AFML-TR-73-114



# ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS

O. L. Deel, P. E. Ruff and H. Mindlin

Battelle
Columbus Laboratories

TECHNICAL REPORT AFML-TR-73-114

JUNE 1973





Approved for public release; distribution unlimited.

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

148

# NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.



Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

Security Classification



**DOCUMENT CONTROL DATA - R & D**

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Battelle<br>Columbus Laboratories<br>505 King Avenue, Columbus, Ohio 43201 | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP<br>NA |

3. REPORT TITLE

Engineering Data on New Aerospace Structural Materials

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Summary Report, April 1972 to April 1973

5. AUTHOR(S) (First name, middle initial, last name)
Omar L. Deel, Paul E. Ruff, and H. Mindlin

| | | |
|---|---|---|
| 6. REPORT DATE<br>June 1973 | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS<br>0 |
| 8a. CONTRACT OR GRANT NO<br>F33615-72-C-1280<br>b. PROJECT NO<br>7381<br>c.<br>Task No. 738106<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>AFML-TR-73-114<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) | |

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

| | |
|---|---|
| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>Air Force Materials Laboratory<br>Wright-Patterson Air Force Base, Ohio 45433 |

13. ABSTRACT

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 X2048-T851 plate, 7050-T73651 plate, 21-6-9 annealed sheet, Ti-8Mo-8V-2Fe-3Al STA sheet, Ti-6Al-2Zr-2Sn-2Mo-2Cr STA plate, and Ti-6Al-6V-2Sn STA isothermal die forgings.

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

DD FORM 1 NOV 65 1473

Security Classification

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Mechanical Properties | | | | | | |
| Fatigue Properties | | | | | | |
| Creep Properties | | | | | | |
| Chemical Composition | | | | | | |
| Physical Properties | | | | | | |
| Aluminum Alloys | | | | | | |
| Stainless Steel | | | | | | |
| Titanium Alloys | | | | | | |
| X-2048 | | | | | | |
| 21-6-9 | | | | | | |
| 7050 | | | | | | |
| Ti-8Mo-8V-2Fe-3Al | | | | | | |
| Ti-6Al-2Zr-2Sn-2Mo-2Cr | | | | | | |
| Ti-6Al-6V-2Sn | | | | | | |

# ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS

O. L. Deel, P. E. Ruff and H. Mindlin





ib

# FOREWORD

This report was prepared by Battelle's Columbus Laboratories, Columbus, Ohio, under Contract F33615-72-C-1280. 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, 1972, to April, 1973. This report was submitted by the authors on April 30, 1973.

This technical report has been reviewed and is approved.

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

# ABSTRACT

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 X2048-T851 plate, 7050-T73651 plate, 21-6-9 annealed sheet, Ti-8Mo-8V-2Fe-3Al STA sheet, Ti-6Al-2Zr-2Sn-2Mo-2Cr STA plate, and Ti-6Al-6V-2Sn STA isothermal die forgings.

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

Preceding page blank

TABLE OF CONTENTS
(Continued)

## LIST OF TABLES

## LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

# LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Continued)

LIST OF ILLUSTRATIONS
(Continued)

LIST OF ILLUSTRATIONS
(Continued)

## LIST OF ILLUSTRATIONS
(Continued)

# 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 five technical reports, AFML-TR-67-418, AFML-TR-68-211, AFML-TR-70-252, AFML-TR-71-249, and AFML-TR-72-196, Volumes I and II.

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) X2048-T851 Plate

(2) 7050-T73651 Plate

(3) 21-6-9 Annealed Sheet

(4) Ti-8Mo-8V-2Fe-3Al STA Sheet

(5) Ti-6Al-2Zr-2Sn-2Mo-2Cr STA Plate

(6) Ti-6Al-6V-2Sn STA Isothermal Die Forgings .

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.

# X2048-T851 Aluminum Alloy

## Material Description

Alloy X2048-T851 is a recent development of the Reynolds Metals Company. The development aim was a thick section alloy with high toughness and stability at moderate temperatures. The goal was to achieve the strength, fatigue resistance, corrosion resistance, and thermal stability of 2024-T851 or 2124-T851 and the toughness of 2219.

The material used for this evaluation was 3-inch plate produced within the following composition limits

| | |
|---|---|
| Copper | 2.8 to 3.8 |
| Manganese | 0.20 to 0.60 |
| Magnesium | 1.2 to 1.8 |
| Zinc | 0.25 max |
| Titanium | 0.10 max |
| Silicon | 0.15 max |
| Iron | 0.20 max |
| Others total | 0.15 max |
| Aluminum | Balance |

## Processing and Heat Treating

Specimens were cut from the plate as shown in Figure 1 and were tested in the as-received -T851 temper.

## Test Results

Tension. Test results for longitudinal and transverse specimens at room temperature, 250 F, 350 F, and 500 F are given in Table I. Short-transverse test results at room temperature only are also given in Table I. Stress-strain curves at temperature are shown in Figures 2 and 3. Effect-of-temperature curves are presented in Figure 6.

Compression. Results of tests in both the longitudinal and transverse directions at room temperature, 250 F, 350 F, and 500 F are given in Table II. Stress-strain and tangent-modulus curves at temperature are shown in Figures 4 and 5. Effect-of-temperature curves are presented in Figure 7.

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

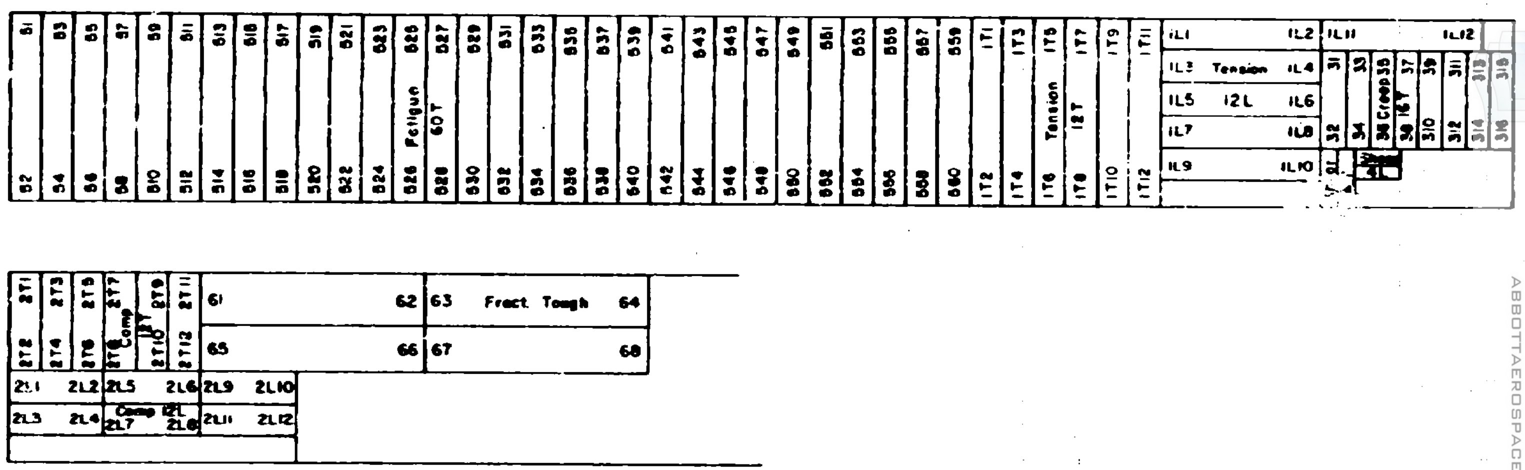



FIGURE 1. SPECIMEN LAYOUT FOR X2048-T851 PLATE

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

Fracture Toughness. Results of slow-bend type tests in both the longitudinal (L-T) and transverse (T-L) directions are given in Table V. The 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. (Higher $K_{Ic}$ values may be achieved with larger specimens. Reference J. G. Kaufman, "Notes for E-24.01 Meeting", held at Battelle's Columbus Laboratories on October 4, 1972.)

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

Creep and Stress-Rupture. Results of tests on longitudinal 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 procedure section of this report. No cracks or failures occurred in the 1000-hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy was determined to be 12.9 x $10^{-6}$ in./in./F for 68 F to 350 F.

Density. The density of this material is 0.0994 lb./in.$^3$.

