2	14.7
Long Transverse at 400 F					
1T-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
Average	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
Average	137.3	102.5	15.3	36.0	14.5
Long Transverse at 600 F					
1T-7	131.1	99.3	15.0	43.8	15.2
1T-8	131.9	100.5	17.0	44.8	14.6
1T-9	133.4	100.6	16.0	32.3	14.7
Average	132.1	100.6	16.0	40.3	14.8
Longitudinal at 800 F					
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	144.9	105.7	15.0	39.3	12.3
Average	139.8	102.0	16.5	47.2	13.4
Long Transverse 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
1T-12	131.8	96.2	18.0	45.5	13.5
Average	132.9	98.8	18.3	48.8	13.4

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

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^3 ksi
Longitudinal at Room Temperature		
2L-1	148.6	16.4
2L-2	151.5	16.2
2L-3	148.2	15.6
Average	149.4	16.1
Long Transverse at Room Temperature		
2T-1	155.7	16.5
2T-2	157.7	16.3
2T-3	150.5	15.6
Average	154.6	16.1
Longitudinal at 400 F		
2L-4	119.2	15.0
2L-5	119.0	14.3
2L-6	110.3	14.8
Average	116.2	14.7
Long Transverse at 400 F		
2T-4	129.1	15.2
2T-5	121.3	15.5
2T-6	116.1	15.2
Average	122.2	15.3
Longitudinal at 600 F		
2L-7	108.4	14.4
2L-8	108.2	14.0
2L-9	102.7	14.0
Average	106.4	14.3
Long Transverse at 600 F		
2T-7	111.9	14.8
2T-8	104.6	15.1
2T-9	105.9	14.4
Average	107.5	14.8
Longitudinal at 800 F		
2L-10	94.9	13.2
2L-11	101.0	13.6
2L-12	97.7	12.8
Average	97.9	13.2
Long Transverse at 800 F		
2T-10	100.6	13.6
2T-11	103.1	13.6
2T-12	102.5	12.9
Average	102.1	13.4

TABLE XXXIII. PIN SHEAR TEST RESULTS FOR DUPLEX ANNEALED Ti-6Al-2Sn-2Zr-2Mo-2Cr FORGED BILLET AT ROOM TEMPERATURE

Specimen Number		Ultimate Shear Strength, ksi
	Longitudinal	
4L-1		104.8
4L-2		100.2
4L-3		106.4
4L-4		99.7
	Average	102.8
	Long Transverse	
4T-1		104.1
4T-2		104.1
4T-3		107.4
4T-4		104.8
	Average	105.1

TABLE XXXIV. IMPACT TEST RESULTS FOR DUPLEX ANNEALED Ti-6Al-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
10L-5		14.5
	Average	14.9
	Long Transverse	
10T-1		16.0
10T-2		15.[illegible]
10T-3		8.0
10T-4		17.0
10T-5		16.0
10T-6		17.0
	Average	14.[illegible]

TABLE XXXV. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS FOR DUPLEX-ANNEALED Ti-6Al-2Sn-2Zr-2Mo-2Cr FORGED BILLET

Specimen Number	W, inches	a, inches	T, inches	P, lbs.	Span, inches	$f(\frac{a}{W})$	K_Q [(a)]
			Longitudinal (L-T)				
6L-1	1.500	0.746	0.750	7,600	6.0	2.64	87.4
6L-2	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
6L-4	1.500	0.763	0.750	7,350	6.0	2.74	87.7
			Long Transverse (T-L)				
6T-1	1.500	0.770	0.750	7,650	6.0	2.78	92.7
6T-2	1.500	0.777	0.750	7,550	6.0	2.82	92.9
6T-3	1.500	0.770	0.750	8,025	6.0	2.78	97.2

(a) Candidate K_Q values are invalid as K_{Ic} values since they do not meet the rigorous standard of a, T, $\geq 2.5 \left(\frac{K_Q}{TYS}\right)^2$. However, they do exceed a 2.2 $\left(\frac{K_Q}{tys}\right)^2$ and as such should be considered marginally valid.

TABLE XXXVI. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED DUPLEX-ANNEALED Ti-6Al-2Sn-2Zr-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE, R = 0.1)

Specimen 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	105	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[a]
	400 F	
5-10	145	6,400
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)
5-23	125	15,400
5-18	115	14,700
5-19	105	218,300
5-20	95	836,600
5-21	85	1,91[illegible],100
5-22	75	9,[illegible]80,300
5-25	70	13,808,600[a]

(a) Did not fail.

(b) Failed on loading.

TABLE XXXVII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) DUPLEX-ANNEALED Ti-6Al-2Sn-2Zr-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE, R = 0.1)

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
5-38	45	153,200
5-36	40	5,069,900
5-39	35	11,645,200[a]
	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[a]
	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[a]

(a) Did not fail.

TABLE XXXVIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent: 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hour	Elongation in 2 Inches, percent	Reduction of Area, percent	Minimum Creep Rate, percent
3-1	135.2	400	--	--	--	--	--	3.401	On Loading	13.6	54.9	--
3-4a	132	400	--	--	--	--	--	2.837	1009.0(b)	3.595	--	0.00010
3-4	128	400	--	0.07	150	>1000	--	0.773	502.6(b)	3.365	--	--
3-11	100	400	160	1500(a)	--	--	--		1007.4(b)	0.950	--	0.000050
3-2	148	600	--	-	--	--	--	--	On Loading	9.1	52.2	--
3-5	131.6	600	--	--	--	--	--	--	On Loading	15.2	57.1	--
3-100	128	600	--	--	--	--	--	2.564	1002.7(b)	2.99	--	0.00050
3-7	115	600	0.9	6.0	47[illegible]	800	--	1.984	789.7(b)	2.988	--	0.00024
3-10	100	600	13	65	800(a)	--	--	0.951	269.0(b)	1.307	--	--
3-12	80	600	30	575	3000(a)	--	--	0.340	934.0(b)	0.570	--	0.00008
3-3	131	800	--	--	--	--	--	--	On Loading	12.1	54.5	--
3-6	120	800	--	0.10	0.25	1.3	10	3.073	330.9	9.1	16.9	0.0079
3-8	85	800	2.0	12	180	1200(a)	--	0.701	238.4(b)	2.232	--	0.00067
3-9	50	800	35	600	4700(a)	--	--	0.280	840.2(b)	0.504	--	0.000073

(a) Estimate.

(b) Test discontinued.

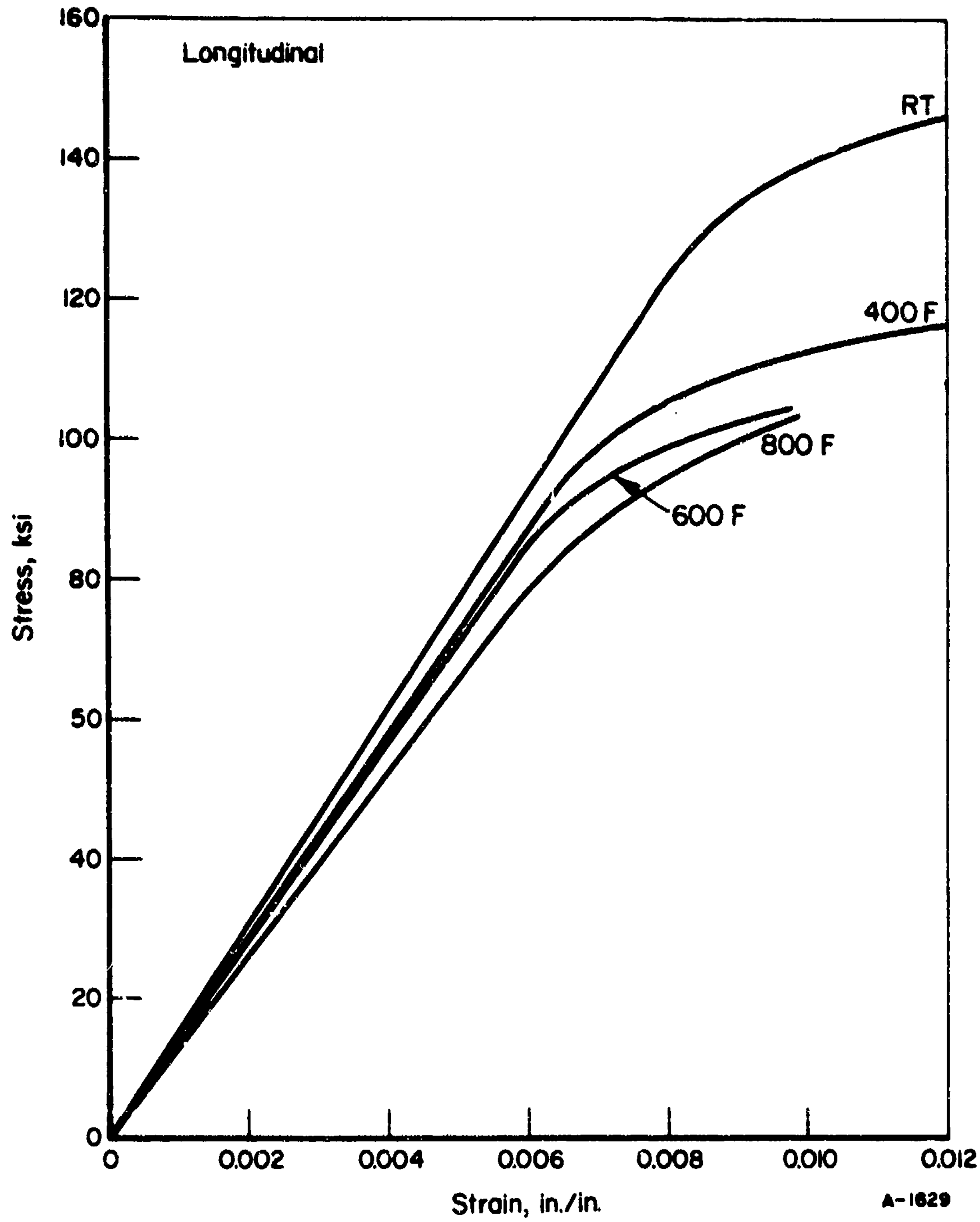


FIGURE 42. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET (LONGITUDINAL)

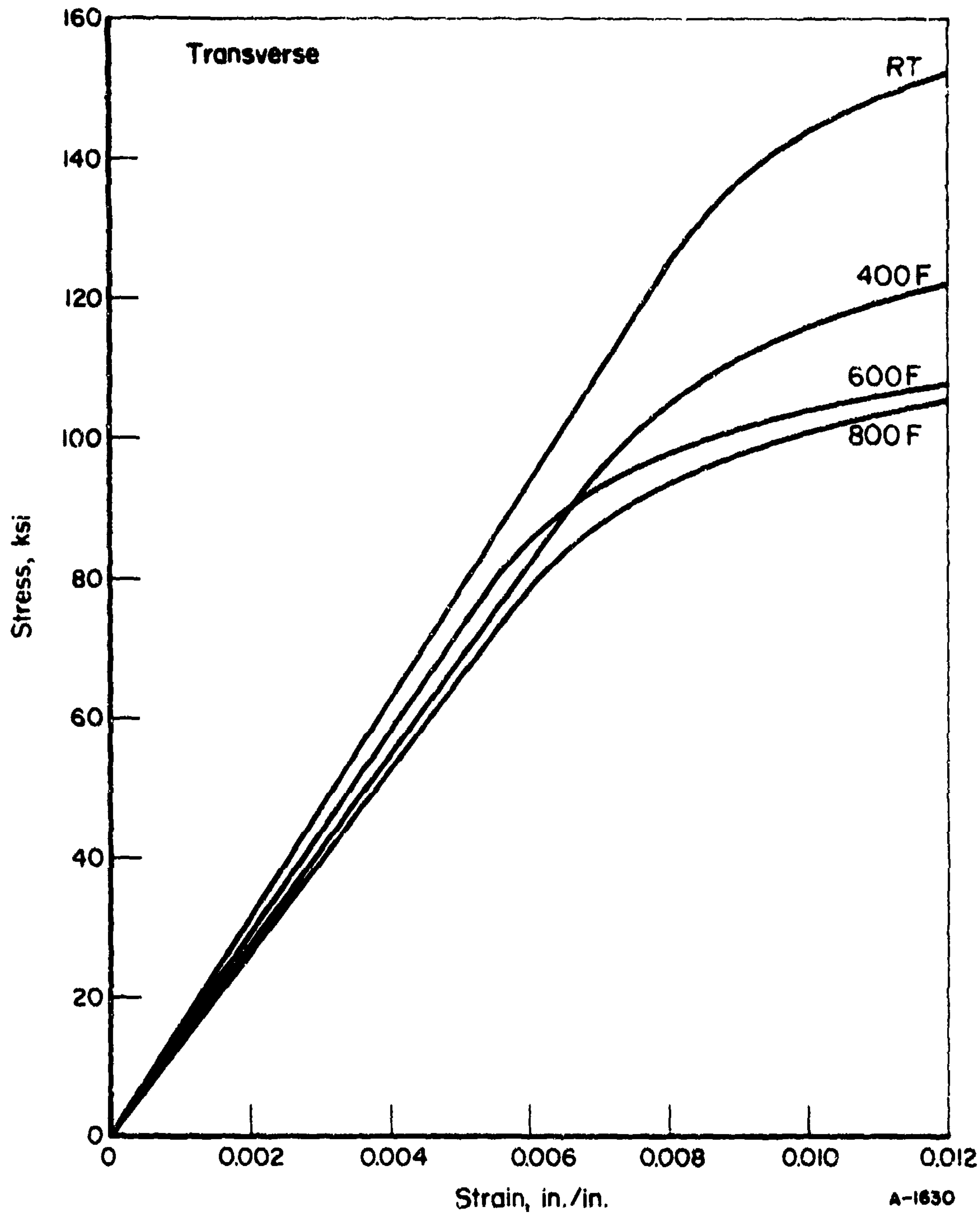


FIGURE 43. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE)

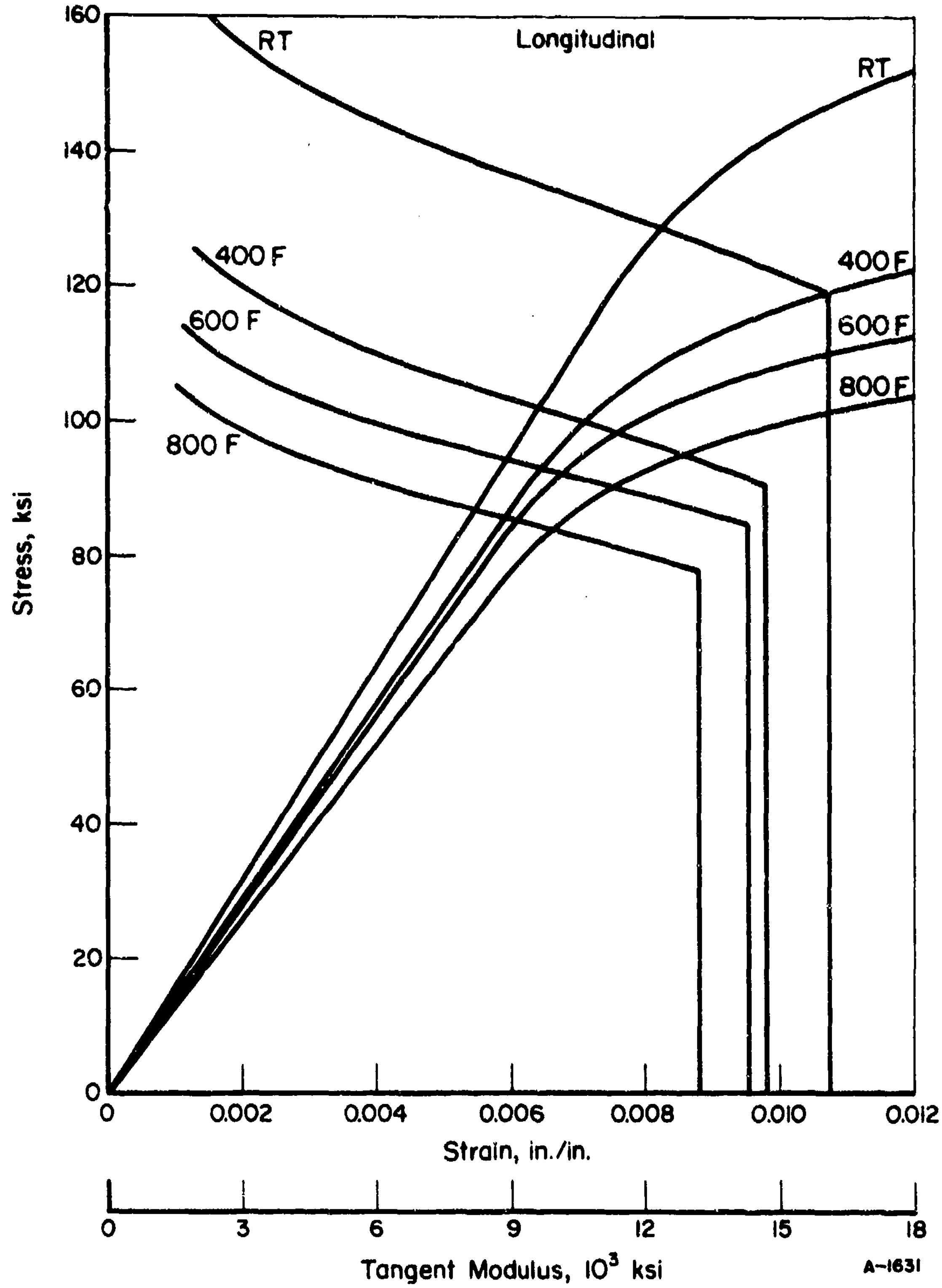


FIGURE 44. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET (LONGITUDINAL)

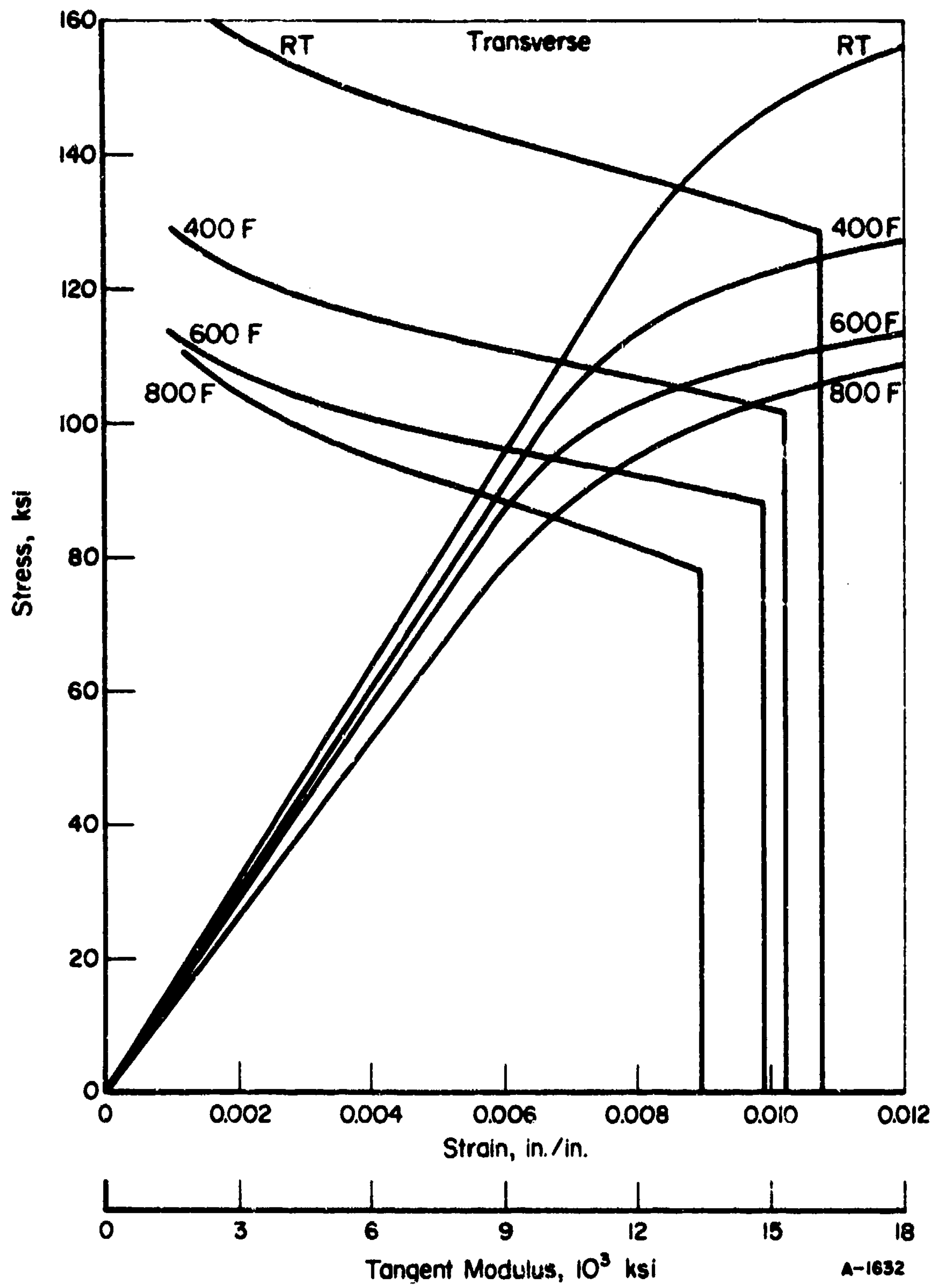


FIGURE 45. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR DUPLEX-ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE)

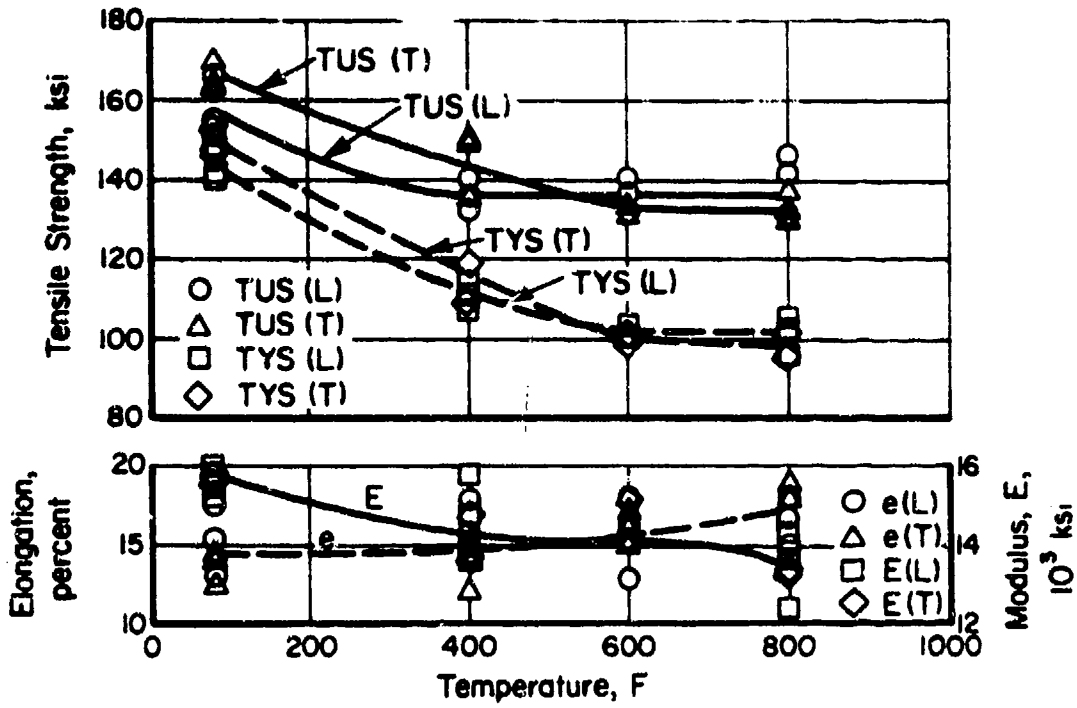


FIGURE 46. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

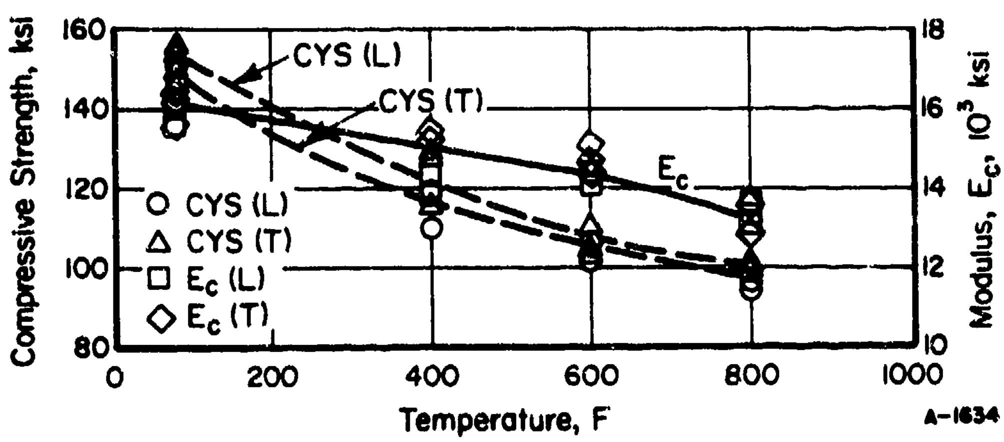


FIGURE 47. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

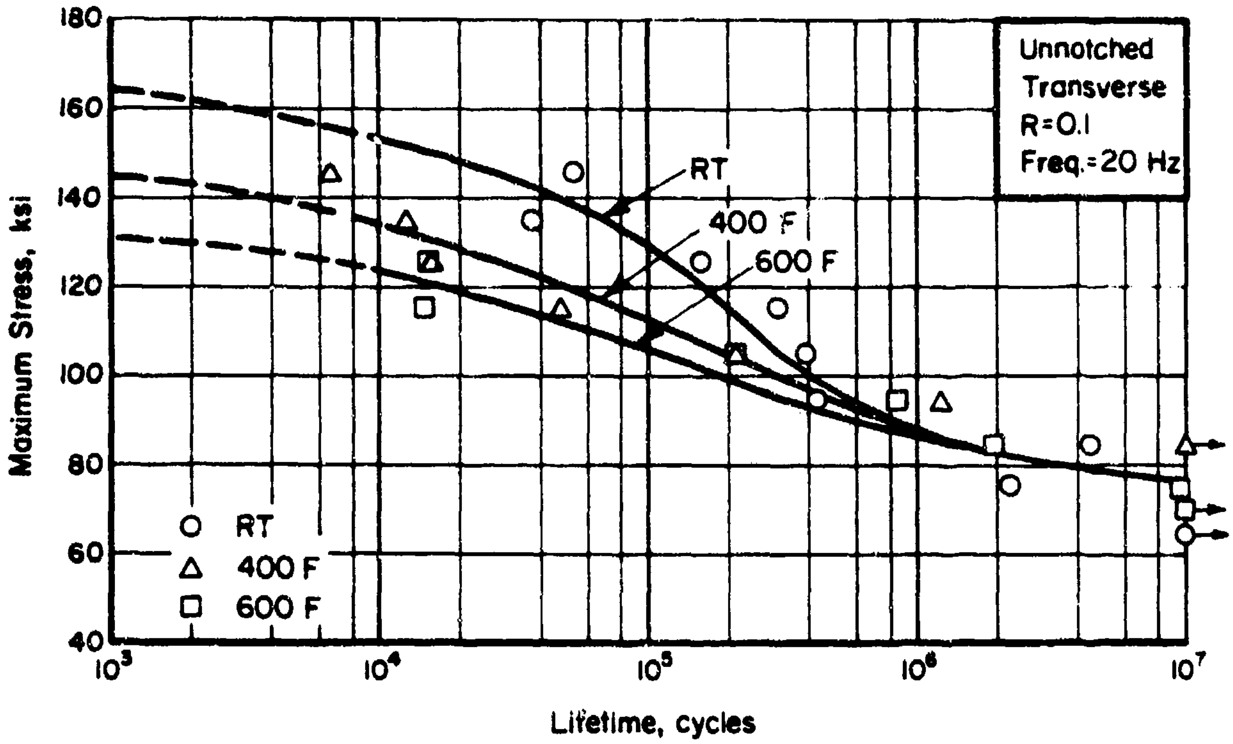


FIGURE 48. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

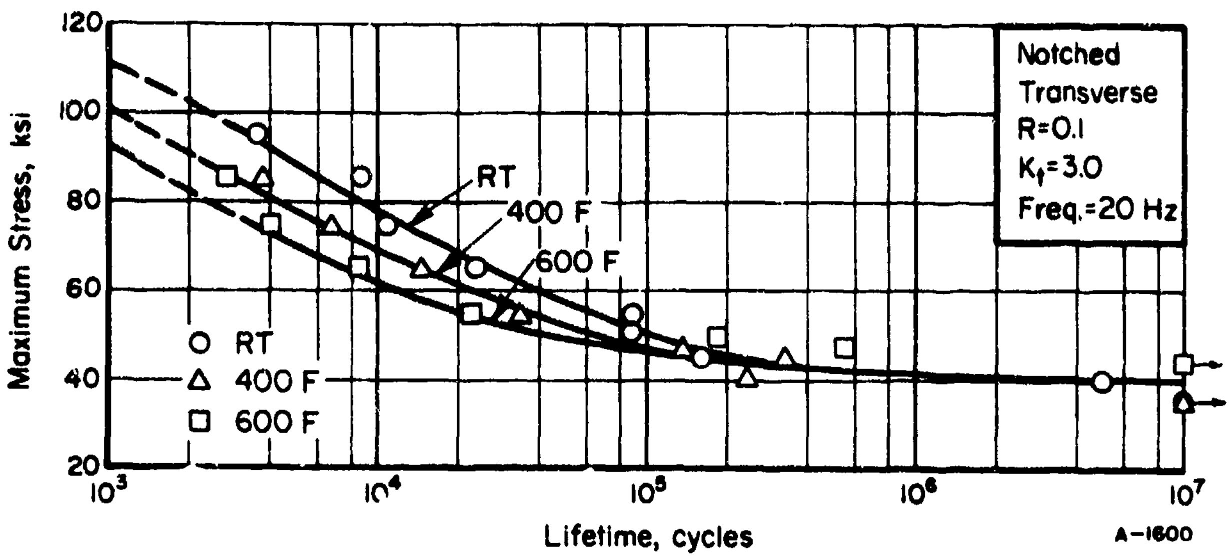


FIGURE 49. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

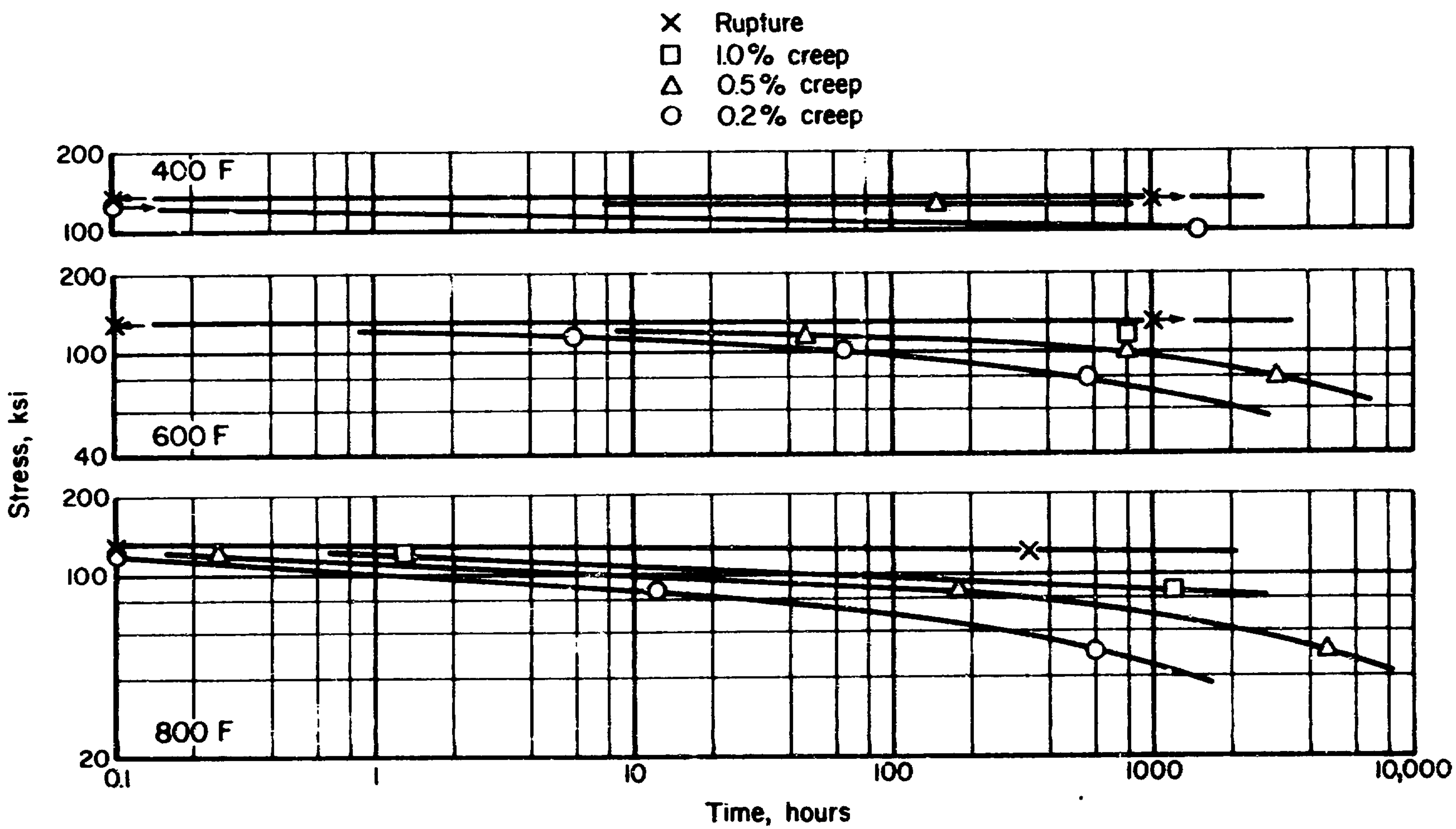


FIGURE 50. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR DUPLEX-ANNEALED Ti-6Al-2Cr-2Sn-2Mo-2Cr FORGED BILLET (LONG TRANSVERSE)

Ti-6Al-2Cb-1Ta-1Mo Alloy Plate

Material Description

6Al-2Cb-1Ta-1Mo titanium alloy is a modification by RMI Company of the Ti-7Al-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-6Al-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 1½-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

Tension. Results of tests in the longitudinal 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.

Compression. 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.

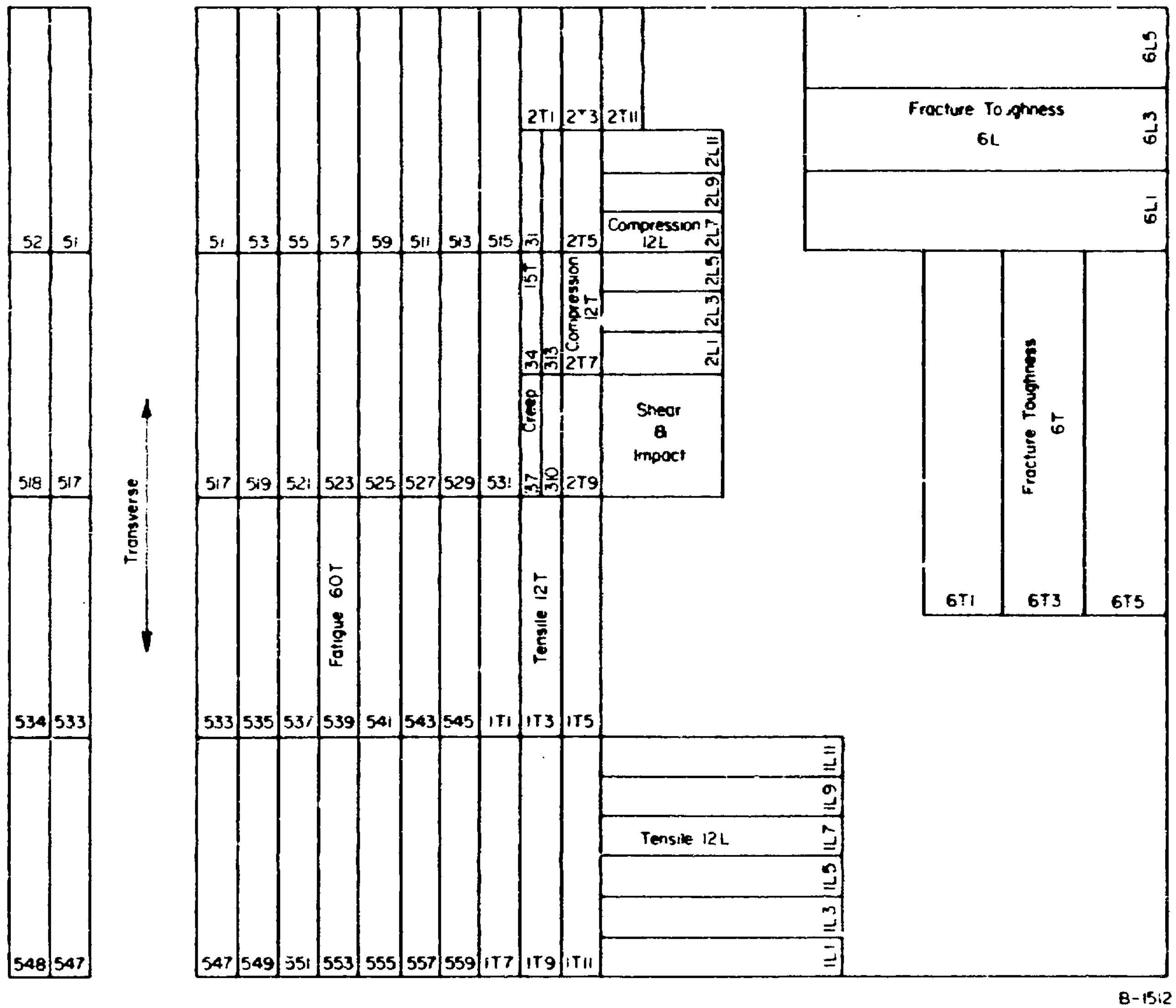


FIGURE 51. SPECIMEN LAYOUT FOR Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

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.

Fracture Toughness. 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_Q values shown in the table are not valid K_{Ic} values since they did not meet the standard of $P_{max}/P_Q = 1.10$. Therefore, as recommended in ASTM E399, R_{sb} values have been calculated and are shown in the table.

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

Creep and Stress-Rupture. 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.

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

Thermal Expansion. The coefficient of thermal expansion for this alloy is 5.2×10^{-6} in./in./F for room temperature to 800 F.

Density. The density of this material is 0.162 lb./in.^{3}.

TABLE XXXIX. TENSILE TEST RESULTS FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in Two Inches, Percent	Reduction in Area, Percent	Tensile Modulus, 10^3 ksi
		Longitudinal at Room Temperature			
1L-1	116.5	103.1	19.0	33.7	16.9
1L-2	117.7	101.1	18.0	35.3	17.1
1L-3	118.5	102.0	18.0	32.4	16.9
Average	117.6	102.1	18.3	33.8	17.0
		Transverse at Room Temperature			
1T-1	119.6	103.5	18.0	32.9	17.3
1T-2	119.7	104.5	17.0	32.4	17.0
1T-3	118.6	103.2	17.0	33.4	16.8
Average	119.3	103.7	17.3	32.9	17.0
		Longitudinal at 400 F			
1L-4	88.1	64.1	18.0	43.4	16.0
1L-5	87.5	63.8	19.0	40.8	16.0
1L-6	87.9	65.7	18.0	43.7	16.1
Average	87.8	64.5	18.3	42.6	16.0
		Transverse at 400 F			
1T-4	89.3	66.6	17.0	42.1	17.3
1T-5	89.6	66.0	17.0	42.0	17.5
1T-6	88.1	64.9	18.0	43.7	17.3
Average	89.0	65.8	17.3	42.6	17.4
		Longitudinal at 600 F			
1L-7	79.7	58.7	20.0	52.3	14.6
1L-8	80.2	57.2	19.0	52.6	13.6
1L-9	80.7	58.1	20.0	50.3	13.9
Average	80.2	58.0	19.6	51.7	14.0
		Transverse at 600 F			
1T-7	79.9	55.0	18.0	47.5	14.5
1T-8	81.0	56.2	18.0	47.1	14.5
1T-9	80.5	57.1	18.0	47.1	15.3
Average	80.5	56.1	18.0	47.2	14.8
		Longitudinal at 800 F			
1L-10	74.4	52.8	20.0	48.8	12.6
1L-11	73.6	53.8	20.0	51.2	12.6
1L-12	74.0	50.7	19.0	50.9	13.1
Average	74.0	52.4	19.7	50.3	12.8
		Transverse at 800 F			
1T-10	74.9	55.8	17.0	49.7	14.0
1T-11	75.8	55.3	18.0	48.4	15.8
1T-12	74.9	55.0	17.0	48.8	13.5
Average	75.2	55.4	17.3	49.0	14.4

TABLE XL. COMPRESSION TEST RESULTS FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^3 ksi
Longitudinal at Room Temperature		
2L-1	107.8	18.0
2L-2	108.1	17.6
2L-3	108.9	17.1
Average	108.3	17.6
Transverse at Room Temperature		
2T-1	112.4	17.3
2T-2	112.0	17.1
2T-3	111.4	18.0
Average	111.9	17.5
Longitudinal at 400 F		
2L-4	72.7	16.6
2L-5	74.9	15.8
2L-6	75.0	15.3
Average	74.2	15.9
Transverse at 400 F		
2T-4	76.8	16.1
2T-5	77.6	15.7
2T-6	77.9	15.1
Average	77.4	15.6
Longitudinal at 600 F		
2L-7	60.8	15.3
2L-8	61.1	14.8
2L-9	60.5	14.8
Average	60.8	15.0
Transverse at 600 F		
2T-7	63.2	15.0
2T-8	63.7	15.3
2T-9	62.7	14.5
Average	63.2	14.9
Longitudinal at 800 F		
2L-10	55.2	13.6
2L-11	54.6	13.6
2L-12	55.9	13.8
Average	55.2	13.7
Transverse at 800 F		
2T-10	58.5	14.0
2T-11	58.0	14.1
2T-12	58.3	13.6
Average	58.3	13.9

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

Specimen Number	Ultimate Shear Strength, ksi
Longitudinal	
4L-1	83.4
4L-2	85.0
4L-3	82.5
4L-4	83.9
Average	83.7
Transverse	
4T-1	84.2
4T-2	82.5
4T-3	84.4
4T-4	84.0
Average	83.8

TABLE XLII. IMPACT TEST RESULTS FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number	Energy, ft-lbs
Longitudinal	
10L-1	40
10L-2	38
10L-3	37
10L-4	40
10L-5	37
10L-6	39
Average	38.5
Transverse	
10T-1	33
10T-2	33
10T-3	33
10T-4	35
10T-5	33
10T-6	36
Average	33.8

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

Specimen Number	W, inches	T, inches	a, inches	Span, inches	P_Q, lbs	P_{max}, lbs	$f\left(\frac{a}{w}\right)$	K_Q (a)	R_{sb} (b)
				Longitudinal (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
				Transverse (T-L)					
6T-1	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

(a) Candidate K_Q values are invalid as K_{Ic} values since they do not meet the standard of a, t, $\geq 2.5\ (K_Q/TYS)^2$ 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 useful comparative measure of toughness of materials where size may be less than sufficient for valid K_{Ic} determination.

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

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[a]
	400 F	
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[a]
	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

(a) Did not fail.

TABLE XLV. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE (Transverse, R = 0.1)

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[a]
	400 F	
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[a]
	600 F	
5-46	75	3,000
5-47	65	5,100
5-48	55	12,500
5-49	45	41,700
5-50	35	463,400
5-51	25	11,537,700[a]

(a) Did not fail.

TABLE XLVI . SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hours	Elongation in 2 In., percent	Reduction of Area, percent	Minimum Creep Rate, percent
3-3	95	400	--	--	--	--	--	--	On Loading	15.2	47.6	--
3-4	90	400	--	--	--	--	0.10	4.395	0.8 (b)	14.4	43.5	5.5
3-3-7	85	400	--	--	--	0.10	45	2.361	782.3 (b)	4.380	--	0.00004
3-8	75	400	0.02	0.07	10	--	--	1.118	25.4 (b)	1.648	--	--
3-11	70	400	0.06	0.5	--	--	--	0.519	186.3 (b)	0.796	--	--
3-12	65	400	0.60	>5000	--	--	--	0.530	573.3 (b)	0.663	--	nil
3-1	82.7	600	--	--	--	--	--	--	On Loading	16.7	55.5	--
3-13	79	600	--	0.05	1300	10,000 (a)	--	5.042	1002.4 (b)	5.521	--	0.00005
3-6	75	600	0.05	1.1	5000 (a)	--	--	2.160	961.0 (b)	2.417	--	0.000006
3-9	70	600	1675 (a)	8300 (a)	--	--	--	1.470	1009.7 (b)	1.562	--	0.000015
3-2	75.5	800	--	--	--	--	--	--	On Loading	16.7	57.0	--
3-14	72	800	0.2	1	11	58	210	3.470	834.1 (b)	14.4	31.0	0.0060
3-5	65	800	7	45	425	1400	3400 (a)	1.341	983.9 (b)	2.141	--	0.00050
3-10	55	800	90	550	4600 (a)	--	--	0.595	914.1 (b)	0.822	--	0.000072

(a) Estimate.

(b) Test discontinued.

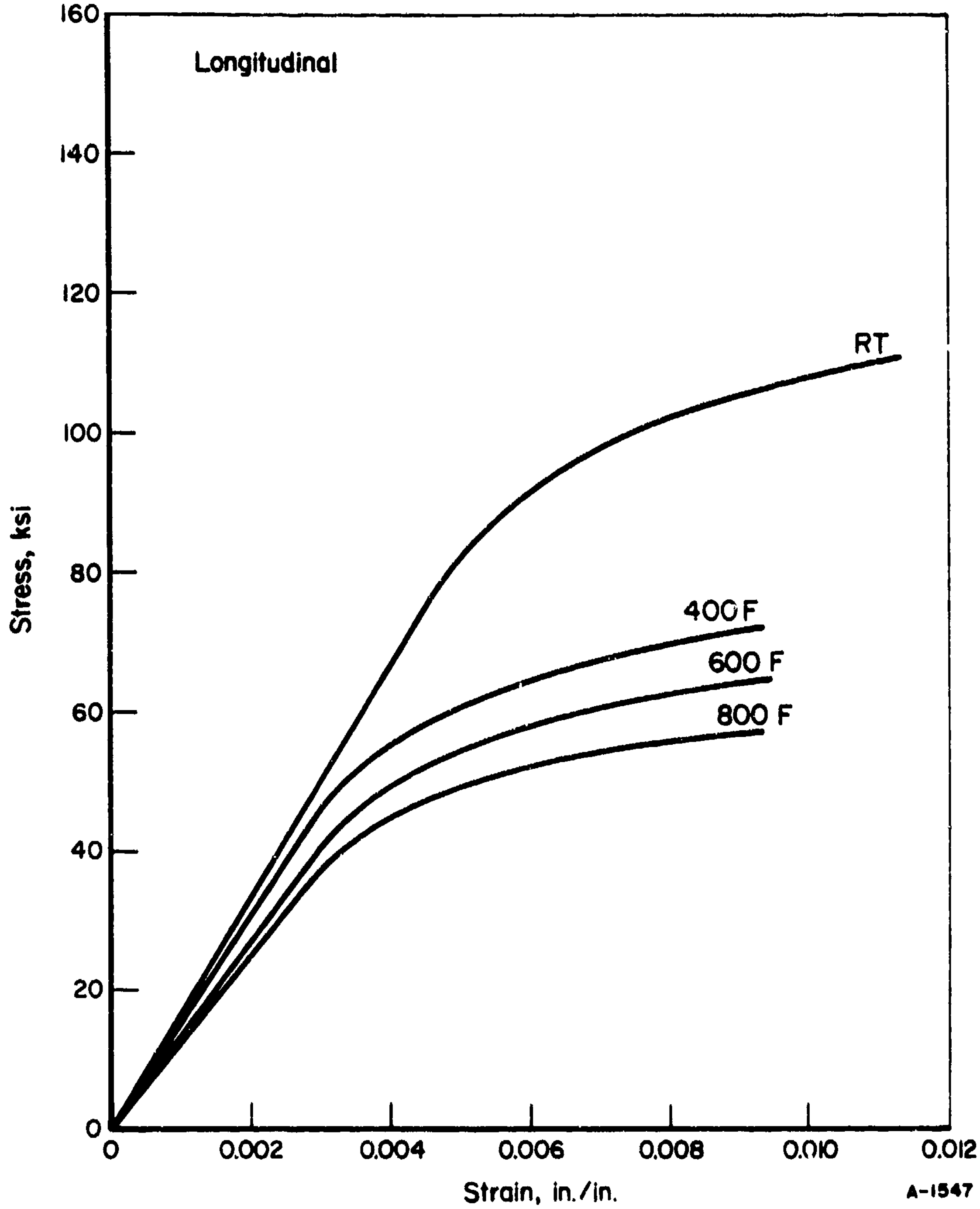


FIGURE 52. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE (Longitudinal)

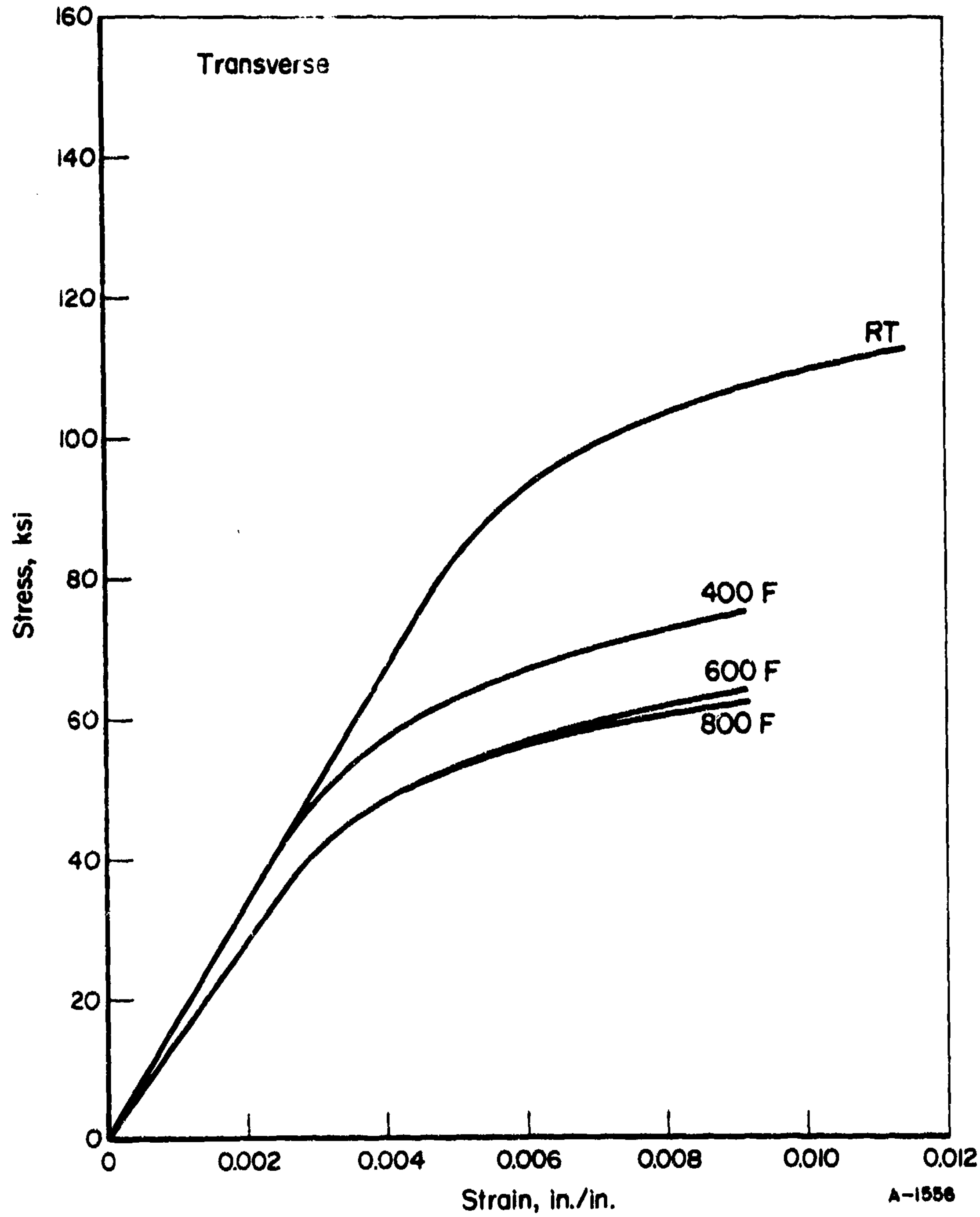


FIGURE 53. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE (Transverse)

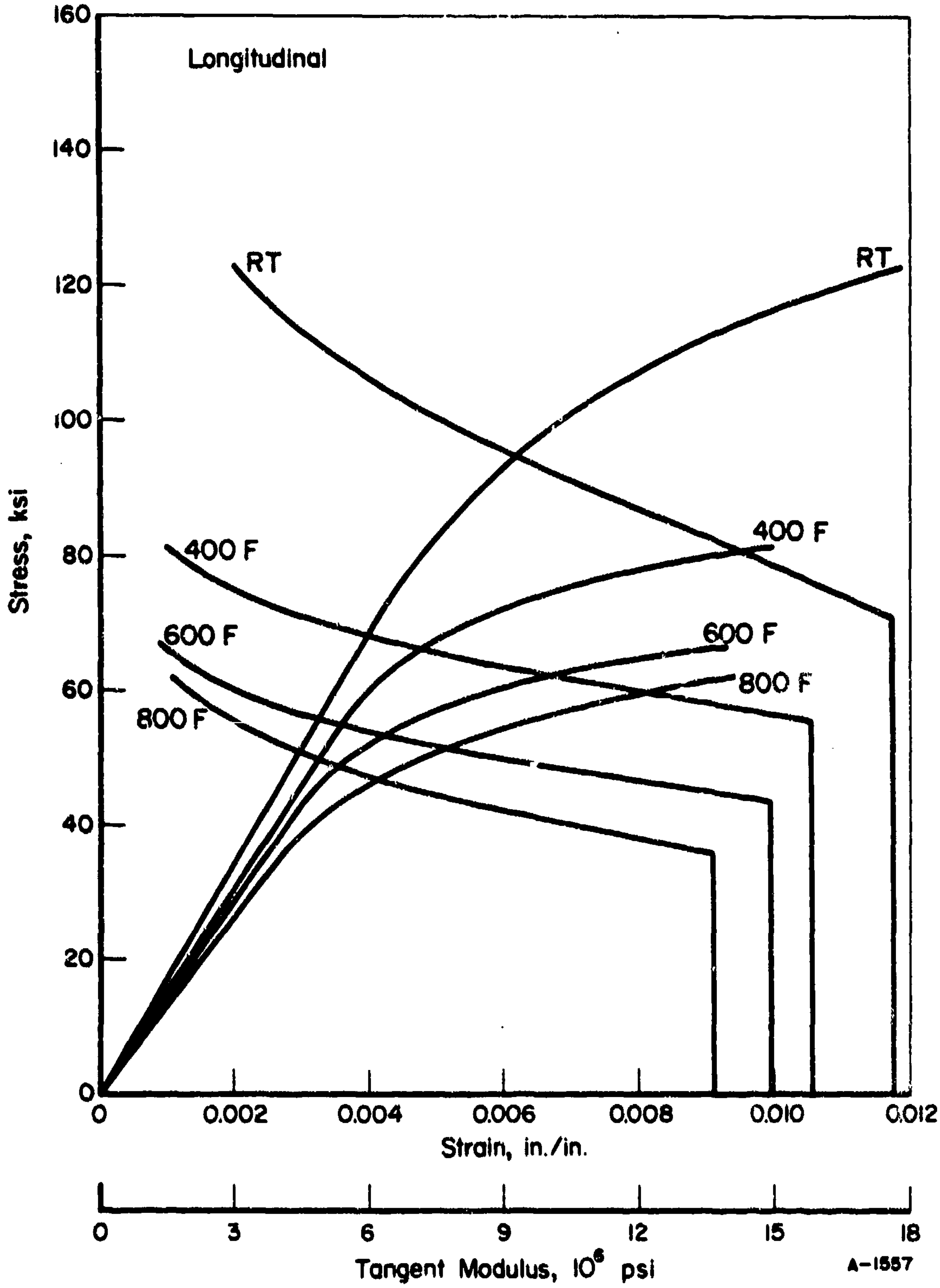


FIGURE 54. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MOUDLUS CURVES AT TEMPERATURE FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE (Longitudinal)

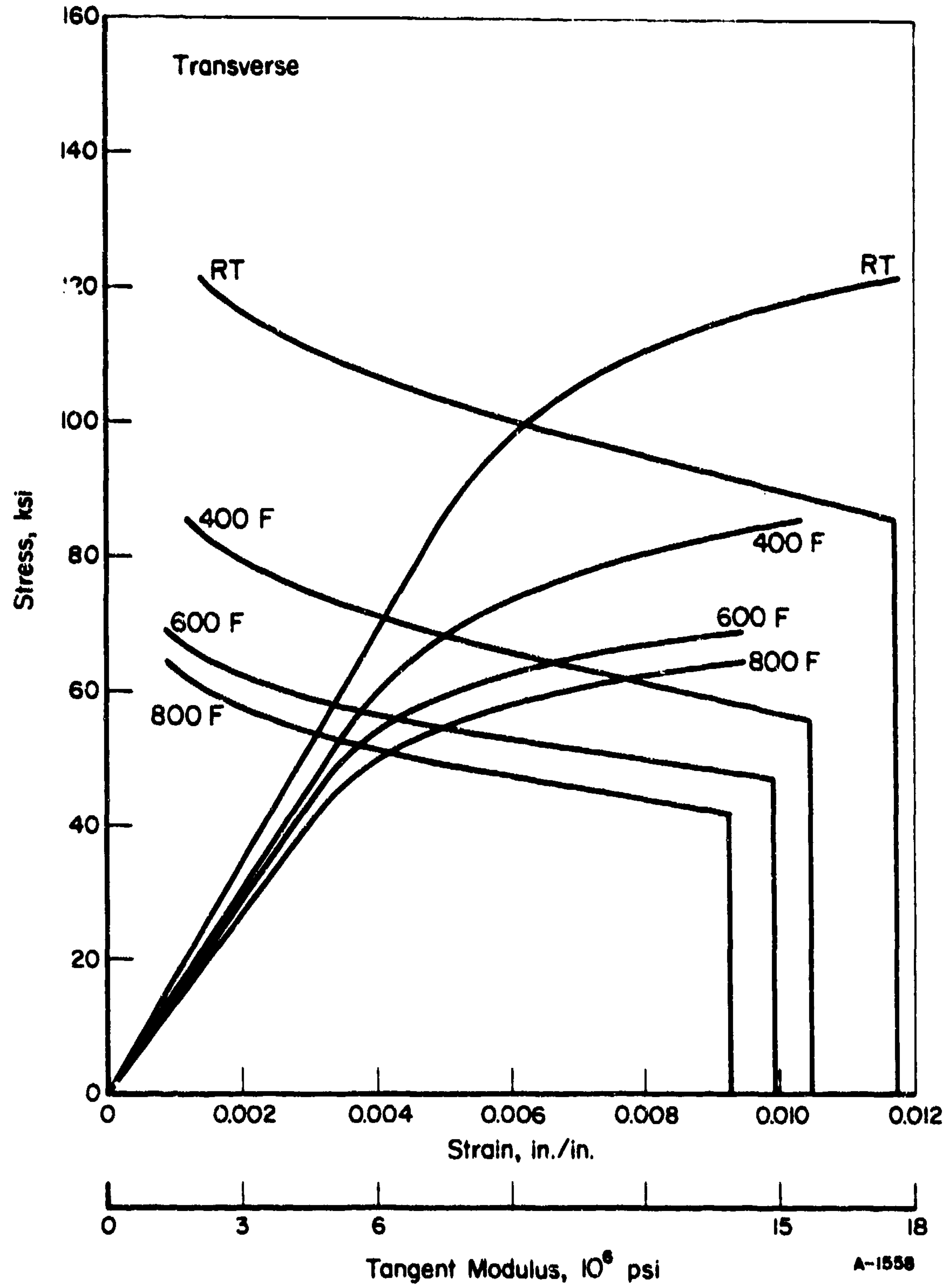


FIGURE 55. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE (TRANSVERSE)

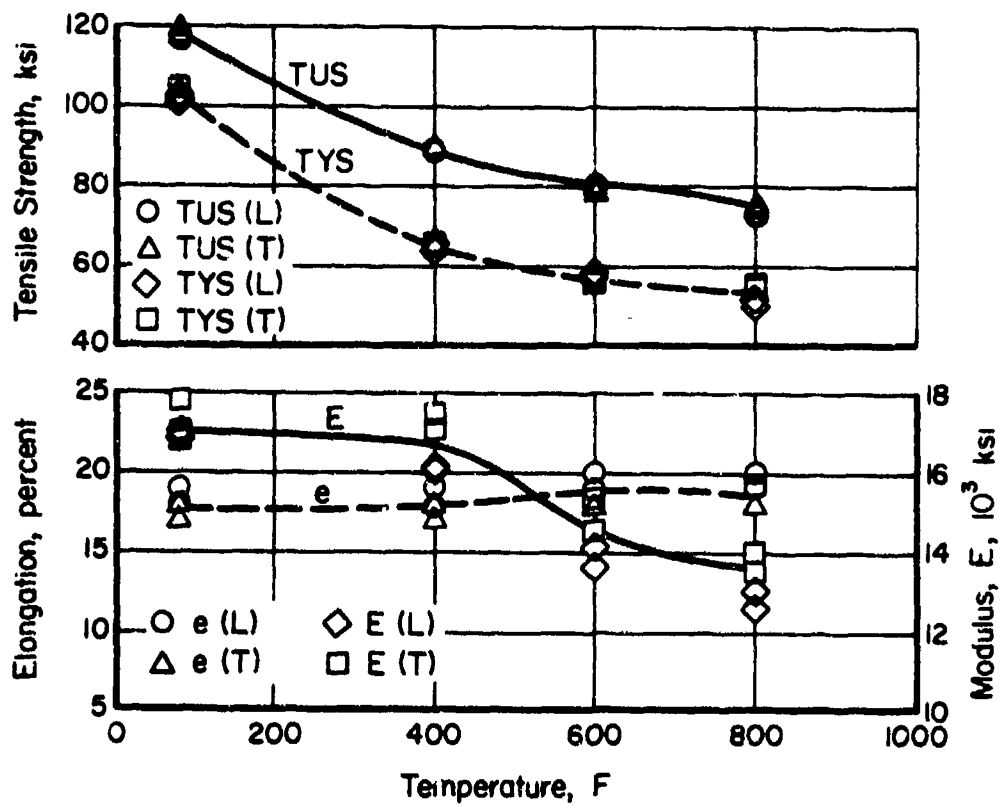


FIGURE 56. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

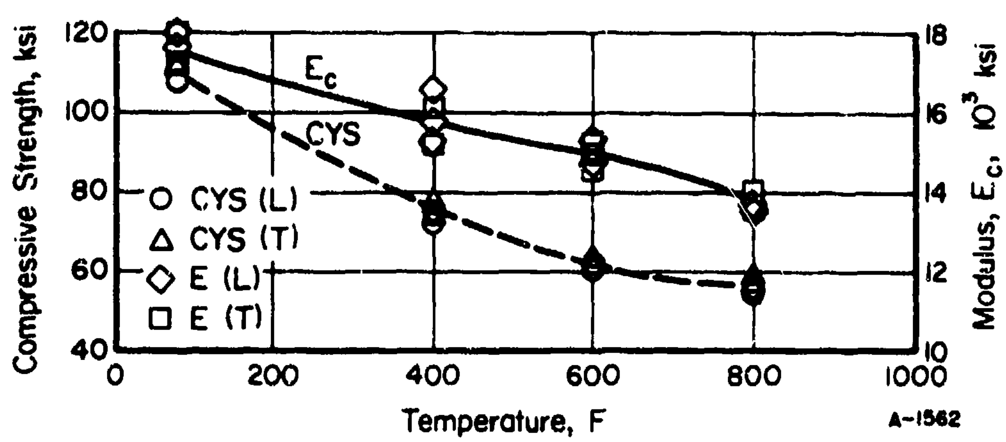


FIGURE 57. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

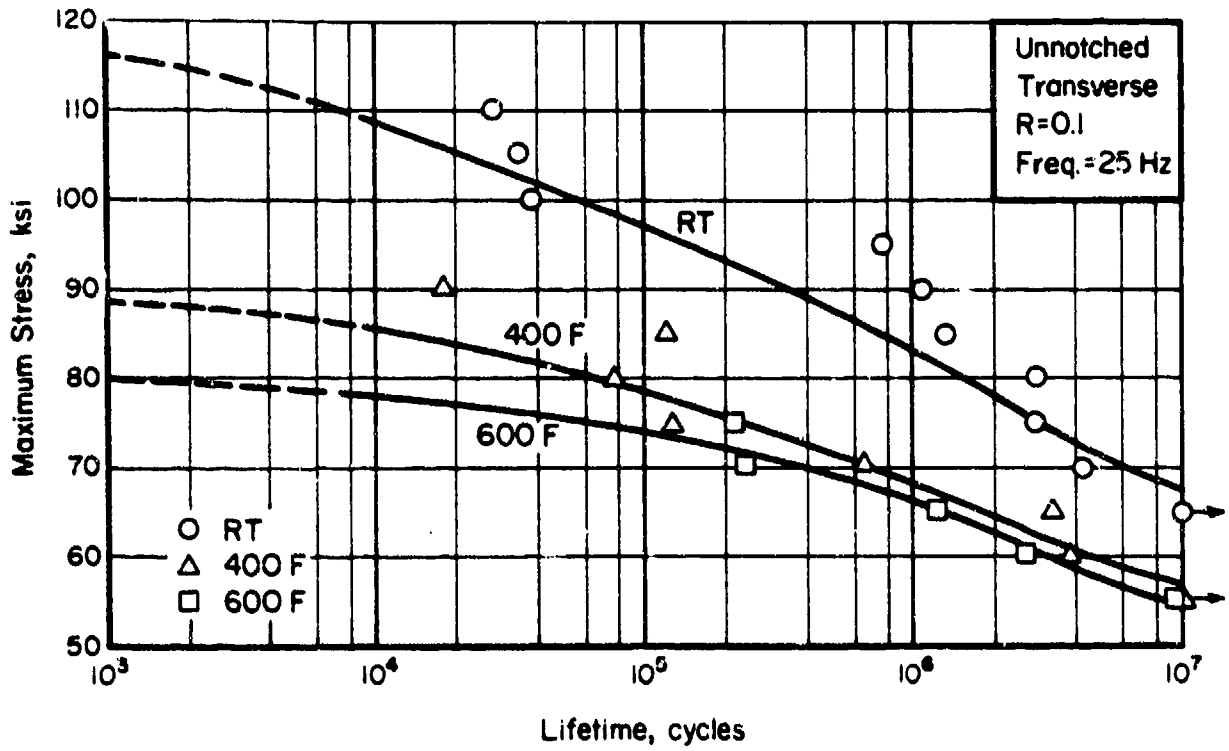


FIGURE 58. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

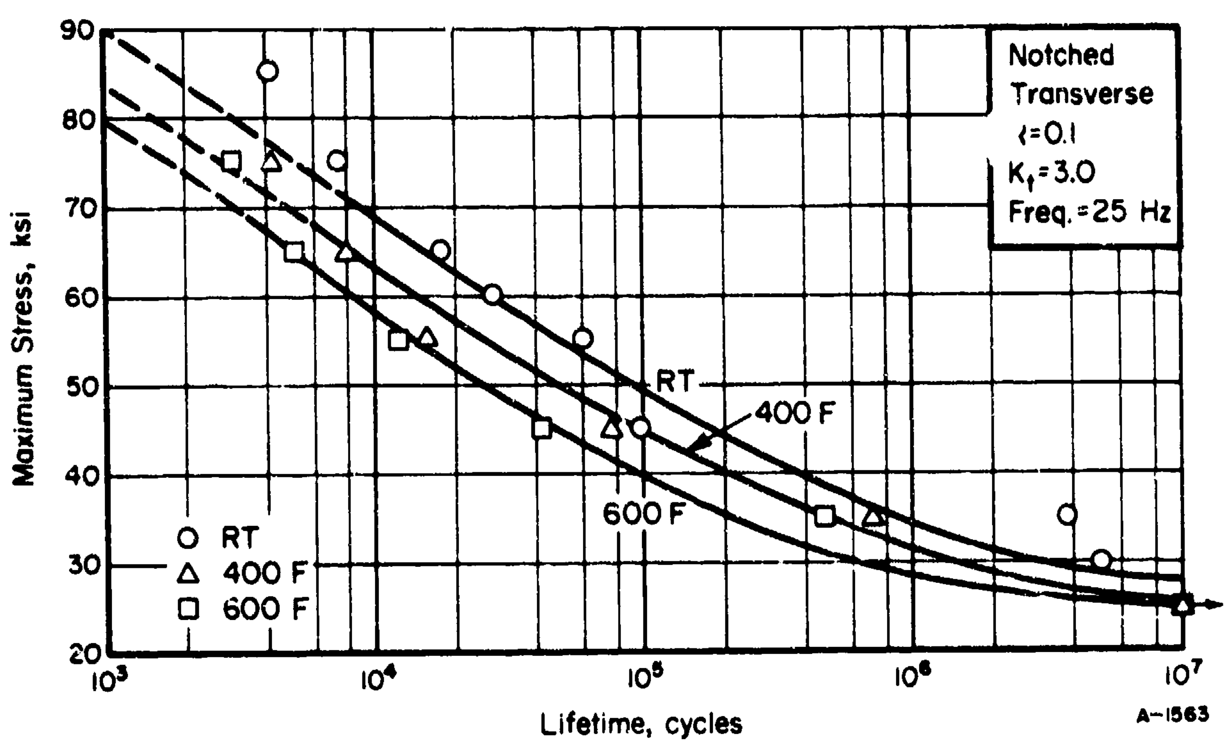


FIGURE 59. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

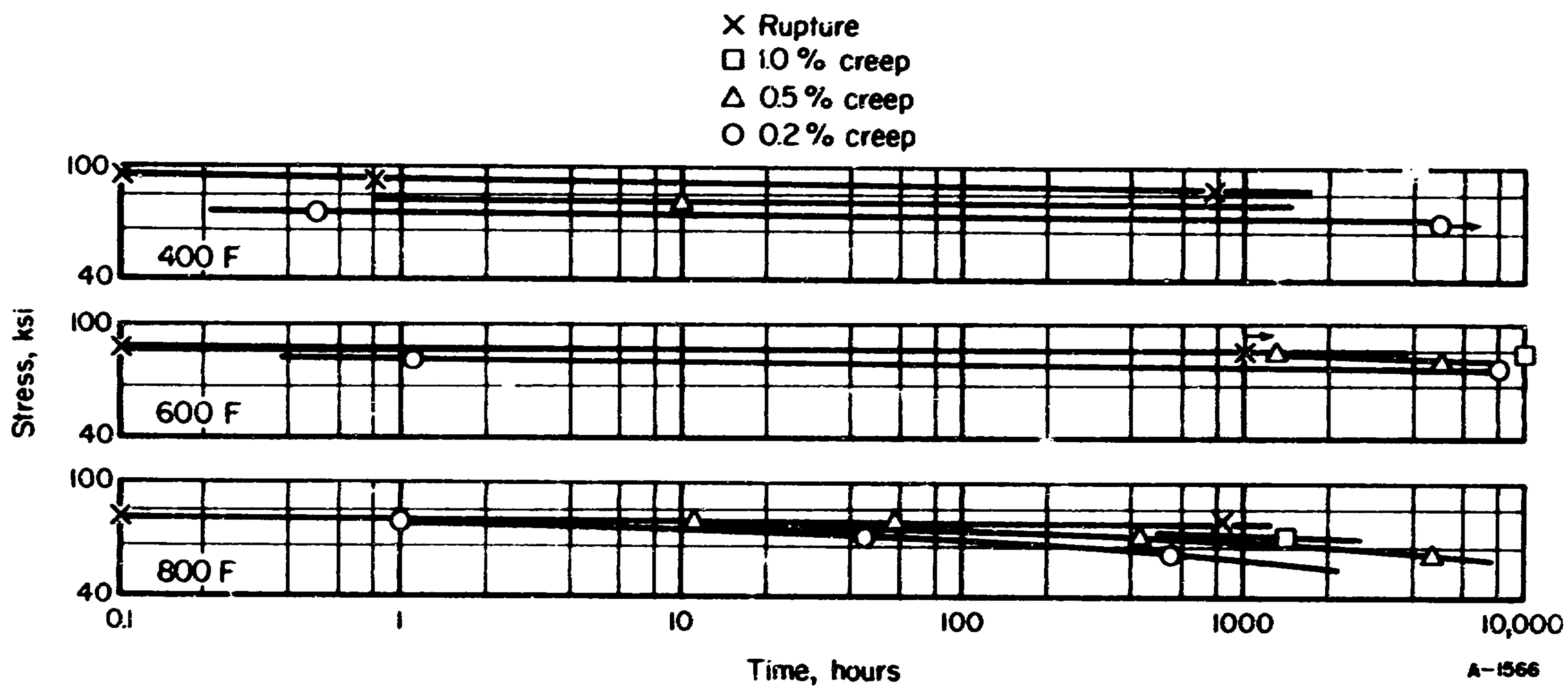


FIGURE 60. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE (Transverse)

Ti-6Al-4V Alloy Plate

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

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.

Compression. 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 specimens at room temperature are given in Table L.

Fracture Toughness. 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.

Fatigue. 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.

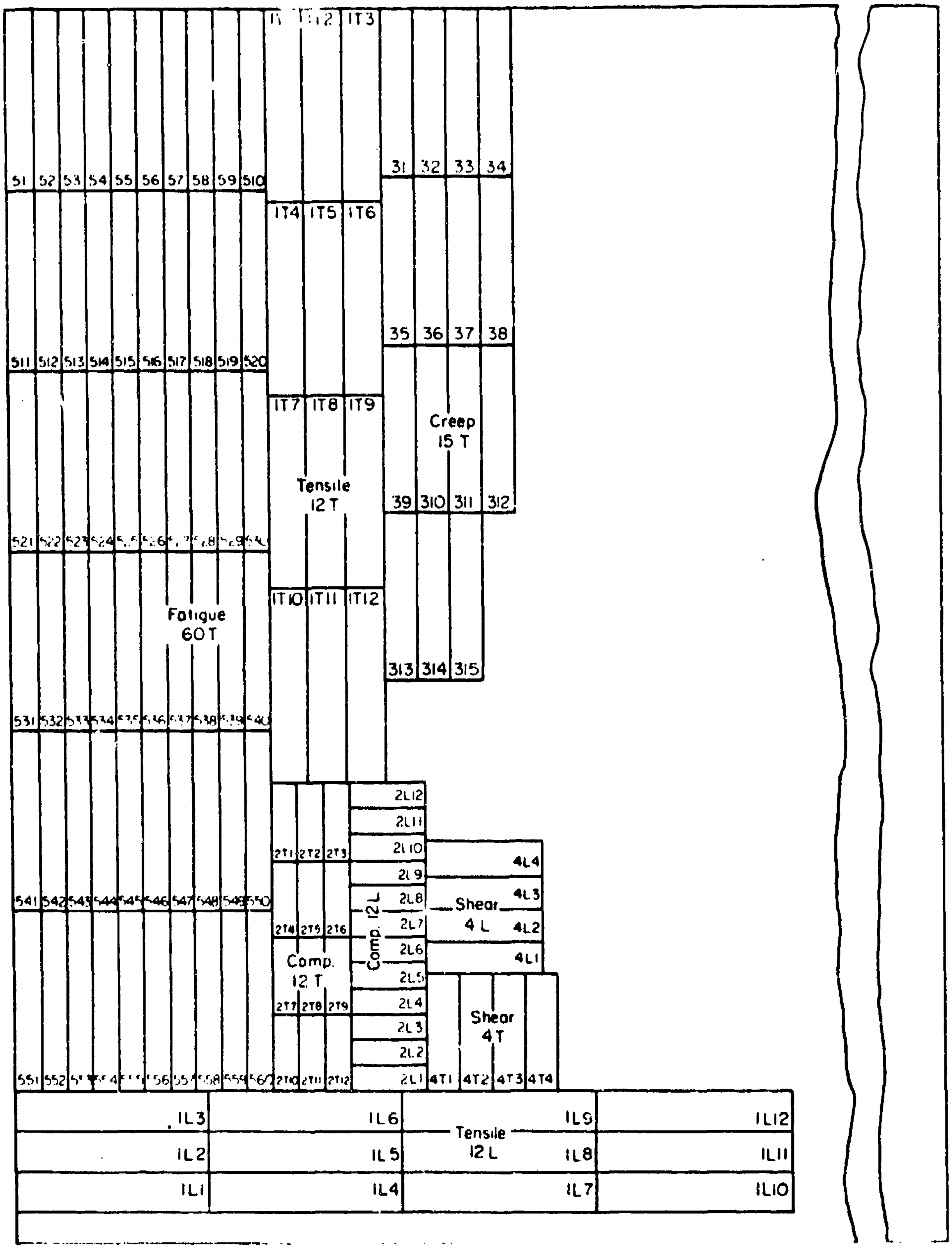


FIGURE 61. SPECIMEN LAYOUT FOR Ti-6Al-4V ALLOY PLATE

Creep and Stress Rupture. 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.

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

Thermal Expansion. The coefficient of thermal expansion for this alloy is 5.0×10^{-6} in./in./F for 70 F to 1200 F.

Density. The density for this material is 0.160 lb./in.^{3}.

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

Specimen Number		Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^3 ksi
Longitudinal at Room Temperature						
1L-1		138.0	130.7	12.0	14.6	17.6
1L-2		134.3	126.1	12.0	23.4	17.5
1L-3		134.9	126.4	12.5	24.8	17.5
	Average	135.8	127.7	12.2	20.9	17.5
Transverse at Room Temperature						
1T-1		136.5	126.8	12.0	27.3	16.8
1T-2		136.0	125.6	12.5	29.3	16.9
1T-3		135.5	127.7	11.5	25.6	17.1
	Average	136.0	126.7	12.0	27.4	16.9
Longitudinal at 400 F						
1L-4		103.2	87.6	16.0	34.3	16.3
1L-5		102.8	84.8	16.0	32.5	16.0
1L-6		103.7	86.0	16.0	36.4	16.0
	Average	103.3	86.1	16.0	34.4	16.1
Transverse at 400 F						
1T-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		104.4	85.9	14.0	30.9	17.1
	Average	103.7	85.6	15.7	32.2	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		92.2	71.4	15.0	35.8	15.2
	Average	92.5	72.1	15.0	35.1	15.9
Transverse at 600 F						
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-9		93.3	72.7	14.0	32.7	15.4
	Average	92.7	71.5	14.3	34.3	15.3
Longitudinal at 800 F						
1L-10		83.1	66.0	24.0	48.2	13.4
1L-11		82.3	64.6	18.0	47.0	13.2
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 800 F						
1T-10		82.4	64.4	18.0	45.5	14.7
1T-11		82.6	63.7	18.0	43.6	14.1
1T-12		82.5	64.2	19.0	45.8	13.0
	Average	82.5	64.1	18.3	45.0	13.9

TABLE XLVIII. COMPRESSION TEST RESULTS FOR BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^3 ksi
	Longitudinal at Room Temperature		
2L-1		132.0	17.0
2L-2		132.3	16.6
2L-3		133.0	17.8
	Average	132.4	17.7
	Transverse at Room Temperature		
2T-1		134.1	17.2
2T-2		134.5	17.9
2T-3		135.7	17.4
	Average	134.8	17.5
	Longitudinal at 400 F		
2L-4		88.8	15.8
2L-5		90.6	16.1
2L-6		89.2	15.4
	Average	89.5	15.8
	Transverse at 400 F		
2T-4		92.3	16.1
2T-5		90.7	15.0
2T-6		91.3	15.2
	Average	91.4	15.4
	Longitudinal at 600 F		
2L-7		73.3	14.7
2L-8		72.9	14.5
2L-9		74.4	15.1
	Average	73.5	14.8
	Transverse at 600 F		
2T-7		76.7	14.7
2T-8		76.2	15.7
2T-9		76.9	15.0
	Average	76.6	15.1
	Longitudinal at 800 F		
2L-10		67.8	14.0
2L-11		68.6	13.6
2L-12		68.4	14.3
	Average	68.3	14.0
	Transverse at 800 F		
2T-10		70.6	13.9
2T-11		69.6	14.2
2T-12		69.4	13.8
	Average	69.9	14.0

TABLE XLVIX. PIN SHEAR TEST RESULTS FOR BETA-ANNEALED Ti-6Al-4V ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number		Ultimate Shear Strength, ksi
	Longitudinal	
4L-1		89.4
4L-2		89.0
4L-3		92.3
4L-4		91.7
	Average	90.6
	Transverse	
4T-1		89.4
4T-2		91.0
4T-3		89.6
4T-4		89.4
	Average	89.9

TABLE L. IMPACT TEST RESULTS FOR BETA-ANNEALED Ti-6Al-4V ALLOY PLATE AT ROOM TEMPERATURE

Specimen Number		Energy, ft./lbs.
	Longitudinal	
10L-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

TABLE LI. RESULTS OF COMPACT TENSION TYPE FRACTURE TOUGHNESS TESTS ON BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

Specimen Number	W, inches	B, inches	a, inches	P_Q lbs.	P_{max}, lbs.	$f(\frac{a}{W})$	K_Q (a)	R_{sc} (b)
				Longitudinal (L-T)				
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
				Transverse (T-L)				
6T-1	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
6T-4	3.0	0.561	1.60	10,875	11,300	10.607	118.7	1.230
6T-5	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

(a) Candidate K_Q values are invalid as K_{Ic} values. Tests do meet the P_{max}/P_Q requirement but do not meet the size requirement.

(b) R_{sc} 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_{Ic} determination.

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

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[a]
	400 F	
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[b]
5-14	70	11,792,700[a]
	600 F	
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[b]
5-20	70	1,261,900[b]
5-21	70	10,328,700

(a) Did not fail.

(b) Failed at thermocouple weld.

TABLE LIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) BETA ANNEALED Ti-6Al-4V PLATE (TRANSVERSE, R = 0.1)

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[a]
	400 F	
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[a]
	600 F	
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[a]

(a) Did not fail.

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

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hours	Elongation in 2 Inches, percent	Reduction of Area, percent	Minimum Creep Rate, percent
3-1	104	400	--	--	--	--	--	--	On loading	14.6	34.5	--
3-6	100	400	--	--	--	--	0.4	3.005	515.3[a]	5.323	--	0.00002
3-4	95[b]	400	--	--	--	0.12	>1000	1.807	553.0[b]	3.240	--	nil
3-9	90	400	--	--	0.1	>1000	--	1.154	258.8[a]	1.958	--	--
3-12	85	400	--	0.07	>1000	--	--	0.738	454.5[a]	1.192	--	--
3-14	80	400	0.15	6000[c]	--	--	--	0.585	1004.5[a]	0.765	--	0.000004
3-2	93.5	600	--	--	--	--	--	--	On loading	13.1	39.5	--
3-7	90	600	0.05	25	2100[c]	--	--	5.031	1127.4[a]	5.450	--	0.000090
3-5	55	600	0.1	750	6000[c]	--	--	2.384	884.0	2.587	--	0.000042
3-10	85	800	0.01	0.07	0.2	0.6	1.5	5.208	4.8	15.4	41.2	1.1
3-8	80	800	0.1	0.2	1.2	4	16	2.808	136.2	18.5	33.6	0.05
3-3	70	800	0.6	2.4	14	58	175	0.954	1031.7	18.5	27.9	0.0084
3-11	55	800	4.0	18.5	195	650[c]	--	0.407	284.0[a]	1.012	--	0.0010
3-13	25	800	400	2225[c]	8000[c]	--	--	0.165	1005.5[a]	0.300	--	0.000053

(a) Test discontinued.

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

(c) Estimate.

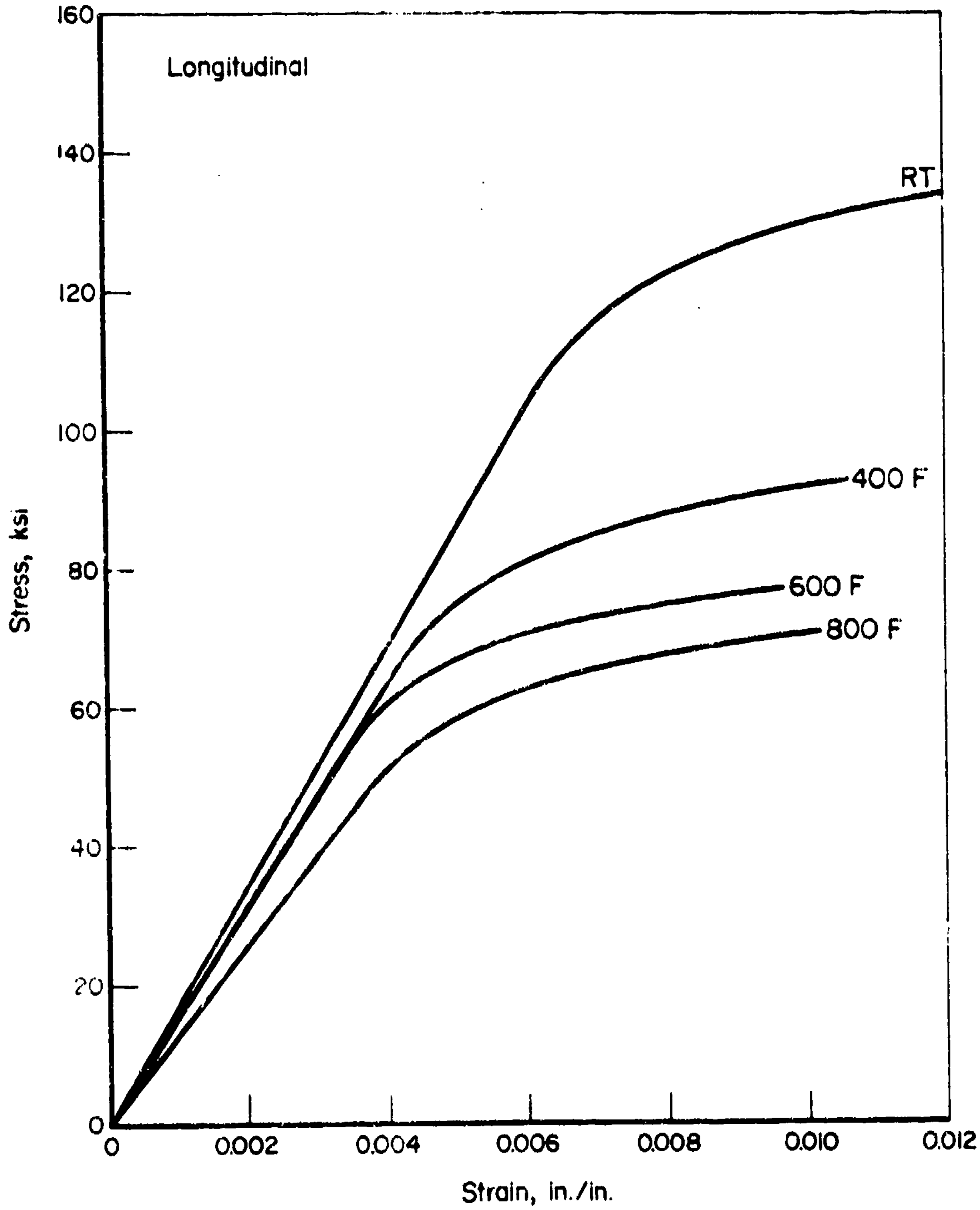


FIGURE 62. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR BETA-ANNEALED Ti-6Al-4V ALLOY PLATE (LONGITUDINAL)

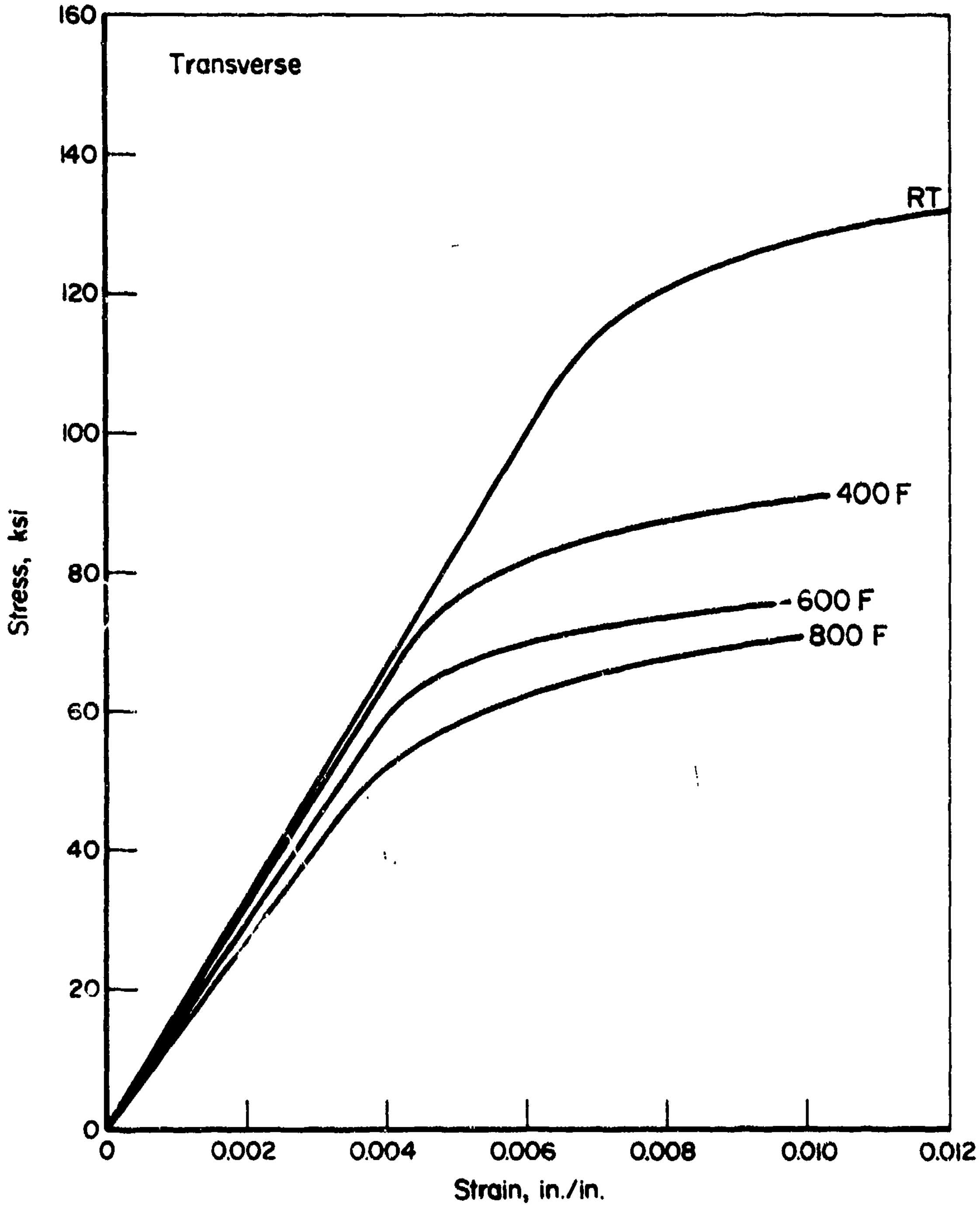


FIGURE 63. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR BETA-ANNEALED Ti-6Al-4V ALLOY PLATE (TRANSVERSE)

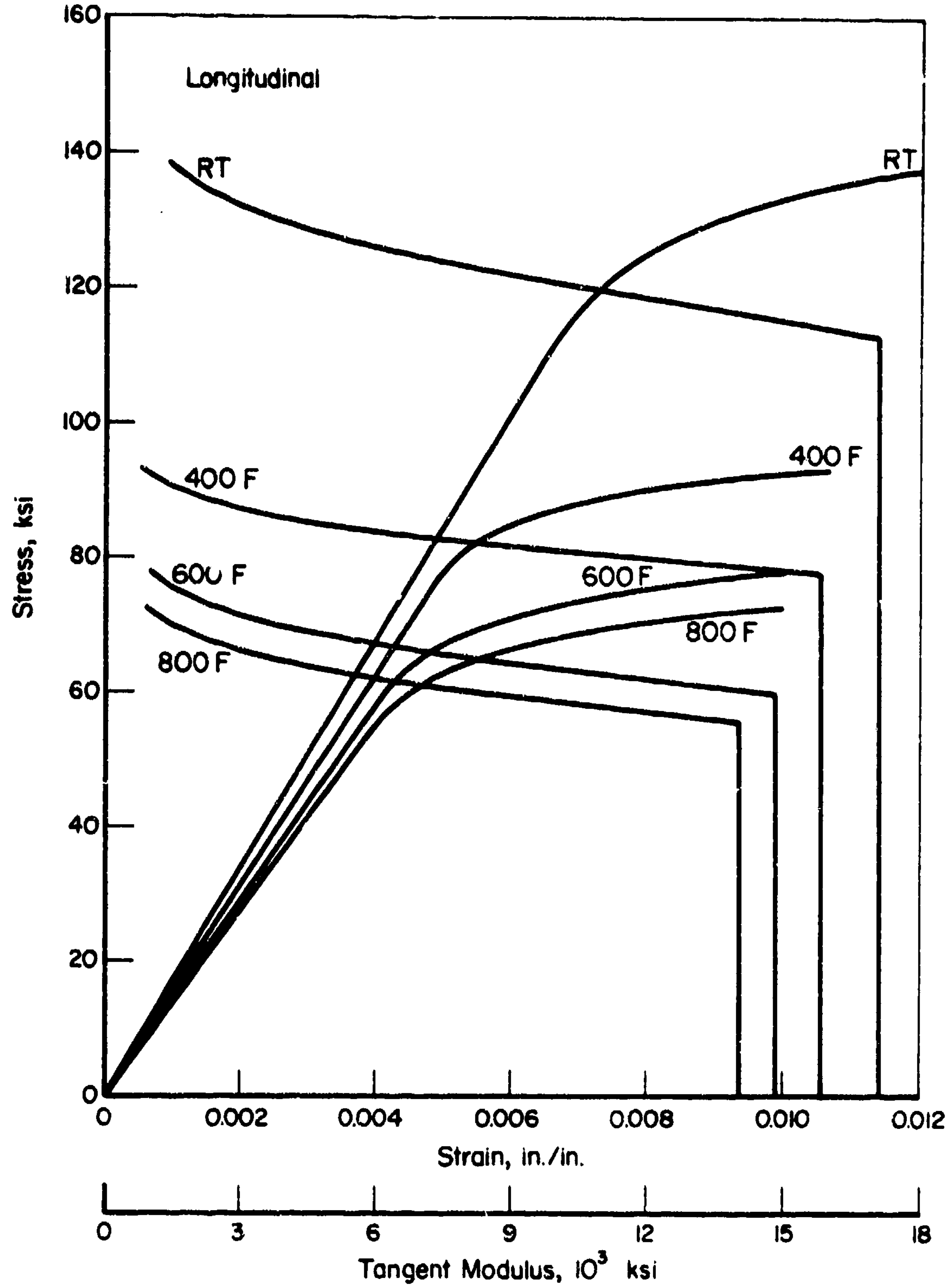


FIGURE 64. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR BETA-ANNEALED Ti-6Al-4V ALLOY PLATE (LONGITUDINAL)