TABLE I. TENSION TEST RESULTS FOR X2048-T851 ALUMINUM 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, $10^6$ psi |
|---|---|---|---|---|---|---|
| | | **Longitudinal at Room Temperature** | | | | |
| 1L-1 | | 66.2 | 60.5 | 8.0 | 15.7 | 10.2 |
| 1L-2 | | 66.2 | 60.3 | 8.5 | 15.8 | 10.3 |
| 1L-3 | | 66.4 | 60.4 | 8.5 | 15.5 | 10.2 |
| | Average | 66.5 | 60.4 | 8.3 | 15.7 | 10.2 |
| | | **Transverse at Room Temperature** | | | | |
| 1T-1 | | 69.4 | 62.4 | 8.0 | 12.5 | 10.8 |
| 1T-2 | | 66.4 | 60.0 | 7.0 | 12.2 | 10.5 |
| 1T-3 | | 66.3 | 60.2 | 6.5 | 10.3 | 10.3 |
| | Average | 67.4 | 60.9 | 7.2 | 11.7 | 10.5 |
| | | **Short Transverse at Room Temperature** | | | | |
| 1ST-1 | | 67.6 | 59.6 | 7.0 | 11.4 | 11.1 |
| 1ST-2 | | 67.4 | 59.0 | 6.0 | 7.8 | 11.2 |
| 1ST-3 | | 66.4 | 58.2 | 6.0 | 9.0 | 11.1 |
| | Average | 67.1 | 58.9 | 6.3 | 9.4 | 11.1 |
| | | **Longitudinal at 250 F** | | | | |
| 1L-4 | | 59.8 | 56.5 | 13.5 | 33.9 | 9.5 |
| 1L-5 | | 60.5 | 57.0 | 12.5 | 28.4 | 9.9 |
| 1L-6 | | 60.1 | 57.0 | 12.0 | 32.6 | 10.4 |
| | Average | 60.1 | 56.8 | 12.7 | 31.6 | 9.9 |
| | | **Transverse at 250 F** | | | | |
| 1T-4 | | 60.4 | 56.5 | 11.5 | 26.3 | 10.0 |
| 1T-5 | | 59.7 | 56.0 | 13.5 | 29.3 | 10.0 |
| 1T-6 | | 59.8 | 56.3 | 13.0 | 27.6 | 9.4 |
| | Average | 60.0 | 56.3 | 12.7 | 27.7 | 9.8 |
| | | **Longitudinal at 350 F** | | | | |
| 1L-7 | | 51.6 | 49.4 | 13.5 | 38.8 | 9.3 |
| 1L-8 | | 51.4 | 49.1 | 14.5 | 38.1 | 9.3 |
| 1L-9 | | 51.1 | 48.8 | 14.5 | 35.0 | 9.4 |
| | Average | 51.4 | 49.4 | 14.2 | 37.3 | 9.3 |
| | | **Transverse at 350 F** | | | | |
| 1T-7 | | 50.5 | 48.7 | 17.0 | 35.1 | 9.3 |
| 1T-8 | | 51.1 | 49.4 | 16.5 | 33.5 | 9.4 |
| 1T-9 | | 49.3 | 48.2 | 16.0 | 33.9 | 9.1 |
| | Average | 50.3 | 48.8 | 16.5 | 34.2 | 9.3 |
| | | **Longitudinal at 500 F** | | | | |
| 1L-10 | | 34.5 | 32.1 | 10.0 | 27.2 | 8.6 |
| 1L-11 | | 33.7 | 31.8 | 8.5 | 21.6 | 8.5 |
| 1L-12 | | 33.7 | 31.3 | 10.0 | 21.5 | 7.9 |
| | Average | 34.0 | 31.7 | 9.5 | 23.4 | 8.3 |
| | | **Transverse at 500 F** | | | | |
| 1T-10 | | 32.3 | 30.5 | 10.0 | 14.7 | 7.5 |
| 1T-11 | | 35.0 | 33.2 | 7.5 | 15.1 | 8.0 |
| 1T-12 | | 32.8 | 31.0 | 7.0 | 15.1 | 7.6 |
| | | 33.4 | 31.6 | 8.2 | 15.0 | 7.7 |

TABLE II. COMPRESSION TEST RESULTS FOR X2048-T851 ALUMINUM PLATE

| Specimen Number | | 0.2 Percent Offset Yield Strength, ksi | Compression Modulus, $10^6$ psi |
|---|---|---|---|
| | | Longitudinal at Room Temperature | |
| 2L-1 | | 62.0 | 11.4 |
| 2L-2 | | 59.0 | 11.1 |
| 2L-3 | | 61.6 | 11.5 |
| | Average | 60.9 | 11.3 |
| | | Transverse at Room Temperature | |
| 2T-1 | | 60.6 | 10.9 |
| 2T-2 | | 61.2 | 11.1 |
| 2T-3 | | 60.0 | 11.4 |
| | Average | 60.6 | 11.1 |
| | | Longitudinal at 250 F | |
| 2L-4 | | 56.2 | 10.1 |
| 2L-5 | | 56.8 | 10.3 |
| 2L-6 | | 57.0 | 10.3 |
| | Average | 56.7 | 10.2 |
| | | Transverse at 250 F | |
| 2T-4 | | 56.8 | 10.3 |
| 2T-5 | | 56.8 | 10.3 |
| 2T-6 | | 54.4 | 10.2 |
| | Average | 56.0 | 10.3 |
| | | Longitudinal at 350 F | |
| 2L-7 | | 51.7 | 9.8 |
| 2L-8 | | 48.8 | 9.4 |
| 2L-9 | | 51.3 | 9.6 |
| | Average | 50.6 | 9.6 |
| | | Transverse at 350 F | |
| 2T-7 | | 52.0 | 9.9 |
| 2T-8 | | 50.3 | 9.7 |
| 2T-9 | | 50.9 | 9.6 |
| | Average | 51.1 | 9.7 |
| | | Longitudinal at 500 F | |
| 2L-10 | | 35.0 | 9.6 |
| 2L-11 | | 35.3 | 9.0 |
| 2L-12 | | 35.3 | 9.7 |
| | Average | 35.2 | 9.4 |
| | | Transverse at 500 F | |
| 2T-10 | | 33.1 | 9.7 |
| 2T-11 | | 32.5 | 9.9 |
| 2T-12 | | 33.1 | 9.7 |
| | Average | 32.9 | 9.7 |

TABLE III. SHEAR TEST RESULTS FOR X2048-T851 ALUMINUM PLATE AT ROOM TEMPERATURE

| Specimen Number | | Ultimate Shear Strength, ksi |
|---|---|---|
| | **Longitudinal** | |
| 4L-1 | | 39.3 |
| 4L-2 | | 39.0 |
| 4L-3 | | 39.8 |
| 4L-4 | | 39.3 |
| | Average | 39.3 |
| | **Transverse** | |
| | | 39.5 |
| 4T-2 | | 40.1 |
| 4T-3 | | 38.8 |
| 4T-4 | | 38.5 |
| | Average | 39.2 |

TABLE IV. CHARPY V-NOTCH TEST RESULTS FOR X2048-T851 ALUMINUM PLATE

| Specimen Number | | Energy, ft./lbs. |
|---|---|---|
| | **Longitudinal** | |
| 10-1L | | 7.0 |
| 10-2L | | 9.0 |
| 10-3L | | 7.0 |
| 10-4L | | 5.0 |
| 10-5L | | 9.0 |
| 10-6L | | 10.0 |
| 10-7L | | 6.5 |
| | Average | 8.9 |
| | **Transverse** | |
| 10-1T | | 4.0 |
| 10-2T | | 4.0 |
| 10-3T | | 5.0 |
| 10-4T | | 4.0 |
| 10-5T | | 5.0 |
| 10-6T | | 5.0 |
| | Average | 4.5 |

TABLE V. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS FOR X2048-T851 ALUMINUM PLATE

| Specimen Number | W, inches | a, inches | T, inches | P, lbs | Span, inches | $f(\frac{a}{W})$ | $K_Q$ (a) |
|---|---|---|---|---|---|---|---|
| | | | Transverse (T-L) | | | | |
| 6-1T | 2.00 | 0.903 | 1.00 | 4,500 | 8.0 | 2.294 | 29.20 |
| 6-2T | 2.00 | 0.936 | 1.00 | 4,100 | 8.0 | 2.410 | 27.95 |
| 6-3T | 2.00 | 0.946 | 1.00 | 4,350 | 8.0 | 2.448 | 30.12 |
| 6-4T | 2.00 | 0.942 | 1.00 | 4,300 | 8.0 | 2.433 | 29.59 |
| 6-5T | 2.00 | 0.911 | 1.00 | 4,350 | 8.0 | 2.321 | 28.56 |
| 6-6T | 2.00 | 0.916 | 1.00 | 4,425 | 8.0 | 2.339 | 29.27 |
| | | | | | | Average | 29.12 |
| | | | Longitudinal (L-T) | | | | |
| 6-1L | 2.00 | 0.876 | 1.00 | 4,925 | 8.0 | 2.205 | 30.72 |
| 6-2L | 2.00 | 0.903 | 1.00 | 4,950 | 8.0 | 2.294 | 32.12 |
| 6-3L | 2.00 | 0.918 | 1.00 | 4,900 | 8.0 | 2.346 | 32.52 |
| 6-4L | 2.00 | 0.947 | 1.00 | 5,075 | 8.0 | 2.452 | 35.19 |
| 6-5L | 2.00 | 0.880 | 1.00 | 4,880 | 8.0 | 2.218 | 30.61 |
| 6-6L | 2.00 | 0.920 | 1.00 | 4,950 | 8.0 | 2.353 | 32.94 |
| | | | | | | Average | 32.35 |

(a) These candidate $K_Q$ values do meet existing ASTM size and crack length criteria and are considered valid $K_{Ic}$ numbers.