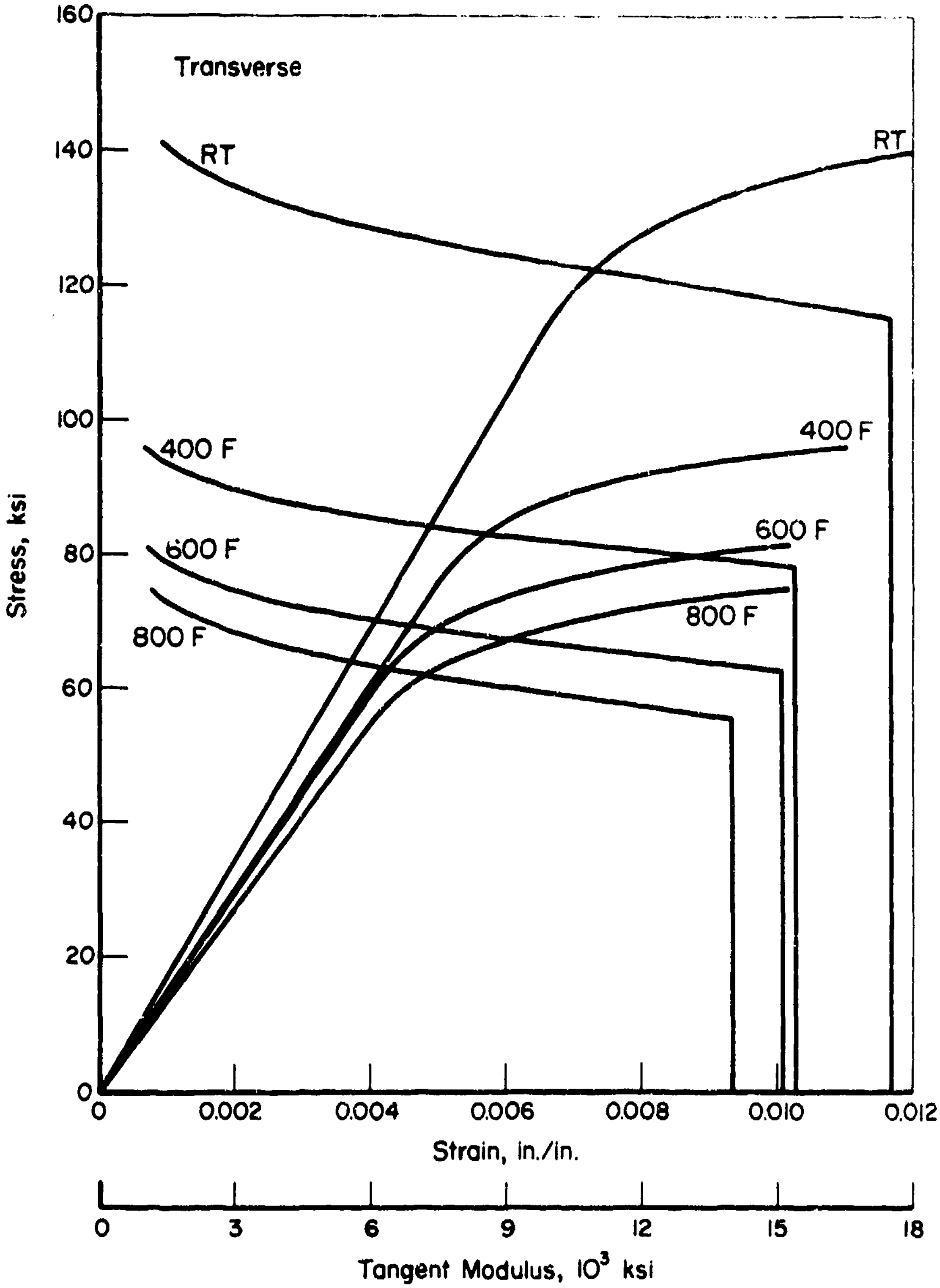


FIGURE 65. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR BFTA-ANNEALED Ti-6Al-4V ALLOY PLATE (TRANSVERSE)

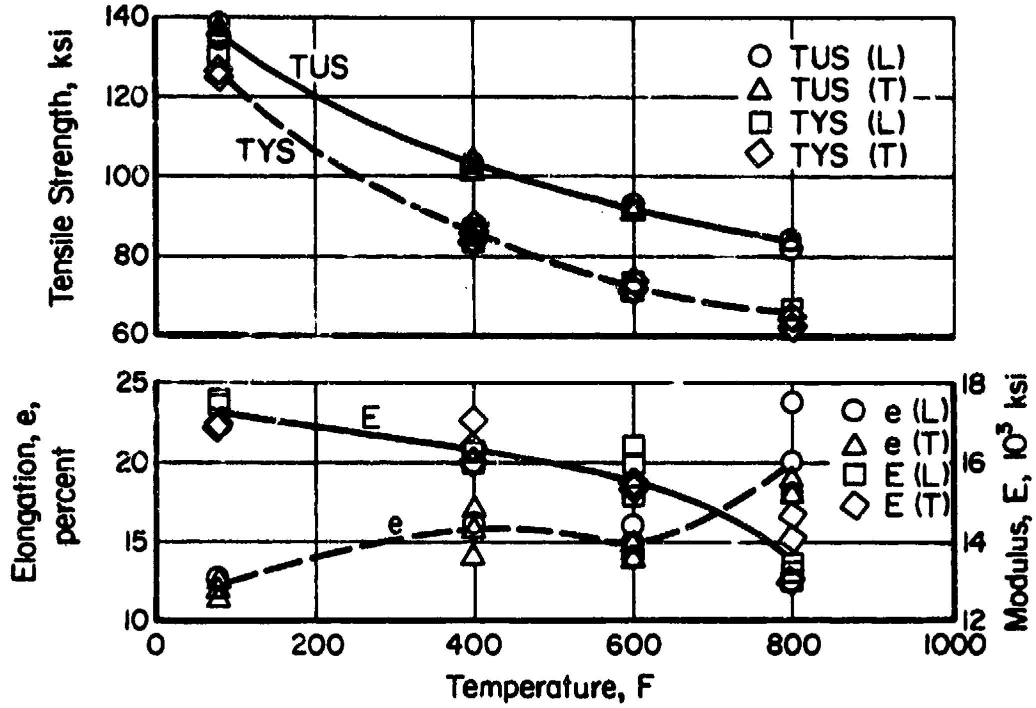


FIGURE 66. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

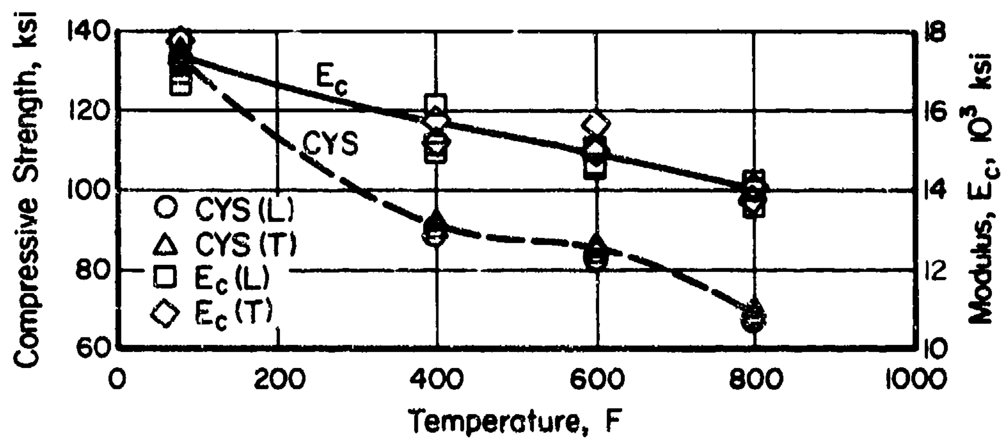


FIGURE 67. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

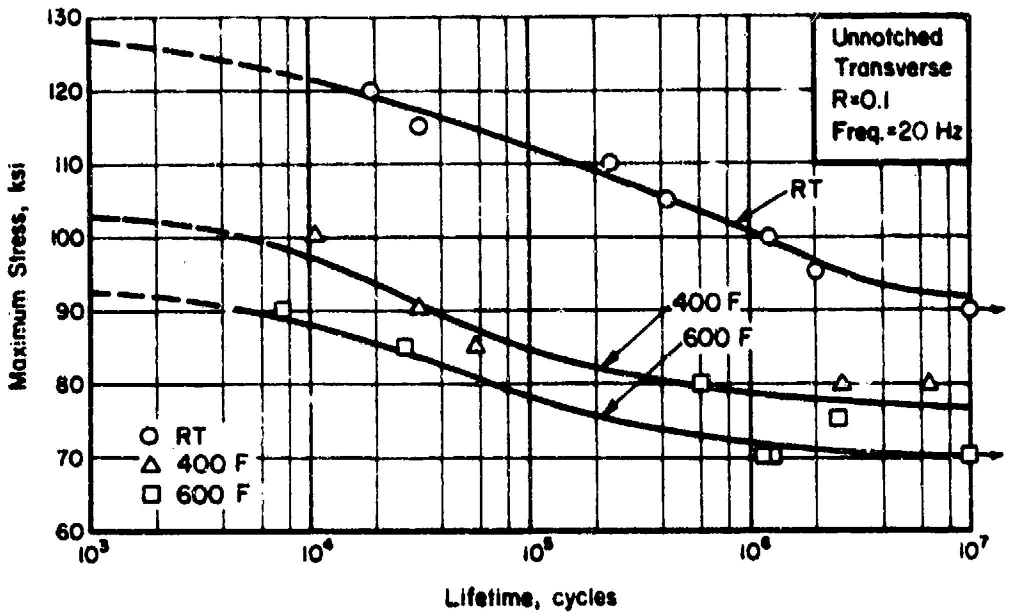


FIGURE 68. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

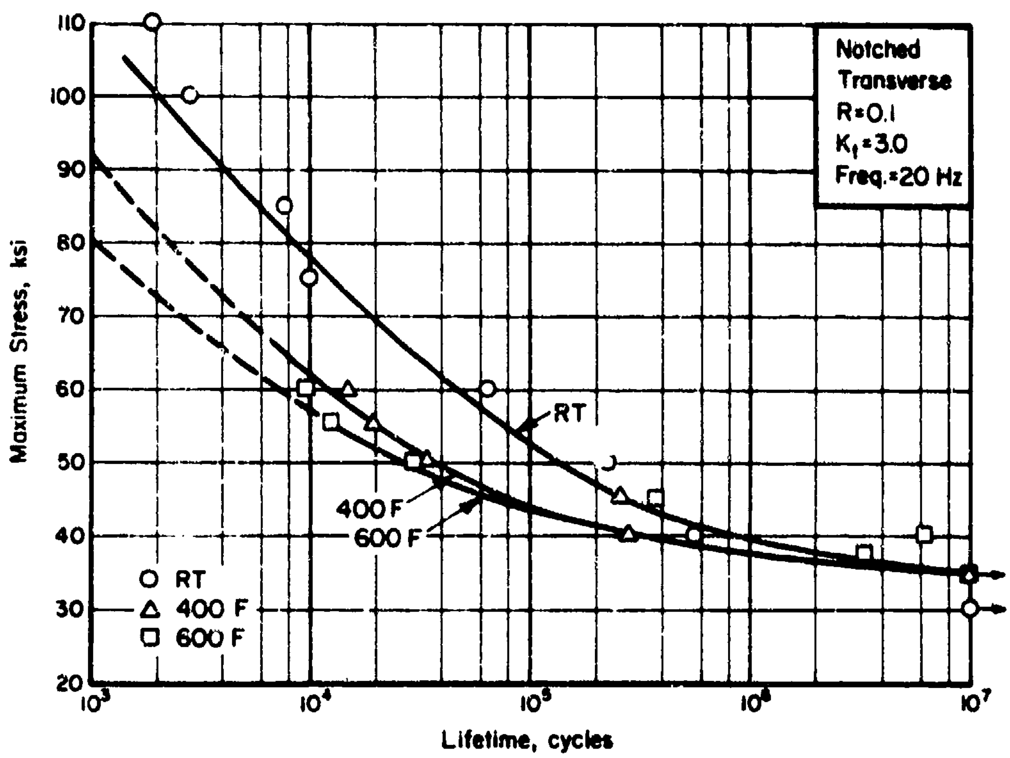


FIGURE 69. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

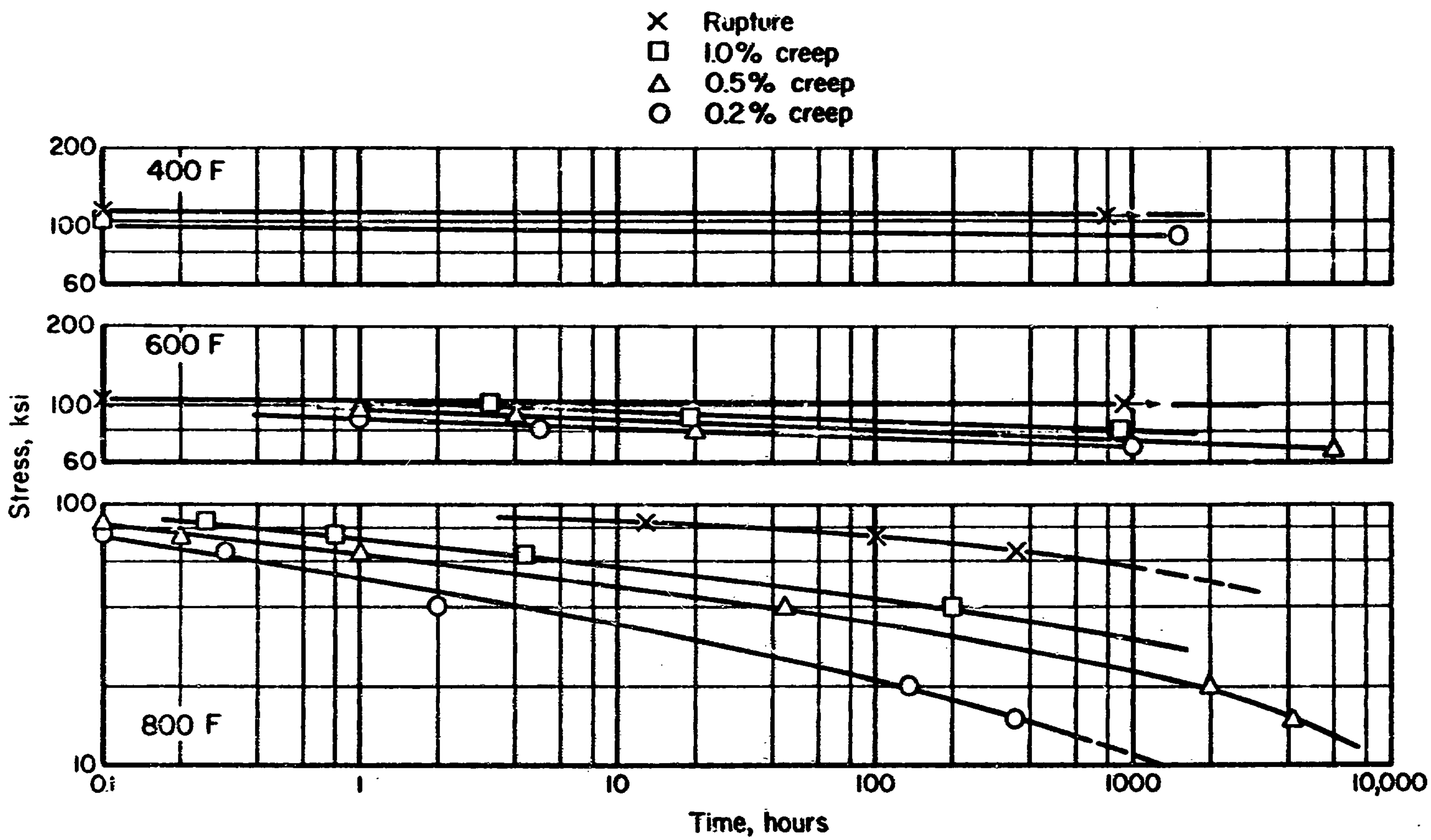


FIGURE 70. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR BETA-ANNEALED Ti-6Al-4V PLATE (TRANSVERSE)

Ti-6Al-4V Alloy Castings

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 6½ inches and tapering from about 1 inch to ½ inch. The material was from TiTech International casting heat number 6-4 2119 and had the following composition:

Chemical Composition	Percent
Carbon	0.28
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 and no specimen layout is shown. The material was received in the annealed condition and no further heat treating was done.

Test Results

Tension. 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.

Compression. 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.

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

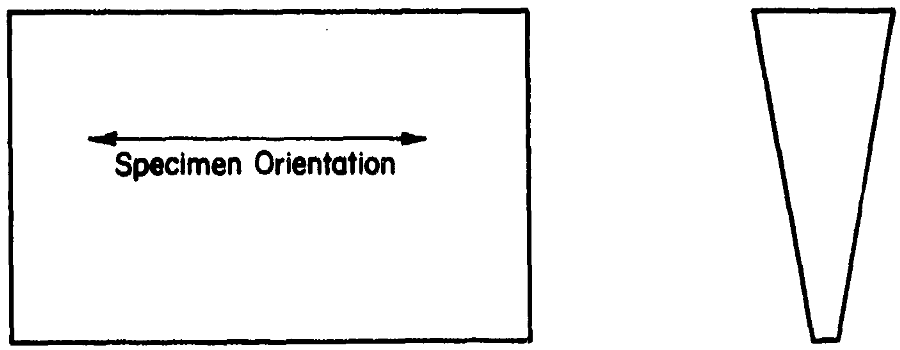
Fracture Toughness. In view of the invalid results obtained from Ti-6Al-4V beta-annealed (preceding section of this report) with approximately the same thickness of material, it was believed that the casting data would also be invalid. However, compact tension type tests were attempted. K_Q values from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

Fatigue. 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.

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

Stress Corrosion. 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. Values for these properties are the same as for wrought Ti-6Al-4V.



Cast Wedge

TABLE LV. TENSILE TEST RESULTS FOR ANNEALED Ti-6Al-4V CASTINGS

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 1-inch, percent	Reduction in Area, percent	Tensile Modulus, 10^3 ksi
		Room Temperature			
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
Average	137.8	130.4	6.5	11.2	17.2
		400 F			
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	100.9	88.4	10.0	21.2	16.8
Average	100.8	88.2	10.2	19.0	16.8
		600 F			
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
Average	84.8	69.8	12.0	24.3	15.2
		800 F			
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
Average	77.5	63.8	12.0	28.4	15.1

TABLE LVI. COMPRESSION TEST RESULTS FOR ANNEALED Ti-6Al-4V CASTINGS

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^3 ksi
		Room Temperature	
2L-1		136.9	16.3
2L-2		138.1	16.4
2L-3		137.4	16.8
	Average	137.5	16.5
		400 F	
2L-4		90.9	16.1
2L-5		93.3	15.7
2L-6		94.6	15.0
	Average	92.9	15.6
		600 F	
2L-7		73.7	14.1
2L-8		74.4	15.3
2L-9		75.7	15.3
	Average	74.6	14.9
		800 F	
2L-10		65.8	13.5
2L-11		69.8	12.7
2L-12		66.9	14.3
	Average	67.5	13.5

TABLE LVII. PIN SHEAR TEST RESULTS FOR ANNEALED Ti-6Al-4V CASTINGS AT ROOM TEMPERATURE

Specimen Number		Ultimate Shear Strength, ksi
4L-1		92.7
4L-2		94.7
4L-3		92.3
4L-4		91.5
	Average	92.8

TABLE LVIII. IMPACT TEST RESULTS FOR ANNEALED Ti-6Al-4V CASTING AT ROOM TEMPERATURE

Specimen Number		Energy, ft/lb
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. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED ANNEALED Ti-6Al-4V CASTINGS (R = 0.1)

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[(a)]
	400 F	
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
	600 F	
5-17	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.

TABLE LX. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) ANNEALED Ti-6Al-4V CASTINGS (R = 0.1)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
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[(a)]
	400 F	
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
	600 F	
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[(a)]

(a) Did not fail.

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

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hours	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent
			0.1	0.2	0.5	1.0	2.0					
3-5	98.7	400	--	--	--	--	--	--	On loading	8.5	22.2	--
3-6	95	400	--	--	--	--	<0.1	1.746	0.1	6.9	13.3	--
3-8	90	400	--	--	0.01	0.13	0.8	0.950	1.8	5.4	11.0	1.2
3-13	85	400	--	--	0.15	3.3	>1000	0.854	623.8(b)	1.964	--	0.00003
3-9	80	400	0.05	0.08	10	>1000	--	0.592	502.7(b)	1.141	--	
3-11	75	400	0.60	>5000	--	--	--	0.554	839.8(b)	0.696	--	0.000001
3-2	85	600	--	--	--	--	--	--	On loading	8.5	26.3	--
3-4	80	600	0.08	260	4500(a)	--	--	2.673	1000.1(b)	2.918	--	0.00007
3-7	75	600	500	2600(a)	--	--	--	1.241	1104.2(b)	1.377	--	0.000046
3-1	80	800	--	--	--	--	--	--	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	0.009
3-3	60	800	1.0	15	75	310	900	0.581	1077.4(b)	2.823	--	0.0014
3-12	40	800	40	200	1100(a)	--	--	0.307	288.3(b)	0.535	--	0.00035
3-14	30	800	50	575	7000(a)	--	--	0.292	695.7(b)	0.500	--	0.00005

(a) Estimate.

(b) Test discontinued.

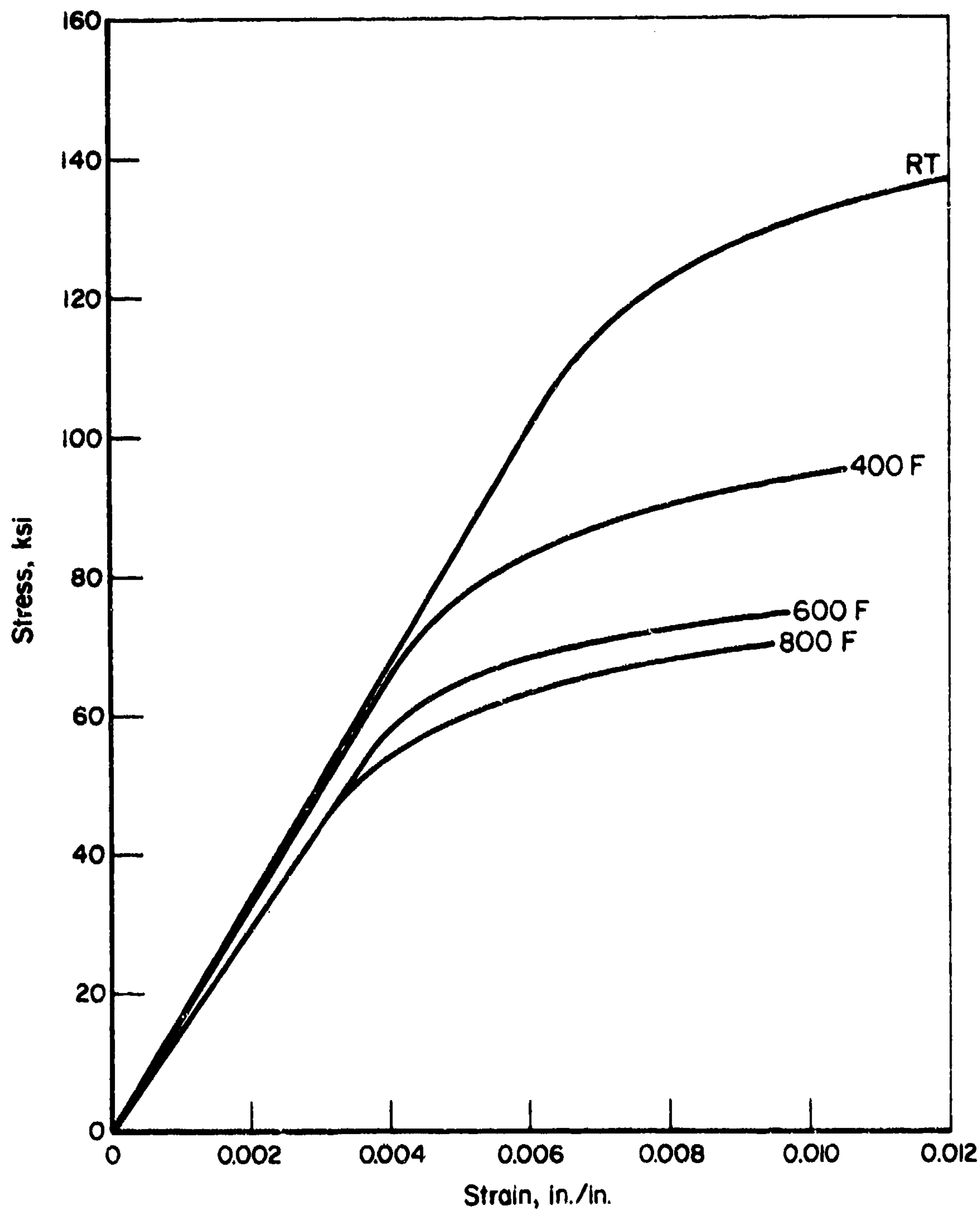


FIGURE 71. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR ANNEALED Ti-6Al-4V CASTINGS

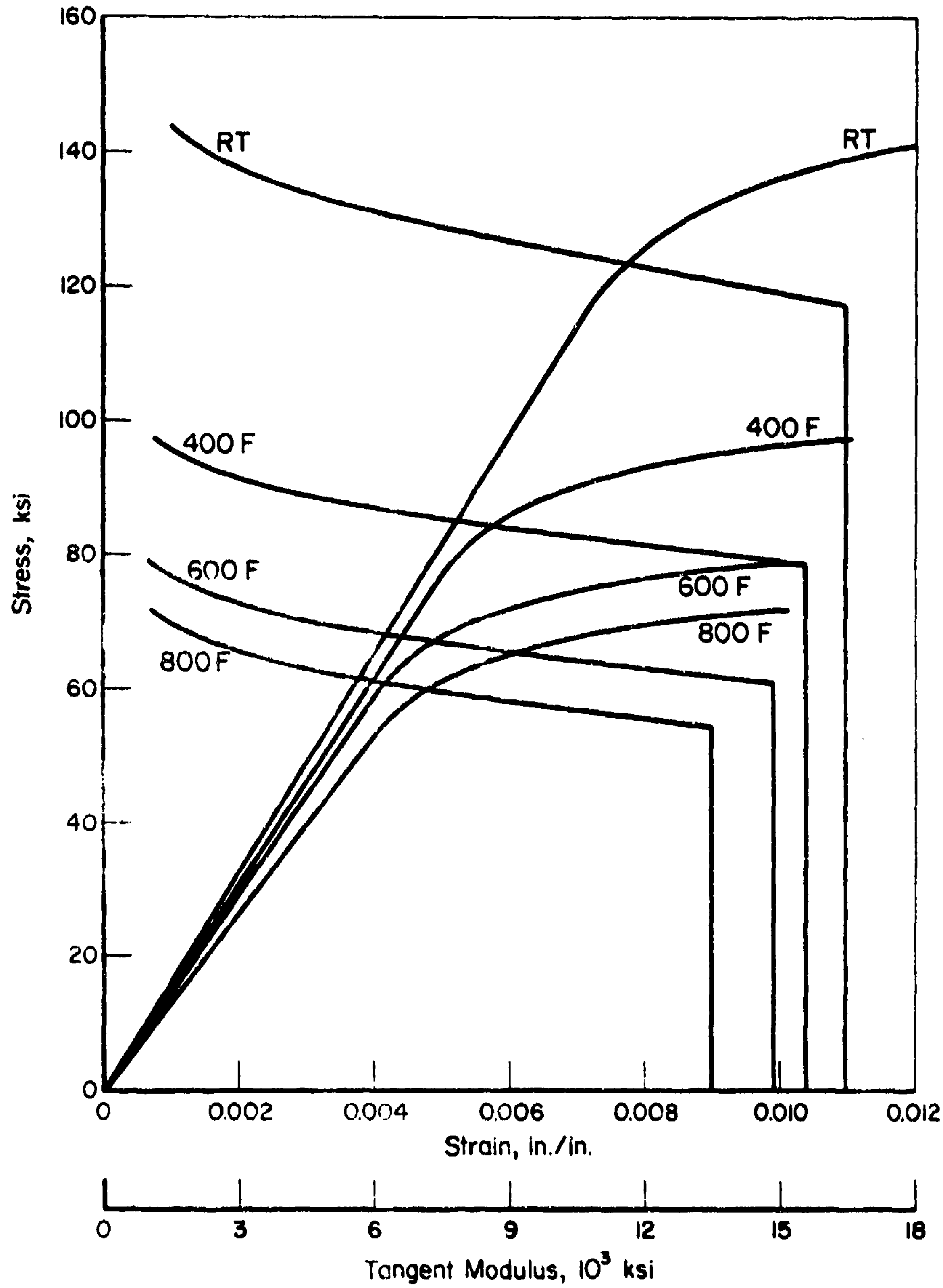


FIGURE 72. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR ANNEALED Ti-6Al-4V CASTINGS

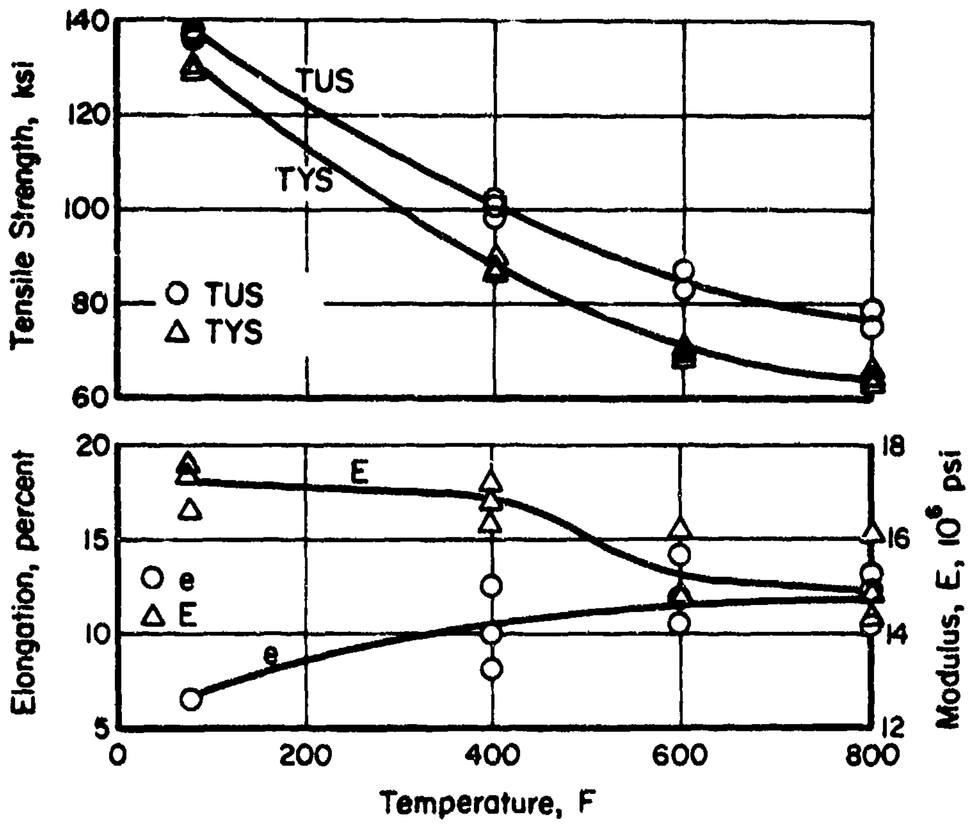


FIGURE 73. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED Ti-6Al-4V ALLOY CASTINGS

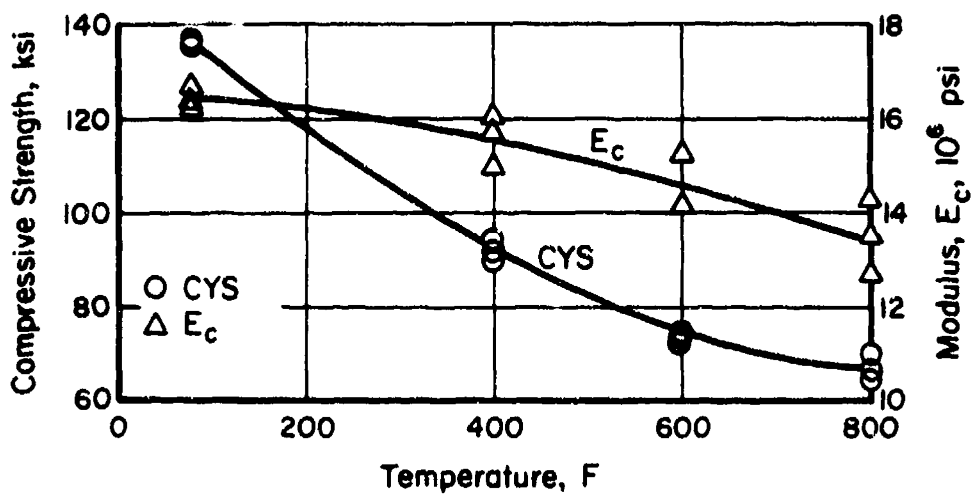


FIGURE 74. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED Ti-6Al-4V ALLOY CASTINGS

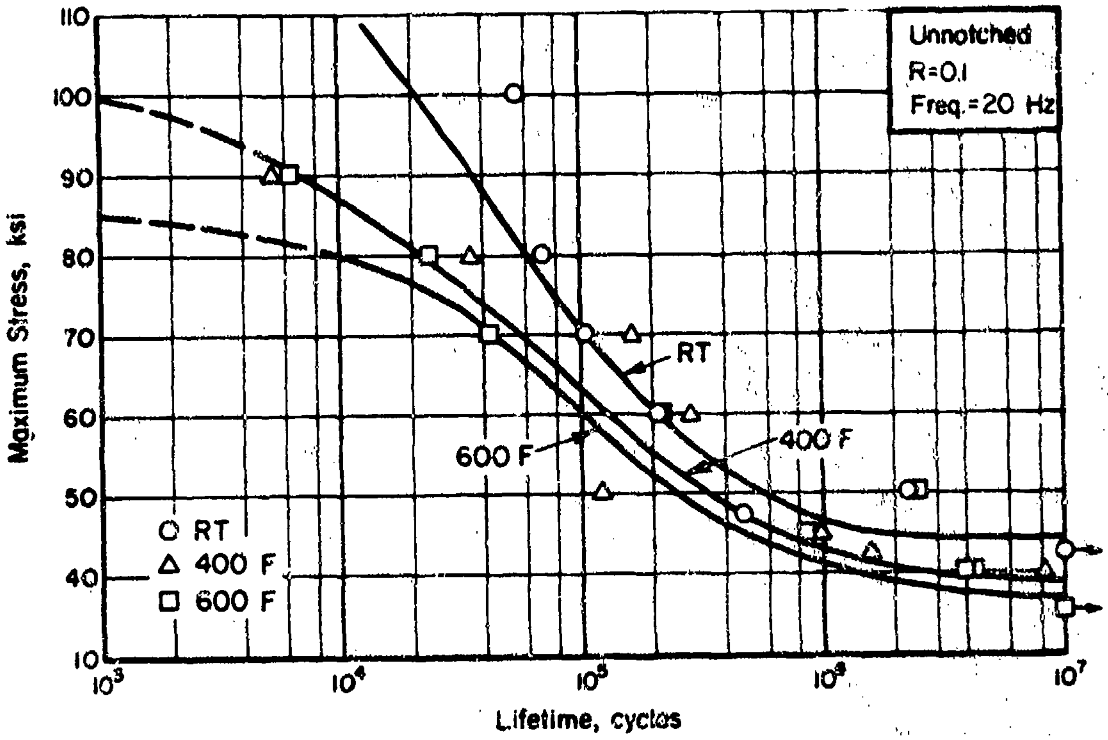


FIGURE 75. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED Ti-6Al-4V ALLOY CASTINGS

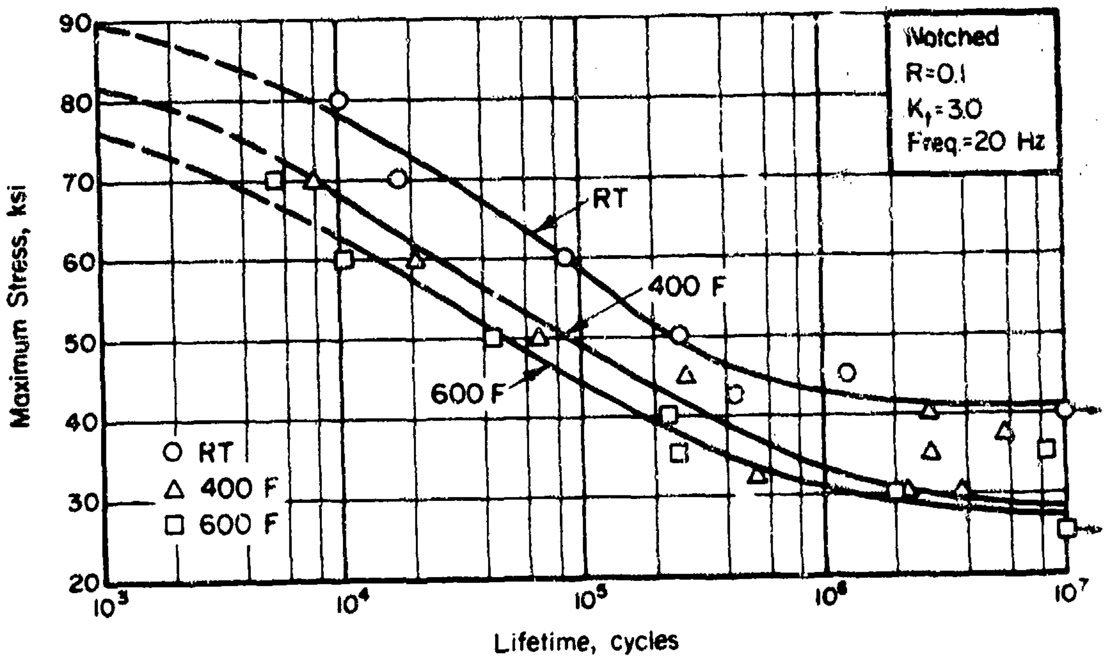


FIGURE 76. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) ANNEALED Ti-6Al-4V ALLOY CASTINGS

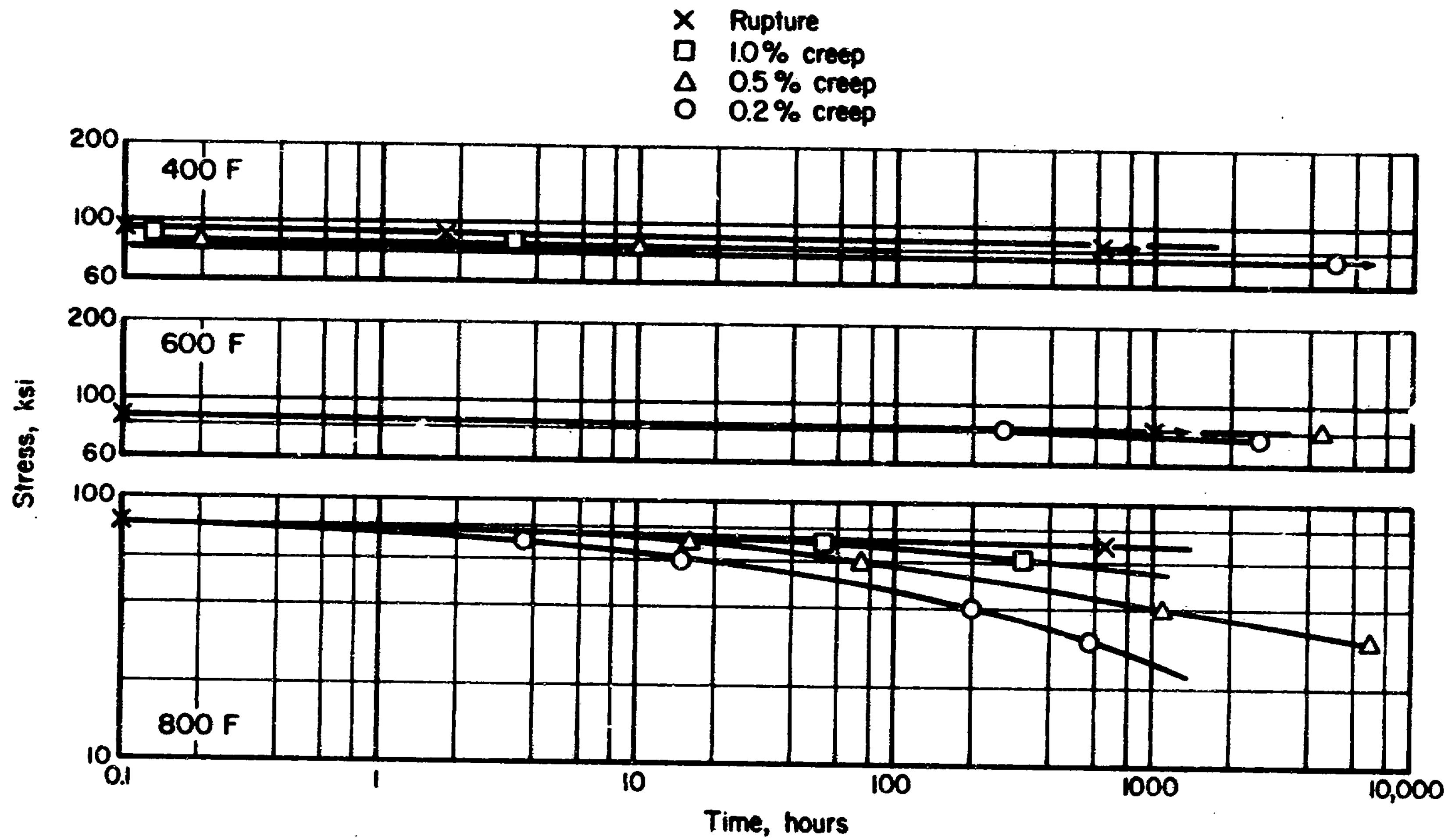


FIGURE 77. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED Ti-6Al-4V ALLOY CASTINGS

Ti-6Al-4V Isothermal Forging

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

Tension. 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.

Compression. Results of transverse compression tests at room temperature, 400 F, 600 F, and 800 F are given in Table LXIII. Typical stress-strain 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.

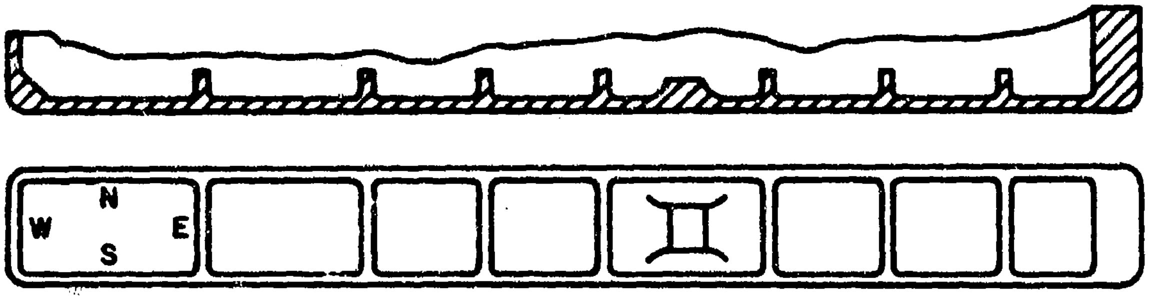
Fracture Toughness. Only one specimen (compact tension) of sufficient dimensions was available from the forging due to the varying thickness. This specimen produced a valid test result of K_{Ic} = 59 ksi $\sqrt{in.}$

Fatigue. 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.

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

Stress Corrosion. 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-6Al-4V ISOTHERMAL FORGINGS (TRANSVERSE)

Specimen Number	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 1 Inch, percent	Reduction in Area, percent	Tensile Modulus, 10^3 psi
		Room Temperature			
1T-1	142.5	134.1	17.0	46.6	16.2
1T-2	144.0	138.0	17.0	45.3	16.6
1T-3	145.2	136.8	17.0	45.2	16.4
Average	143.9	136.3	17.0	45.7	16.4
		400 F			
1T-4	110.7	102.1	17.5	47.8	15.1
1T-5	111.3	104.6	18.0	50.0	15.9
1T-6	109.6	100.0	17.0	45.3	14.7
Average	110.5	102.2	17.5	47.7	15.2
		600 F			
1T-7	98.7	92.7	18.5	55.8	14.7
1T-8	100.1	92.7	18.0	54.8	14.9
1T-9	101.6	94.7	19.0	51.7	13.9
Average	99.8	93.4	18.5	54.1	14.5
		800 F			
1T-10	87.0	75.6	20.5	64.8	12.5
1T-11	85.7	79.1	21.0	62.1	13.2
1T-12	89.6	80.3	23.0	60.0	13.0
Average	87.4	78.3	21.5	62.3	12.9

TABLE LXIII. COMPRESSION TEST RESULTS FOR Ti-6Al-4V ISOTHERMAL FORGINGS (TRANSVERSE)

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^3 ksi
		Room Temperature	
2T-1		136.2	16.5
2T-2		135.7	16.9
2T-3		136.0	16.0
	Average	135.9	16.5
		400 F	
2T-4		100.2	15.9
2T-5		102.1	15.5
2T-6		101.9	14.9
	Average	101.4	15.4
		600 F	
2T-7		94.5	13.9
2T-8		93.2	14.2
2T-9		92.0	13.7
	Average	93.2	13.9
		800 F	
2T-10		81.9	13.2
2T-11		79.6	12.6
2T-12		77.4	13.0
	Average	79.6	12.9

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

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

TABLE LXV. CHARPY V-NOTCH TEST RESULTS FOR Ti-6A1-4V ISOTHERMAL FORGINGS (TRANSVERSE)

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

TABLE LXVI. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED Ti-6Al-4V ISOTHERMAL FORGINGS (TRANSVERSE, R=0.1)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	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	10,099,250[a]
	400 F	
5-11	110	16,180
5-12	105	26,260
5-20	100	605,000
5-13	95	1,609,000
5-21	90	325,800[b]
5-19	90	1,765,000
5-14	90	2,530,760
5-22	80	597,200[b]
5-10	80	10,100,000[a]
	600 F	
5-15	90	50,100[b]
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[a]

(a) Did not fail.

(b) Failed in grip.

TABLE LXVII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) Ti-6Al-4V ISOTHERMAL FORGINGS (TRANSVERSE, R = 0.1)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room 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(a)
	400 F	
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(a)
	600 F	
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(a)

(a) Did not fail.

TABLE LXVIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR Ti-6Al-4V ISOTHERMAL FORGING

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hours	Elongation in 2 Inches, percent	Reduction of Area, percent	Minimum Creep Rate, percent
			0.1	0.2	0.5	1.0	2.0					
3-1	112.5	400	--	--	--	--	--	--	On loading	19.2	61.7	--
3-8	109	400	--	--	--	--	0.05	3.827	791.6(a)	7.650(a)	--	0.00034
3-3	105	400	--	--	--	0.1	10	2.662	666.7(a)	5.520	--	0.00040
3-15	95	400	25	1500(b)	--	--	--	0.834	1103.2(a)	1.031	--	0.000013
3-2	105.3	600	--	--	--	--	--	--	On loading	20.0	70.2	--
3-4	100	600	--	0.07	1.0	3.2	30	4.788	933.4(a)	8.082	--	0.00054
3-11	90	600	0.10	1.0	4	19	500(b)	1.931	116.3(a)	3.360	--	--
3-13	80	600	1.5	5.0	20	900(b)	--	0.573	43.4(a)	1.207	--	--
3-14	70	600	170	1000	6000(b)	--	--	0.430	1102.8(a)	0.639	--	0.000063
3-6	85	800	--	--	0.1	0.25	0.7	1.465	12.9	30.0	75.2	1.2
3-5	75	800	--	0.1	0.2	0.8	2.6	0.981	100.2	40.0	78.0	0.15
3-7	65	800	0.07	0.3	1.0	4.4	19	0.781	360.7	44.6	80.0	0.046
3-9	40	900	0.4	2.0	45	200(b)	--	0.400	66.1(a)	0.984	--	0.0035
3-10	20	800	14	137	2000(b)	--	--	0.219	257.6(a)	0.457	--	0.00015
3-12	15	800	30	350	4100(b)	--	--	0.165	500.6(a)	0.388	--	0.000075

(a) Test discontinued.

(b) Estimated.

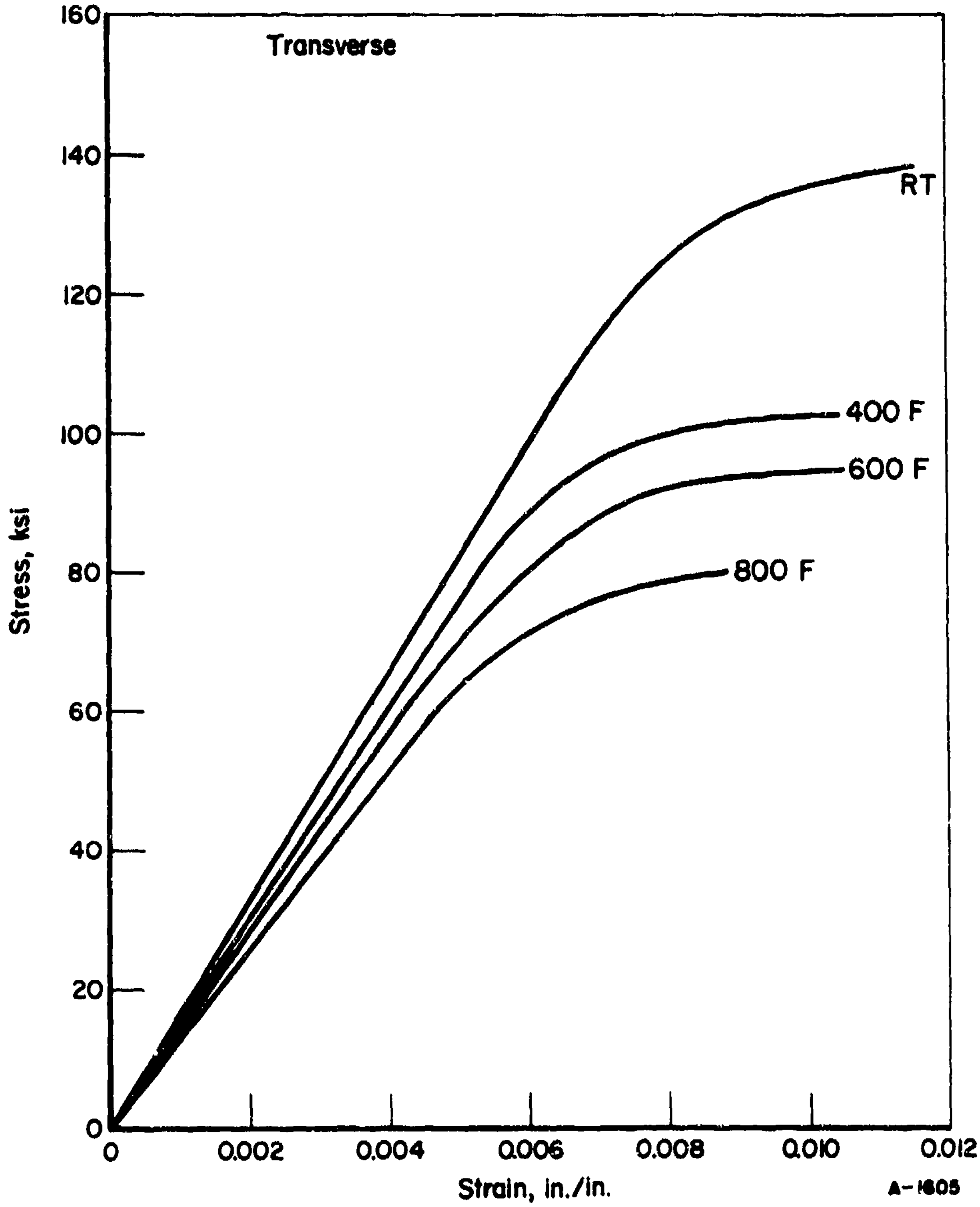


FIGURE 78. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR Ti-6Al-4V ISOTHERMAL FORGINGS (TRANSVERSE)

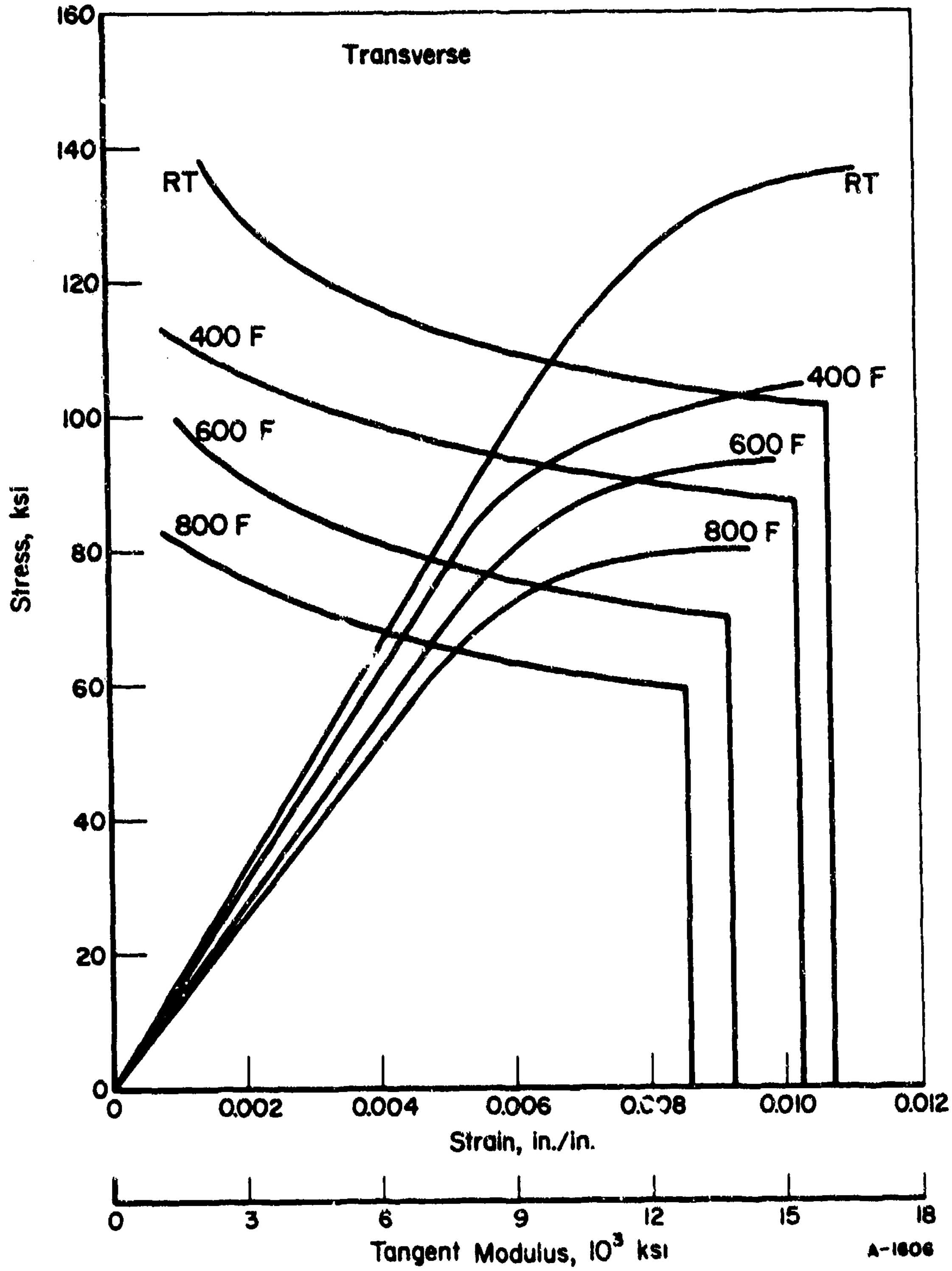


FIGURE 79. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR Ti-6Al-4V ISOTHERMAL FORGINGS

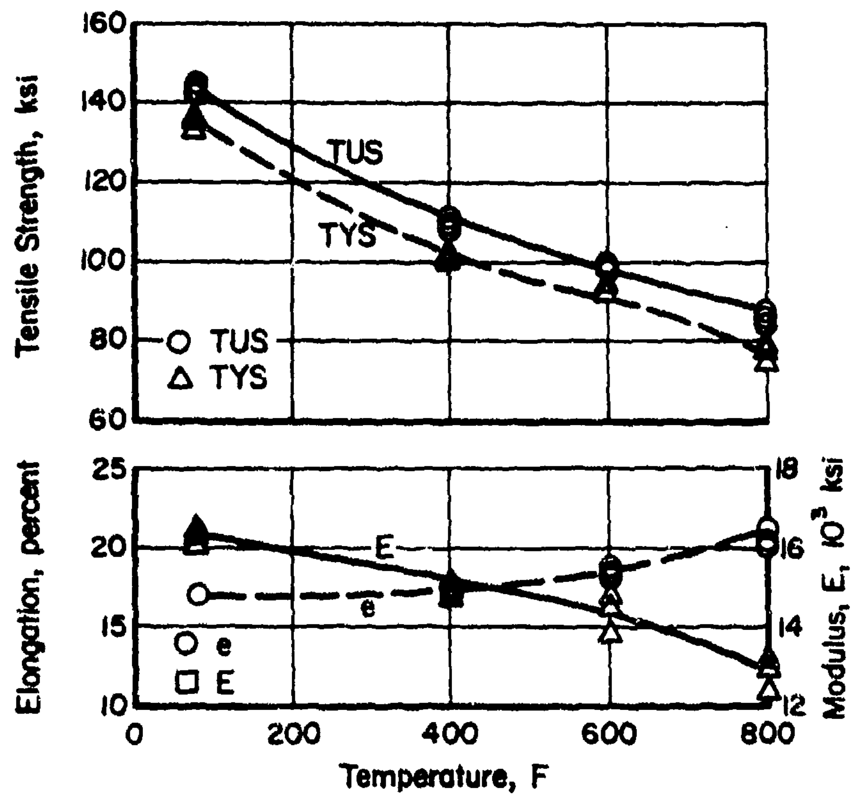


FIGURE 80. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-4V ISOTHERMAL FORGINGS

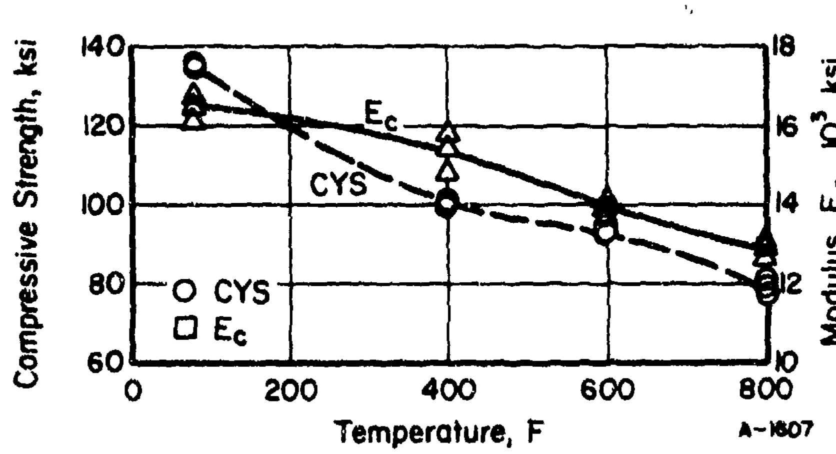


FIGURE 81. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-4V ISOTHERMAL FORGINGS

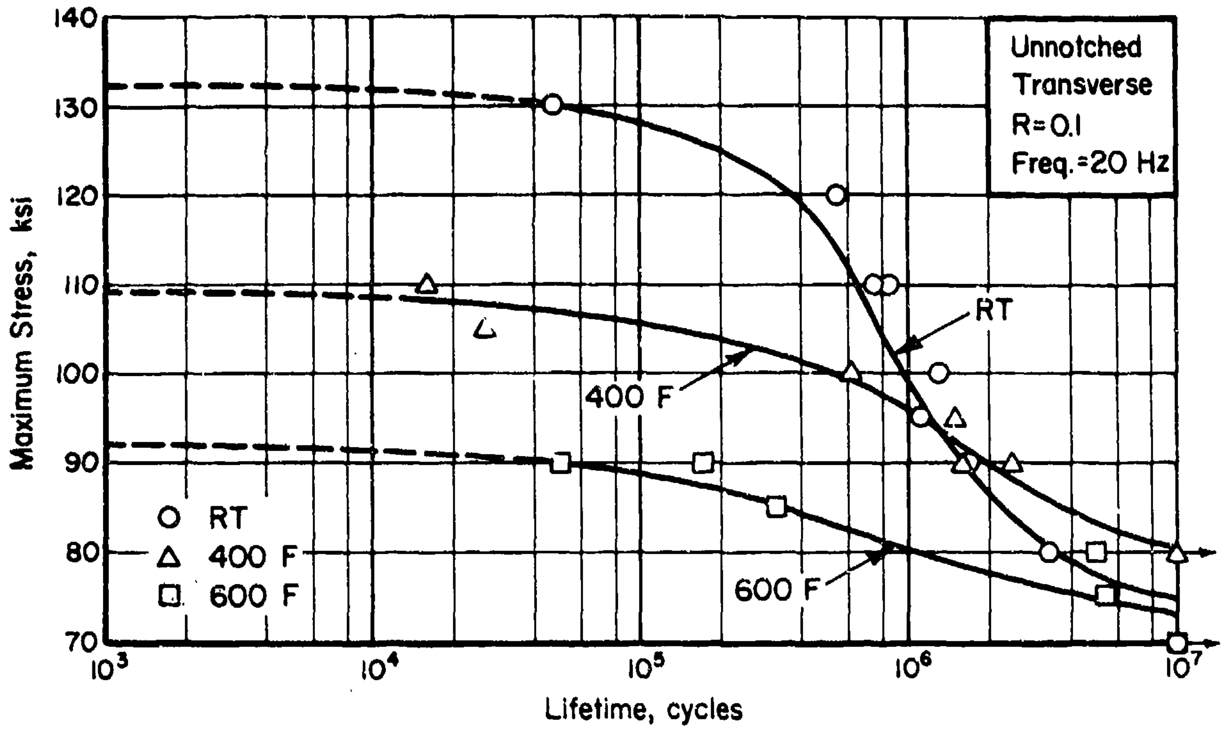


FIGURE 82. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED Ti-6Al-4V ISOTHERMAL FORGINGS

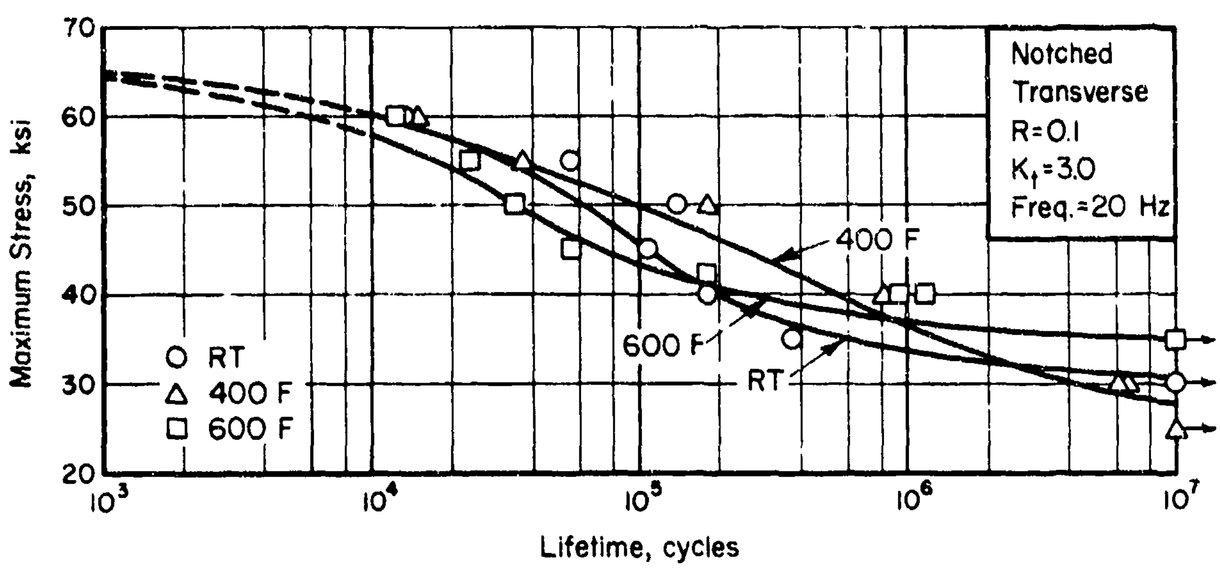


FIGURE 83. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) Ti-6Al-4V ISOTHERMAL FORGINGS

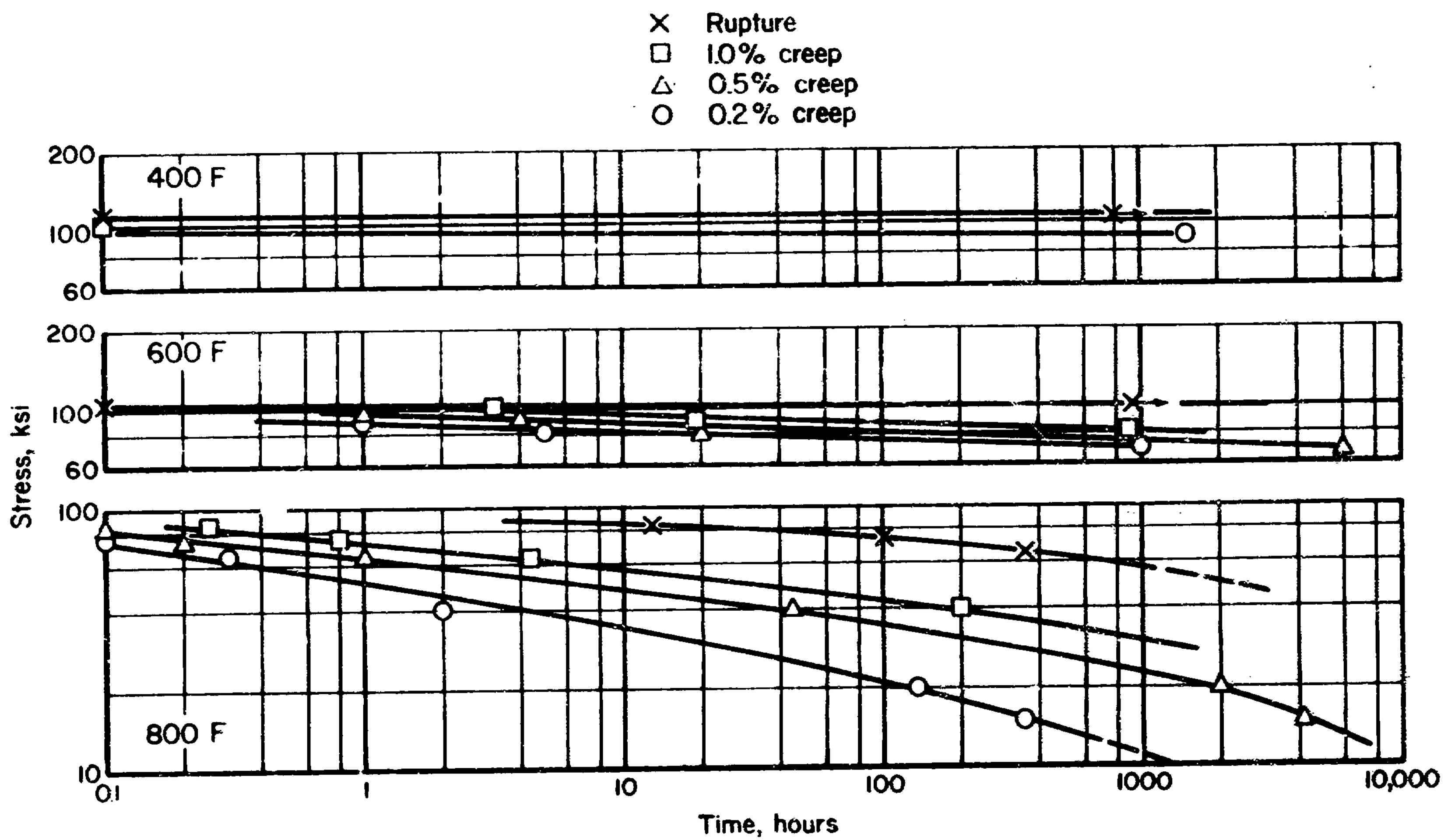


FIGURE 84. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR Ti-6Al-4V ISOTHERMAL FORGINGS (TRANSVERSE)

Incoloy 903 Alloy Sheet

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. Effect-of-temperature curves are shown in Figure 90.

Compression. 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.

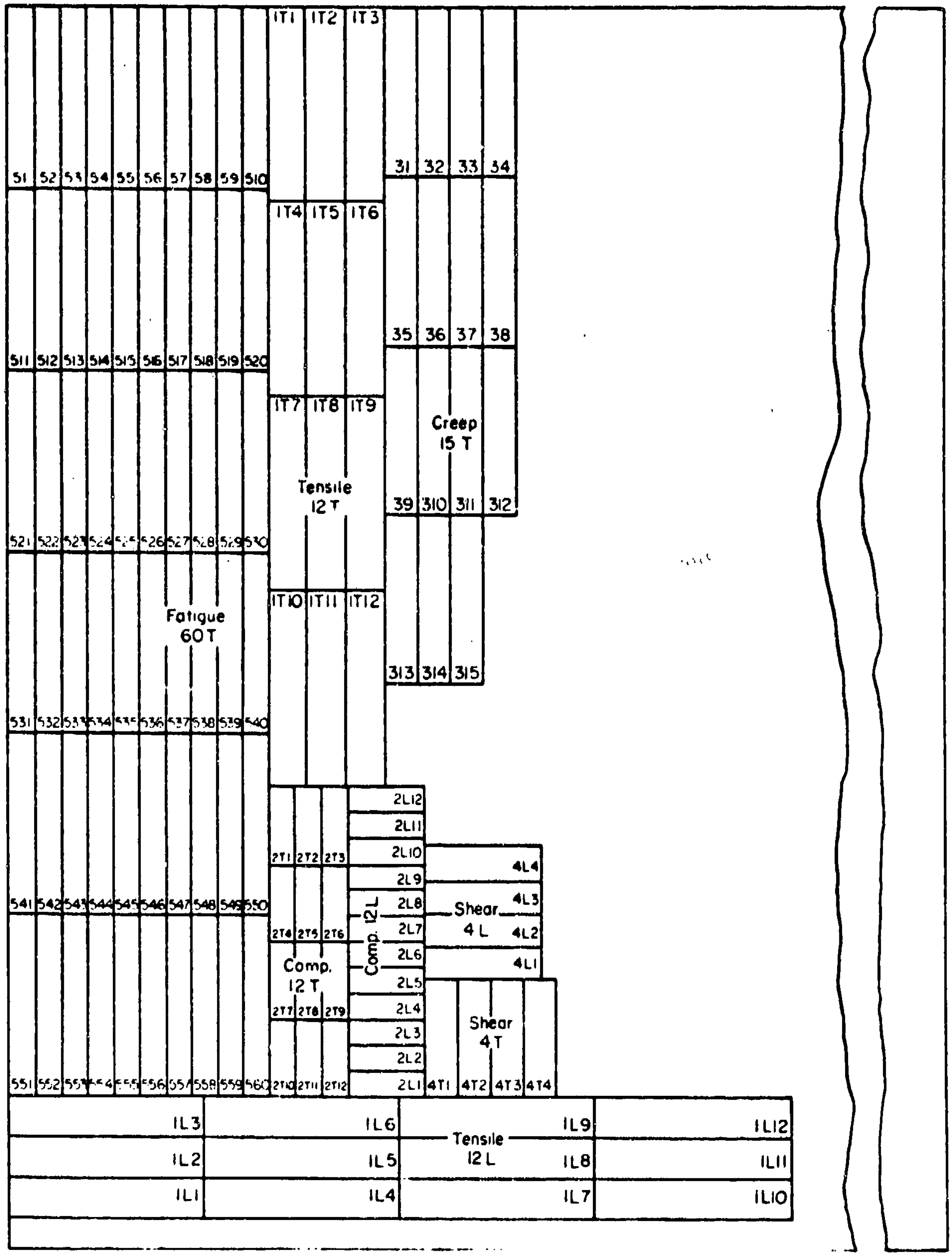


FIGURE 85. SPECIMEN LAYOUT FOR INCOLOY 903 SHEET

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.

Fatigue. 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.

Creep and Stress Rupture. Tests were conducted at 1000 F, 1200 F, and 1400 F for transverse specimens. Test results are given in Table LXXV. Log-stress 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.

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

Thermal Expansion. The coefficient of thermal expansion for this alloy is 5.6×10^{-5} in./in./F (RT to 1200 F)

Density. The density of this alloy is 0.294 $lb/in.^3$.

TABLE LXIX. TENSILE TEST RESULTS FOR HEAT-TREATED INCOLOY 903 SHEET

Specimen Number		Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, 10^3 ksi
		Longitudinal at Room Temperature			
1L-1		193.5	156.1	14.5	23.2
1L-2		191.2	156.0	13.5	26.3
1L-3		190.8	154.3	13.0	24.6
	Average	191.9	155.5	13.7	24.7
		Transverse at Room Temperature			
1T-1		194.4	168.5	16.0	27.7
1T-2		191.9	161.4	17.0	25.5
1T-3		192.7	165.2	15.0	24.2
	Average	193.0	165.0	16.0	25.8
		Longitudinal 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		170.9	139.0	17.6	21.0
	Average	170.7	140.8	17.3	21.6
		Transverse 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		171.9	140.2	15.5	21.4
	Average	170.1	142.6	15.8	22.2
		Longitudinal 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	21.4
	Average	166.6	134.8	17.2	22.2
		Transverse 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
		Longitudinal 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
		Transverse at 1200 F			
1T-10		131.9	120.3	17.5	20.1
1T-11		129.6	121.3	17.0	22.6
1T-12		133.4	119.7	17.5	20.7
	Average	131.6	120.4	17.3	21.1

TABLE LXX. COMPRESSION TEST RESULTS FOR HEAT-TREATED INCOLOY 903 SHEET

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^3 ksi
Longitudinal at Room Temperature			
2L-1		168.7	24.5
2L-2		168.0	25.2
2L-3		164.2	26.0
	Average	167.0	25.2
Transverse at Room Temperature			
2T-1		176.2	26.0
2T-2		174.6	24.0
2T-3		171.9	22.9
	Average	174.2	24.3
Longitudinal at 800 F			
2L-4		152.6	22.4
2L-5		152.0	24.3
2L-6		153.7	21.7
	Average	152.2	22.8
Transverse at 800 F			
2T-4		160.0	25.0
2T-5		159.0	22.2
2T-6		163.7	23.8
	Average	160.9	23.7
Longitudinal at 1000 F			
2L-7		138.7	21.6
2L-8		142.6	24.0
2L-9		143.0	23.5
	Average	141.4	23.0
Transverse at 1000 F			
2T-7		144.7	23.7
2T-8		144.5	21.9
2T-9		147.8	24.1
	Average	145.6	23.2
Longitudinal at 1200 F			
2L-10		122.7	21.1
2L-11		125.0	22.1
2L-12		119.7	20.9
	Average	122.5	21.4
Transverse at 1200 F			
2T-10		130.2	23.1
2T-11		124.8	22.0
2T-12		120.4	21.5
	Average	125.1	22.2

TABLE LXXI. SHEAR TEST RESULTS FOR HEAT-TREATED INCOLOY 903 SHEET AT ROOM TEMPERATURE

Specimen Number		Ultimate Shear Strength, ksi
	Longitudinal	
4L-1		124.4
4L-2		119.6
4L-3		127.8
	Average	123.9
	Transverse	
4T-1		127.3
4T-2		127.4
4T-3		125.6
	Average	127.8

TABLE LXXII. FRACTURE TOUGHNESS TEST RESULTS (T-L) FOR HEAT-TREATED INCOLOY 903 SHEET AT ROOM TEMPERATURE

Specimen Number	Thickness, B, inch	Width, w, inch	Maximum Stress, ksi	Initial Precrack, inches	Apparent SIF, K_{app}, ksi-in.$^{1/2}$	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

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

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	160	100
5-2	150	3,000
5-3	140	12,800
5-4	130	92,100
5-5	120	198,200
5-6	110	462,100
5-7	100	528,790
5-8	90	4,683,200
5-9	80	10,000,000[a]
	800 F	
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
5-18	70	11,402,000[a]
	1000 F	
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
5-28	65	10,000,000[a]

(a) Did not fail.

TABLE LXXIV. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE, R = 0.1)

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[a]
	800 F	
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[a]
	1000 F	
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]

(a) Did not fail.

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

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hours	Elongation in 2 Inches, percent	Minimum Creep Rate, percent
			0.1	0.2	0.5	1.0	2.0				
3-1	66	1000	--	--	--	--	--	20.205	31.4	22.3	--
3-2	50	1000	--	--	--	--	--	2.863	49.2	4.6	(a)
3-3	40	1000	--	--	--	0.2	--	0.907	196.3(c)	2.8	(a)
3-4	30	1000	--	--		--	--	0.053	1510.7(c)	-0.102	(a)
3-6	60	1200	--	--	--	--	--	0.379	6.2(b)	1.9	(a)
3-5	50	1200	--	--	--	--	--	0.397	68.0(c)	0	(a)
3-8	40	1200	--	--	--	--	--	0.132	1080.7	0.149	nil
3-7	40	1400	4	10	20	28	--	0.400	38.9	8.8	0.013
3-9	20	1400	20	55	150	150	290	0.144	456.0	16.3	0.0022

(a) Negative creep occurred.

(b) Failed through pin hole.

(c) Test discontinued.

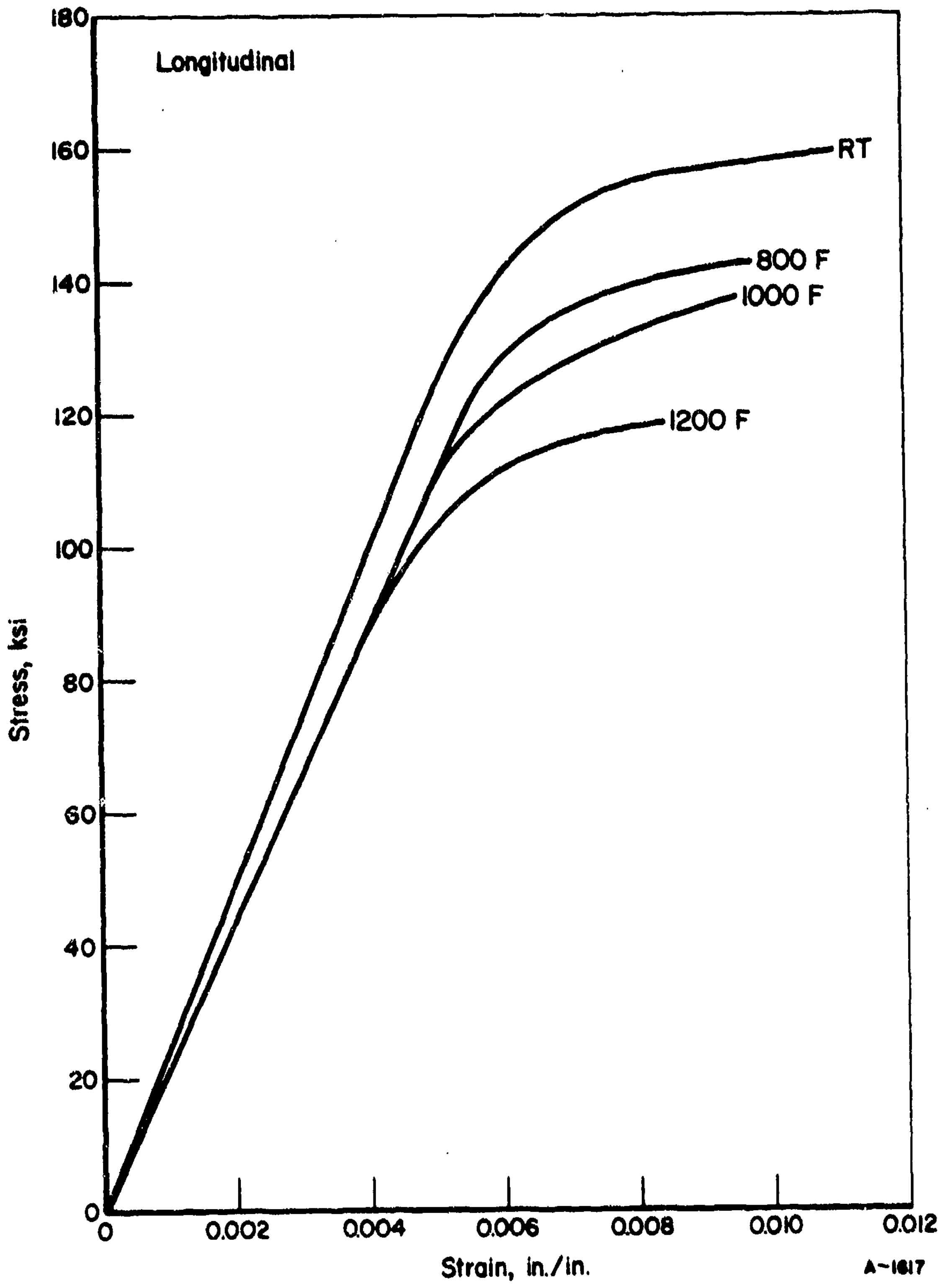


FIGURE 86. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR HEAT-TREATED INCOLOY 903 SHEET (LONGITUDINAL)

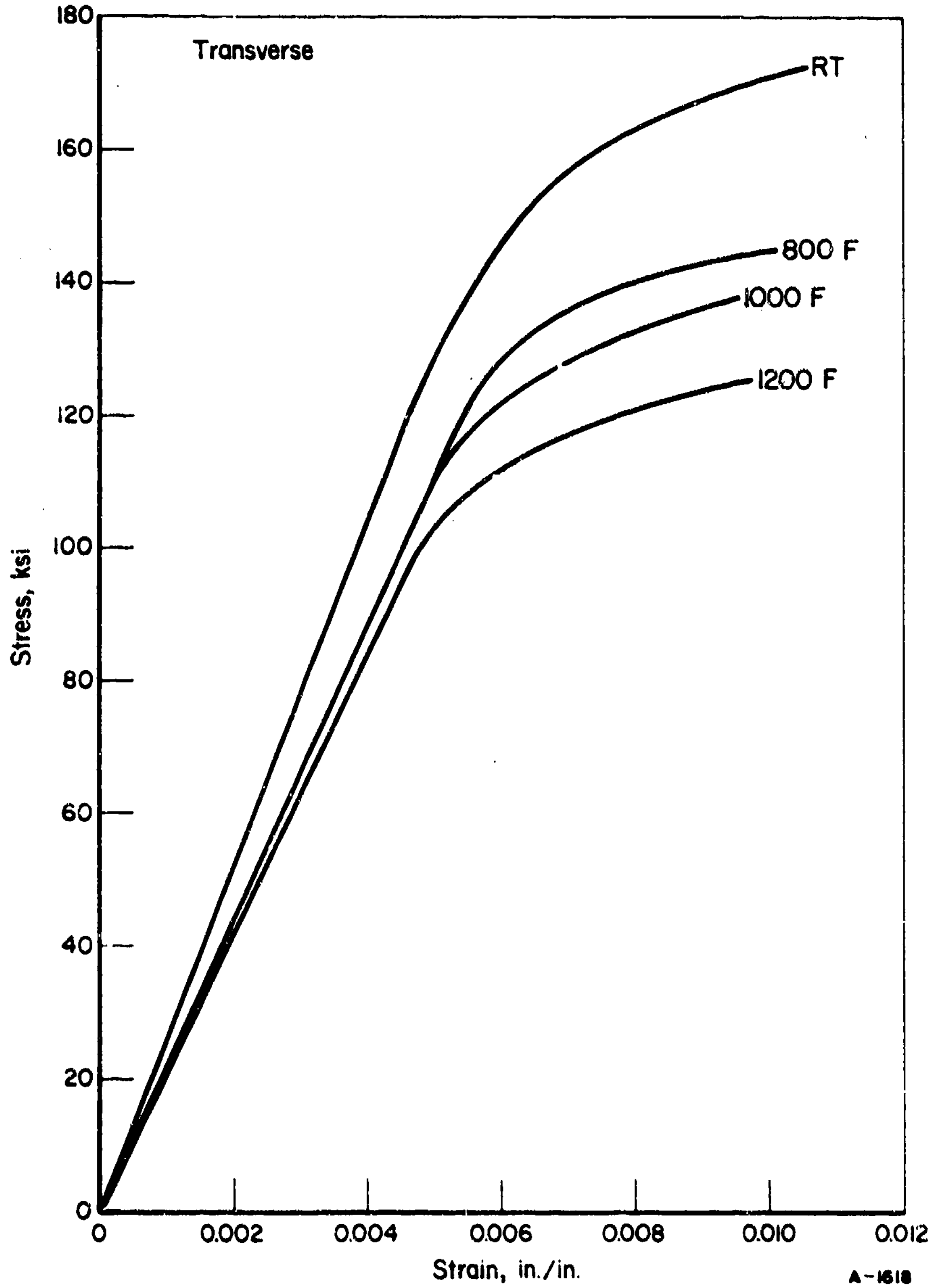


FIGURE 87. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE)

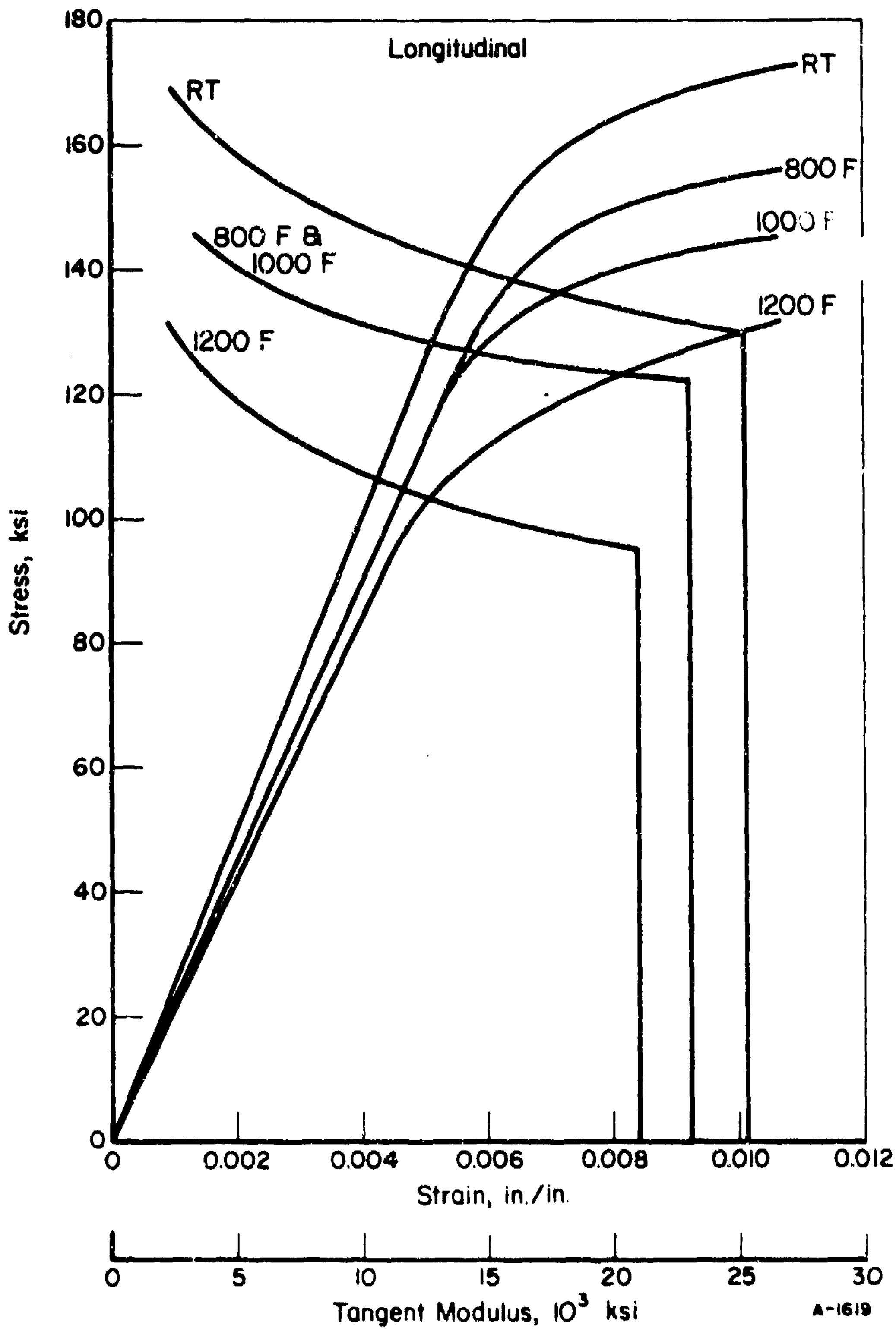


FIGURE 88. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR HEAT-TREATED INCOLOY 903 SHEET (LONGITUDINAL)

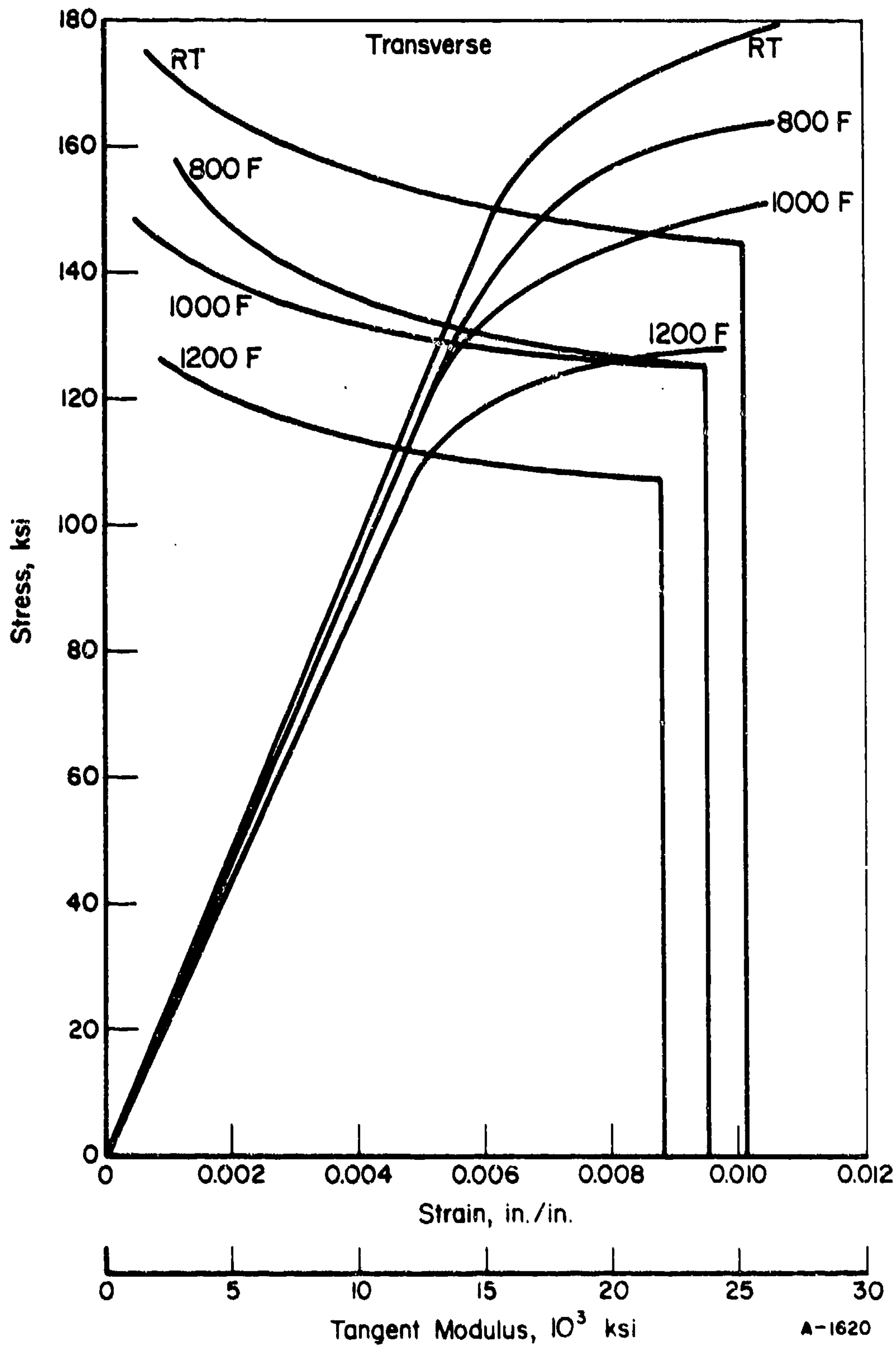


FIGURE 89. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE)