TABLE VI. AXIAL LOAD FATIGUE TEST RESULTS FOR X2048-T851 ALUMINUM PLATE (UNNOTCHED, R = 0.1) (LONGITUDINAL)

| 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 | 3,658,400 |
| 5-9 | 30.0 | 11,340,800(a) |
| | 250 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) |
| | 350 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 | 256,800 |
| 5-28 | 25.0 | 14,461,900 |

(a) Did not fail.

(b) Failed at Radius.

TABLE VII. AXIAL LOAD FATIGUE RESULTS FOR X2048-T851 ALUMINUM PLATE (NOTCHED, $K_t$ = 3.0, R = 0.1) (LONGITUDINAL)

| 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] |
| | 250 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] |
| | 350 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 VIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR X2048-T851 ALUMINUM PLATE (LONGITUDINAL)

| 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 | | | | | |
| 3-3 | 60 | 250 | -- | -- | -- | -- | -- | 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 | 350 | -- | -- | -- | -- | -- | 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.

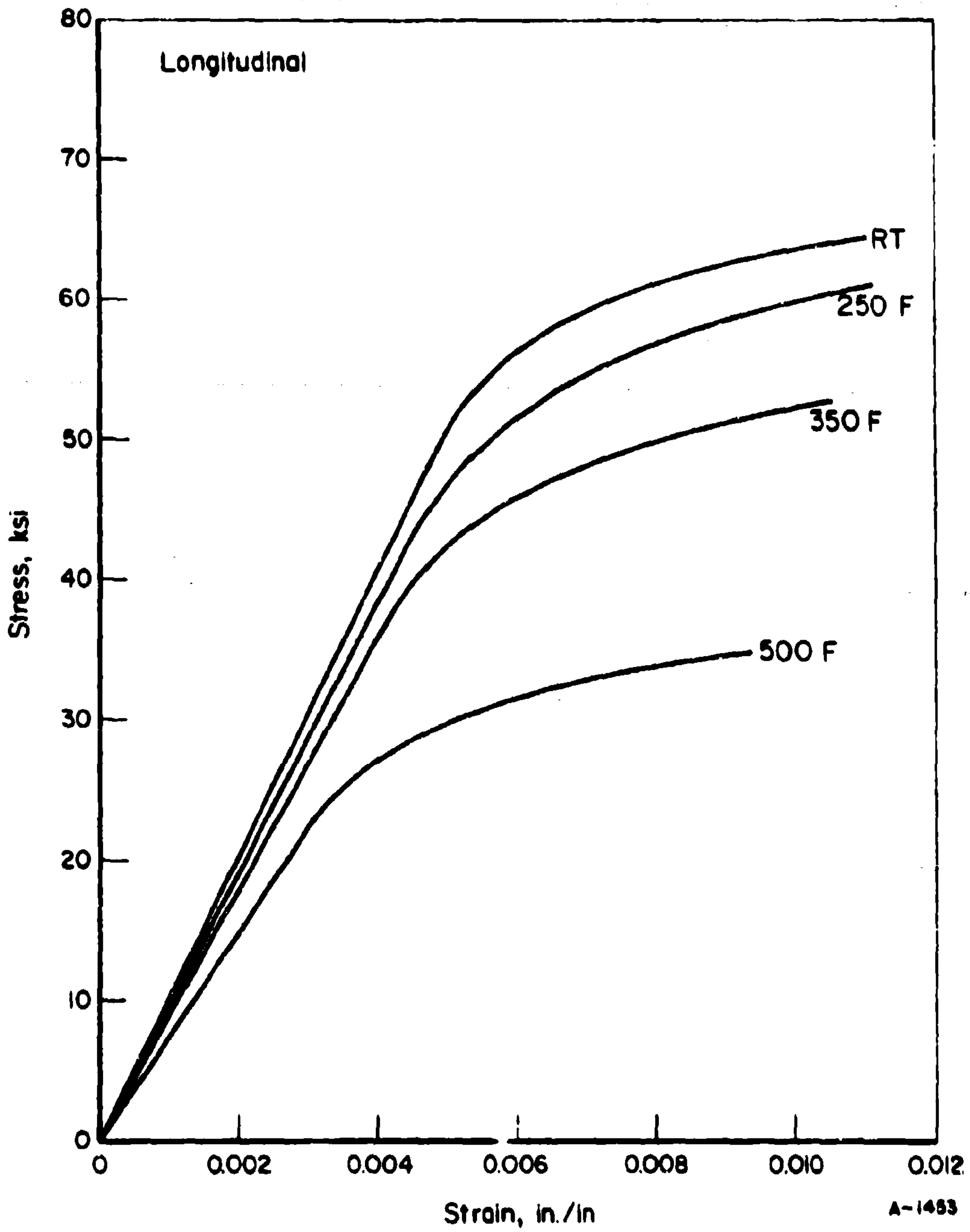



FIGURE 2. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR X2048-T851 PLATE (LONGITUDINAL)

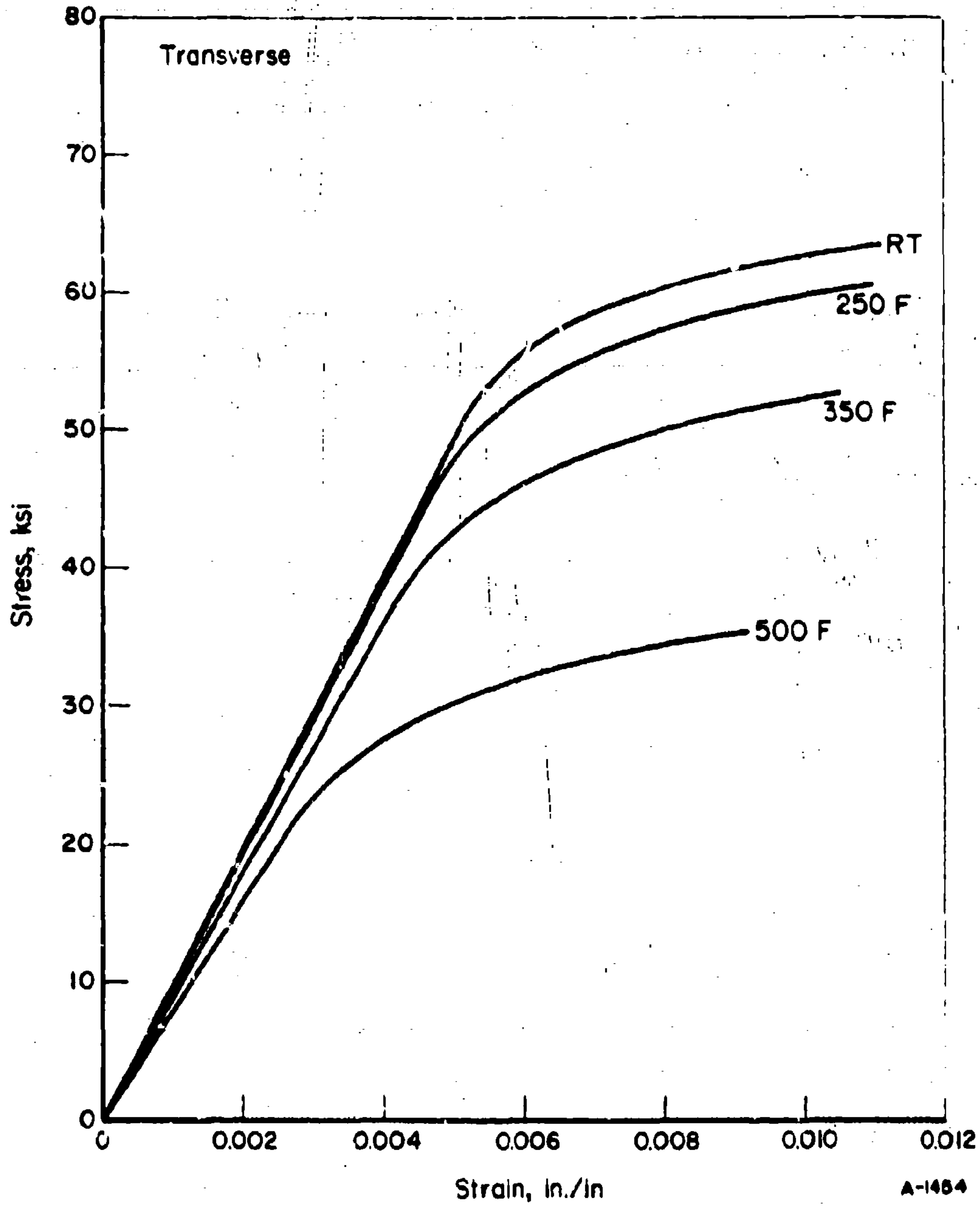



FIGURE 3. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR X2048-T851 PLATE (TRANSVERSE)

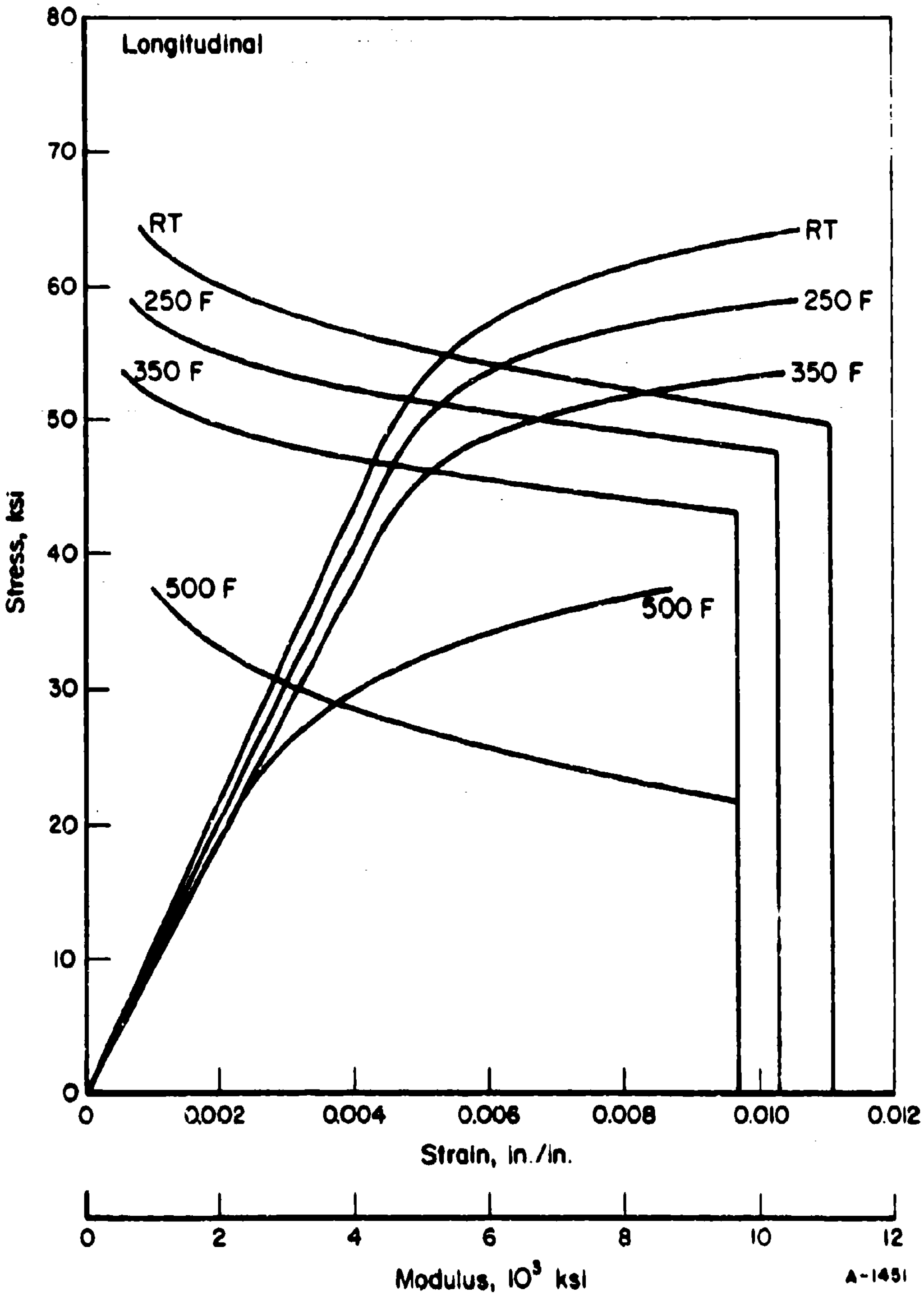



FIGURE 4. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR X2048-T851 PLATE (LONGITUDINAL)

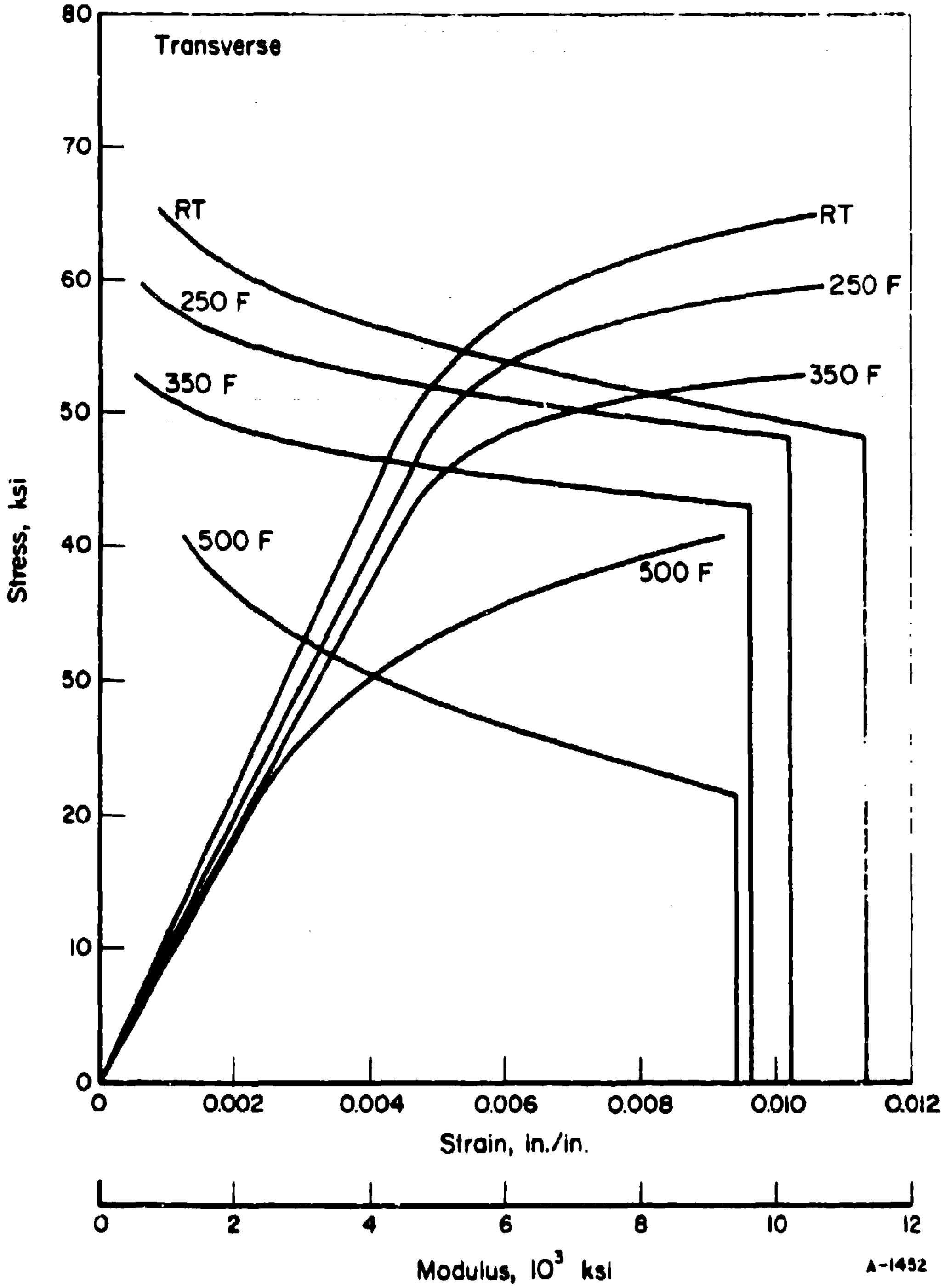



FIGURE 5. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR X2048-T851 PLATE (TRANSVERSE)