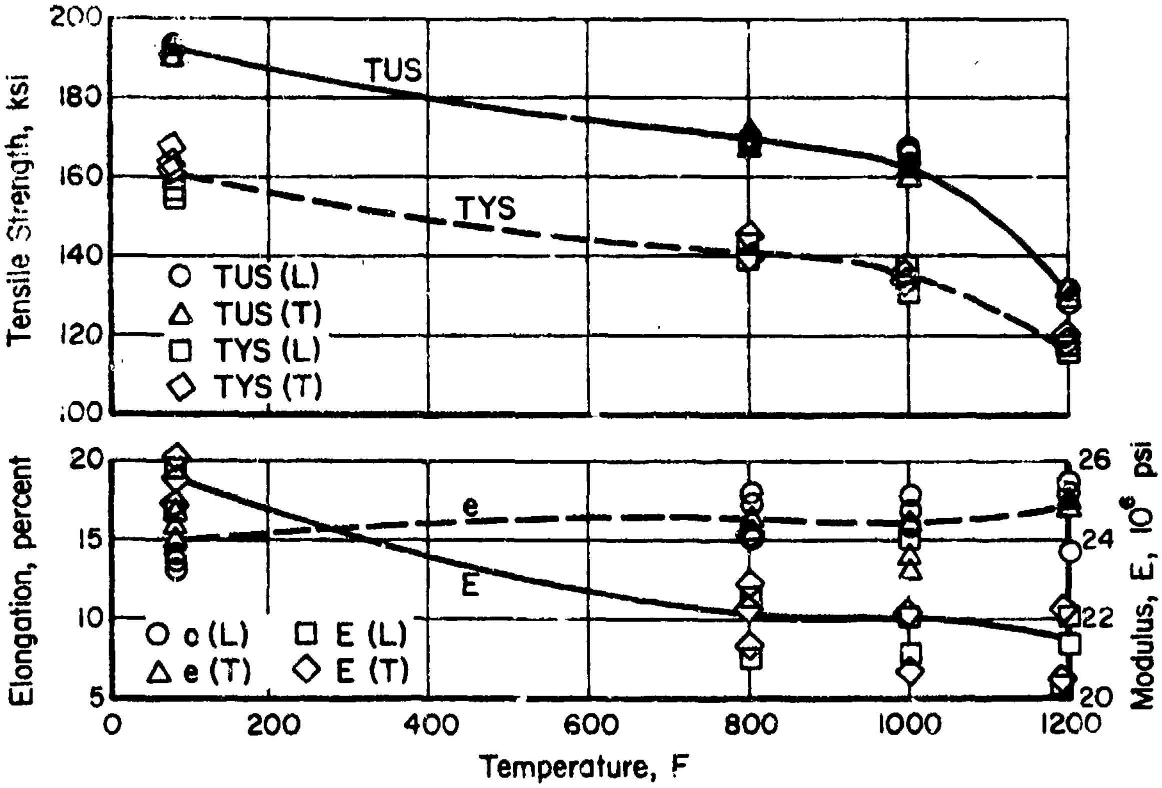


FIGURE 90. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHEET

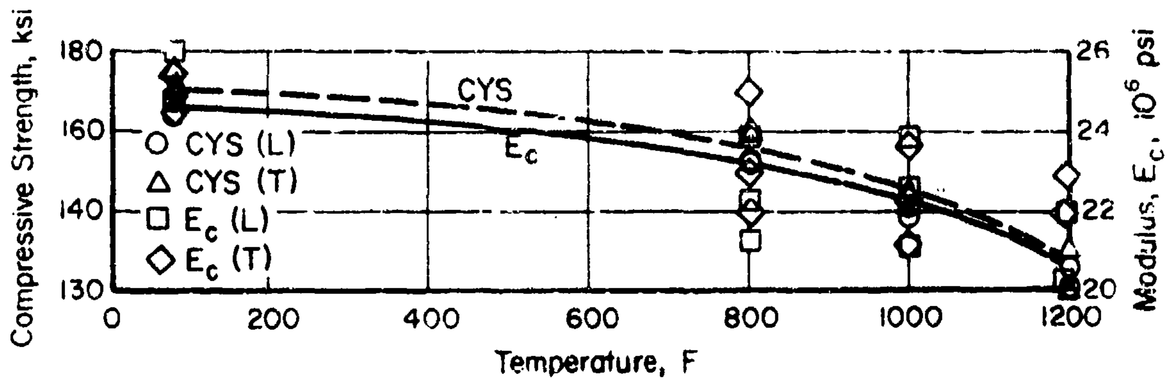


FIGURE 91. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHEET

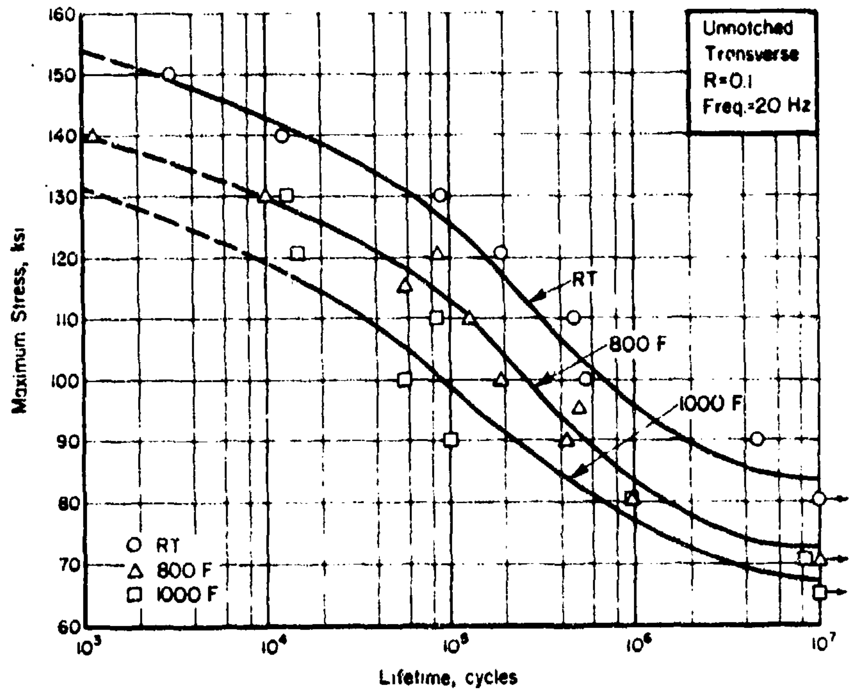


FIGURE 92. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED HEAT-TREATED INCOLOY 903 SHEET

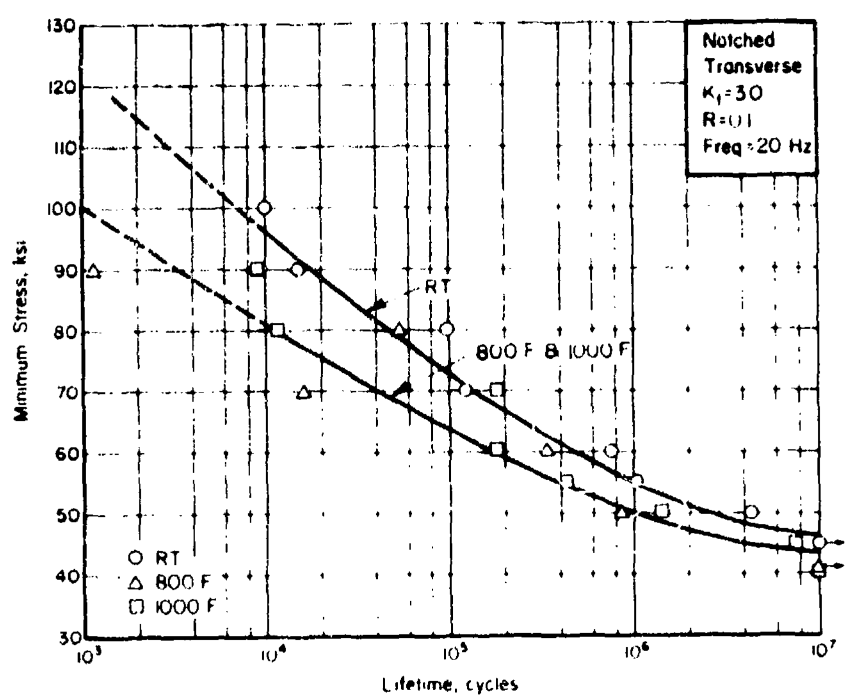


FIGURE 93. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) HEAT-TREATED INCOLOY 903 SHEET

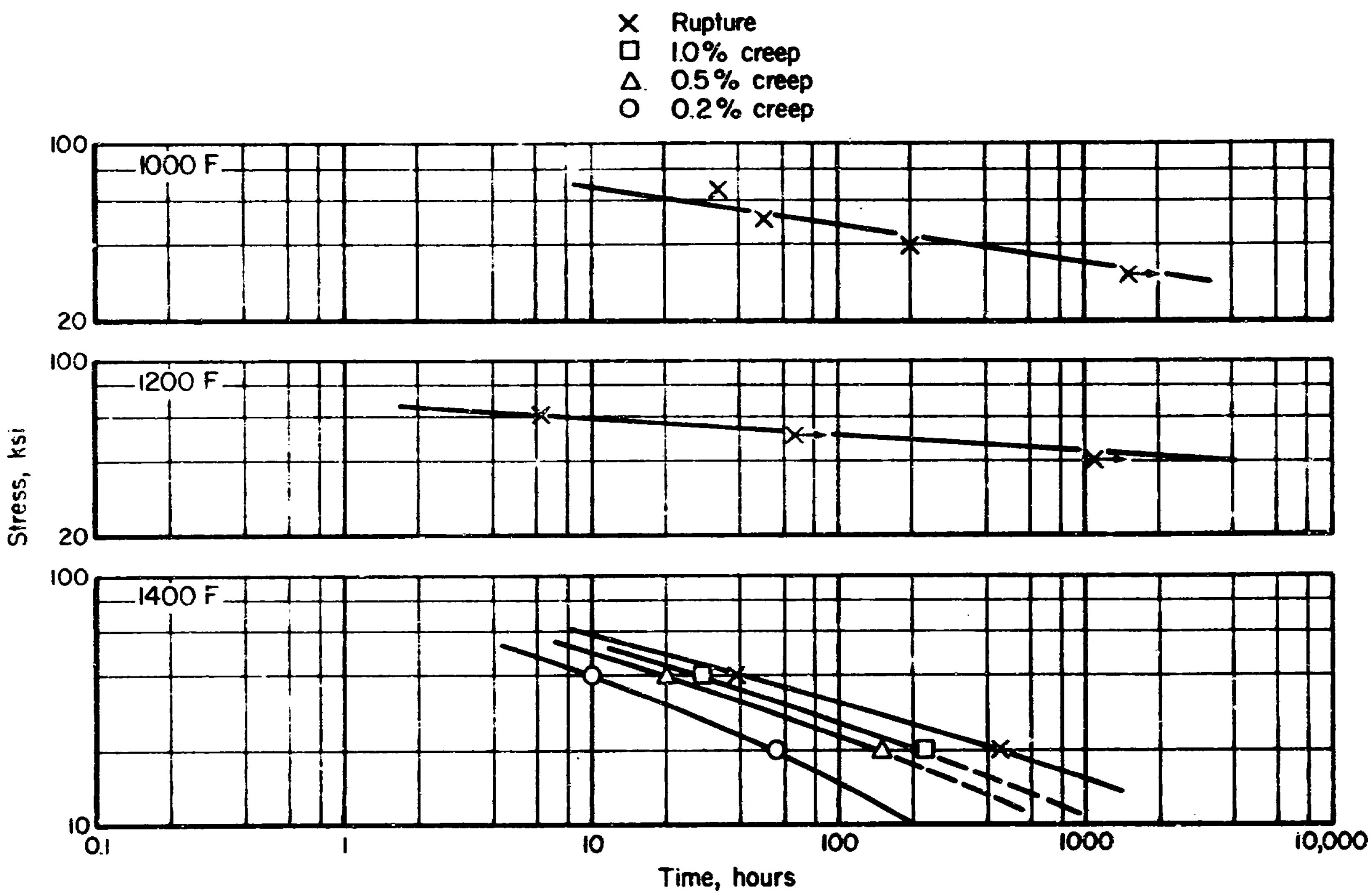


FIGURE 94. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE)

201.0 T7 Aluminum Castings

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.

Fatigue. 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.

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.

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

Thermal Expansion. The coefficient of thermal expansion is 13.2×10^{-6} in./in./F.

Density. The density of this alloy is 0.101 $lb./in.^3$.

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

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

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

Specimen Number		0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^3 ksi
		Room Temperature	
2-1		62.0	11.1
2-2		61.6	11.2
2-3		59.0	10.9
	Average	60.9	11.1
		300 F	
2-4		55.8	9.8
2-5		52.0	10.1
2-6		53.0	10.0
	Average	53.6	9.9
		400 F	
2-7		52.0	9.6
2-8		46.0	9.9
2-9		46.6	9.7
	Average	48.2	9.7
		500 F	
2-10		33.1	9.1
2-11		29.7	8.9
2-12		30.0	8.9
	Average	30.9	9.0

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

Specimen Number		Ultimate 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

TABLE LXXX. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 201-T7 ALUMINUM ALLOY CASTINGS

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
5-8	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[a]
	300 F	
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[b]
5-19	25.0	11,538,190[a]
	400 F	
5-20	60.0	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

(a) Did not fail.

(b) Failed at Radius.

TABLE LXXXI. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) 201-T7 ALUMINUM ALLOY CASTINGS

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-31	40.0	7,500
5-32	30.0	21,600
5-34	25.0	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(a)
	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(a)
	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.

TABLE LXXXII. SUMMARY CREEP AND RUPTURE DATA FOR 201-T7 ALUMINUM ALLOY CASTINGS

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, percent: 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hours	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent
3-3	60	300	--	--	--	--	--	2.710	0.1	8.9	22.4	--
3-4	50	"	0.15	0.50	3.1	11	36	0.674	77.8	7.4	26.4	0.037
3-5	46	"	10	80	1150	1900 (a)	--	0.507	1363.2 (b)	1.315	--	0.0004
8-8	40	"	60	1375	5650 (a)	--	--	0.574	1325.4 (b)	0.770	--	0.00007
3-10	50	400	--	--	--	--	--	2.655	0.02	12.6	41.1	--
3-12	42	"	0.17	1.0	5	17	29	0.541	34.8	5.9	10.1	0.055
3-9	35	"	17	62	180	275	325	0.367	333.7	3.7	3.9	0.0023
3-2	25	"	125	410	1475 (a)	3165 (a)	--	0.274	1033.1 (b)	0.655	--	0.00028
3-7	20	500	0.2	0.6	1.6	3.5	5.4	0.274	6.7	8.2	27.0	0.25
3-1	10	500	12	52	160	277	352	0.141	416.6	14.1	54.5	0.0027
3-6	6.5	"	105	310	1200 (a)	--	--	0.118	527.3 (b)	0.397	--	0.00032
3-11	4.5	"	200	1000	--	--	--	0.056	984.5 (b)	0.255	--	0.00008

(a) Estimate.

(b) Test discontinued.

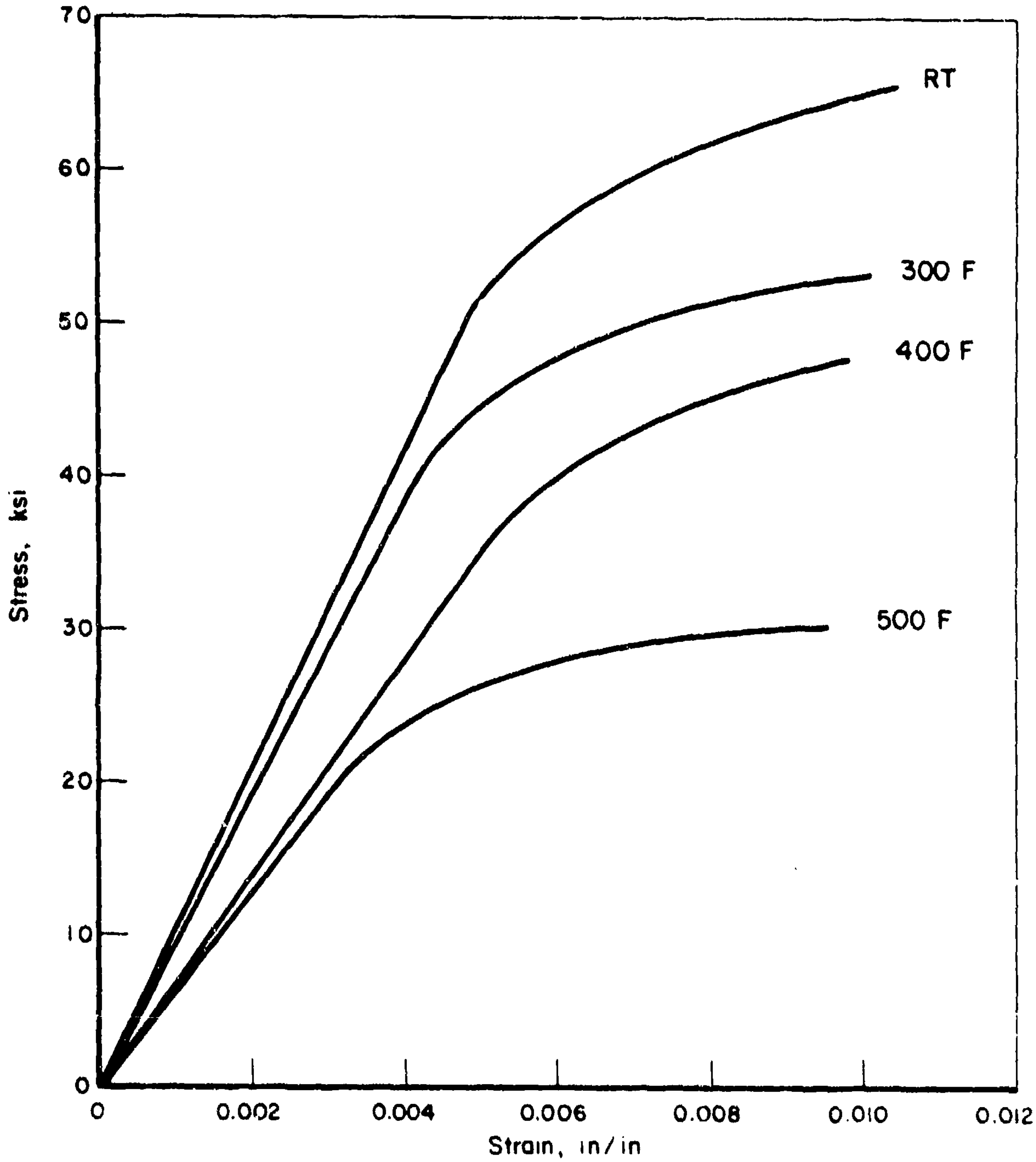


FIGURE 95. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 201-T7 ALUMINUM ALLOY CASTINGS

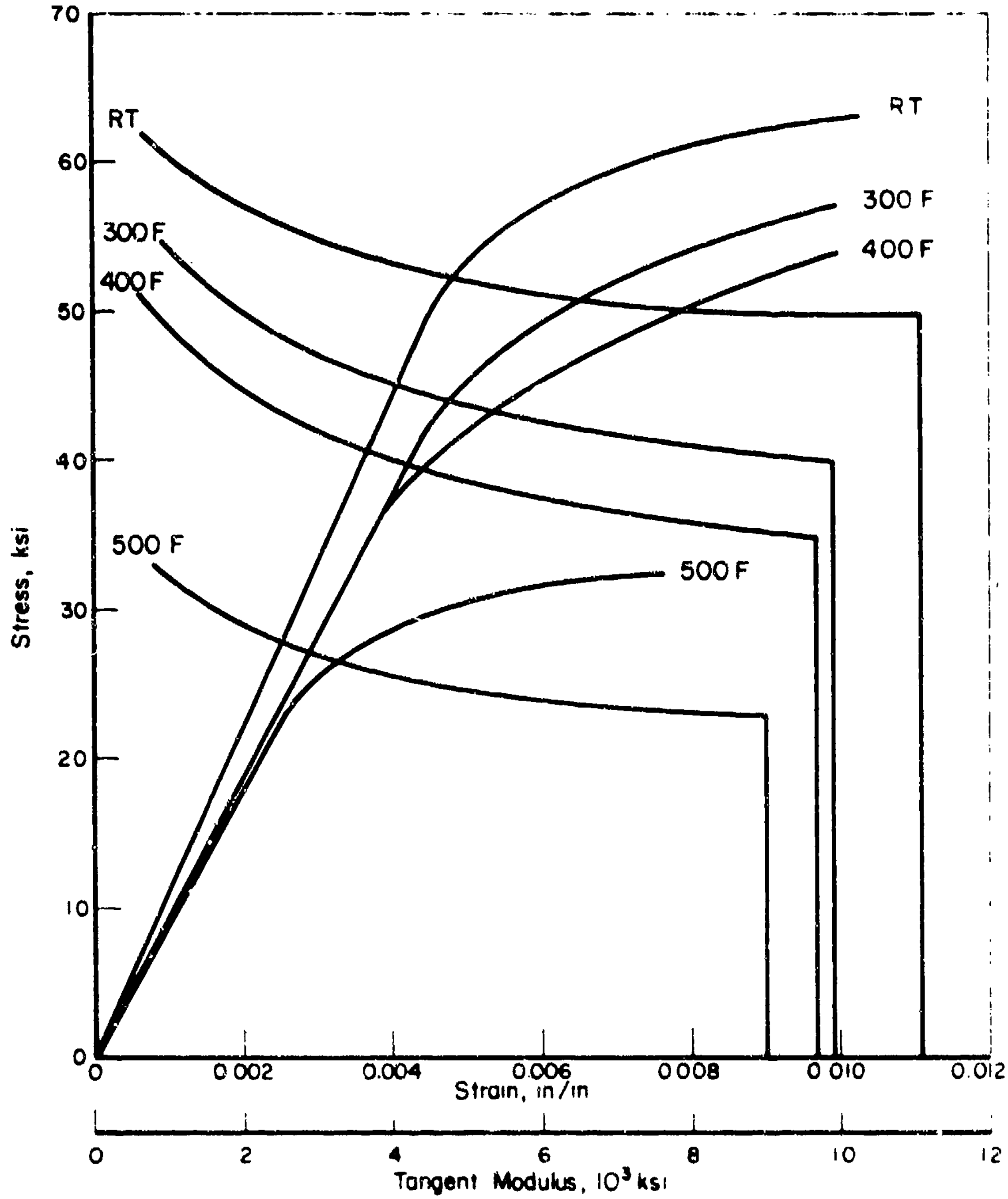


FIGURE 96. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 201-T7 ALUMINUM ALLOY CASTINGS

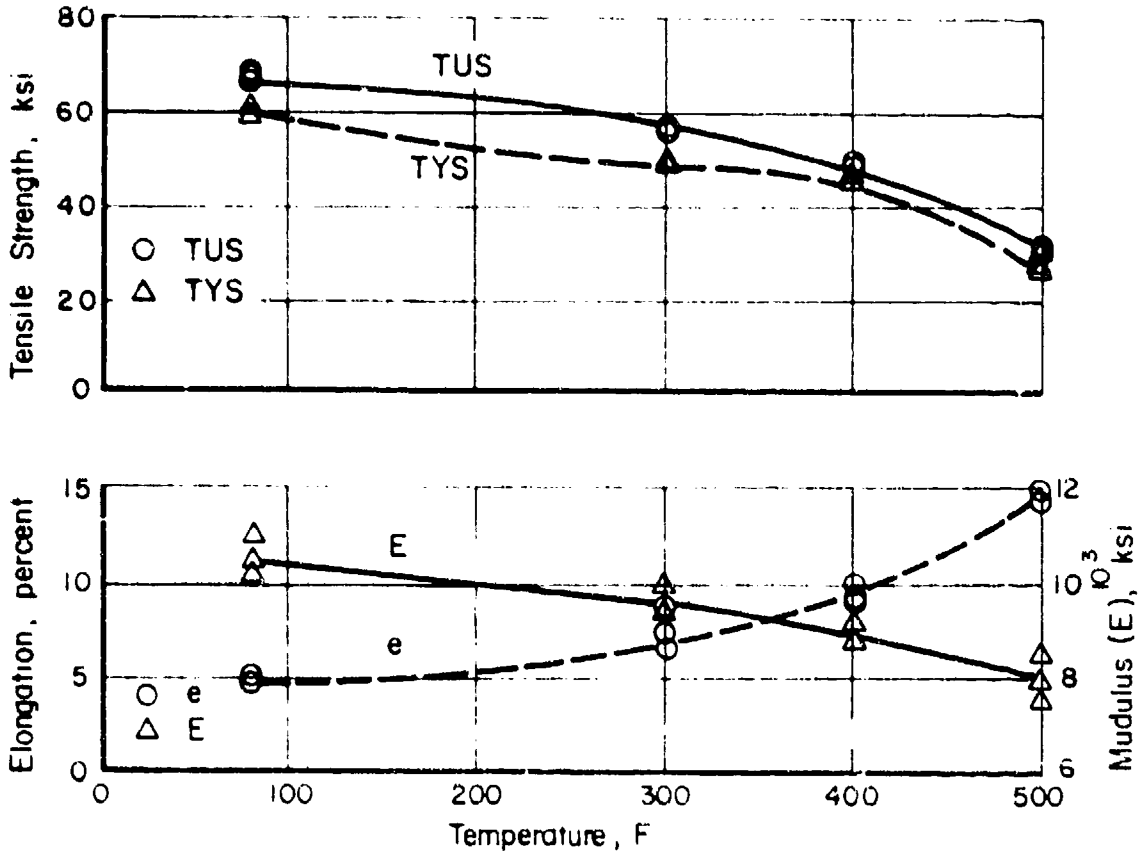


FIGURE 97. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 201-T7 ALUMINUM ALLOY CASTINGS

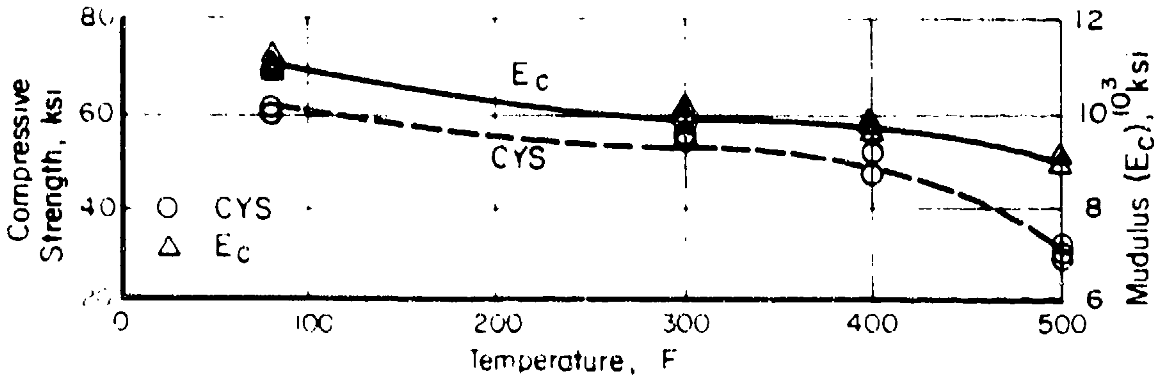


FIGURE 98. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 201-T7 ALUMINUM ALLOY CASTINGS

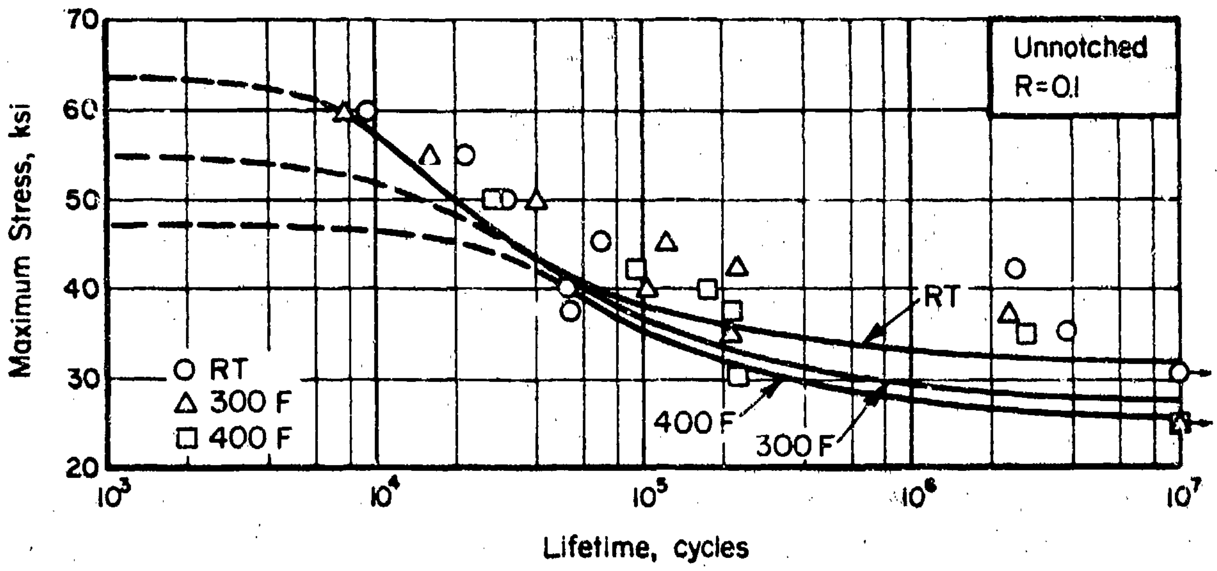


FIGURE 99. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 201-T7 ALUMINUM ALLOY CASTING

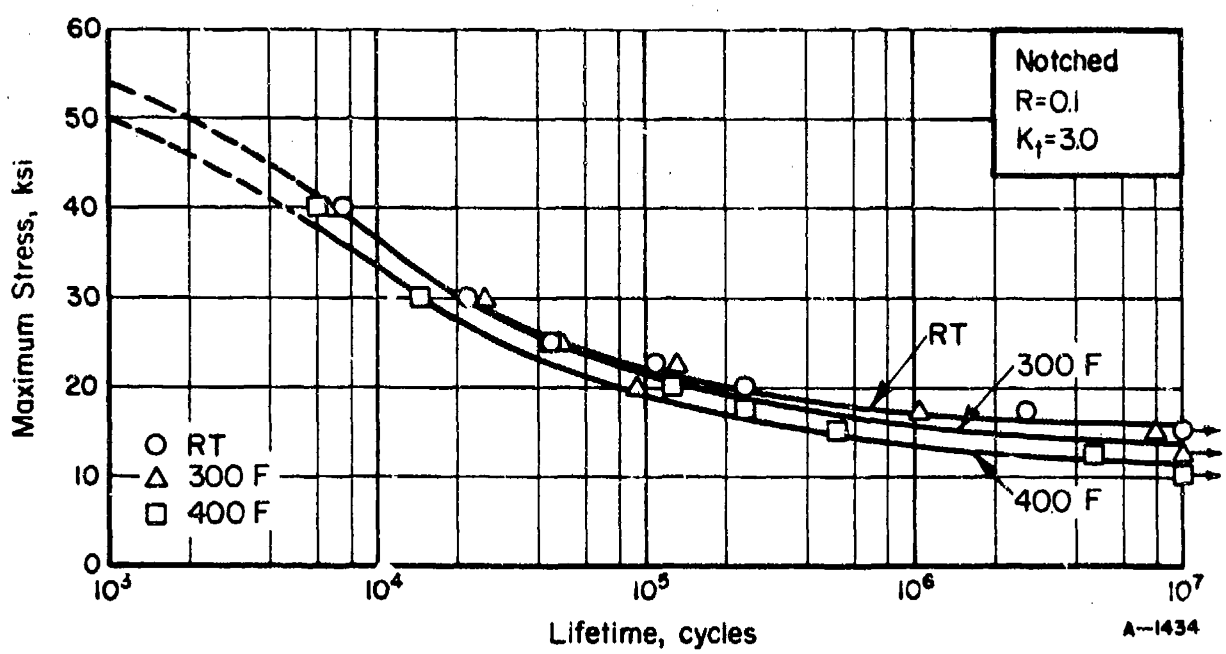


FIGURE 100. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) 201-T7 ALUMINUM ALLOY CASTINGS

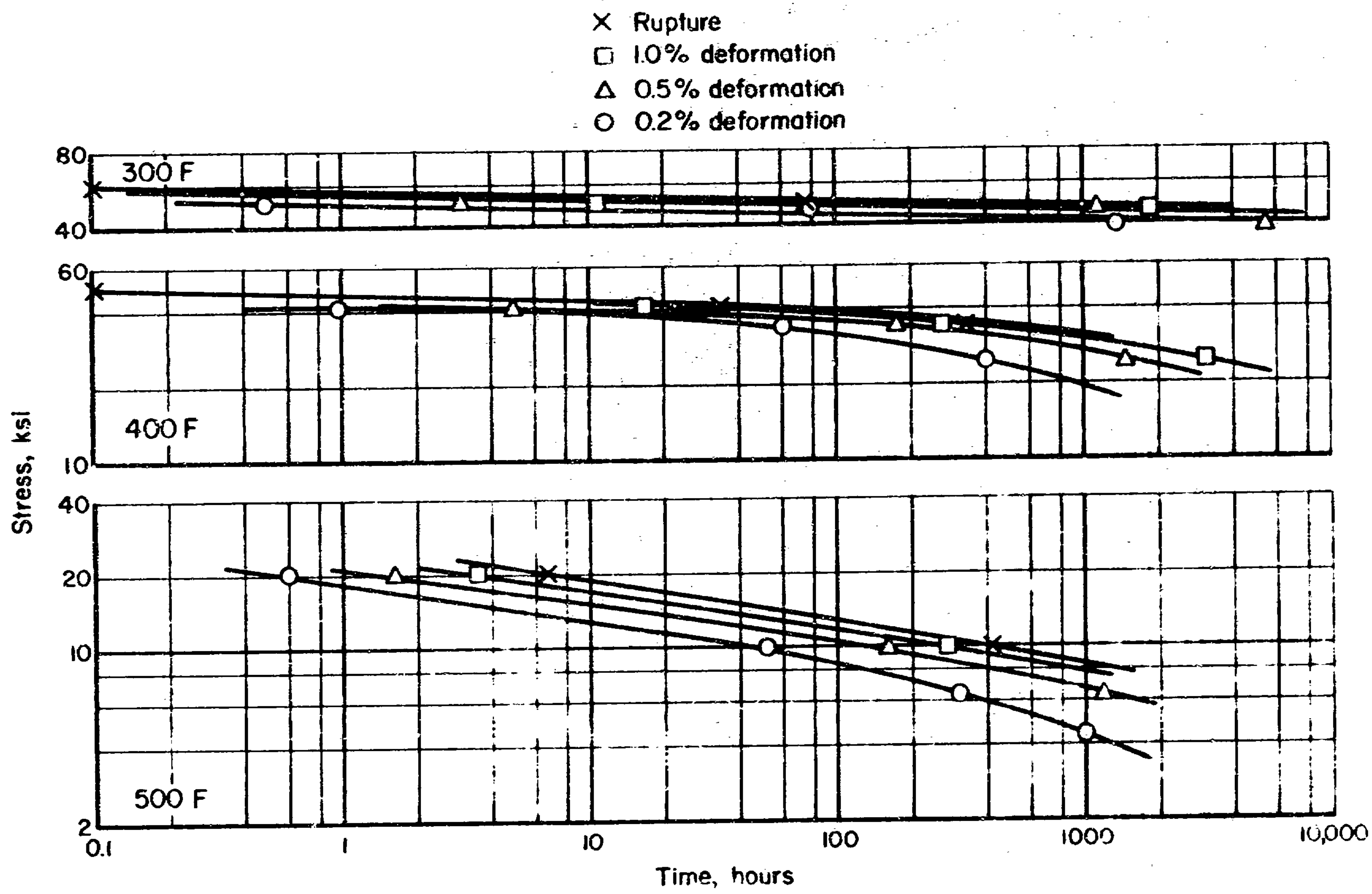


FIGURE 101. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR 201-T7 ALUMINUM ALLOY CASTINGS

DISCUSSION OF PROGRAM RESULTS

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 newer alloy is open to question. Many criteria, such as forming characteristics, oxidation 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_t = 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.

TABLE LXXXIII. FATIGUE STRENGTHS AT ROOM TEMPERATURE FOR PROGRAM ALLOYS

Alloy	Fatigue Strength at 10^7 cycles, ksi	
	Unnotched	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
Ti-6-2-2-2-2	76	40

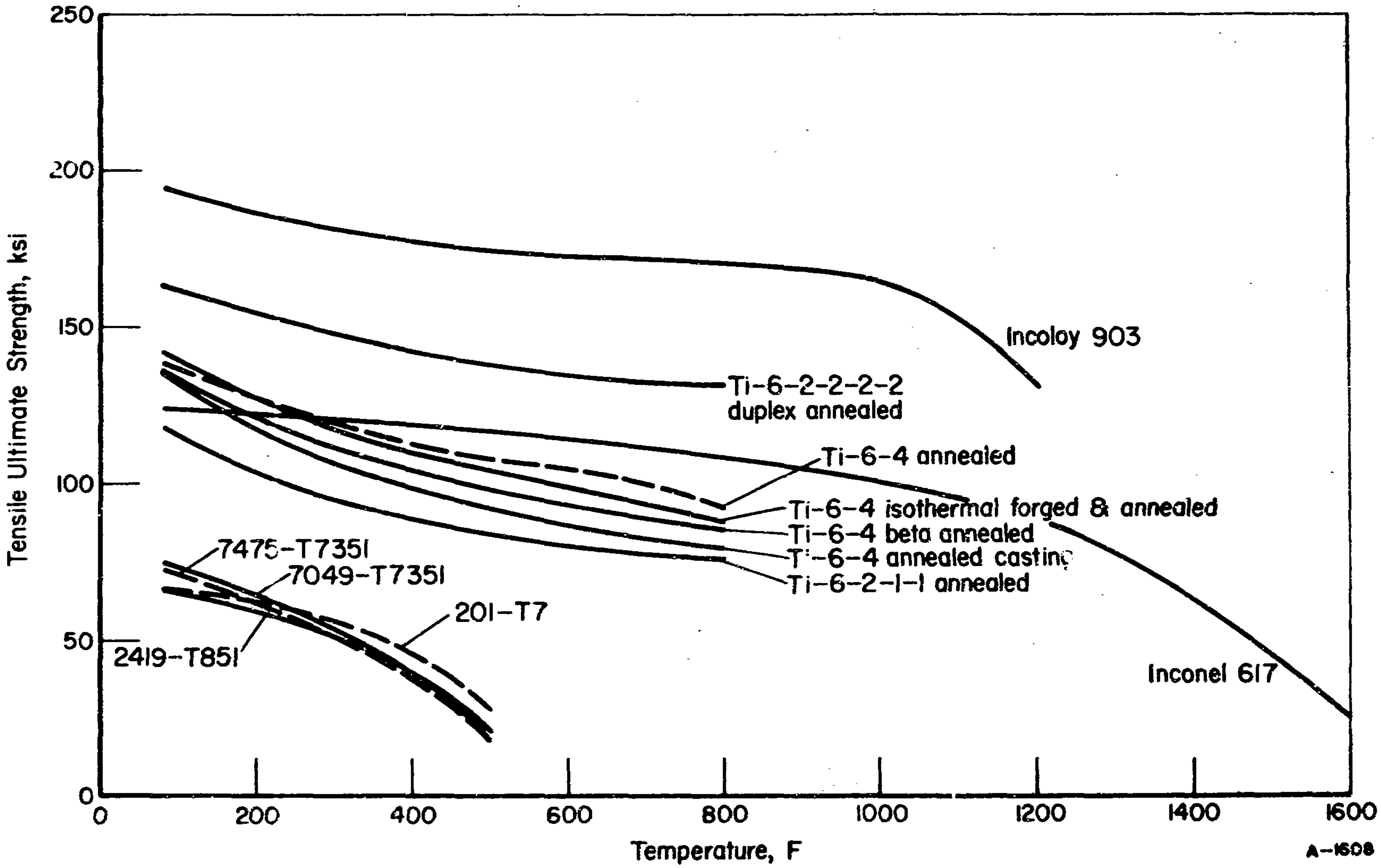


FIGURE 102. TENSILE ULTIMATE STRENGTH AS A FUNCTION OF TEMPERATURE

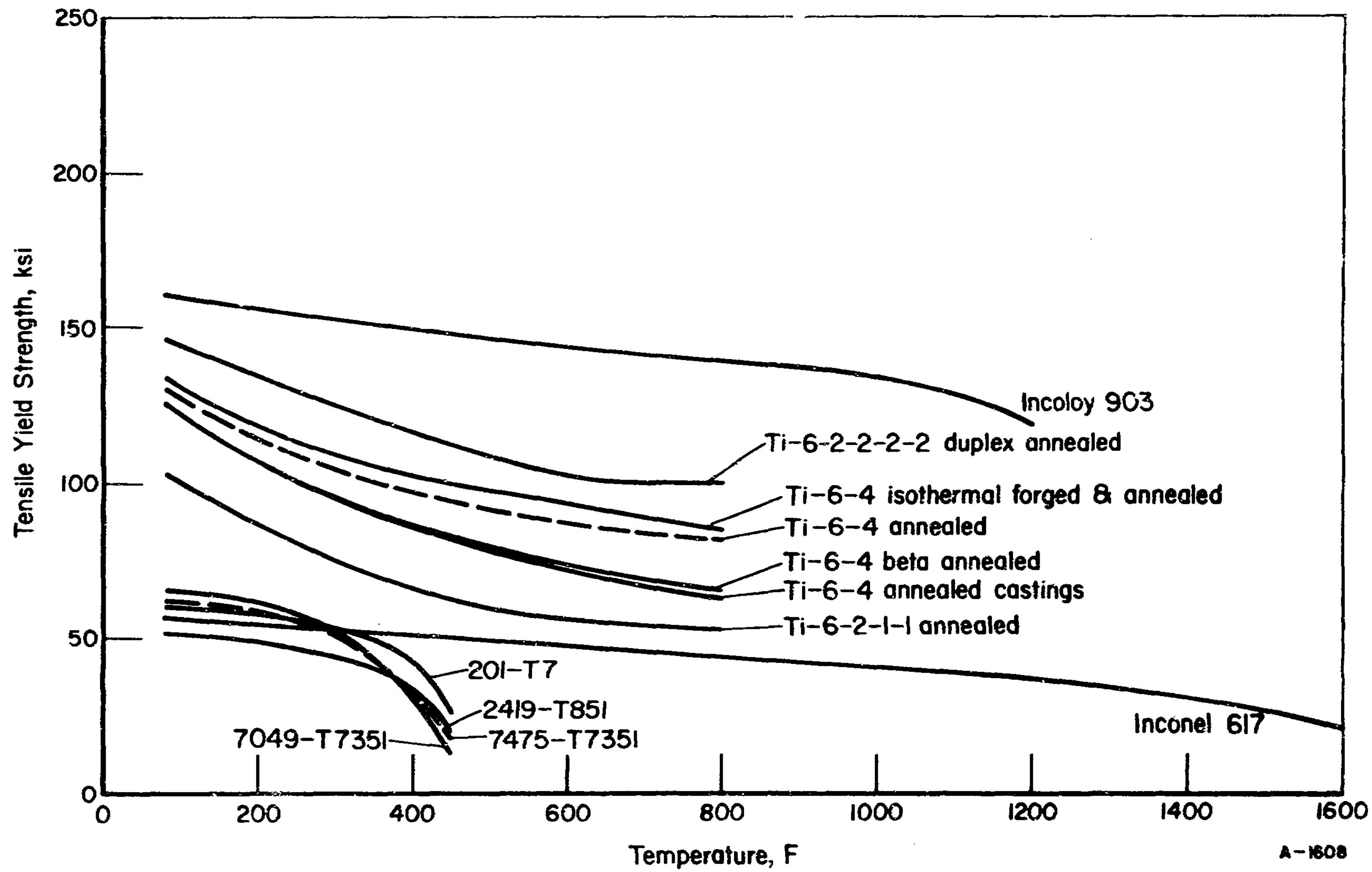


FIGURE 103. TENSILE YIELD STRENGTH AS A FUNCTION OF TEMPERATURE

CONCLUSIONS

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-6Al-2Zr-2Sn-2Mo-2Cr duplex-annealed forging
(6) Ti-6Al-2Cb-1Ta-1Mo annealed plate
(7) Ti-6Al-4V beta-annealed plate
(8) Ti-6Al-4V annealed castings
(9) Ti-6Al-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.

APPENDIX I

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_t

(d) Reduction in area, RA

(e) Modulus of elasticity, E_t.

(2) Compression

(a) Compressive yield strength, CYS

(b) Modulus of elasticity, E_c.

(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

---

* "R" represents the algebraic ratio of the minimum stress to the maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" 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) Stress 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

Assigned Number	Test Type
7	Stress corrosion
8	Thermal expansion
9	Bend
10	Impact
11	Density

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 integral 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 elevated 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 until fracture.

Compression

Procedures for conducting compression tests are outlined in ASTM Method E9-70 along with temperature control provisions of E-21-70. All sheet and thin plate tests were carried out in Baldwin Universal testing machines using a North American type compression fixture as shown in Reference 7. 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-Alumel 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 extensometer 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 shear strength.

Bend

The procedures for conducting bend tests are described in Report MAB-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 for 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 ± 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 stress-corrosion 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

σ = 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.

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 x 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 $\pm$ 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 Lepel 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 10^3 and 10^7 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 electro-hydraulic 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 method of the ASTM procedure.

The thin sheet center through-crack tension panels were initially saw-cut 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

$$.002\ E < \dot{S} < .005\ E \text{ ksi/min}$$

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

APPENDIX II

SPECIMEN DRAWINGS

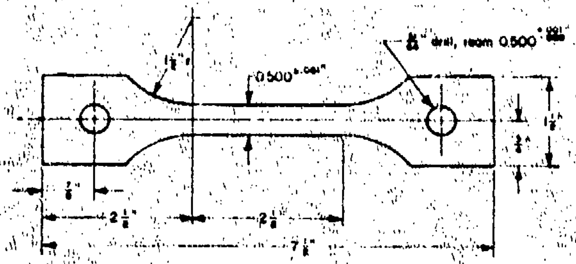


FIGURE 104. SHEET AND THIN-PLATE TENSILE SPECIMEN

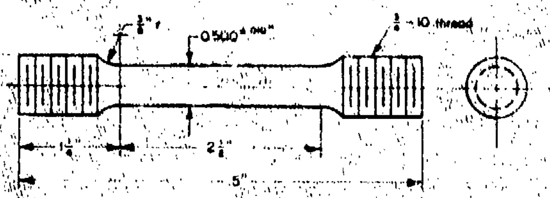


FIGURE 105. ROUND TENSILE SPECIMEN

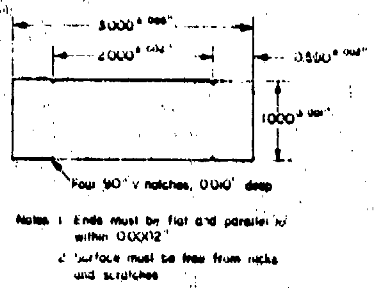


FIGURE 106. SHEET COMPRESSION SPECIMEN

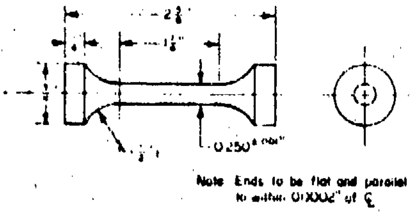


FIGURE 107. ROUND COMPRESSION SPECIMEN

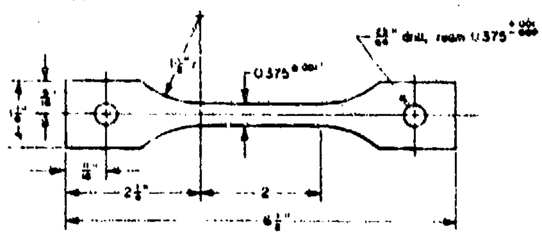
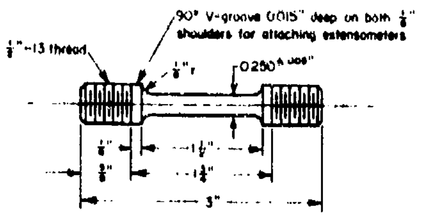


FIGURE 108. SHEET CREEP – AND STRESS-RUPTURE SPECIMEN



A-1363

FIGURE 109. ROUND CREEP – AND STRESS-RUPTURE SPECIMEN

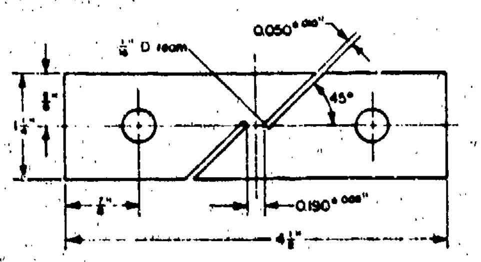


FIGURE 110 SHEET SHEAR TEST SPECIMEN

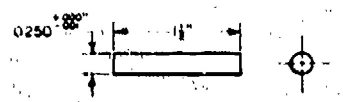


FIGURE 111. PIN SHEAR SPECIMEN

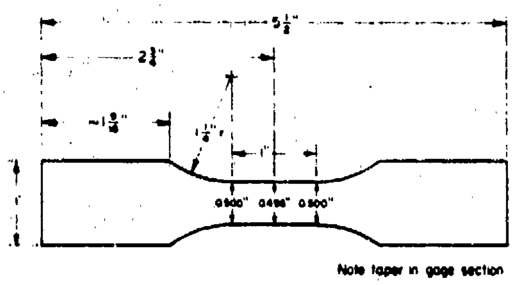


FIGURE 112. UNNOTCHED SHEET FATIGUE SPECIMEN

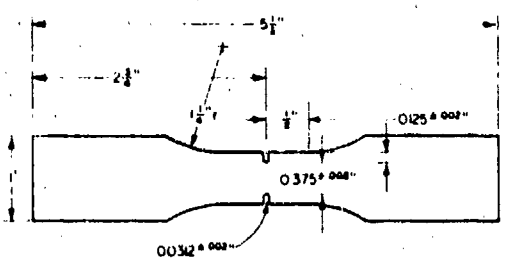


FIGURE 113. NOTCHED SHEET FATIGUE SPECIMEN

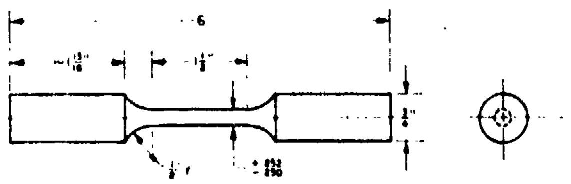


FIGURE 114. UNNOTCHED ROUND FATIGUE SPECIMEN

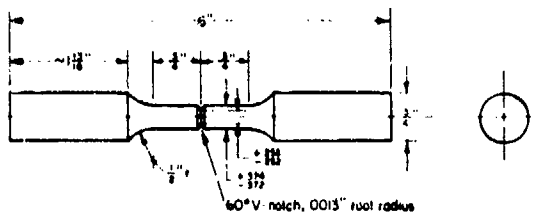


FIGURE 115. NOTCHED ROUND FATIGUE SPECIMEN

A-1226

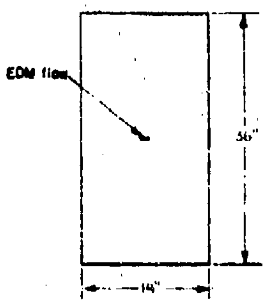


FIGURE 116. SHEET FRACTURE TOUGHNESS SPECIMEN

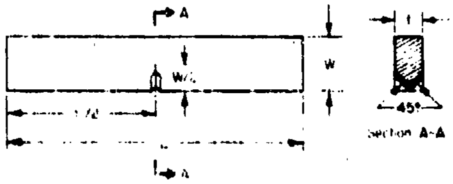


FIGURE 117. SLOW BEND FRACTURE TOUGHNESS SPECIMEN

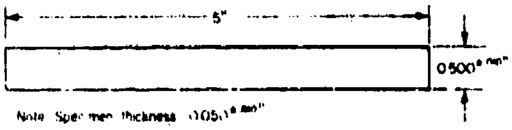


FIGURE 118. STRESS-CORROSION SPECIMEN

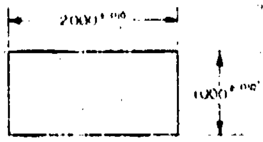


FIGURE 119. THERMAL-EXPANSION SPECIMEN

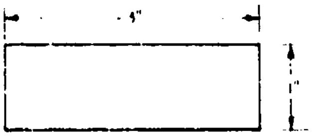
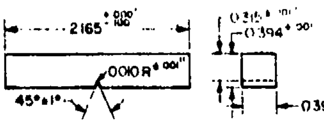


FIGURE 120. SHEET BEND SPECIMEN



A-1365

FIGURE 121. NOTCHED IMPACT SPECIMEN

APPENDIX III

DATA SHEETS

MECHANICAL-PROPERTY DATA
7049-T7351 ALUMINUM ALLOY

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

7049-T7351 Aluminum Plate

Material Description

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:

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

Processing and Heat Treating

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

7049-T7351 Alloy Data[a]

Thickness: 3-inch plate

Property	Temperature, F RT	250	350	500
Tension				
TUS (longitudinal), ksi	75.5	59.0	45.4	13.1
TUS (transverse), ksi	74.6	60.8	47.0	17.2
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	31.8
e (transverse), percent in 2 in.	10.7	15.5	17.3	28.8
RA (longitudinal), percent	36.1	53.5	64.9	86.3
RA (transverse), percent	25.6	43.4	54.6	83.2
E (longitudinal), 10^3 ksi	10.2	9.3	8.0	6.0
E (transverse), 10^3 ksi	10.4	9.5	8.4	5.7
Compression				
CYS (longitudinal), ksi	64.1	56.8	44.4	16.7
CYS (transverse), ksi	69.2	59.8	47.5	17.0
E_c (longitudinal), 10^3 ksi	10.8	9.4	8.1	6.9
E_c (transverse), 10^3 ksi	10.9	9.7	8.3	7.0
Shear[b]				
SUS (longitudinal), ksi	46.1	U[c]	U	U
SUS (transverse), ksi	45.4	U	U	U
Impact[d]				
V-notch Charpy, ft.lb.				
(longitudinal)	5.8	U	U	U
(transverse)	3.3	U	U	U
Fracture Toughness[e]				
K_{Ic} (L-T), ksi $\sqrt{in.}$	34.0	U	U	U
K_{Ic} (T-L), ksi $\sqrt{in.}$	28.1	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^5 cycles, ksi	65	60	47	U
10^6 cycles, ksi	44	39	36	U
10^7 cycles, ksi	35	26	23	U
Notched, K_t = 3.0, R = 0.1				
10^5 cycles, ksi	55	53	53	U
10^6 cycles, ksi	19	17	17	U
10^7 cycles, ksi	11	10	10	U

7049-T7351 Alloy Data
(Continued)

Property	RT	Temperature, F 250	350	500
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA(c)	32	11	3
0.2% plastic deformation, 1000 hr, ksi	NA	24	6	2
Stress Rupture (transverse)				
Rupture, 100 hr, ksi	NA	42	18	6
Rupture, 1000 hr, ksi	NA	37	12	4
Stress Corrosion (transverse)(g)	No Cracks			
80% TYS, 1000 hr maximum				
Coefficient of Thermal Expansion				
12.9×10^{-6} in./in./F (70 to 212 F)				
Density				
0.099 $lb./in.^3$				

(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 6L and 6T tests.