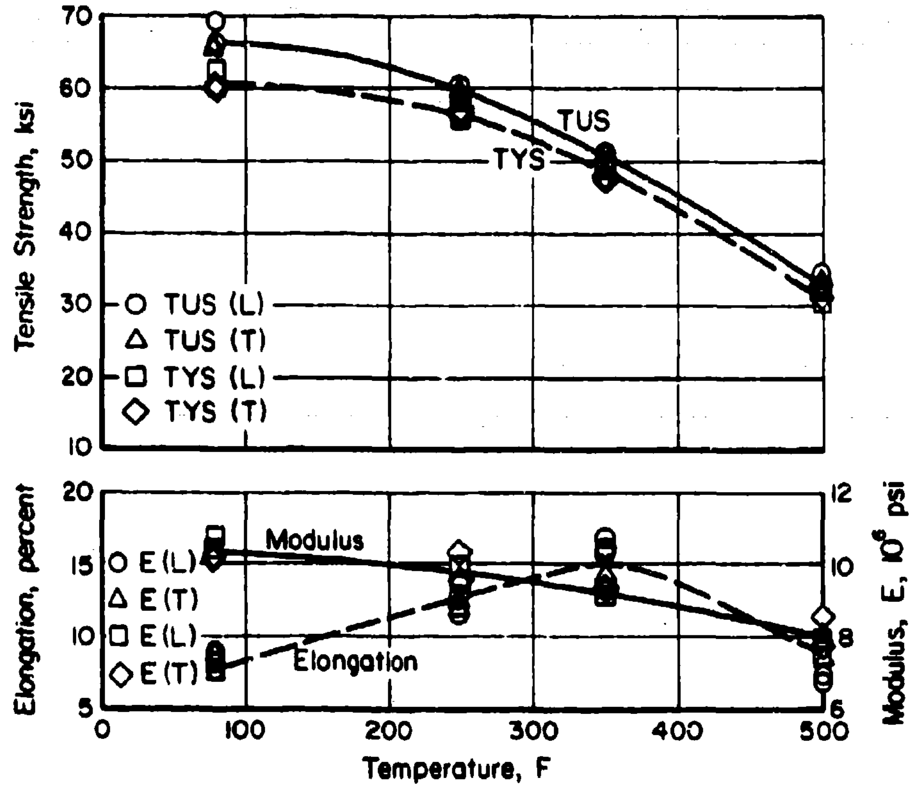



FIGURE 6. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF X2048-T851 PLATE

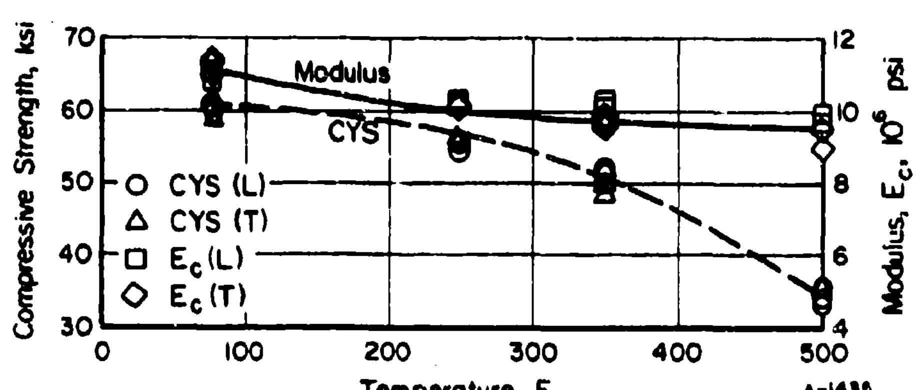



FIGURE 7. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF X2048-T851 PLATE

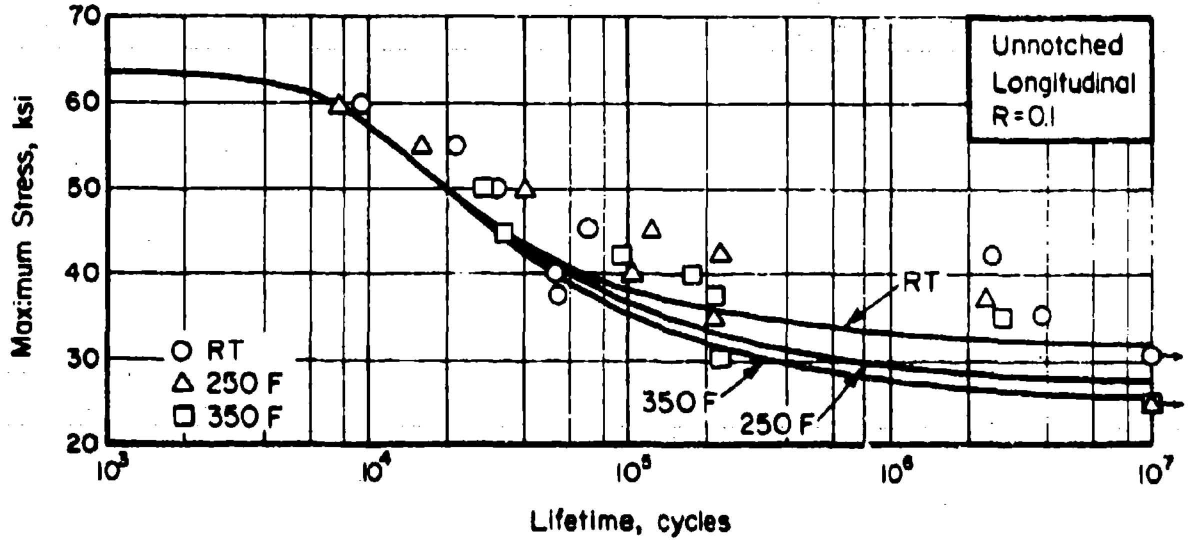



FIGURE 8. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED X2048-T851 PLATE (LONGITUDINAL)

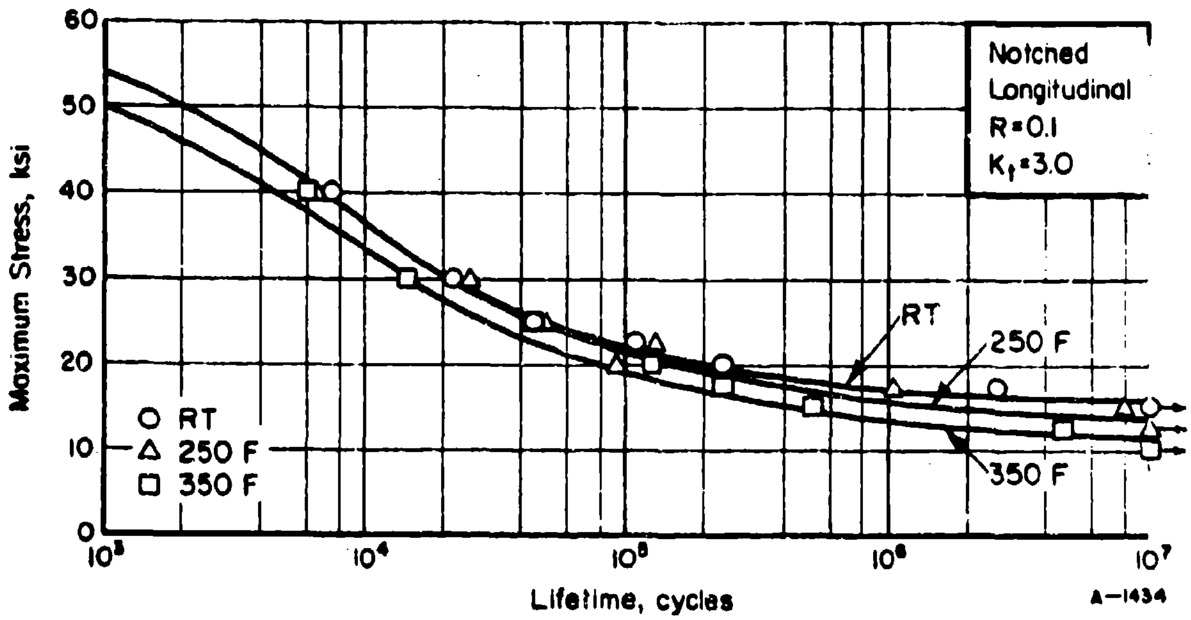



FIGURE 9. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) X2048-T851 PLATE (LONGITUDINAL)

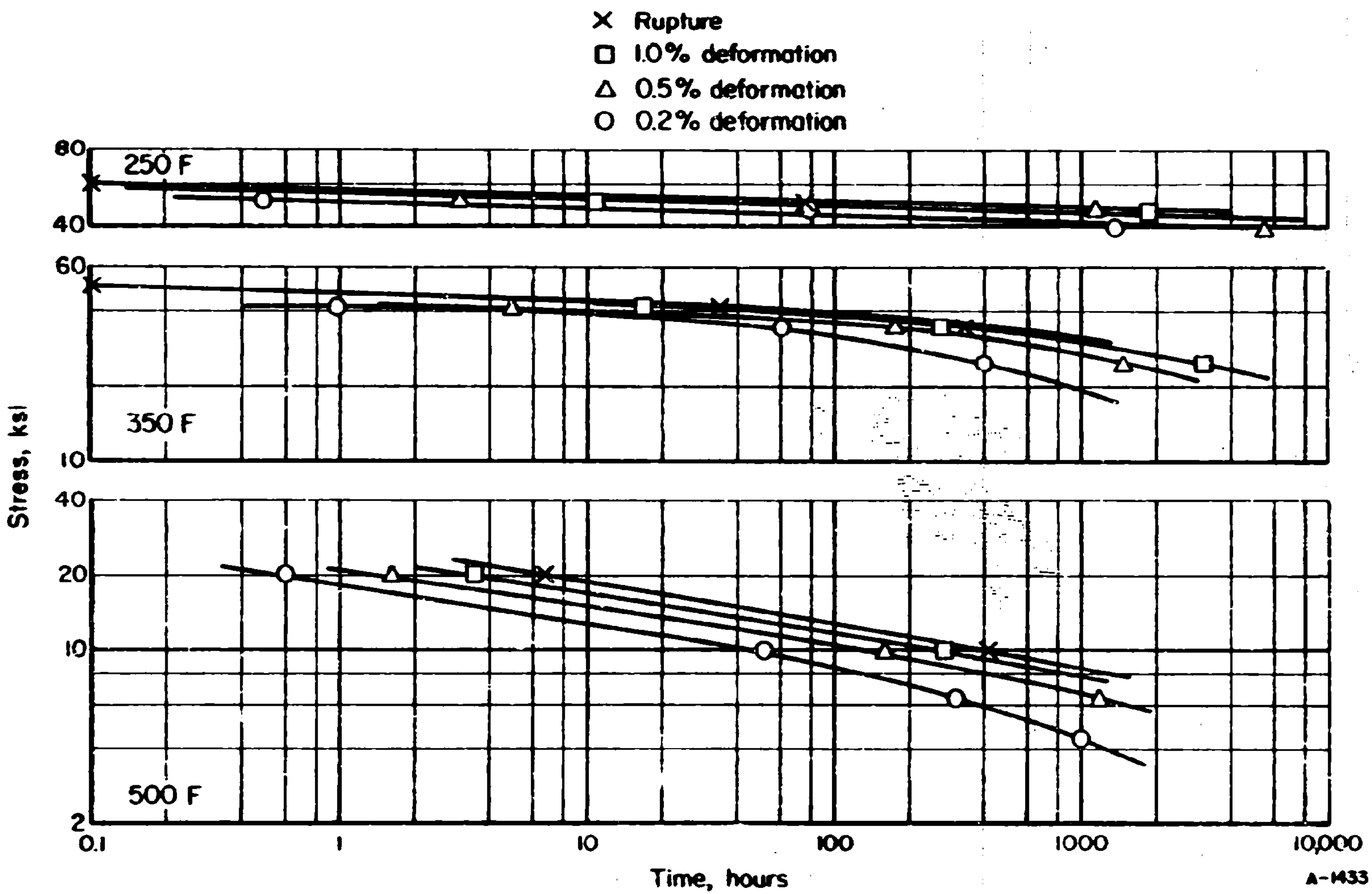



FIGURE 10. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR X2048-T851 PLATE (LONGITUDINAL)

# 7050-T73651 Aluminum Alloy

## Material Description

Alloy 7050 is an Al-Zn-Mg-Cu alloy developed by the Alcoa Research Laboratories supported by the Naval Air Systems Command and the Air Force Materials Laboratory. When heat treated and aged to the -T73 temper, thick 7050 plate and hand forgings exhibit strengths equal to or exceeding those of 7079-T6XX products combined with improved fracture toughness and a high resistance to exfoliation and stress-corrosion cracking. The alloy differs from conventional 7XXX series aluminum alloys in that zirconium is added and chromium and manganese are restricted in order to minimize quench sensitivity.

The material used in this evaluation was 1-inch plate from Heat S-416420 produced within the following composition limits

| | |
|---|---|
| Copper | 2.0 to 2.8 |
| Iron | 0.15 max |
| Silicon | 0.12 max |
| Manganese | 0.10 max |
| Magnesium | 1.9 to 2.6 |
| Zinc | 5.7 to 6.7 |
| Chromium | 0.04 max |
| Titanium | 0.06 max |
| Aluminum | Balance . |

## Processing and Heat Treating

The specimen layout is shown in Figure 11. Specimens were tested in the as-received -T73651 temper.

## Test Results

Tension. Test results for both longitudinal and transverse specimens at room temperature, 250 F, 350 F, and 500 F are given in Table IX. Typical stress-strain curves at temperature are presented in Figures 12 and 13. Effect-of-temperature curves are shown in Figure 16.

Compression. Test results for longitudinal and transverse specimens at room temperature, 250 F, 350 F, and 500 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.

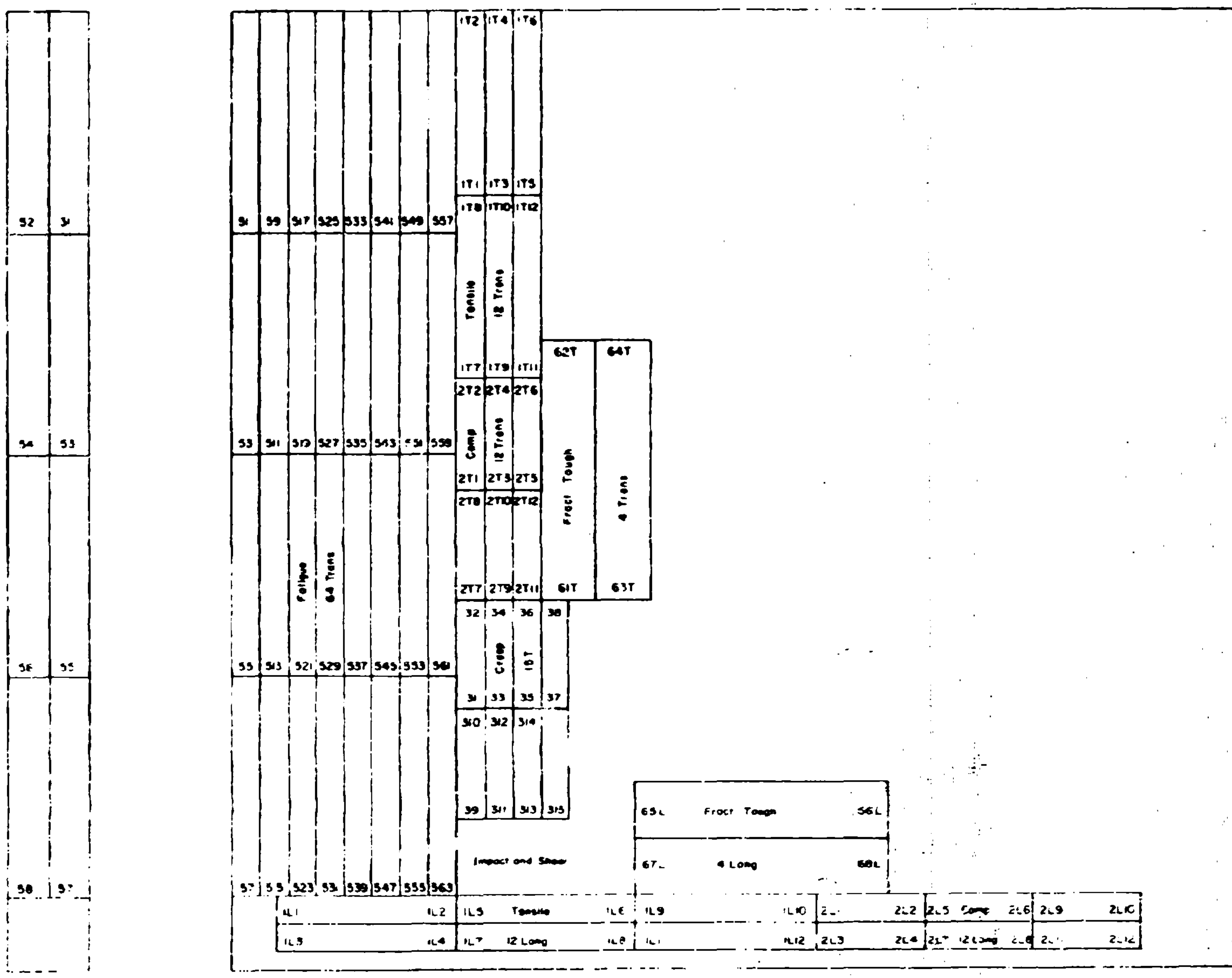



FIGURE 11. SPECIMEN LAYOUT FOR 7050-T73651 PLATE

Shear. Results of pin-type shear tests for longitudinal and transverse specimens at room temperature are given in Table XI.

Impact. Charpy V-notch test results for longitudinal and transverse specimens at room temperature are presented in Table XII.

Fracture Toughness. Results of slow-bend type tests in both the longitudinal (L-T) and transverse (T-L) directions are given in Table XIII. The candidate $K_Q$ values shown in the Table are considered valid $K_{Ic}$ values by existing ASTM criteria.

Fatigue. Axial load fatigue test results at a stress ratio of R = 0.1 are given in Tables XIV and XV for unnotched and notched transverse specimens. These tests were conducted at room temperature, 250 F, and 350 F. S-N curves are presented in Figures 18 and 19.

Creep and Stress-Rupture. Tests were conducted at 250 F, 350 F, and 500 F on transverse specimens. Tabular test results are given in Table XVI. Log-stress versus log-time curves are presented in Figure 20.

Stress Corrosion. Tests were performed 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 $12.8 \times 10^{-6}$ in./in./F from 68 F to 212 F.