(e) Specimens were slow-bend type 1-inch thick x 2-inches wide with a span of 8 inches. K_{Ic} 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.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2 NaCl

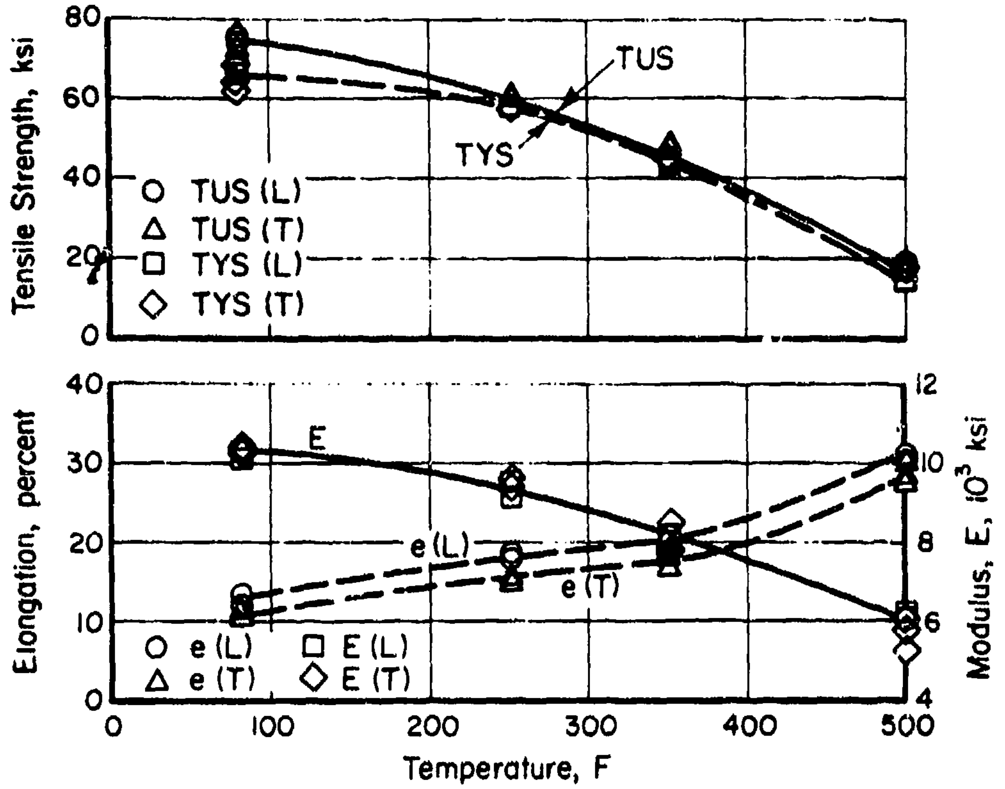


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE

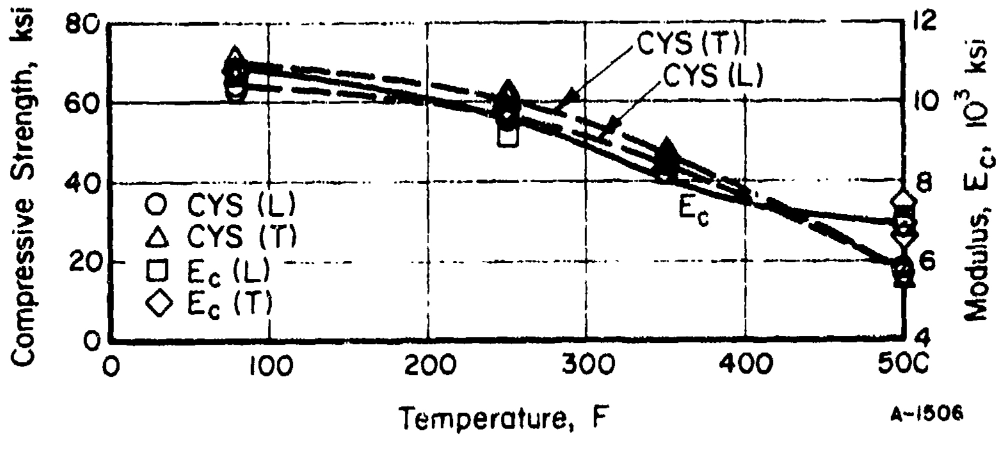


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T7351 ALUMINUM ALLOY PLATE

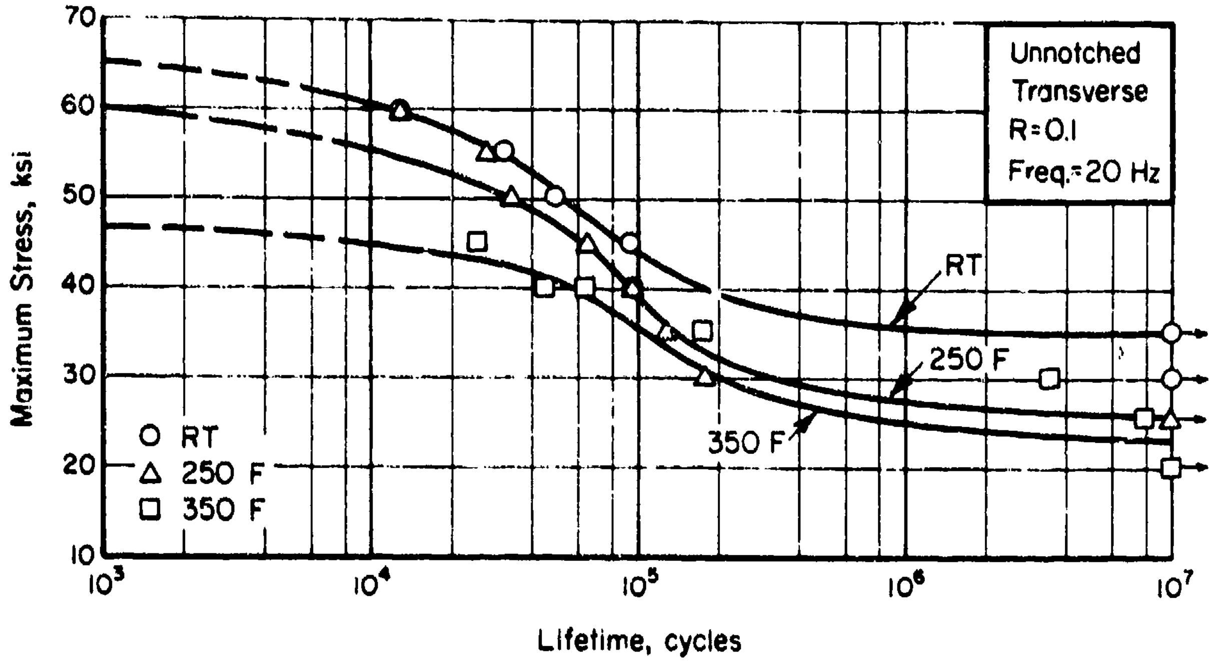


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7049-T7351 ALUMINUM ALLOY PLATE

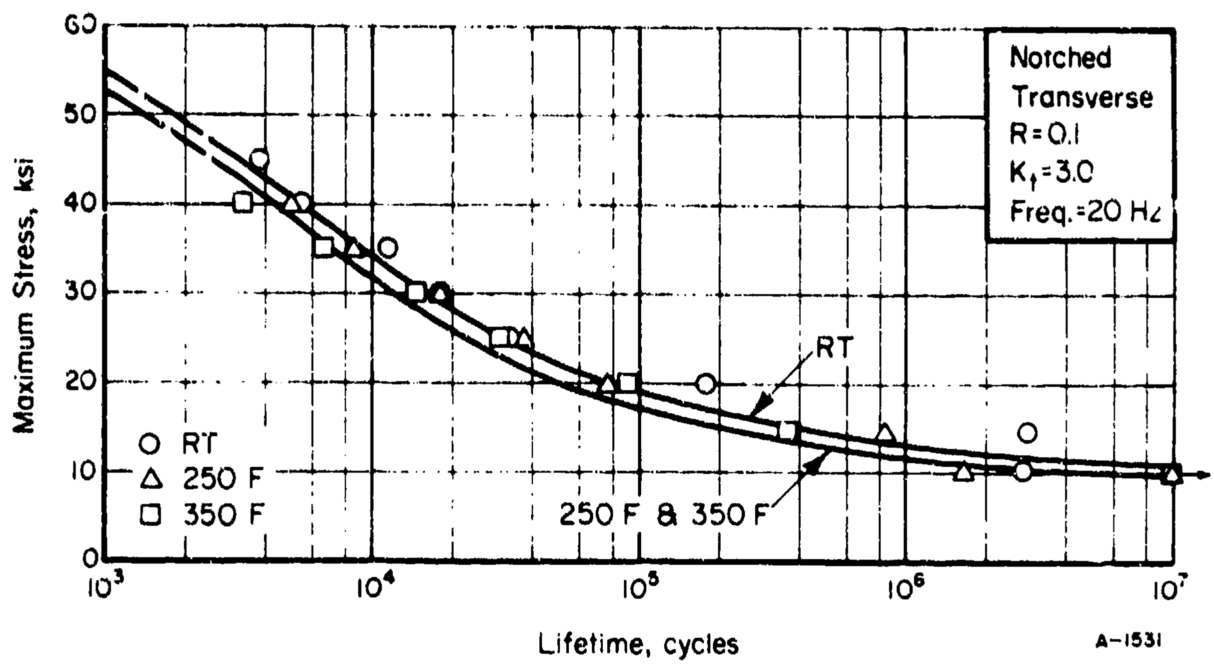
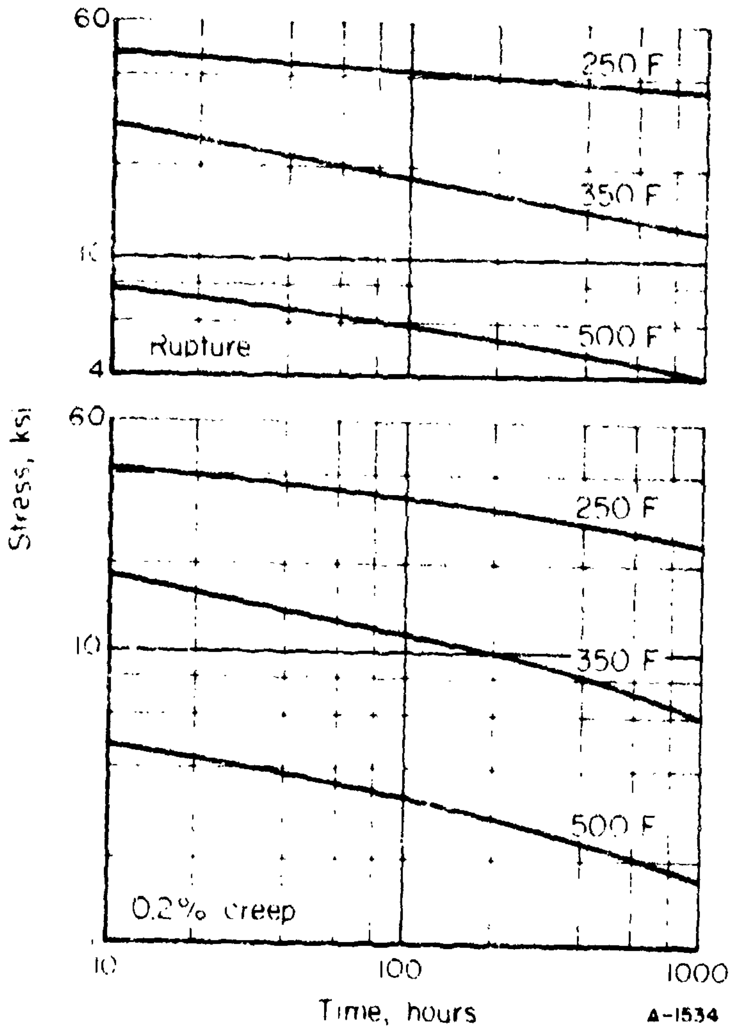


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) 7049-T7351 ALUMINUM ALLOY PLATE


60
250 F
350 F
10
500 F
Rupture
4
60
250 F
10
350 F
500 F
0.2% creep
10
100
1000
Stress, ksi
Time, hours
A-1534

[illegible]

MECHANICAL-PROPERTY DATA
INCONEL 617 ALLOY

ANNEALED 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

Inconel 617 Alloy

Material Description

Inconel Alloy 617 is a solid-solution, nickel-chromium-cobalt-molybdenum 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. 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 0.047-inch-thick sheet from 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	54.0

Processing and Heat Treating

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

INCONEL ALLOY 617 DATA[a]

Thickness: 0.047-inch nominal
Condition: Cold-rolled and annealed

Properties	Temperature, F RT	800	1200	1600
<u>Tension</u>				
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	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 (longitudinal), 10^3 ksi	27.0	23.6	23.1	17.0
E (transverse), 10^3 ksi	30.5	24.8	29.8	16.6
<u>Compression</u>				
CYS (longitudinal), ksi	61.9	48.9	41.0	30.9
CYS (transverse), ksi	61.5	49.9	41.6	31.6
E_c (longitudinal), 10^3 ksi	30.4	27.9	24.1	20.0
E_c (transverse), 10^3 ksi	33.7	29.7	27.5	24.2
<u>Shear</u>[b]				
SUS (longitudinal), ksi	106.6	U[c]	U	U
SUS (transverse), ksi	107.6	U	U	U
<u>Bend</u> (transverse)				
Minimum Radius	0T	U	U	U
<u>Fracture Toughness</u>				
K_c, T-L, ksi $\sqrt{in.}$	(d)	U	U	U
<u>Axial Fatigue (transverse)</u>[e]				
Unnotched, R = 0.1				
10^3 cycles, ksi	115	95	88	U
10^5 cycles, ksi	93	67	67	U
10^7 cycles, ksi	67	60	60	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	80	65	61	U
10^5 cycles, ksi	52	46	43	U
10^7 cycles, ksi	32	36	31	U

INCONEL ALLOY 617 DATA (Continued)

Properties	RT	800	1200	1600
	Temperature, F			
Creep (transverse)				
0.2 plastic deformation, 100 hr, ksi	NA	(f)	43	7
0.2 plastic deformation, 1000 hr, ksi	NA	(f)	39	5
Rupture (transverse)				
Rupture, 100 hr, ksi	NA	103	62	14
Rupture, 1000 hr, ksi	NA	102	48	9
Stress Corrosion (transverse)(g)				
80% TYS, 1000 hr maximum	no cracks	U	U	U
Coefficient of Thermal Expansion				
7.6×10^{-6} in./in./F (RT to 500 F)				
8.0×10^{-6} in./in./F (RT to 1200 F)				
8.7×10^{-6} in./in./F (RT to 1600 F)				
Density				
0.302 lb/in.^{3}				

(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) Sheet shear type specimen: average of four tests in each direction.

(c) U, unavailable; NA, not applicable.

(d) Specimens were 16-inches wide by 36-inches long with a saw-cut flaw in the center. Net stress at fracture was greater than the tensile yield strength of the material, therefore, the test was not valid for K_c.

(e) "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.

(f) No appreciable deformation.

(g) Room-temperature three-point bend test. Alternate immersion in 3-1/2% NaCl.

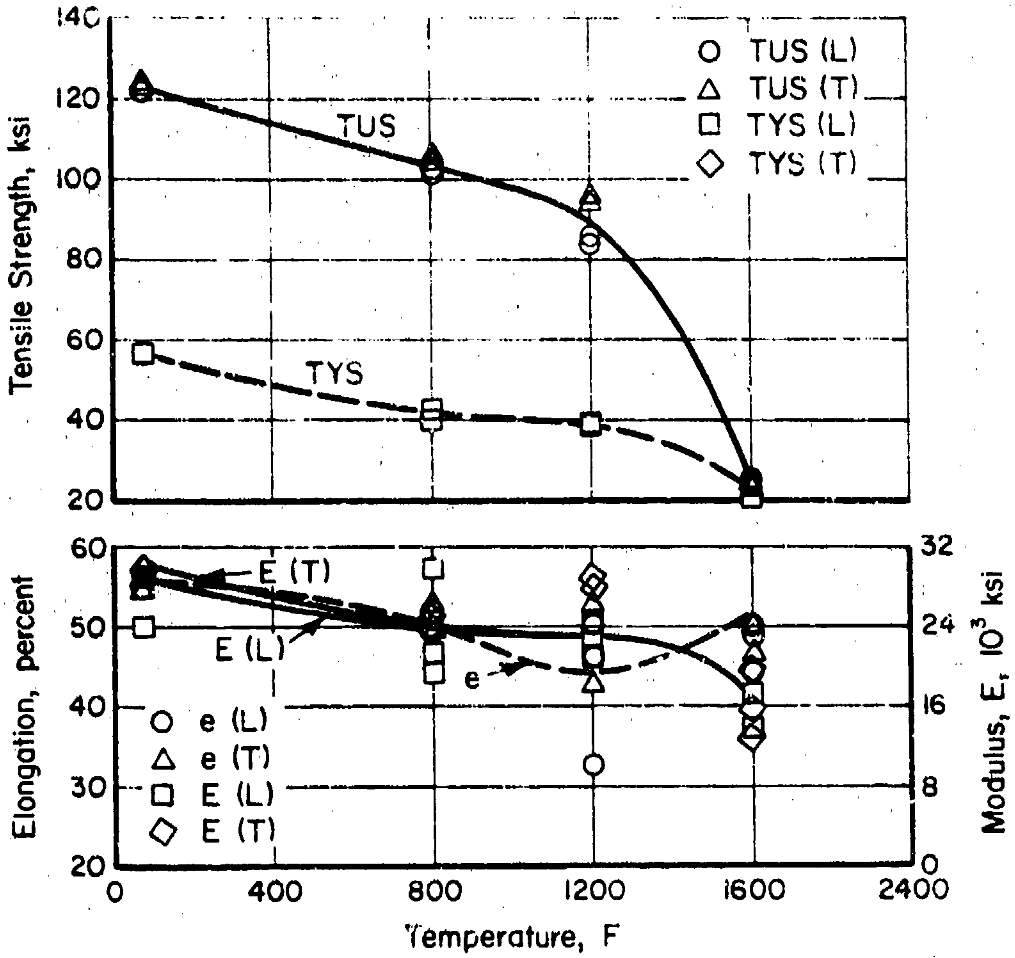


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED INCONEL ALLOY 617 SHEET

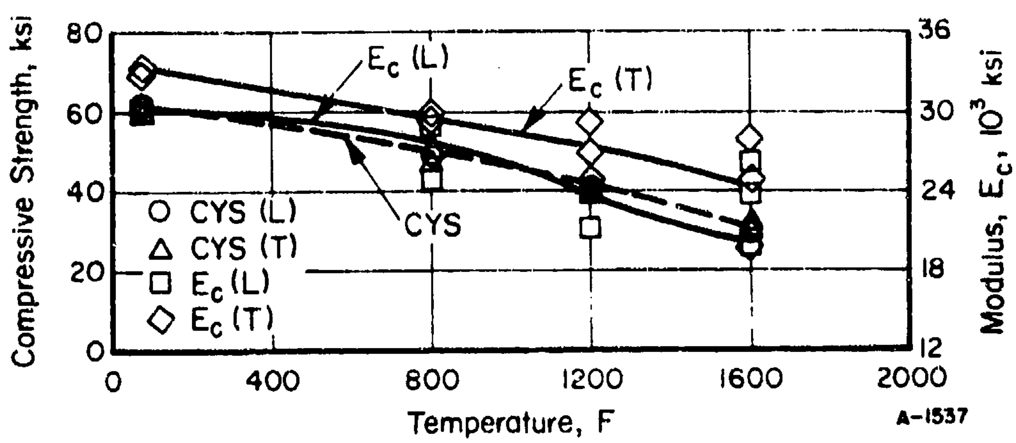


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED INCONEL ALLOY 617 SHEET

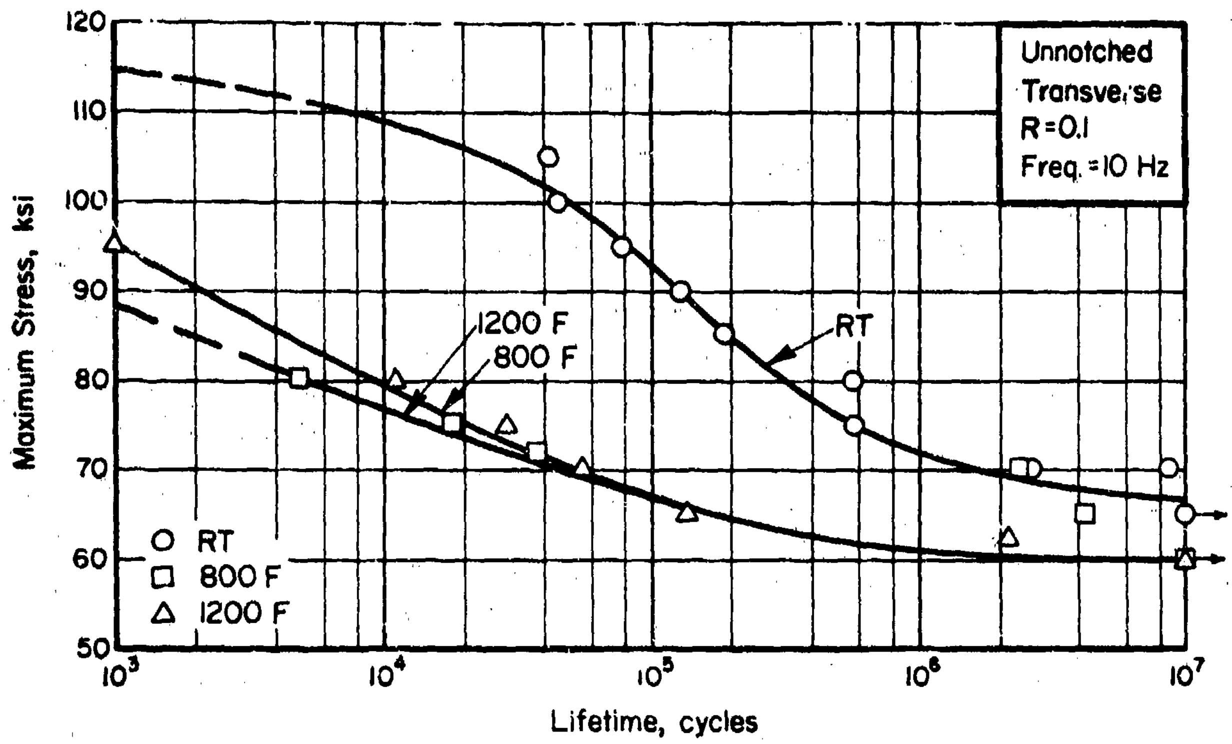


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED INCONEL ALLOY 617 SHEET

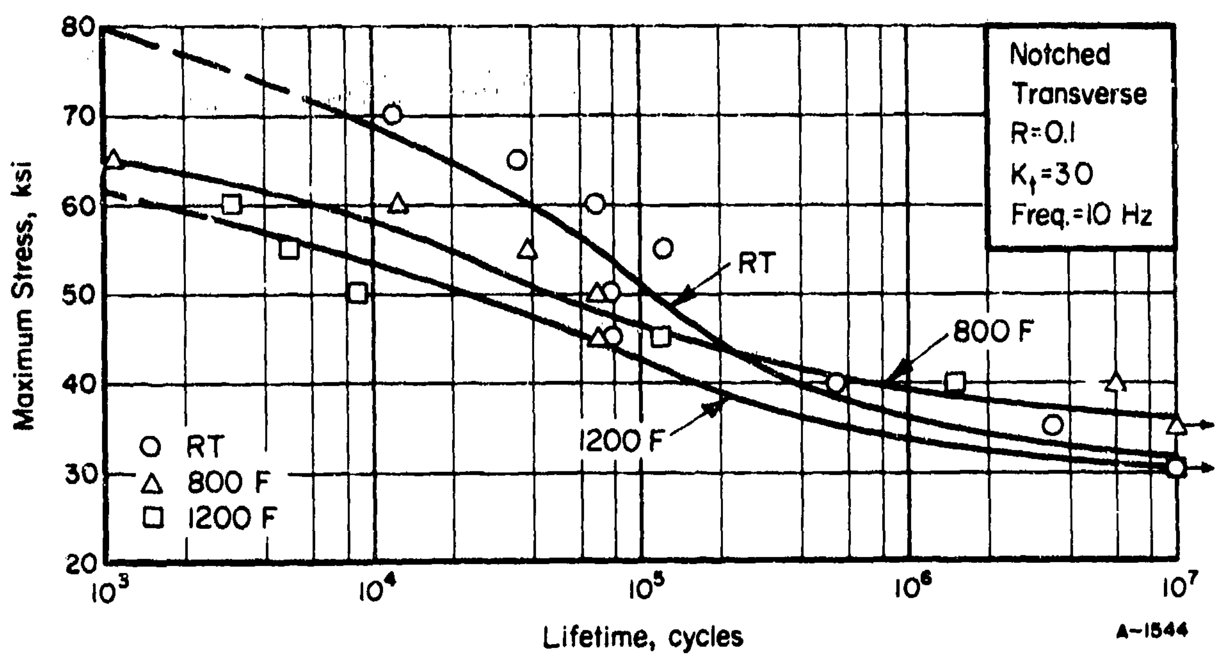


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t=3.0) ANNEALED INCONEL ALLOY 617 SHEET

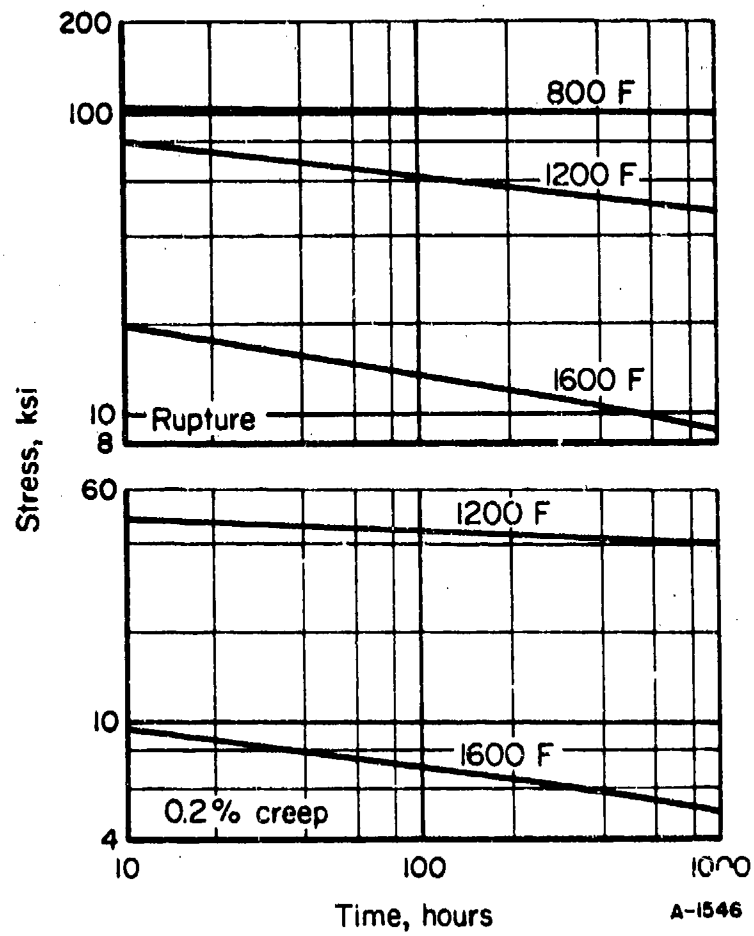


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED INCONEL ALLOY 617 SHEET

MECHANICAL-PROPERTY DATA
7475 ALUMINUM ALLOY

-T7351 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

7475 Aluminum Alloy

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 produced within the following composition 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[a]

Thickness: 2 inches

Properties	Temperature, F 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), 10^3 ksi	10.2	9.0	7.8	7.1
E (transverse), 10^3 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_c (longitudinal), 10^3 ksi	10.6	9.4	8.9	7.8
E_c (transverse), 10^3 ksi	10.5	9.9	9.6	7.7
Shear[b]				
SUS (longitudinal), ksi	45.7	U[c]	U	U
SUS (transverse), ksi	45.0	U	U	U
Impact[d]				
V-notch Charpy, ft/lb				
(longitudinal)	17.1	U	U	U
(transverse)	5.9	U	U	U
Fracture Toughness				
K_{Ic}, ksi√in.	(e)	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^3 cycles, ksi	63	55	45	U
10^5 cycles, ksi	53	48	41	U
10^7 cycles, ksi	48	37	27	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	52	50	45	U
10^5 cycles, ksi	24	20	17	U
10^7 cycles, ksi	13	11	10	U

Properties	Temperature, F			
	RT	250	350	500
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA	38	17	4
0.2% plastic deformation, 1000 hr, ksi	NA	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)(g)				
80% TYS, 1000 hr maximum	no cracks			
Coefficient of Thermal Expansion				
12.9 x 10 in./in./F (68 - 212 F)				
Density				
0.101 lb/in.^{3}				

(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.

(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_Q 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_{Ic} values.

(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.

(g) Room-temperature three-point bend test. Alternate immersion in 3.5% NaCl.

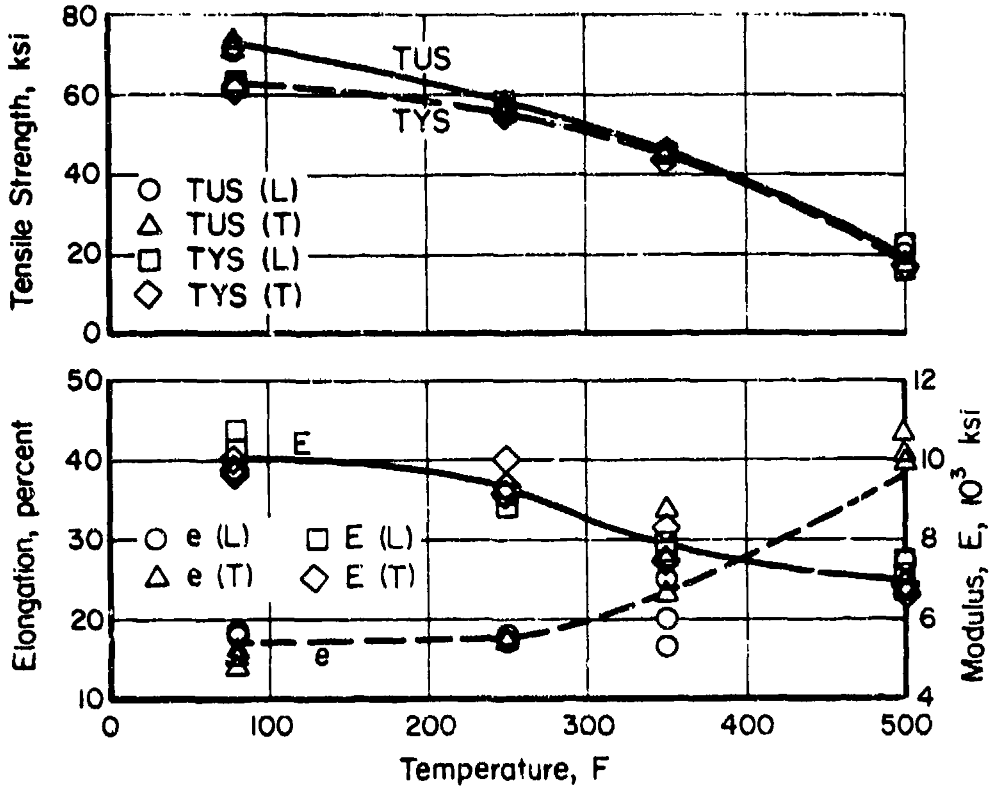


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7475-T7351 ALLOY PLATE

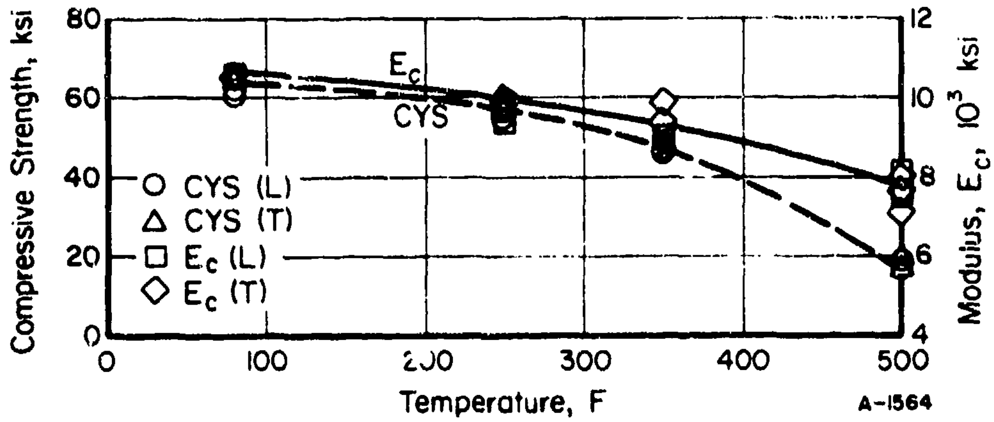


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7475-T7351 ALLOY PLATE

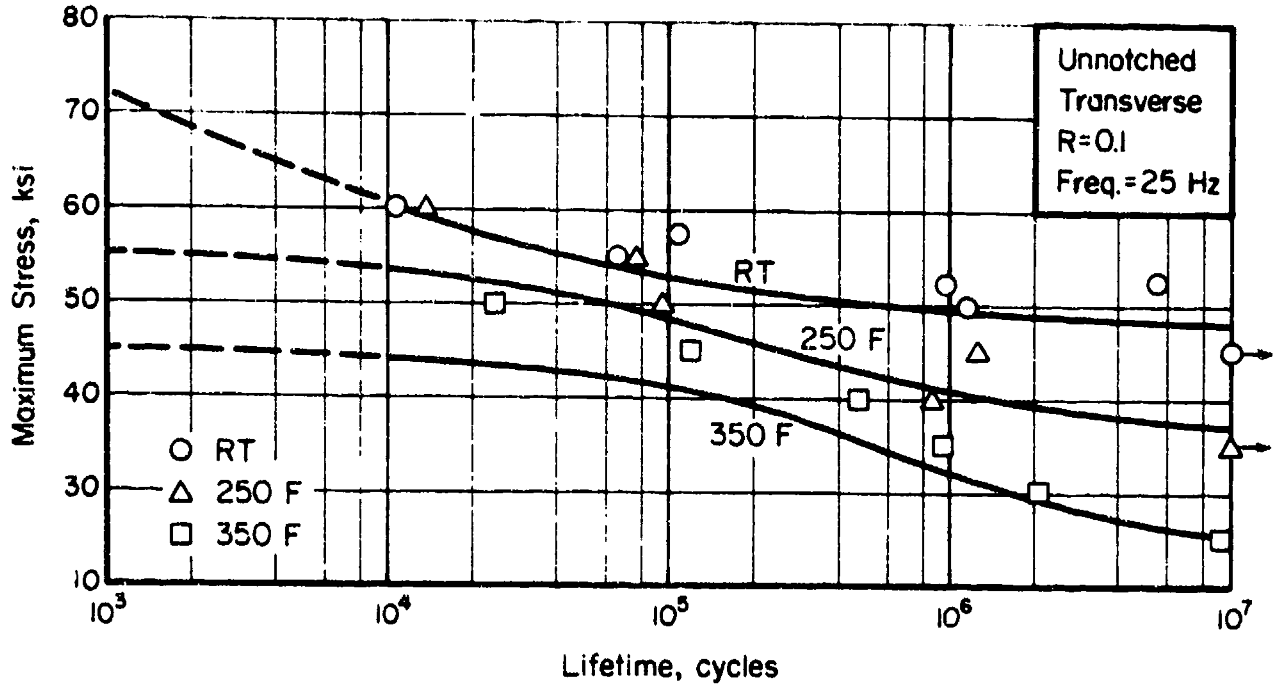


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7475-T7351 ALLOY PLATE

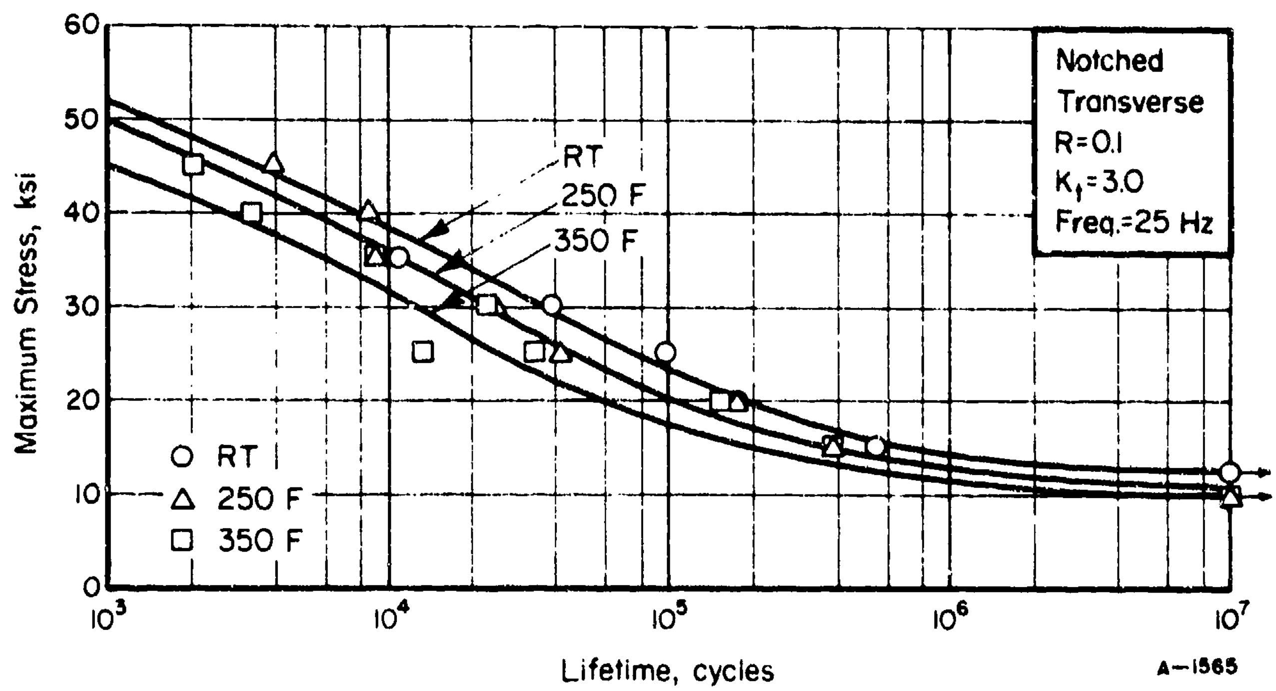


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) 7475-T7351 ALLOY PLATE

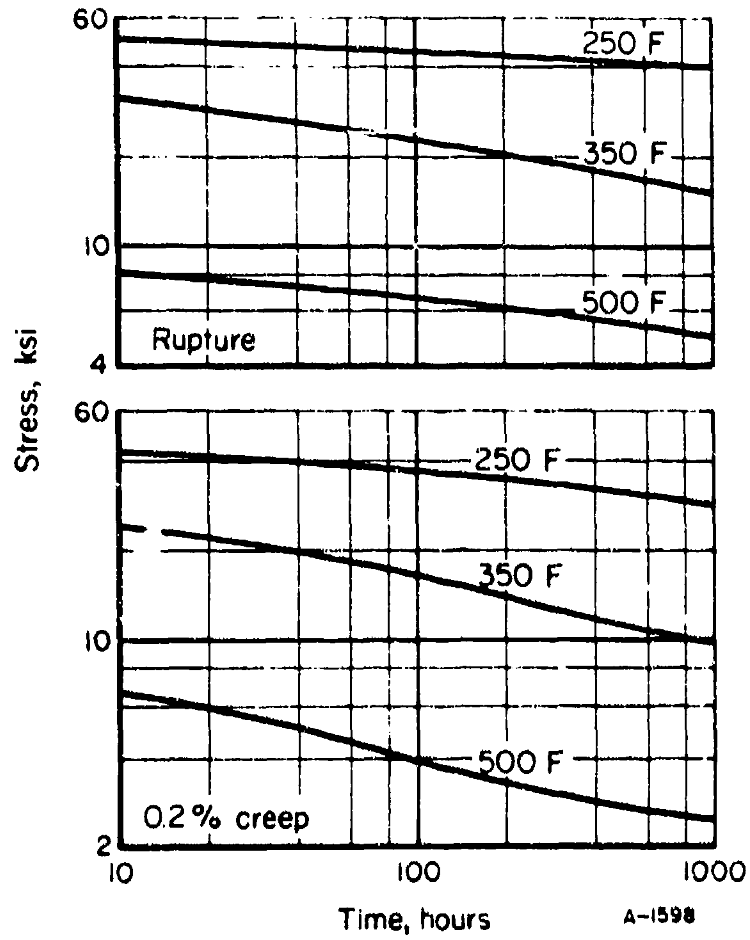


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7475-T7351 ALLOY PLATE (TRANSVERSE)

MECHANICAL-PROPERTY DATA
2419 ALUMINUM ALLOY

–T851 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

2419 Aluminum 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 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 to 6.8
Manganese	0.20 to 0.40
Magnesium	0.02 max.
Zinc	0.10 max.
Titanium	0.02 to 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 alloy was evaluated in the overaged and stress-relieved -T851 temper.

2419-T851 Alloy Data

Condition: -T851
Thickness: 2-inch plate

Properties	Temperature, F RT	250	350	500
Tension				
TUS (longitudinal), ksi	66.7	55.4	45.5	22.2
TUS (transverse), ksi	66.4	54.9	44.5	23.1
TYS (longitudinal), ksi	52.4	46.8	41.4	20.9
TYS (transverse), ksi	52.1	45.6	39.7	21.7
e (longitudinal), percent in 2 in.	11.0	15.0	14.5	18.0
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), 10^3 ksi	10.4	10.4	9.1	7.4
E (transverse), 10^3 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_c (longitudinal), 10^3 ksi	10.8	10.5	10.0	9.3
E_c (transverse), 10^3 ksi	10.7	10.4	9.8	9.0
Shear				
SUS (longitudinal), ksi	39.4	U	U	U
SUS (transverse), ksi	39.5	U	U	U
Impact				
V-notch Charpy, ft-lb				
(longitudinal)	5.5	U	U	U
(transverse)	4.3	U	U	U
Fracture Toughness				
K_{Ic} (L-T), ksi√in.	35.3	U	U	U
K_{Ic} (T-L), ksi√in.	30.2	U	U	U
Axial Fatigue (transverse)(f)				
Unnotched, R = 0.1				
10^3 cycles, ksi	66	55	45	U
10^5 cycles, ksi	42	42	39	U
10^7 cycles, ksi	36	30	26	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	50	48	45	U
10^5 cycles, ksi	19	17	17	U
10^7 cycles, ksi	11	10	10	U

2419-T851 Alloy Data (Continued)

Properties	Temperature, F RT	250	350	500
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA	36	23	9.4
0.2% plastic deformation, 1000 hr, ksi	NA	32	18	6.2
Stress Rupture (transverse)				
Rupture, 100 hr, ksi	NA	44	31	14
Rupture, 1000 hr, ksi	NA	41	26	9.4
Stress Corrosion (transverse)(g)				
80% TYS, 1000 hr maximum	No cracks			
Coefficient of Thermal Expansion				
12.4×10^{-6} in./in./F (70 to 212 F)				
Density				
0.102 lb/in.^{3}				

(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 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_{Ic} values are valid by existing ASTM criteria.