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

TABLE IX. TENSION TEST RESULTS FOR 7050-T73651 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, $10^6$ psi |
|---|---|---|---|---|---|---|
| | | | **Longitudinal at Room Temperature** | | | |
| 1L-1 | | 82.1 | 73.4 | 12.0 | 30.8 | 10.3 |
| 1L-2 | | 82.9 | 74.0 | 12.0 | 30.0 | 10.4 |
| 1L-3 | | 82.8 | 73.9 | 11.5 | 29.9 | 10.1 |
| | Average | 82.6 | 73.8 | 11.8 | 30.2 | 10.3 |
| | | | **Transverse at Room Temperature** | | | |
| 1T-1 | | 81.4 | 72.4 | 10.0 | 23.3 | 10.6 |
| 1T-2 | | 81.4 | 72.7 | 10.5 | 25.2 | 10.5 |
| 1T-3 | | 81.7 | 72.6 | 11.0 | 24.9 | 10.4 |
| | Average | 81.5 | 72.5 | 10.5 | 24.5 | 10.5 |
| | | | **Longitudinal at 250 F** | | | |
| 1L-4 | | 65.1 | 65.0 | 15.5 | 47.6 | 9.3 |
| 1L-5 | | 64.8 | 64.8 | 15.5 | 48.2 | 9.4 |
| 1L-6 | | 65.2 | 65.2 | 15.5 | 48.5 | 9.5 |
| | Average | 65.0 | 64.9 | 15.5 | 48.1 | 9.4 |
| | | | **Transverse at 250 F** | | | |
| 1T-4 | | 64.4 | 63.8 | 13.5 | 39.1 | 9.3 |
| 1T-5 | | 64.6 | 64.2 | 13.5 | 40.3 | 10.1 |
| 1T-6 | | 64.5 | 64.2 | 13.0 | 36.8 | 9.7 |
| | Average | 64.5 | 64.1 | 13.3 | 38.[illegible] | 9.7 |
| | | | **Longitudinal at 350 F** | | | |
| 1L-7 | | 52.7 | 52.3 | 17.0 | 58.8 | 8.8 |
| 1L-8 | | 54.6 | 54.4 | 16.5 | 57.2 | 8.4 |
| 1L-9 | | 54.0 | 54.0 | 17.0 | 58.3 | 8.9 |
| | Average | 53.7 | 53.5 | 16.8 | 58.1 | 8.7 |
| | | | **Transverse at 350 F** | | | |
| 1T-7 | | 53.0 | 52.8 | 14.5 | 48.8 | 8.9 |
| 1T-8 | | 53.2 | 52.8 | 15.0 | 47.5 | 8.1 |
| 1T-9 | | 54.3 | 54.3 | 14.5 | 47.2 | 9.1 |
| | Average | 53.5 | 53.3 | 14.7 | 47.8 | 8.7 |
| | | | **Longitudinal at 500 F** | | | |
| 1L-10 | | 21.6 | 21.2 | 25.0 | 80.3 | 8.4 |
| 1L-11 | | 22.2 | 21.8 | 22.0 | 79.8 | 8.1 |
| 1L-12 | | 19.9 | 19.7 | 24.5 | 83.0 | 8.7 |
| | Average | 21.2 | 20.9 | 23.8 | 81.0 | 8.4 |
| | | | **Transverse at 500 F** | | | |
| 1T-10 | | 19.9 | 19.7 | 23.0 | 80.8 | 8.5 |
| 1T-11 | | 23.5 | 23.5 | 22.5 | 75.4 | 8.6 |
| 1T-12 | | 19.4 | 19.4 | 25.0 | 83.2 | 8.8 |
| | Average | 20.9 | 20.8 | 23.5 | 79.8 | 8.7 |

TABLE X. COMPRESSION TEST RESULTS FOR 7050-T73651 ALUMINUM ALLOY PLATE

| Specimen Number | | 0.2 Percent Offset Yield Strength, ksi | Compressive Modulus, $10^6$ psi |
|---|---|---|---|
| **Longitudinal at Room Temperature** | | | |
| 2L-1 | | 73.1 | 10.8 |
| 2L-2 | | 73.3 | 10.8 |
| 2L-3 | | 72.7 | 10.8 |
| | Average | 73.0 | 10.8 |
| **Transverse at Room Temperature** | | | |
| 2T-1 | | 75.4 | 11.2 |
| 2T-2 | | 75.2 | 10.9 |
| 2T-3 | | 75.2 | 11.0 |
| | Average | 75.3 | 11.0 |
| **Longitudinal at 250 F** | | | |
| 2L-4 | | 64.4 | 9.5 |
| 2L-5 | | 64.8 | 9.6 |
| 2L-6 | | 63.7 | 9.4 |
| | Average | 64.3 | 9.5 |
| **Transverse at 250 F** | | | |
| 2T-4 | | 66.4 | 10.0 |
| 2T-5 | | 66.1 | 9.9 |
| 2T-6 | | 65.7 | 10.1 |
| | Average | 66.1 | 10.0 |
| **Longitudinal at 350 F** | | | |
| 2L-7 | | 54.2 | 9.0 |
| 2L-8 | | 54.7 | 9.0 |
| 2L-9 | | 52.1 | 9.1 |
| | Average | 53.7 | 9.1 |
| **Transverse at 350 F** | | | |
| 2T-7 | | 54.8 | 9.4 |
| 2T-8 | | 54.8 | 9.6 |
| 2T-9 | | 52.1 | 9.3 |
| | Average | 55.1 | 9.4 |
| **Longitudinal at 500 F** | | | |
| 2L-10 | | 20.1 | 8.5 |
| 2L-11 | | 21.2 | 7.9 |
| 2L-12 | | 21.3 | 7.8 |
| | Average | 20.9 | 8.1 |
| **Transverse at 500 F** | | | |
| 2T-10 | | 22.6 | 8.2 |
| 2T-11 | | 21.0 | 7.9 |
| 2T-12 | | 22.5 | 8.0 |
| | Average | 22.0 | 8.0 |

TABLE XI. SHEAR TEST RESULTS FOR 7050-T73651 ALUMINUM ALLOY PLATE AT ROOM TEMPERATURE

| Specimen Number | | Ultimate Shear Strength, ksi |
|---|---|---|
| | Longitudinal | |
| 4L-1 | | 46.8 |
| 4L-2 | | 46.5 |
| 4L-3 | | 50.2 |
| 4L-4 | | 51.3 |
| | Average | 48.7 |
| | Transverse | |
| 4T-1 | | 47.5 |
| 4T-2 | | 47.9 |
| 4T-3 | | 48.2 |
| 4T-4 | | 48.3 |
| | Average | 47.9 |

TABLE XII. IMPACT TEST RESULTS FOR 7050-T73651 ALUMINUM ALLOY PLATE AT ROOM TEMPERATURE

| Specimen Number | | Energy, ft. lbs. |
|---|---|---|
| | Longitudinal | |
| 10L-1 | | 26.5 |
| 10L-2 | | 44.0 |
| 10L-3 | | 29.0 |
| 10L-4 | | 57.0 |
| 10L-5 | | 22.0 |
| 10L-6 | | 30.0 |
| | Average | 34.7 |
| | Transverse | |
| 10T-1 | | 6.0 |
| 10T-2 | | 6.0 |
| 10T-3 | | 5.5 |
| 10T-4 | | 6.0 |
| 10T-5 | | 5.5 |
| 10T-6 | | 5.0 |
| | Average | 5.7 |

TABLE XIII. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS FOR 7050-T73651 ALUMINUM ALLOY PLATE

| Specimen Number | w, inches | a, inches | T, inches | P, lbs. | Span, inches | $f(\frac{a}{w})$ | $K_Q$ [a] |
|---|---|---|---|---|---|---|---|
| | | | Longitudinal (L-T) | | | | |
| 6-1L | 2.00 | 1.00 | 1.00 | 5,000 | 8.0 | 2.664 | 37.68 |
| 6-2L | 2.00 | 0.990 | 1.00 | 5,100 | 8.0 | 2.622 | 37.83 |
| 6-3L | 2.00 | 0.992 | 1.00 | 4,950 | 8.0 | 2.622 | 36.35 |
| 6-4L | 2.00 | 1.01 | 1.00 | 5,100 | 8.0 | 2.708 | 39.07 |
| 6-5L | 2.00 | 1.00 | 1.00 | 5,000 | 8.0 | 2.664 | 37.68 |
| 6-6L | 2.00 | 0.964 | 1.00 | 5,190 | 8.0 | 2.508 | 36.90 |
| | | | | | | Average | 37.68 |
| | | | (Transverse (T-L) | | | | |
| 6-1T | 2.00 | 0.963 | 1.00 | 5,200 | 8.0 | 2.510 | 36.90 |
| 6-2T | 2.00 | 0.963 | 1.00 | 5,200 | 8.0 | 2.510 | 36.90 |
| 6-3T | 2.00 | 1.00 | 1.00 | 5,000 | 8.0 | 2.663 | 37.70 |
| 6-4T | 2.00 | 0.997 | 1.00 | 4,900 | 8.0 | 2.652 | 36.75 |
| 6-5T | 2.00 | 0.990 | 1.00 | 4,900 | 8.0 | 2.623 | 36.30 |
| 6-6T | 2.00 | 0.978 | 1.00 | 5,200 | 8.0 | 2.573 | 37.80 |
| | | | | | | Average | 36.99 |

(a) These candidate $K_Q$ values do meet existing ASTM size and crack length criteria and are considered valid $K_{Ic}$ numbers.