(f) "R" represents the albebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3½% NaCl.

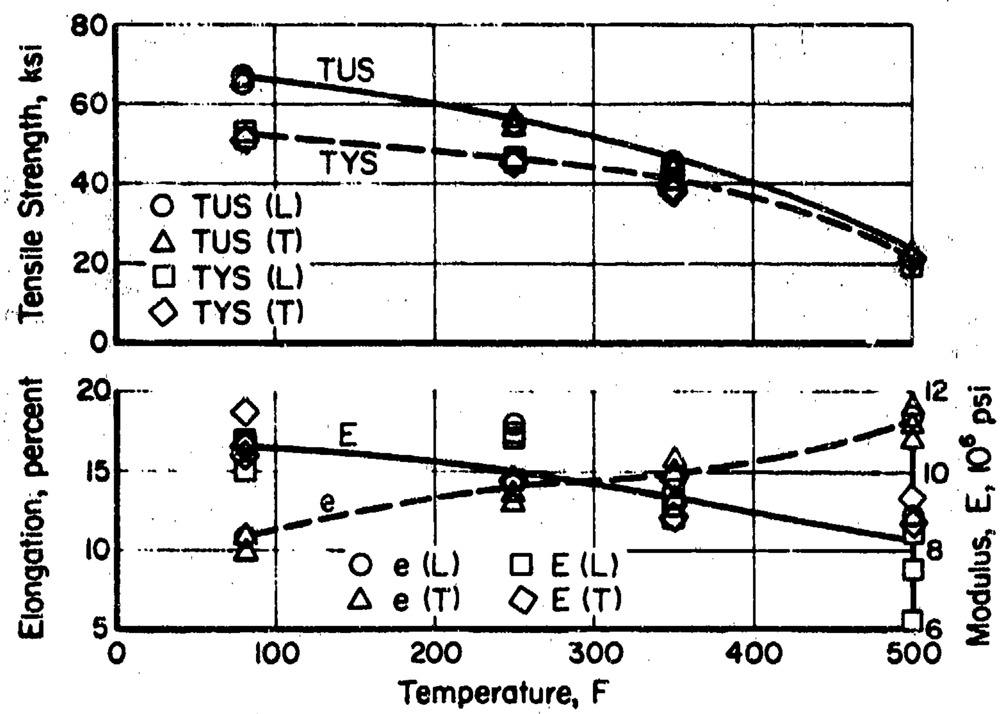


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 2419-T851 ALLOY PLATE

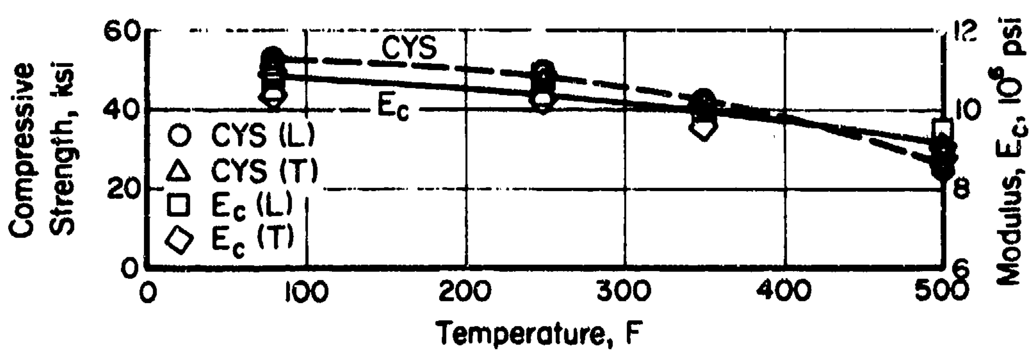


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 2419-T851 ALLOY PLATE

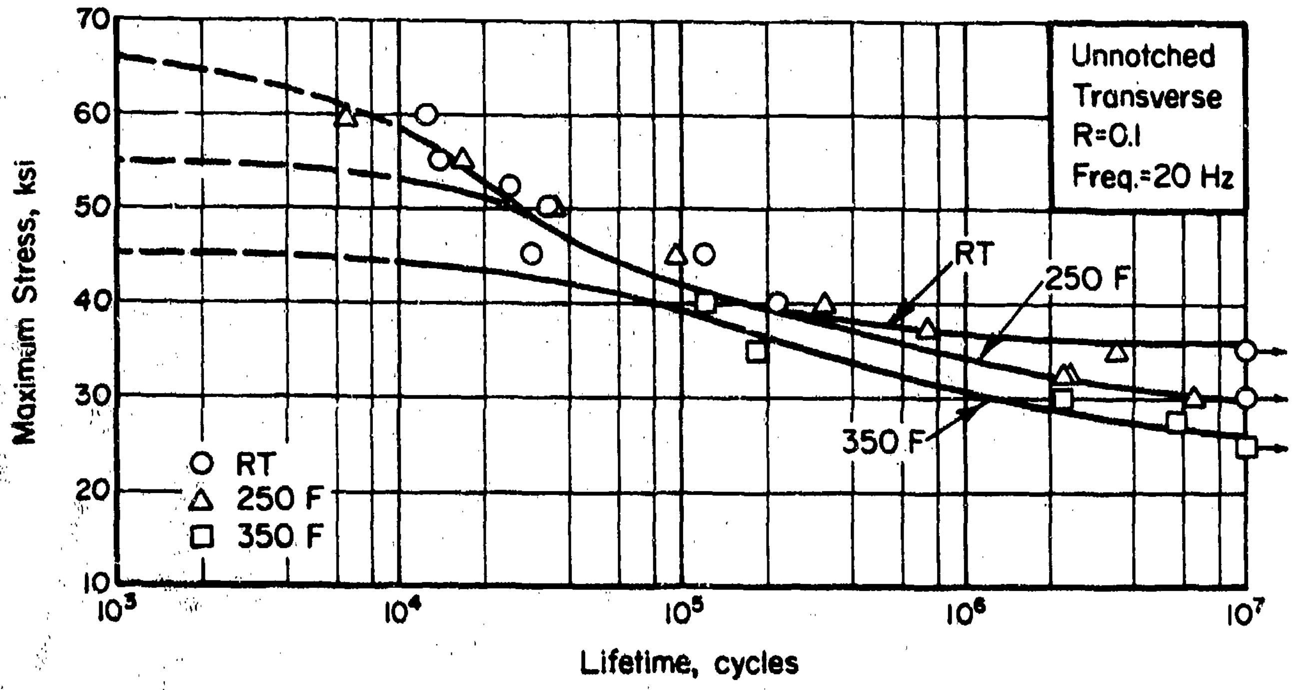


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 2419-T851 ALUMINUM ALLOY PLATE

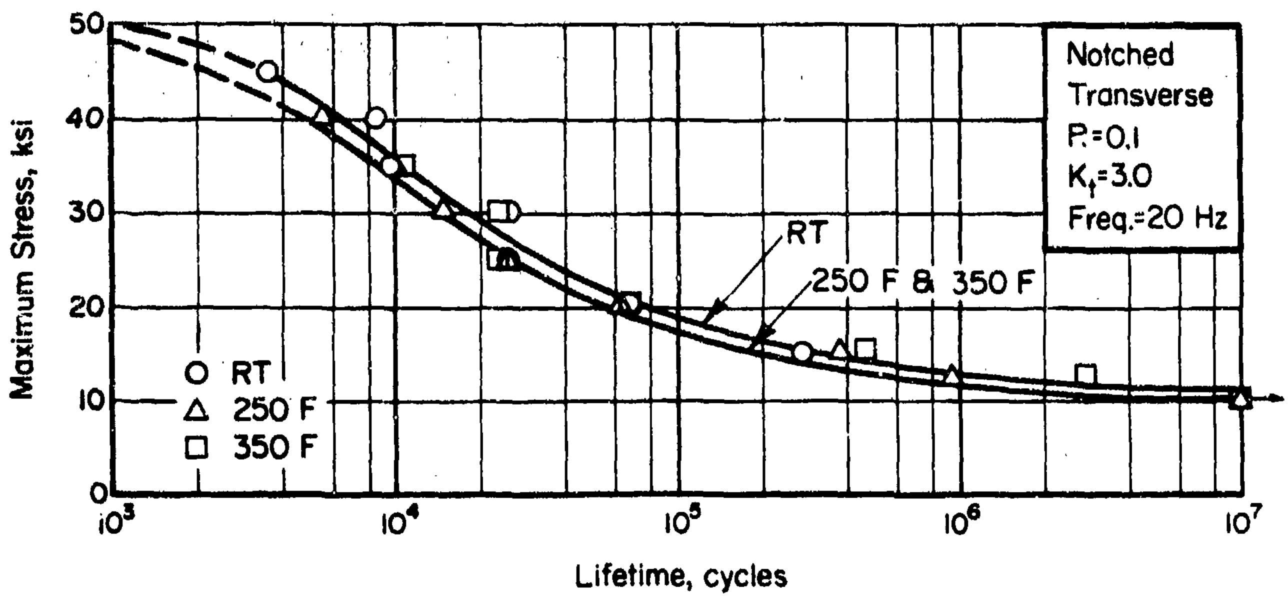


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) 2419-T851 ALUMINUM ALLOY PLATE

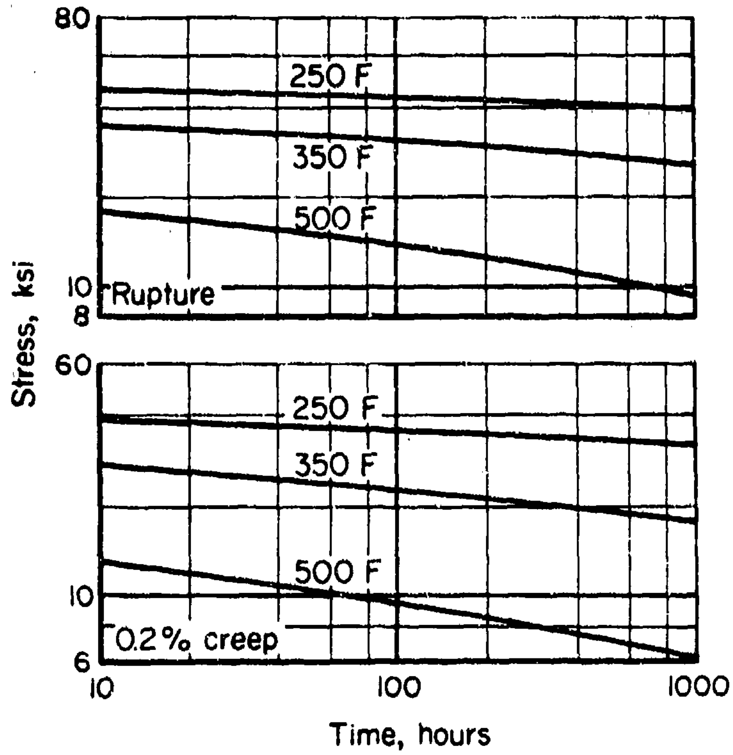


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 2419-T851 ALUMINUM ALLOY PLATE

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

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

Ti-6Al-2Zr-2Sn-2Mo-2Cr Alloy

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
Al	5.8
Sn	2.1
Zr	1.8
Mo	2.0
Cr	1.9
Si	0.21
Fe	0.06
C	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-6Al-2Zr-2Sn-2Mo-2Cr ALLOY DATA[a]

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

Properties	Temperature, F RT	400	600	800
Tension				
TUS (longitudinal), ksi	158.4	[illegible]	137.3	139.8
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	[illegible]	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), 10^3 ksi	15.6	14.7	14.5	13.4
E (transverse), 10^3 ksi	15.8	13.9	14.8	13.4
Compression				
CYS (longitudinal), ksi	149.4	116.2	106.4	[illegible]
CYS (transverse), ksi	154.6	122.2	107.5	102.1
E_c (longitudinal), 10^3 ksi	16.1	[illegible]	14.3	[illegible]
E_c (transverse), 10^3 ksi	16.1	[illegible]	14.8	13.4
Shear[b]				
SUS (longitudinal), ksi	102.5	U[c]	U	U
SUS (transverse), ksi	[illegible]	U	U	U
Impact[d]				
V-notch Charpy, ft. lbs.				
(longitudinal)	14.9	U	U	U
(transverse)	14.9	U	U	U
Fracture Toughness[e]				
K_{Ic}, L-T, edge, ksi√in.	45.1	U	U	U
K_{Ic}, L-T, center, ksi√in.	51.8	U	U	U
K_{Ic}, ST-L, center, ksi√in.	62.0	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R=0.1				
10^3 cycles, ksi	164	144	134	U
10^5 cycles, ksi	130	112	106	U
10^7 cycles, ksi	76	76	76	U
Notched, K_t=3.0, R=0.1				
10^3 cycles, ksi	110	100	92	U
10^5 cycles, ksi	50	46	46	U
10^7 cycles, ksi	40	40	40	U

Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY DATA
(Continued)

Properties	Temperature, F			
	RT	400	600	800
Creep (transverse)				
0.2% plastic deformation, 100 hr., ksi	NA	107	96	70
0.2% plastic deformation, 1000 hr., ksi	NA	102	70	44
Stress-Rupture (transverse)				
Rupture, 100 hr., ksi	NA	133.5	129	121
Rupture, 1000 hr., ksi	NA	133	128.5	118
Stress Corrosion (transverse)(g)	no cracks			
Coefficient of Thermal Expansion				
5.1×10^{-6} in./in./F (68 to 800 F)				
Density				
0.165 lb./in.^{3}				

(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 in each direction.

(c) U, unavailable; NA, not applicable.

(d) Average of 6 tests in each direction.

(e) 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, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

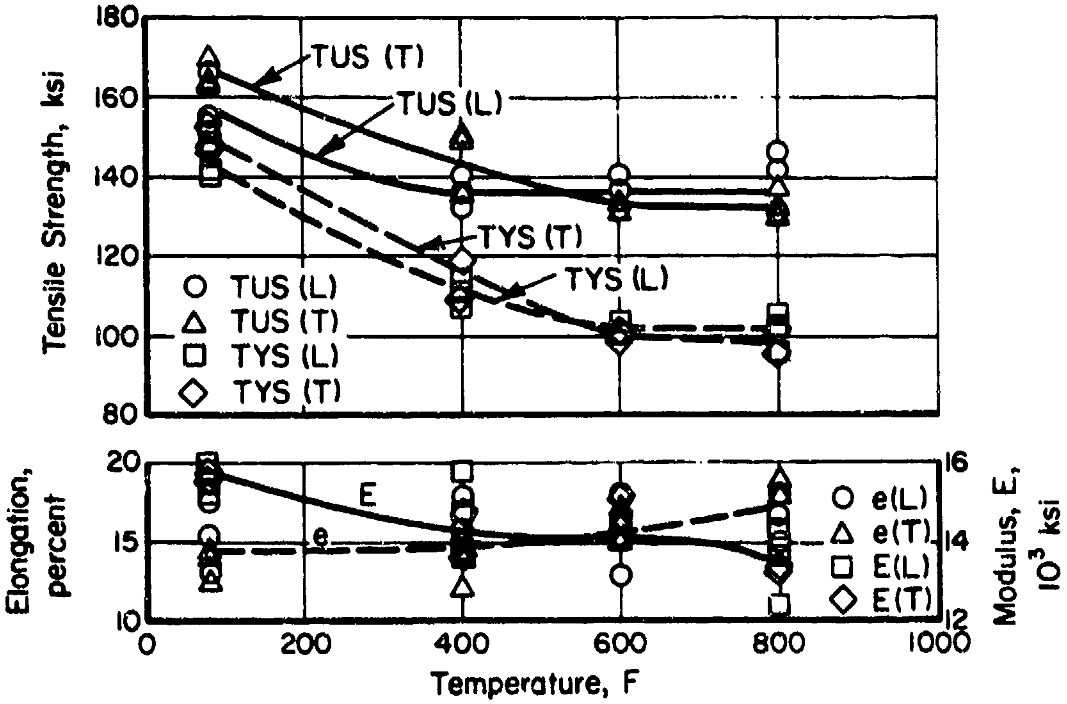


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

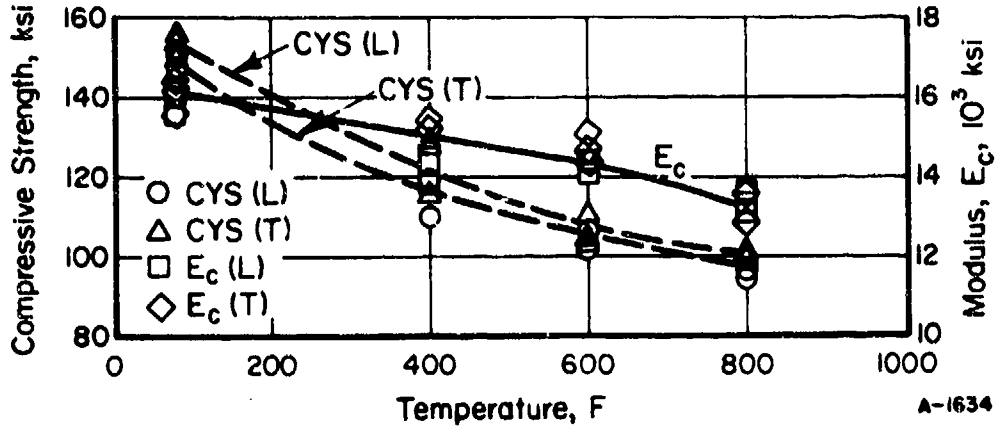


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

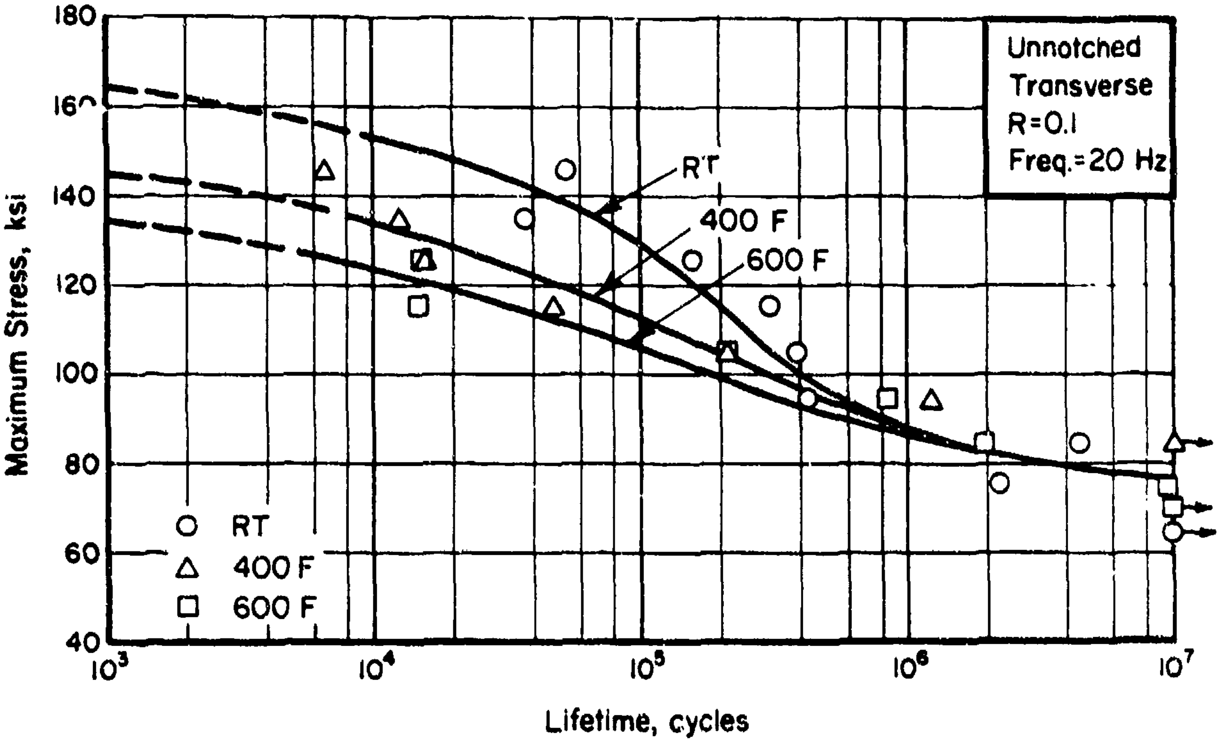


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

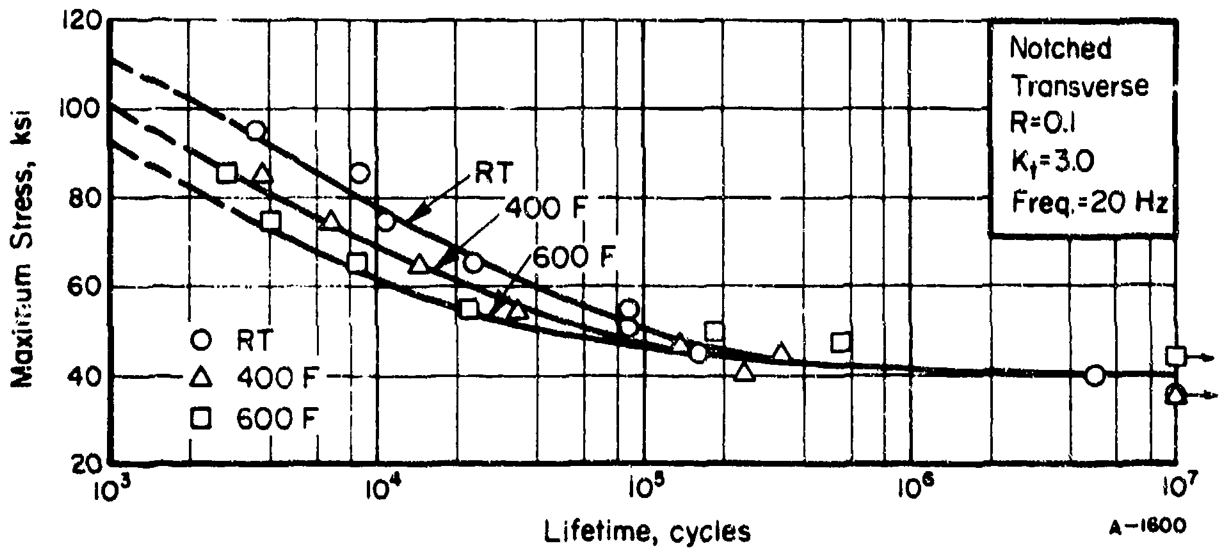


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) DUPLEX ANNEALED Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET

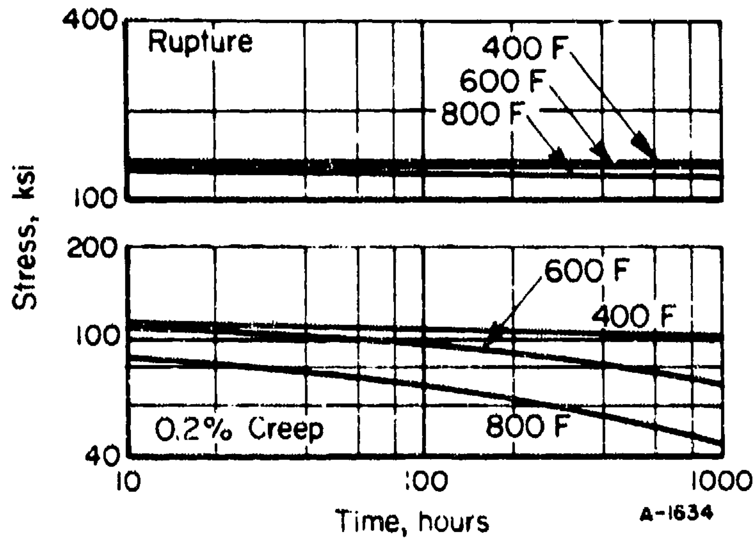


FIGURE 5. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR Ti-6Al-2Zr-2Sn-2Mo-2Cr FORGED BILLET (TRANSVERSE)

MECHANICAL-PROPERTY DATA
6Al-2Cb-1Ta-1Mo TITANIUM ALLOY

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-6Al-2Cb-1Ta-1Mo Alloy

Material Description

6Al-2Cb-1Ta-1Mo titanium alloy is a modification by RMI Company of the Ti-7Al-2Cb-1Ta composition. The modification was developed specifically for salt-water 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-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 1½-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-6Al-2Cb-1Ta-1Mo Alloy Data[a]

Condition: Annealed
Thickness: $1\frac{1}{2}$-inch plate

Properties	Temperature, F			
	RT	400	600	800
Tension				
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), percent	32.9	42.6	47.2	49.0
E (longitudinal), 10^3 ksi	17.0	16.0	14.0	12.8
E (transverse), 10^3 ksi	17.0	17.4	14.8	14.4
Compression				
CYS (longitudinal), ksi	1[illegible].3	74.2	60.8	55.2
CYS (transverse), ksi	111.9	77.4	63.2	58.3
E_c (longitudinal), 10^3 ksi	17.6	15.9	15.0	13.7
E_c (transverse), 10^3 ksi	17.5	15.6	14.9	13.9
Shear[b]				
SUS (longitudinal), ksi	83.7	U[c]	U	U
SUS (transverse), ksi	83.8	U	U	U
Impact[d]				
V-notch Charpy, ft/lb				
(longitudinal)	38.5	U	U	U
(transverse)	33.8	U	U	U
Fracture Toughness				
K_{Ic}, ksi $\sqrt{in.}$	(e)	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^5 cycles, ksi	115	90	80	U
10^6 cycles, ksi	97	78	74	U
10^7 cycles, ksi	68	57	54	U

Ti-6Al-2Cb-1Ta-1Mo Alloy Data (continued)

Properties	Temperature, F			
	RT	400	600	800
Notched, K_t = 3.0, R = 0.1				
10^5 cycles, ksi	90	83	80	U
10^6 cycles, ksi	49	45	40	U
10^7 cycles, ksi	28	26	25	U
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA(c)	67	73	61
0.2% plastic deformation, 1000 hr, ksi	NA	66	72	52
Stress Rupture (transverse)				
Rupture, 100 hr, ksi	NA	88	81	73
Rupture, 1000 hr, ksi	NA	87	80	72
Stress Corrosion(g)				
80% TYS, 1000 hr maximum	No cracks			
Coefficient of Thermal Expansion				
5.2×10^{-6} in./in./F(RT to 1200 F)				
Density				
0.162 lb/in.^{3}				

(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.

(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.

(g) Room temperature three-point bend test. Alternate immersion in 3½% NaCl.

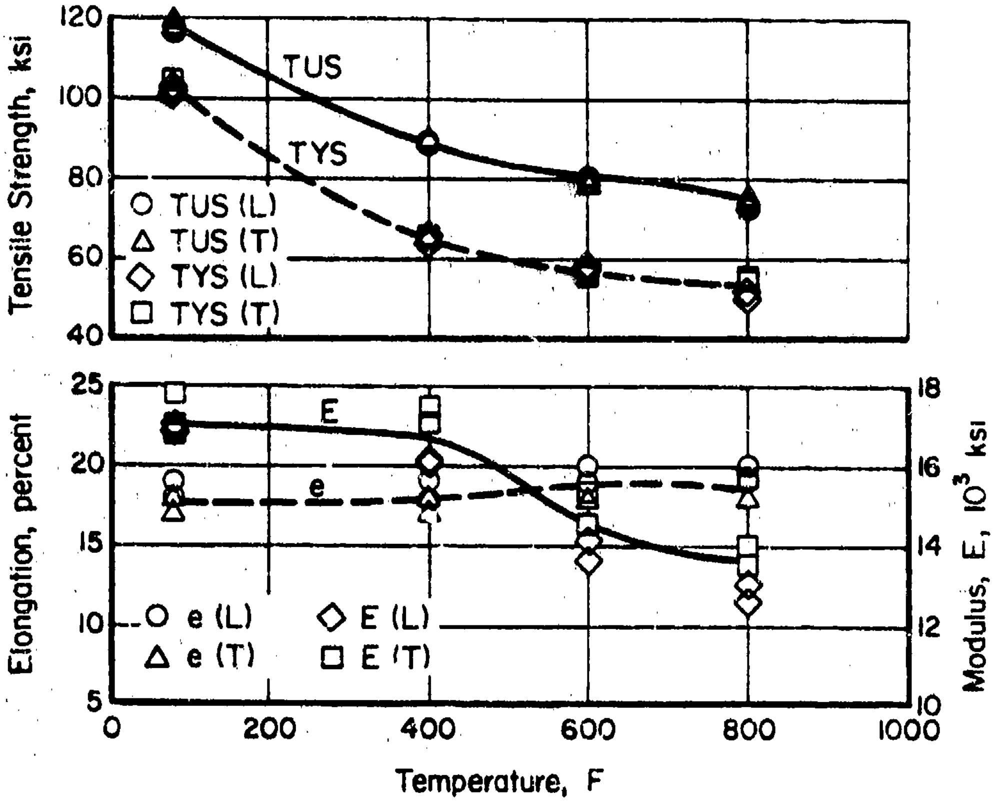


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

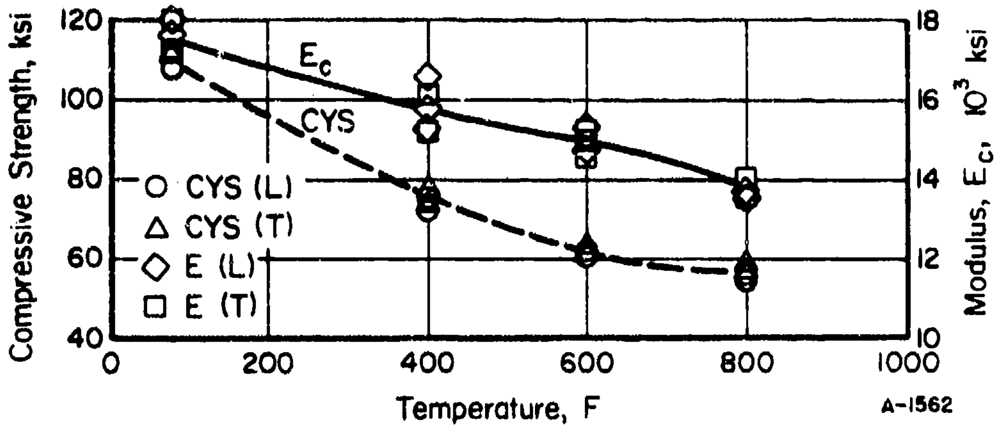


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

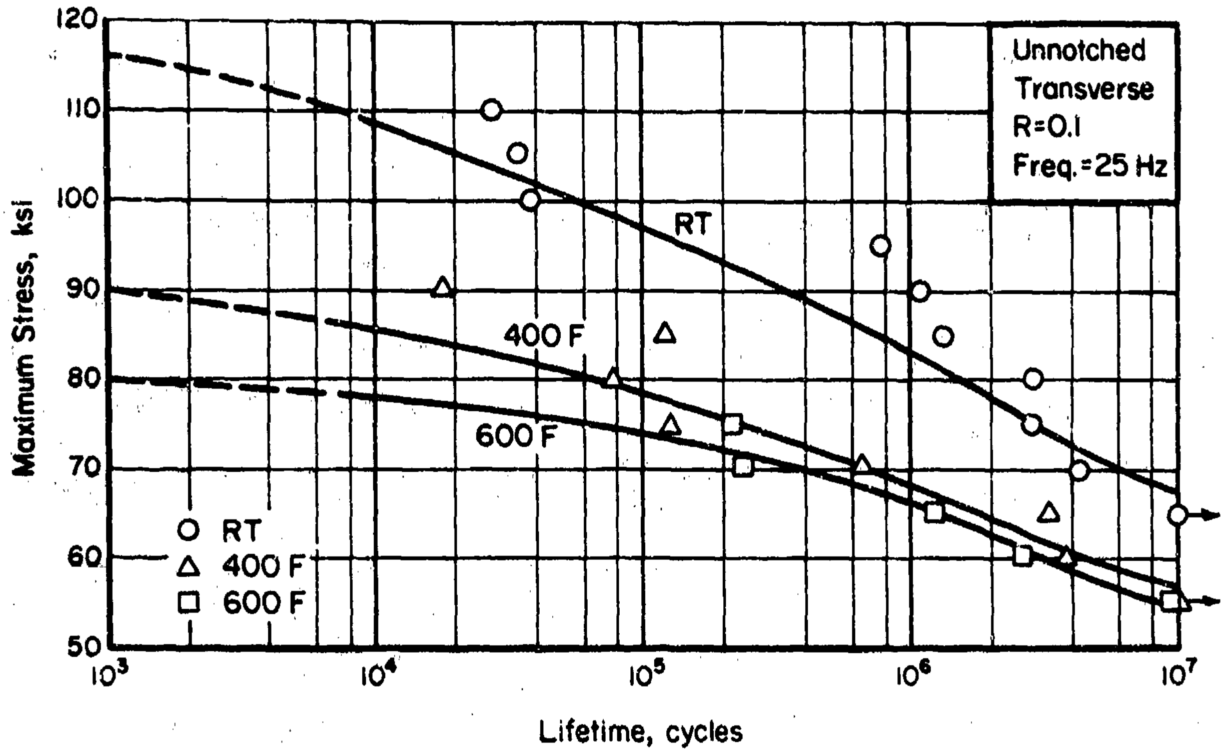


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

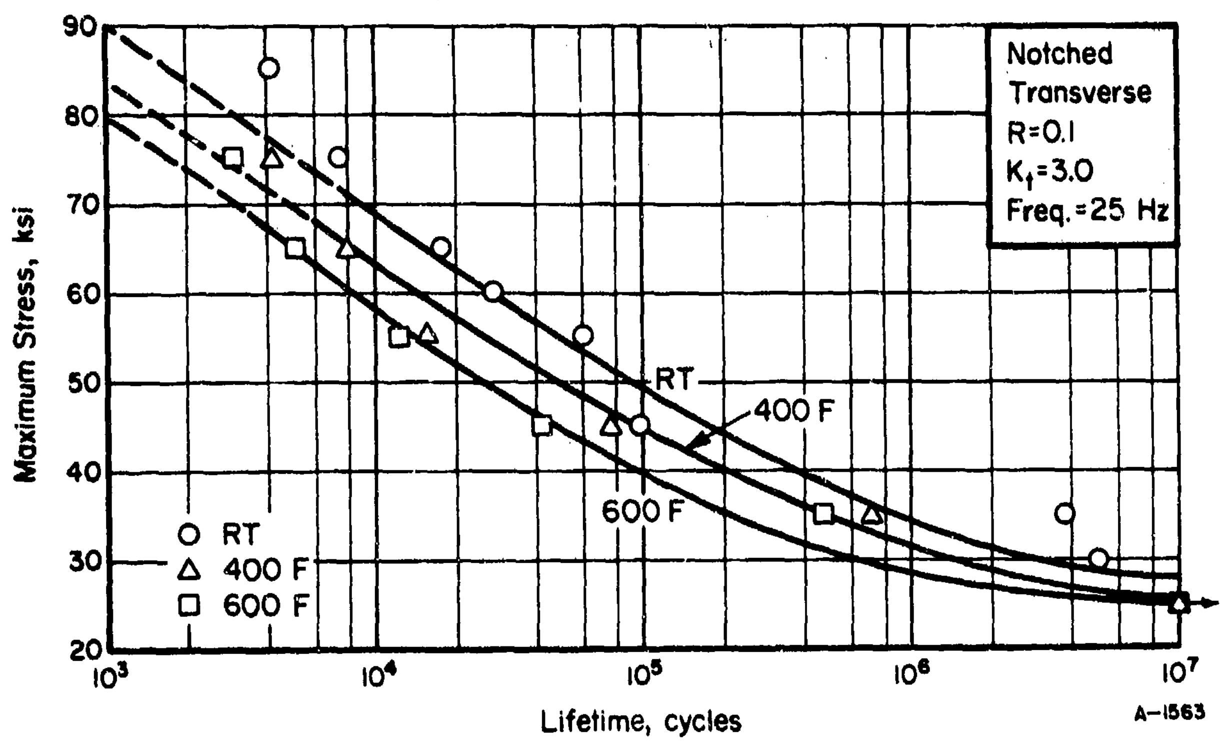


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

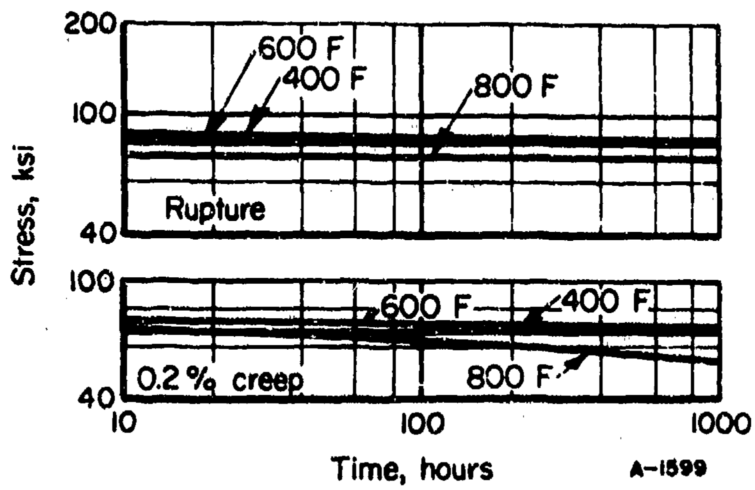


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED Ti-6Al-2Cb-1Ta-1Mo ALLOY PLATE

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

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-6Al-4V Alloy

Material Description

Ti-6Al-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-6Al-4V ALLOY DATA[a]

Condition: Beta annealed
Thickness: 0.57 plate

Properties	Temperature, F			
	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), 10^3 ksi	17.5	16.1	15.9	13.2
E (transverse), 10^3 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_c (longitudinal), 10^3 ksi	17.1	15.8	14.8	14.0
E_c (transverse), 10^3 ksi	17.5	15.4	15.1	14.0
Shear[b]				
SUS (longitudinal), ksi	90.6	U[c]	U	U
SUS (transverse), ksi	89.9	U	U	U
Impact[d]				
V-notch Charpy, ft.lbs.				
(longitudinal)	23.6	U	U	U
(transverse)	23.2	U	U	U
Fracture Toughness	(e)			
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^5 cycles, ksi	126	102	92	U
10^6 cycles, ksi	112	85	78	U
10^7 cycles, ksi	92	77	70	U
Notched, K_t = 3.0, R = 0.1				
10^5 cycles, ksi	110	92	80	U
10^6 cycles, ksi	53	44	43	U
10^7 cycles, ksi	35	35	35	U

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

Properties	RT	400	600	800
	Temperature, F			
Creep (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)(g)				
80% TYS, 1000 hr., maximum	no cracks			
Coefficient of Thermal Expansion				
5.0×10^{-6} in./in./F (RT to 800 F)				
Density				
0.160 lb./in.^{3}				

(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 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_{max}/P_Q requirement but not the size requirement of E399-72. Specimen strength ratios (R_{sc}) were calculated and are 1.28 for L-T specimens; 1.22 for T-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_t" represents the Neuber-Peterson Theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3½% NaCl.

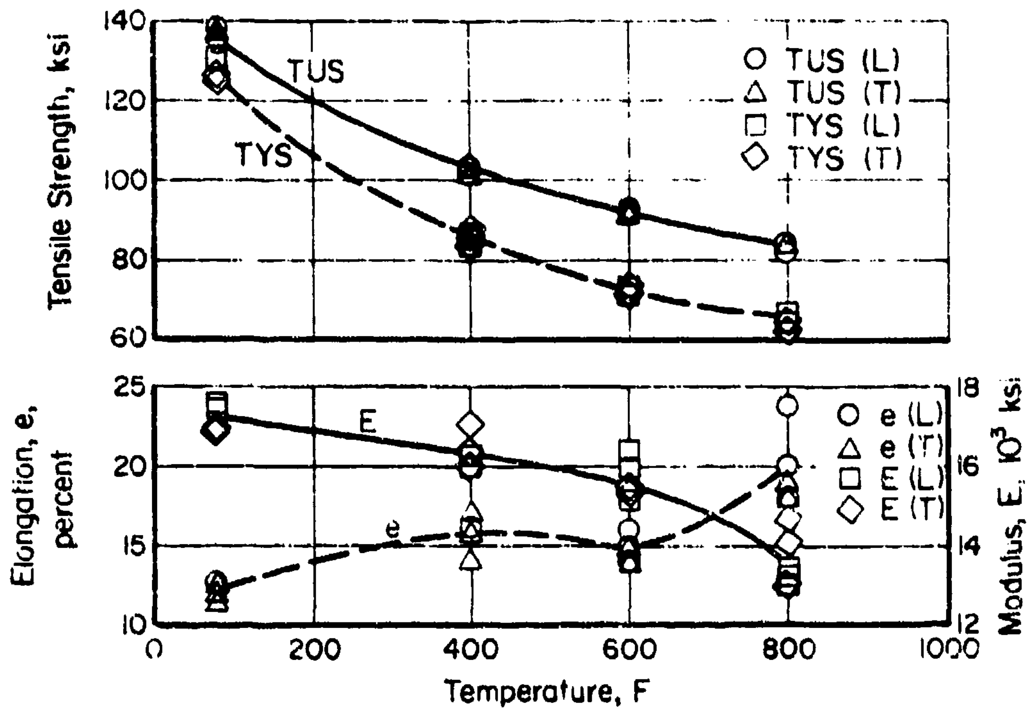


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

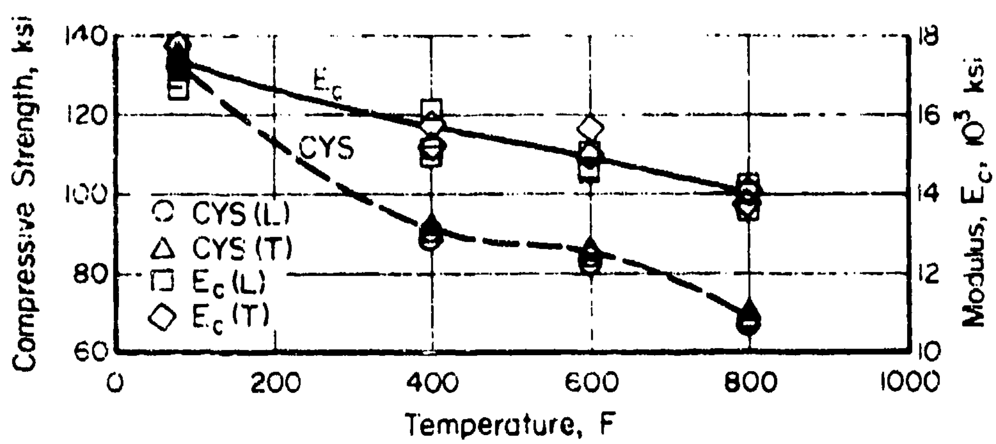


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

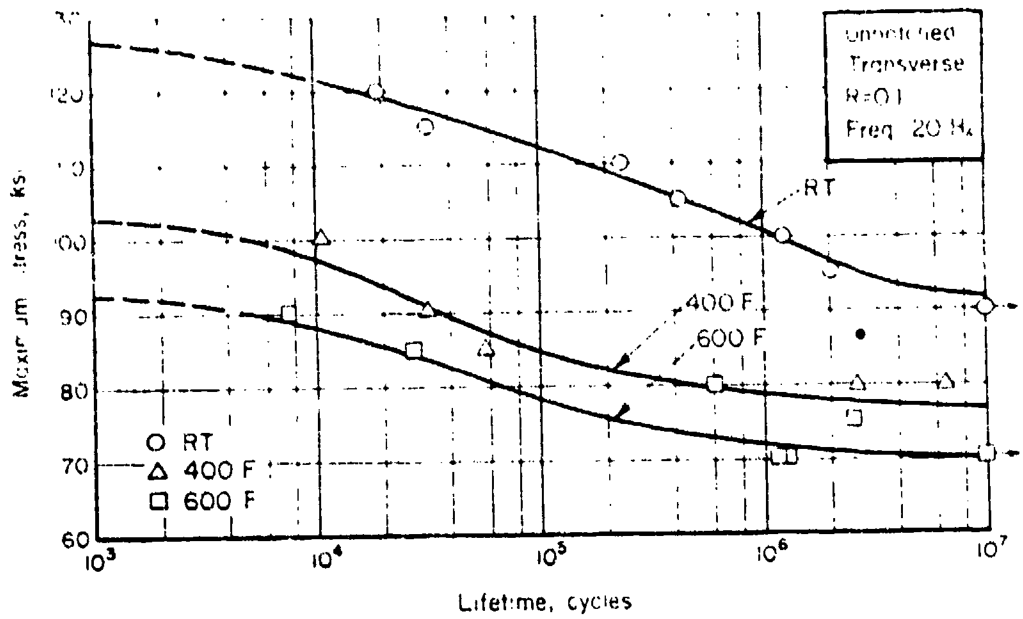


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

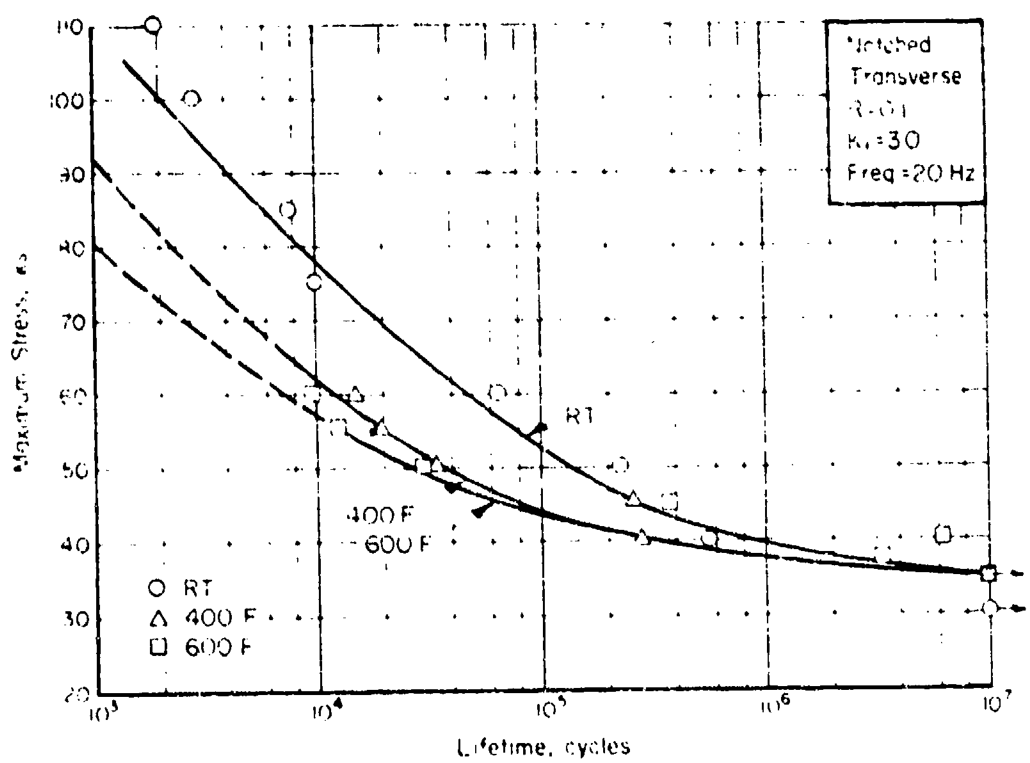


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) BETA-ANNEALED Ti-6Al-4V ALLOY PLATE

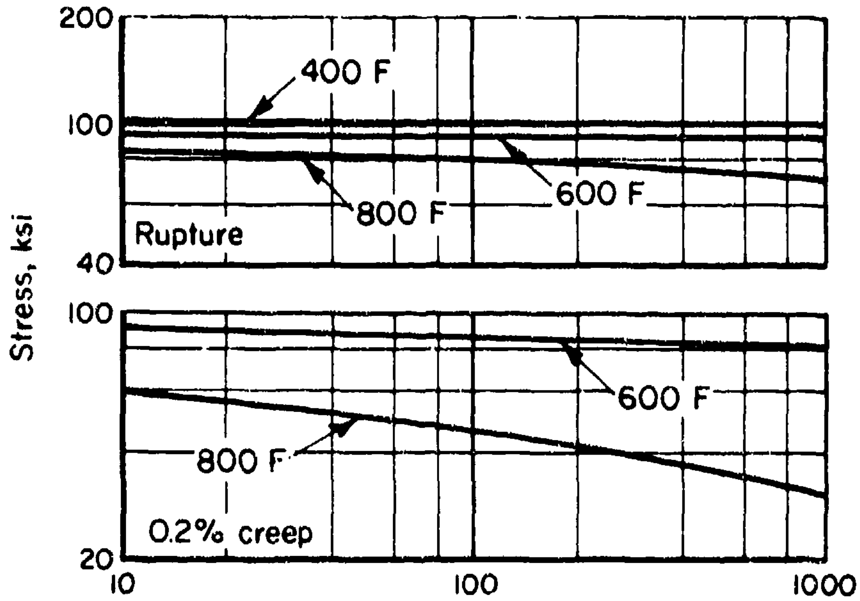


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR BETA-ANNEALED Ti-6Al-4V ALLOY PLATE (TRANSVERSE)

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

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-6Al-4V Isothermal Forging

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[a]

Condition: Isothermally Forged and Annealed
Thickness: Various

Properties	Temperature, F RT	400	600	800
Tension				
TUS (transverse), ksi	143.9	110.5	99.8	87.4
TYS (transverse), ksi	136.3	102.2	93.4	78.3
e (transverse), percent in 1 in.	17.0	17.5	18.5	21.5
RA (transverse), percent	45.7	47.7	54.1	62.3
E (transverse), 10^3 ksi	16.4	15.2	14.5	12.9
Compression				
CYS (transverse), ksi	135.9	101.4	93.2	79.6
E_c (transverse), 10^3 ksi	16.5	15.4	13.9	12.9
Shear				
SUS (transverse), ksi	97.2	U[c]	U	U
Impact				
V-notch Charpy, ft.lbs. (transverse)	16.9[d]	U	U	U
Fracture Toughness				
K_{Ic}, ksi $\sqrt{in.}$	59.0[e]	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^3 cycles, ksi	135	110	95	U
10^5 cycles, ksi	128	105	89	U
10^7 cycles, ksi	75	80	73	U
Notched				
10^3 cycles, ksi	65	65	65	U
10^5 cycles, ksi	46	50	43	U
10^7 cycles, ksi	31	28	35	U

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

Properties	Temperature, F			
	RT	400	600	800
Creep (Transverse)				
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)				
Rupture, 100 hr, ksi	NA	112	102	101
Rupture, 1000 hr, ksi	NA	111	101	57
Stress Corrosion (transverse)(g)				
80% TYS, 1000 hr, maximum				
Coefficient of Thermal Expansion				
5.0×10^{-6} in./in./F (RT to 800 F)				
Density				
0.160 lb./in.^{3}				

(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) 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_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

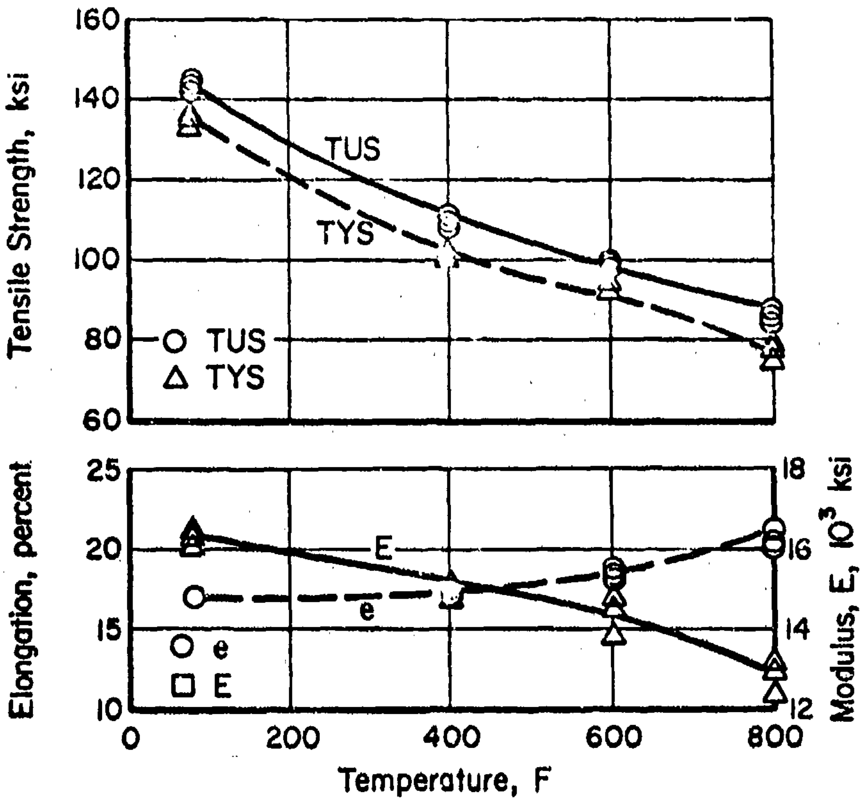


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-4V ISOTHERMAL FORGINGS

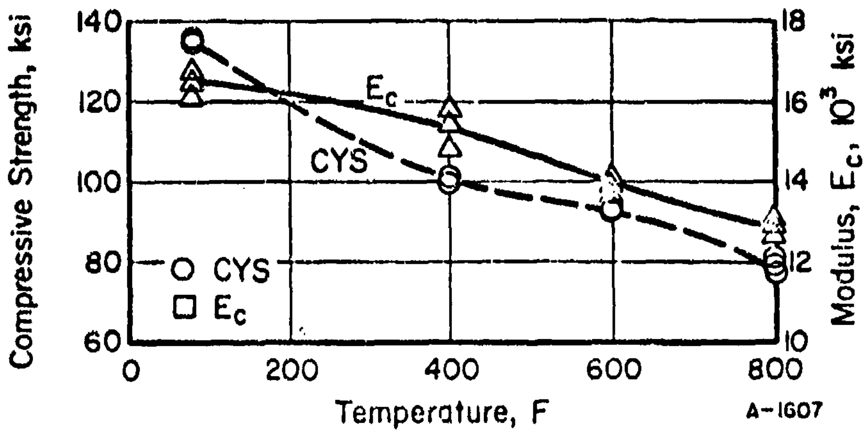


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-4V ISOTHERMAL FORGINGS

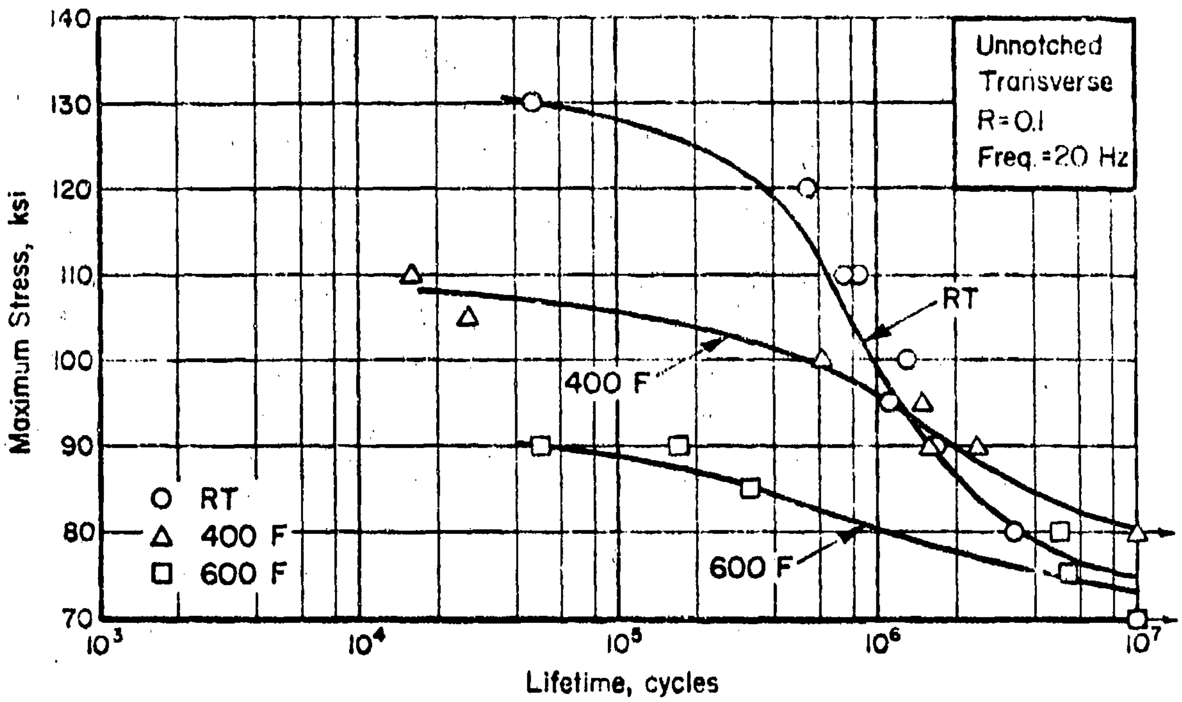


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED Ti-6Al-4V ISOTHERMAL FORGINGS

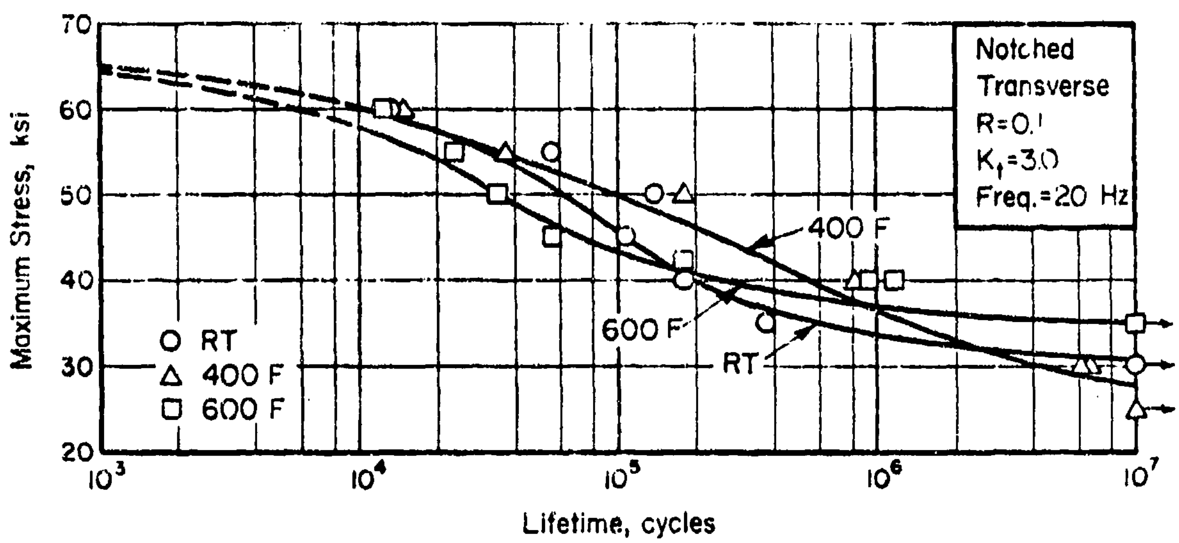


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) Ti-6A-4V ISOTHERMAL FORGINGS

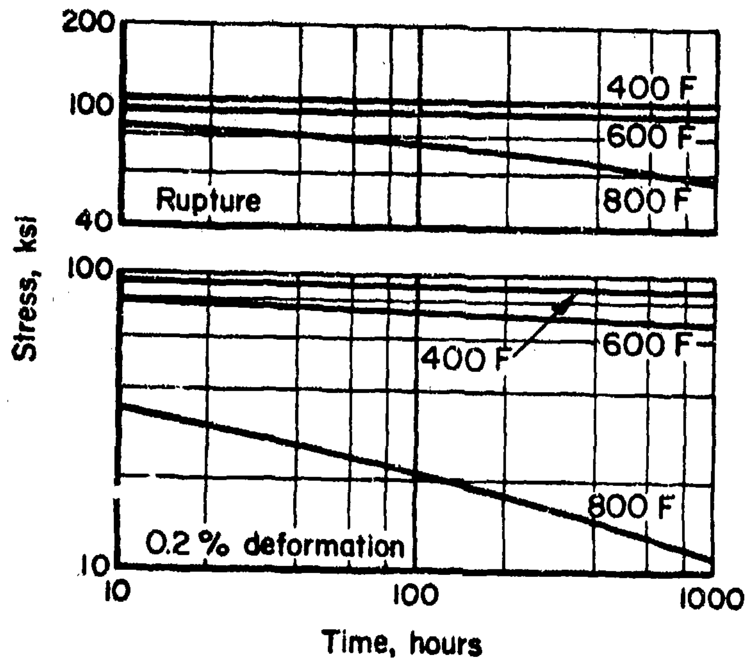


FIGURE 5. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR Ti-6Al-4V ISOTHERMAL FORGINGS

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

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-6Al-4V Alloy Castings

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[a]

Condition: Annealed
Thickness: 0.5 to 1 inch

Properties	Temperature, F RT	400	600	800
Tension				
TUS (longitudinal), ksi	137.8	100.8	84.8	77.5
TYS (longitudinal), ksi	130.4	88.2	69.8	63.8
e (longitudinal), percent in 1 in.	6.5	10.2	12.0	12.0
RA (longitudinal), percent	11.2	19.0	24.3	28.4
E (longitudinal), 10^3 ksi	17.2	16.8	15.2	15.1
Compression				
CYS (longitudinal), ksi	137.5	92.9	74.6	67.5
E_c (longitudinal), 10^3 ksi	16.5	15.6	14.9	13.5
Shear				
SUS (longitudinal), ksi	92.8[b]	U[c]	U	U
Impact				
V-notch Charpy, ft.lbs. (longitudinal)	16.2[d]	U	U	U
Fracture Toughness	(e)	U	U	U
Axial Fatigue (longitudinal)[f]				
Unnotched, R = 0.1				
10^3 cycles, ksi	130	130	84	U
10^5 cycles, ksi	70	63	60	U
10^7 cycles, ksi	44	39	37	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	90	82	76	U
10^5 cycles, ksi	58	49	44	U
10^7 cycles, ksi	41	29	27	U

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

Properties	Temperature, F 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	69
Stress Corrosion (longitudinal)[(g)]				
80% TYS, 1000 hr, maximum	no cracks			
Coefficient of Thermal Expansion				
5.0×10^{-6} in./in./F (RT to 800 F)				
Density				
0.160 lb./in.^{3}				

(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) 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_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3½% NaCl.

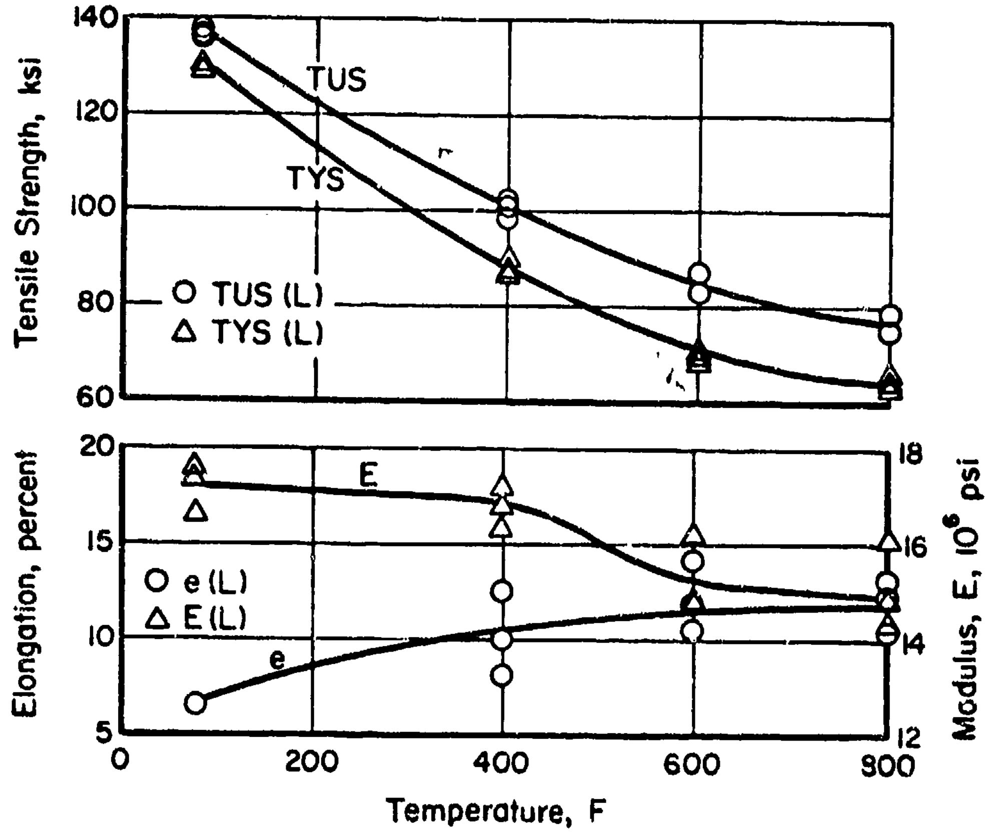


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED Ti-6Al-4V CASTINGS

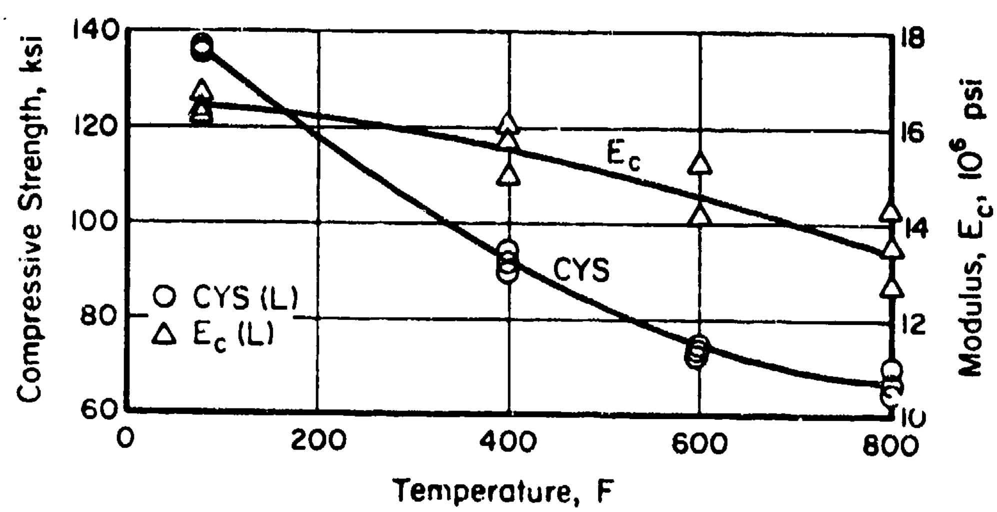


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSION PROPERTIES OF ANNEALED Ti-6Al-4V CASTINGS

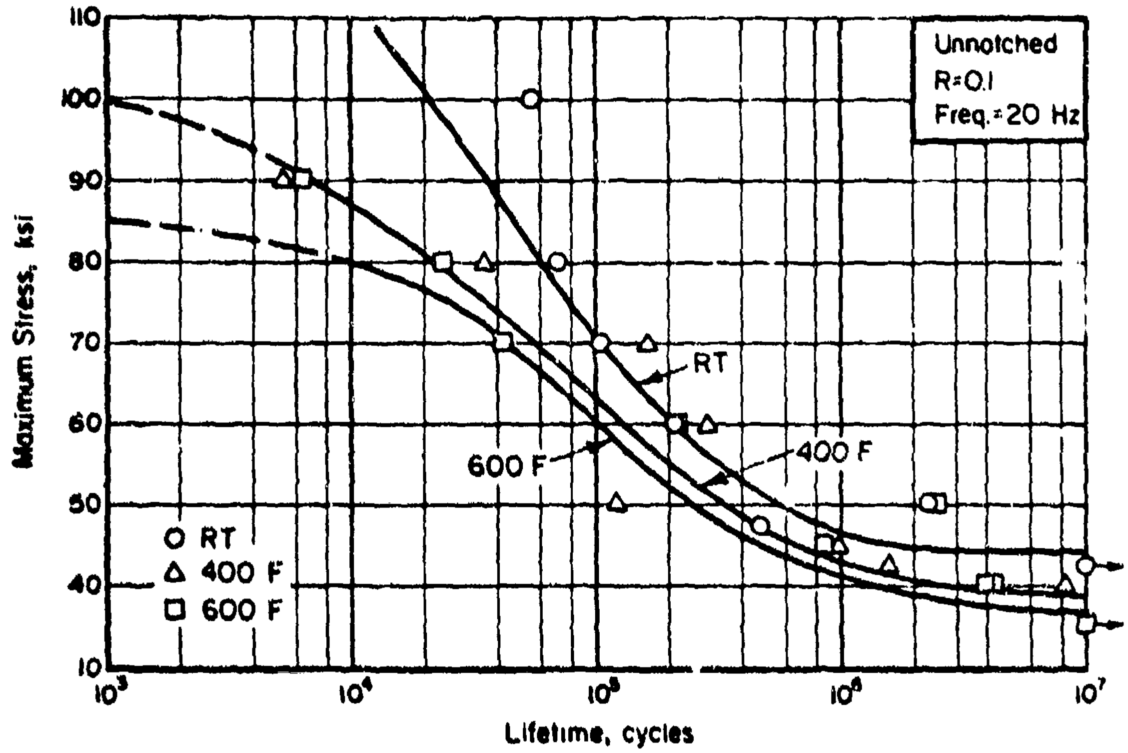


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED Ti-6Al-4V CASTINGS

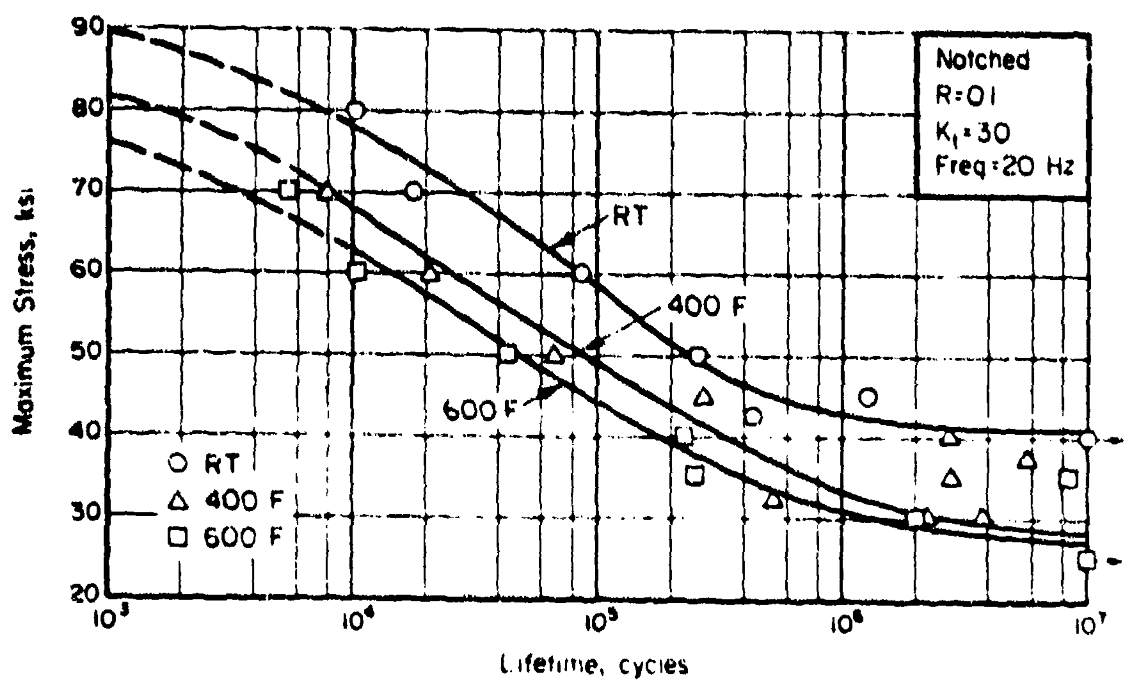


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) ANNEALED Ti-6Al-4V CASTINGS

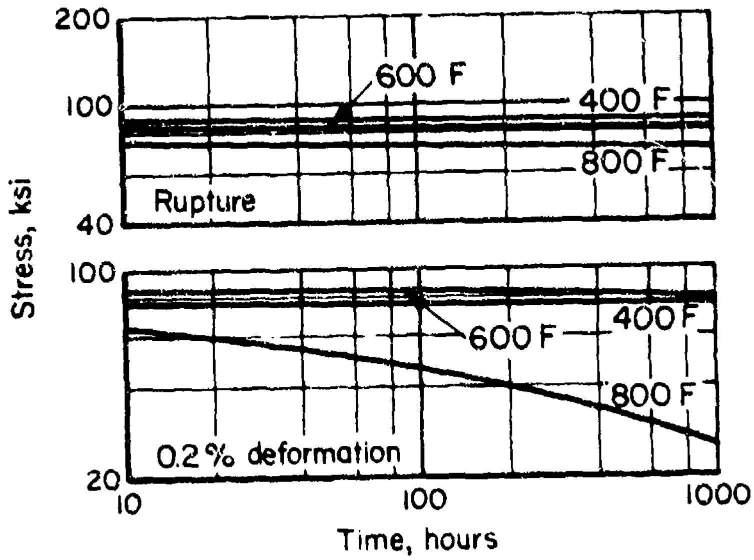


FIGURE 5. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED Ti-6Al-4V CASTINGS

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

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[a]

Condition: Heat Treated
Thickness: .0635 inch

Properties	RT	800	1000	1200
	Temperature, F			
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), 10^3 ksi	24.7	21.6	22.6	21.4
E (transverse), 10^3 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_c (longitudinal), 10^3 ksi	25.2	22.8	23.0	21.4
E_c (transverse), 10^3 ksi	24.3	23.7	23.2	22.2
Shear[b]				
SUS (longitudinal), ksi	123.9	U[c]	U	U
SUS (transverse), ksi	127.8	U	U	U
Fracture Toughness				
K_c (T-L) ksi√in.	244.5[d]			
Axial Fatigue (Transverse)[e]				
Unnotched, R = 0.1				
10^3 cycles, ksi	154	140	131	U
10^5 cycles, ksi	125	112	98	U
10^7 cycles, ksi	84	73	67	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	120	100	100	U
10^5 cycles, ksi	73	64	64	U
10^7 cycles, ksi	46	44	44	U

Incoloy 903 Alloy Data (Continued)

	Temperature, F			
	RT	800	1000	1200
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi		(no creep)		15
0.2% plastic deformation, 1000 hr, ksi				14
Stress Rupture (transverse)				
Rupture, 100 hr, ksi	NA	48	50	31
Rupture, 1000 hr, ksi	NA	35	44	15
Stress Corrosion (transverse)(f)				
80% TYS, 1000 hr, maximum	no cracks			
Coefficient of Thermal Expansion				
5.6×10^{-6} in./in./F				
Density				
0.294 lb./in.^{3}				

(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) Sheet-shear type specimen; average of 3 tests in each direction.

(c) U, unavailable; NA, not applicable.

(d) Specimens were 18 x 36 with a center flaw. Value is average of 4 tests.

(e) "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.

(f) Room-temperature three-point bend test. Alternate immersion in 3½% NaCl.

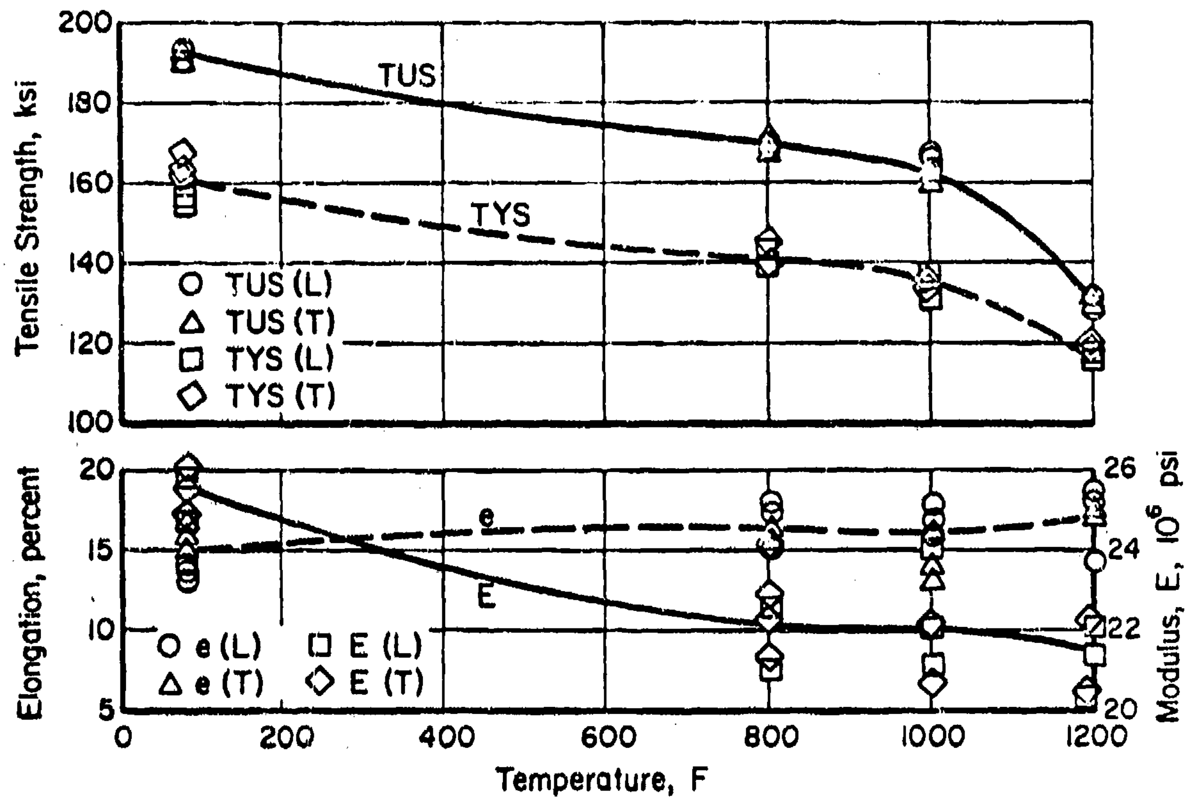


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHEET

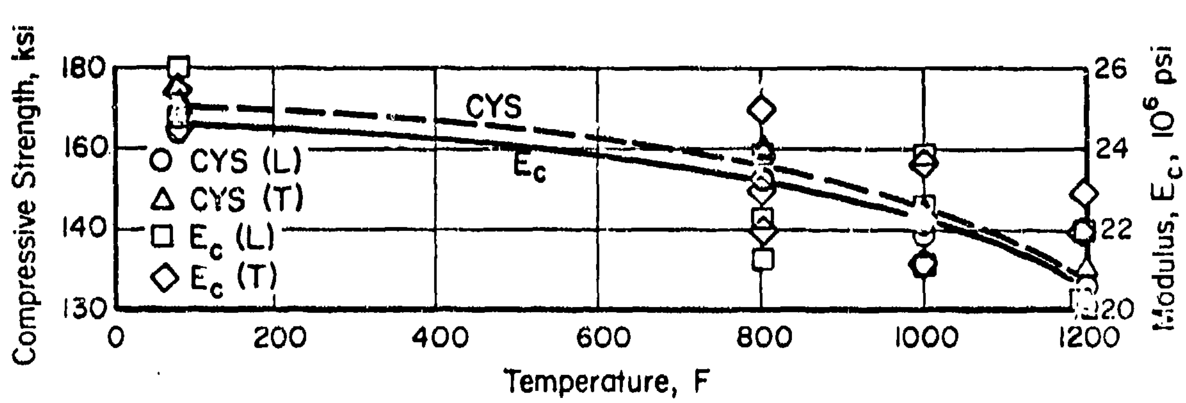


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF HEAT-TREATED INCOLOY 903 SHEET

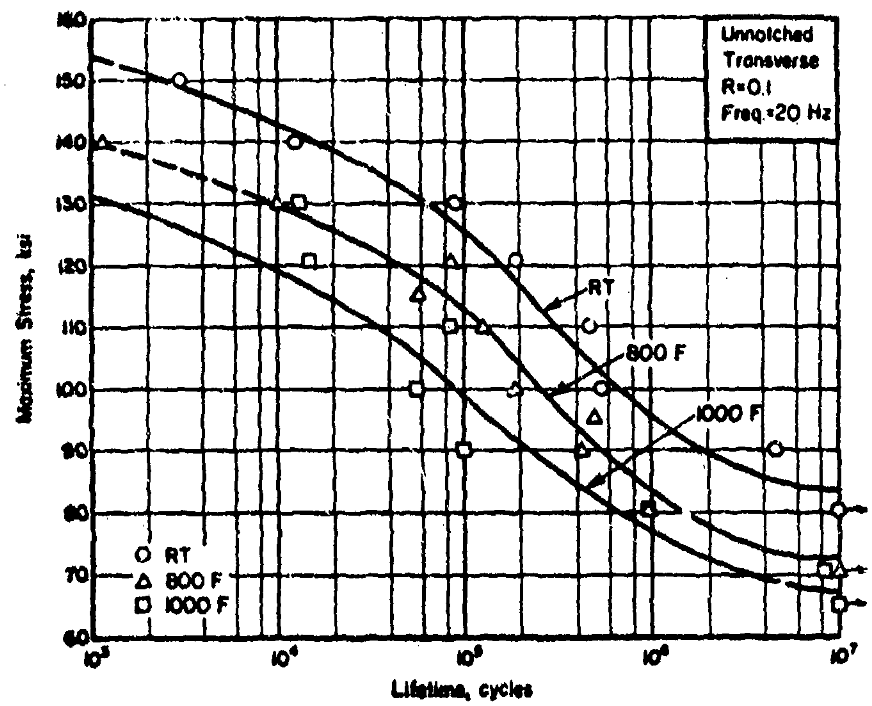


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED HEAT-TREATED INCOLOY 903 SHEET

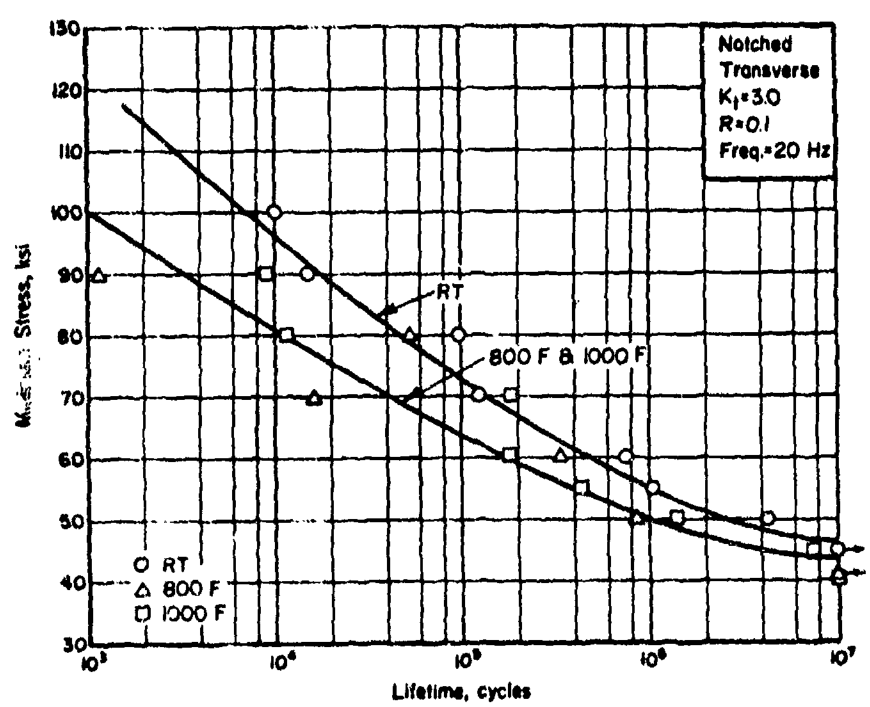


FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED (K_t = 3.0) HEAT-TREATED INCOLOY 903 SHEET

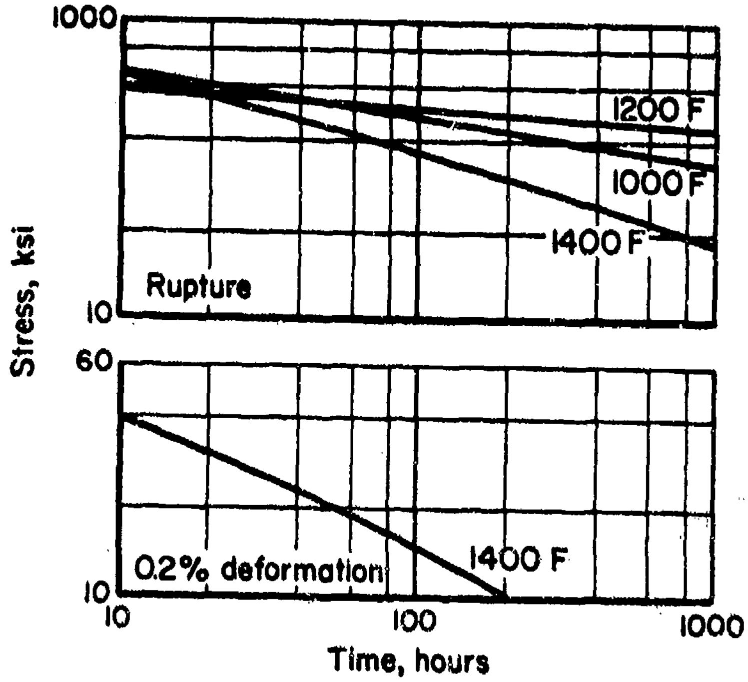


FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR HEAT-TREATED INCOLOY 903 SHEET (TRANSVERSE)

MECHANICAL-PROPERTY DATA
201.0 ALUMINUM ALLOY

-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

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 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[(a)]

Condition: -T7
Thickness: Various

Properties	Temperature, F 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), 10^3 ksi	10.5	9.6	8.8	8.0
Compression				
CYS (longitudinal), ksi	60.9	53.6	48.2	30.9
E_c (longitudinal), 10^3 ksi	11.1	9.9	9.7	9.0
Shear				
SUS (longitudinal), ksi	39.3[(b)]	U[(c)]	U	U
Impact				
V-notch Charpy, ft.lbs. (longitudinal)	5.0[(d)]	U	U	U
Axial Fatigue (transverse)[(e)]				
Unnotched, R = 0.1				
10^3 cycles, ksi	62	62	62	U
10^5 cycles, ksi	37	36	35	U
10^7 cycles, ksi	31	27	25	
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	54	54	50	U
10^5 cycles, ksi	22	21	19	U
10^7 cycles, ksi	16	14	12	U

201-T7 Alloy Data (Continued)

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	U	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_t" represents the Neuber-Peterson theoretical stress concentration factor.

(f) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

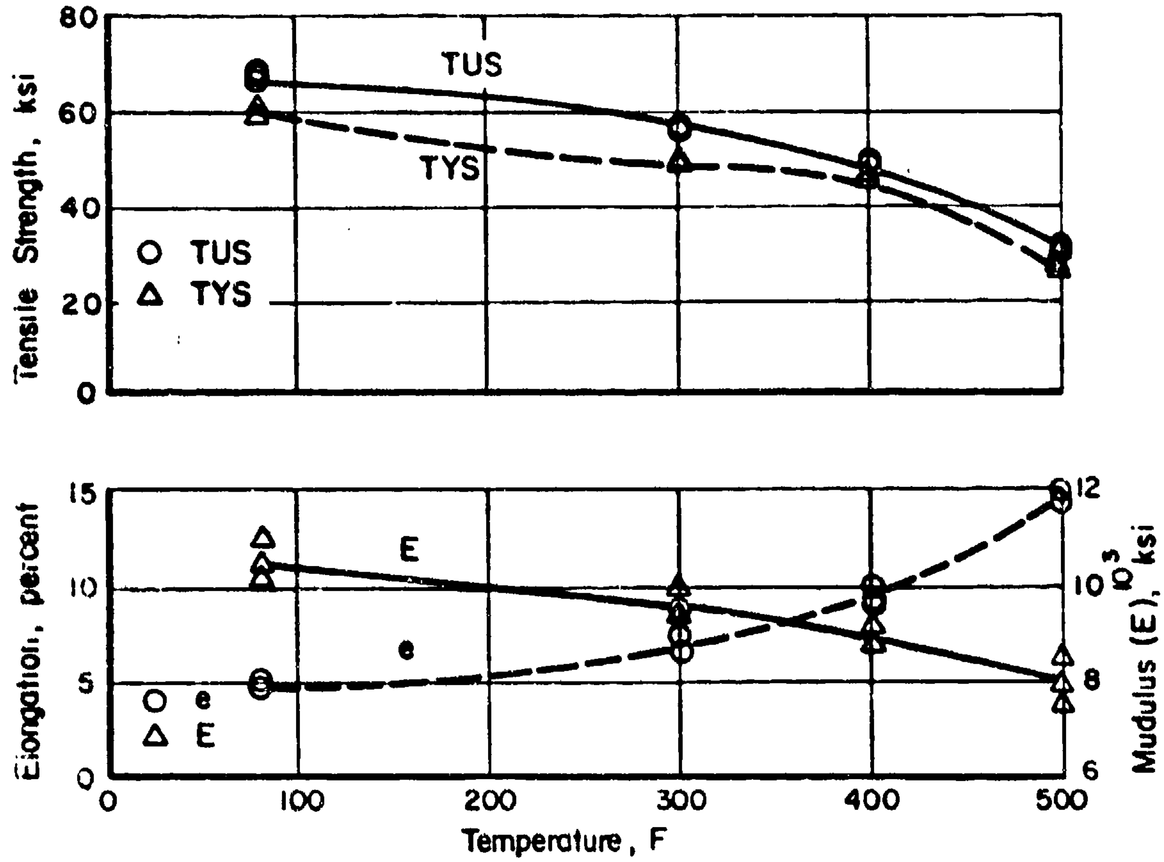


FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 201-T7 ALUMINUM ALLOY CASTINGS

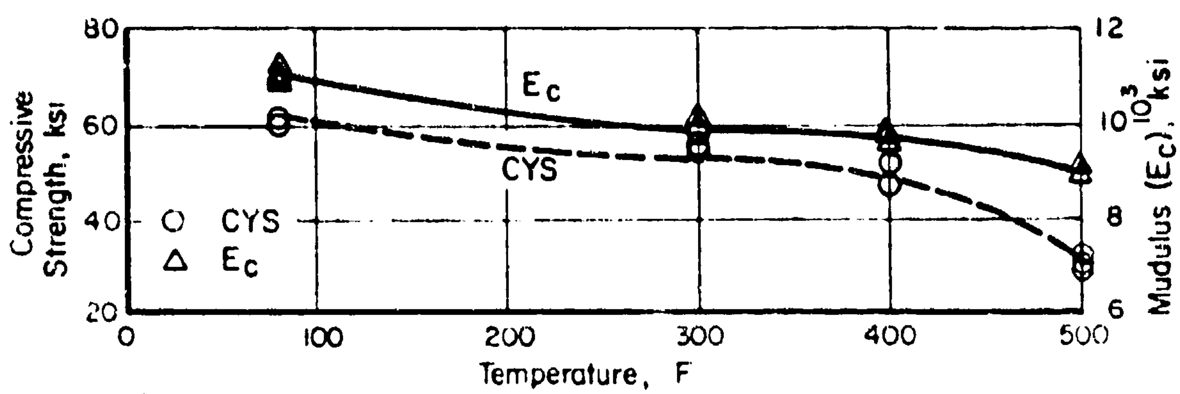


FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 201-T7 ALUMINUM ALLOY CASTINGS

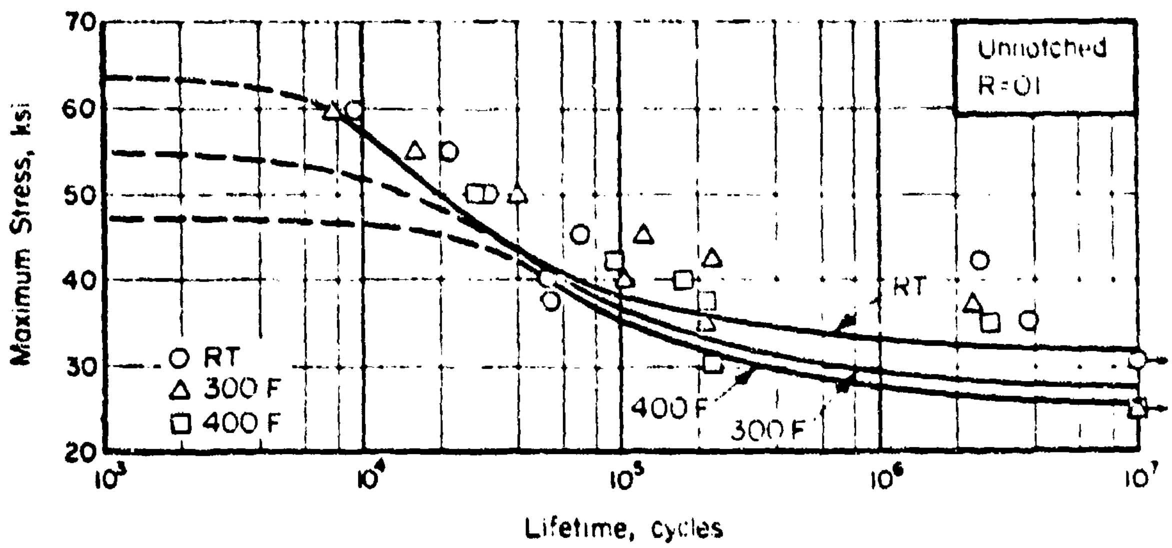
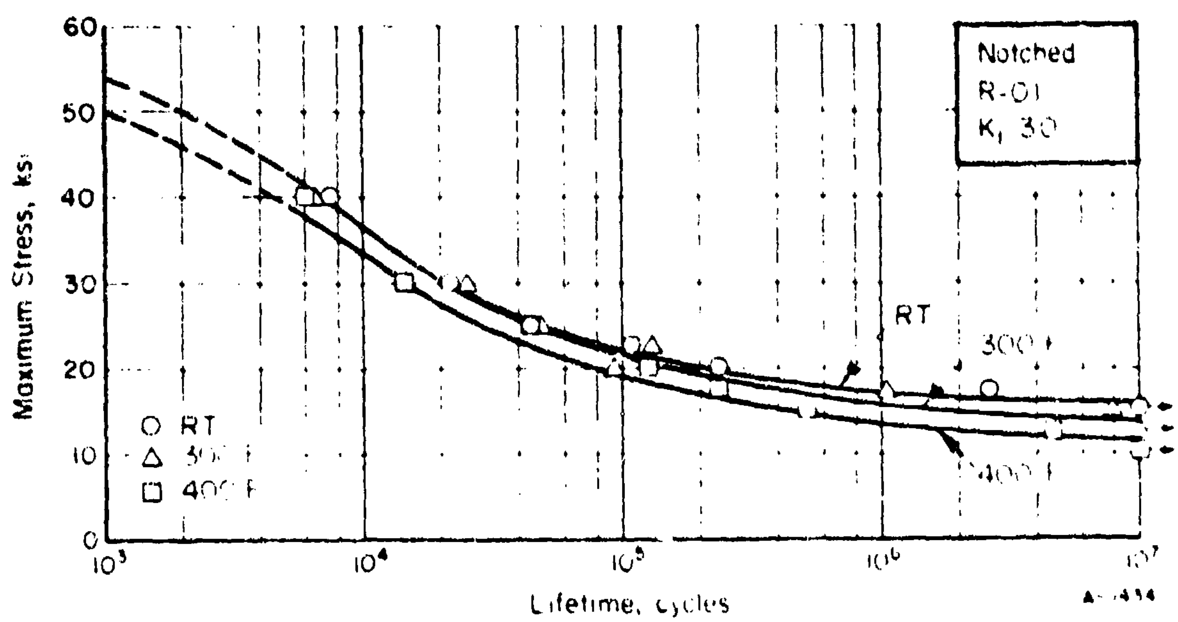


FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 201-T7 ALUMINUM ALLOY CASTING



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