TABLE XIV. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 7050-T73651 ALUMINUM PLATE (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-7 | 60.0 | 11,580 |
| 5-6 | 50.0 | 46,700 |
| 5-5 | 46.0 | 55.420 |
| 5-1 | 40.0 | 84,500 |
| 5-3 | 37.5 | 296,600 |
| 5-2 | 35.0 | 4,527,400 |
| 5-4 | 30.0 | 12,500,000(a) |
| | 250 F | |
| 5-16 | 60.0 | 9,390 |
| 5-14 | 50.0 | 21,680 |
| 5-13 | 45.0 | 29,390 |
| 5-9 | 40.0 | 77,100 |
| 5-10 | 37.5 | 133,200 |
| 5-11 | 35.0 | 99,900 |
| 5-25 | 32.5 | 1,086,400 |
| 5-8 | 30.0 | 363,800 |
| 5-15 | 25.0 | 443,400 |
| 5-22 | 20.0 | 10,151,300(a) |
| | 350 F | |
| 5-17 | 60.0 | 220 |
| 5-19 | 50.0 | 26,350 |
| 5-20 | 45.0 | 60,460 |
| 5-18 | 40.0 | 83,690 |
| 5-21 | 35.0 | 88,990 |
| 5-23 | 30.0 | 401,600 |
| 5-24 | 25.0 | 10,604,650(a) |

(a) Did not fail.

TABLE XV. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ($K_t$=3.0) 7050-T73651 ALUMINUM PLATE (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-32 | 37.5 | 11,500 |
| 5-31 | 35.0 | 15,600 |
| 5-33 | 32.5 | 14,800 |
| 5-34 | 30.0 | 21,900 |
| 5-36 | 27.5 | 25,400 |
| 5-35 | 25.0 | 42,200 |
| 5-37 | 20.0 | 70,800 |
| 5-38 | 15.0 | 363,800 |
| 5-39 | 10.0 | 10,480,000[a] |
| | 250 F | |
| 5-40 | 37.5 | 7,200 |
| 5-41 | 35.0 | 13,000 |
| 5-42 | 32.5 | 14,400 |
| 5-43 | 30.0 | 17,100 |
| 5-44 | 25.0 | 36,900 |
| 5-46 | 20.0 | 127,300 |
| 5-45 | 15.0 | 293,600 |
| 5-47 | 10.0 | 10,000,480[a] |
| | 350 F | |
| 5-48 | 37.5 | 3,670 |
| 5-49 | 35.0 | 8,190 |
| 5-50 | 32.5 | 43,510 |
| 5-51 | 30.0 | 42,450 |
| 5-52 | 25.0 | 87,300 |
| 5-53 | 20.0 | 89,950 |
| 5-54 | 15.0 | 521,300 |
| 5-55 | 10.0 | 12,237,900[a] |

(a) Did not fail.

TABLE XVI. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR 7050 ALUMINUM PLATE (TRANSVERSE)

| Specimen Number | Stress, ksi | Temper-ature, 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3-10 | 60 | 250 | 0.04 | 0.07 | 0.18 | 0.38 | 0.85 | 0.803 | 3.9 | 13.2 | 43.2 | 1.35 |
| 3-1 | 50 | 250 | 30 | 70 | 195 | 305 | 415 | 0.553 | 472.5 | 9.8 | 46.1 | 0.0125 |
| 3-11 | 45 | 250 | 15 | 110(a) | 605(a) | 900(a) | -- | 0.504 | 576.1(b) | 0.993 | -- | 0.00053 |
| 3-13 | 35 | 250 | 425 | 2700(a) | 8700(a) | -- | -- | 0.315 | 1007.3(b) | 0.432 | -- | 0.00005 |
| 3-4 | 45 | 350 | 0.02 | 0.03 | 0.07 | 0.13 | 0.22 | 0.603 | 0.4 | 16.7 | 60.5 | 7.2 |
| 3-10 | 32 | 350 | 1.5 | 3.8 | 6.9 | 10 | -- | 0.405 | 13.0 | 14.4 | 63.5 | 0.041 |
| 3-2 | 25 | 350 | 11 | 43 | 103 | 133 | 145 | 0.306 | 155.2 | 17.4 | 70.4 | 0.0031 |
| 3-8 | 20 | 350 | 35 | 30(a) | 305(a) | 420 | 490 | 0.315 | 502.7 | 21.2 | 75.9 | 0.0011 |
| 3-12 | 12 | 350 | 675 | 1600(a) | 4800(a) | -- | -- | 0.156 | 1028.9(b) | 0.317 | -- | 0.000095 |
| 3-5 | 12 | 500 | 0.01 | 0.02 | 0.06 | 0.1 | 0.19 | 0.303 | 0.4 | 25.0 | 89.5 | 10.0 |
| 3-7 | 9 | 500 | 3 | 8.5 | 14.3 | 23.6 | 29.5 | 0.155 | 37.7 | 25.7 | 87.6 | 0.034 |
| 3-3 | 7 | 500 | 6 | 15 | 40 | 70 | 101 | 0.121 | 139.9 | 25.8 | 91.2 | 0.011 |
| 3-14 | 5 | 500 | 10 | 40 | 220 | 525(a) | 775 | 0.102 | 1126.9(b) | 26.5 | 91.0 | 0.0014 |
| 3-9 | 4 | 500 | 25 | 320 | 910 | 1550(a) | -- | 0.045 | 1148.0(b) | 0.720 | -- | 0.00031 |

(a) Estimated.

(b) Test discontinued.

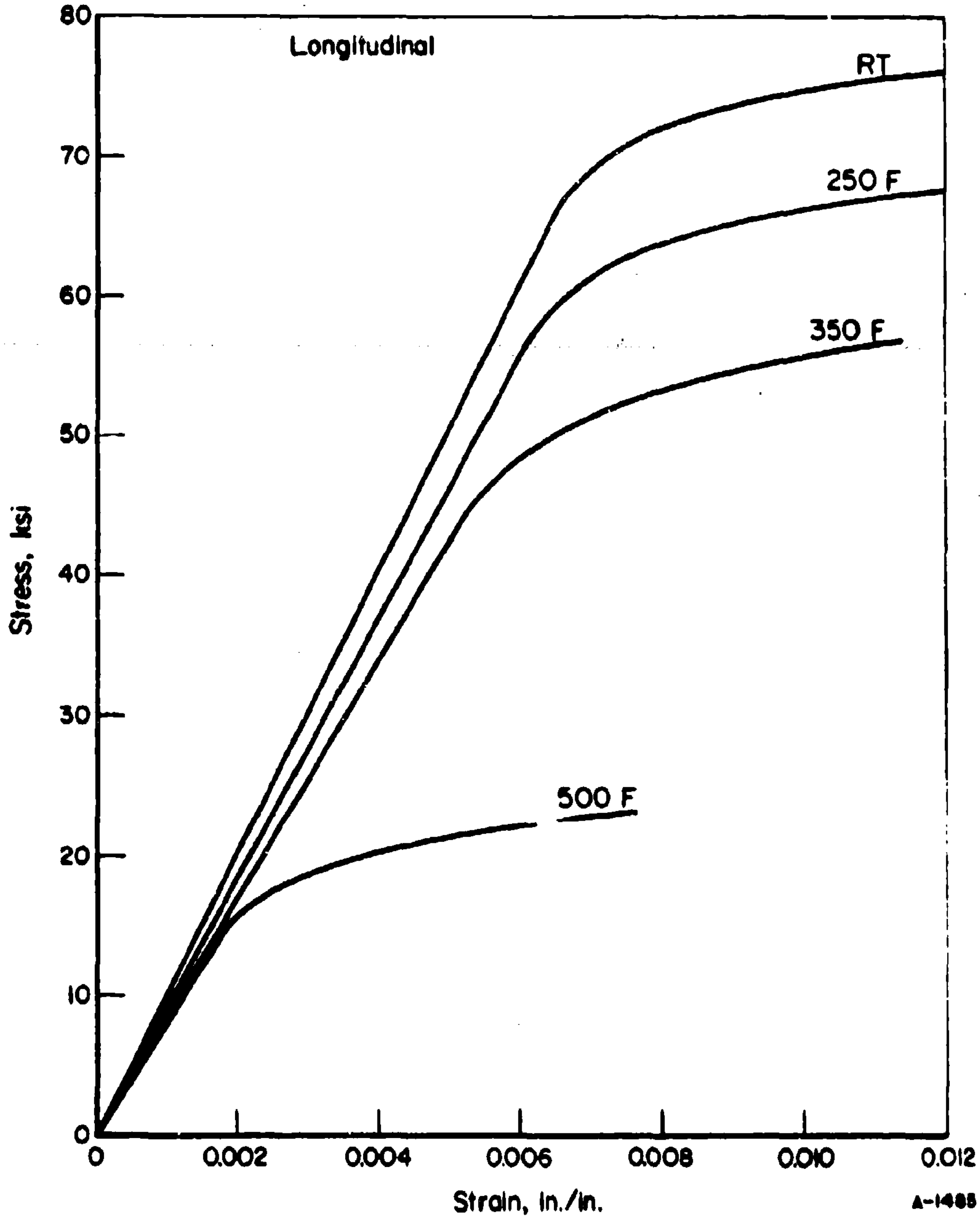



FIGURE 12. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7050-T73651 PLATE (LONGITUDINAL)

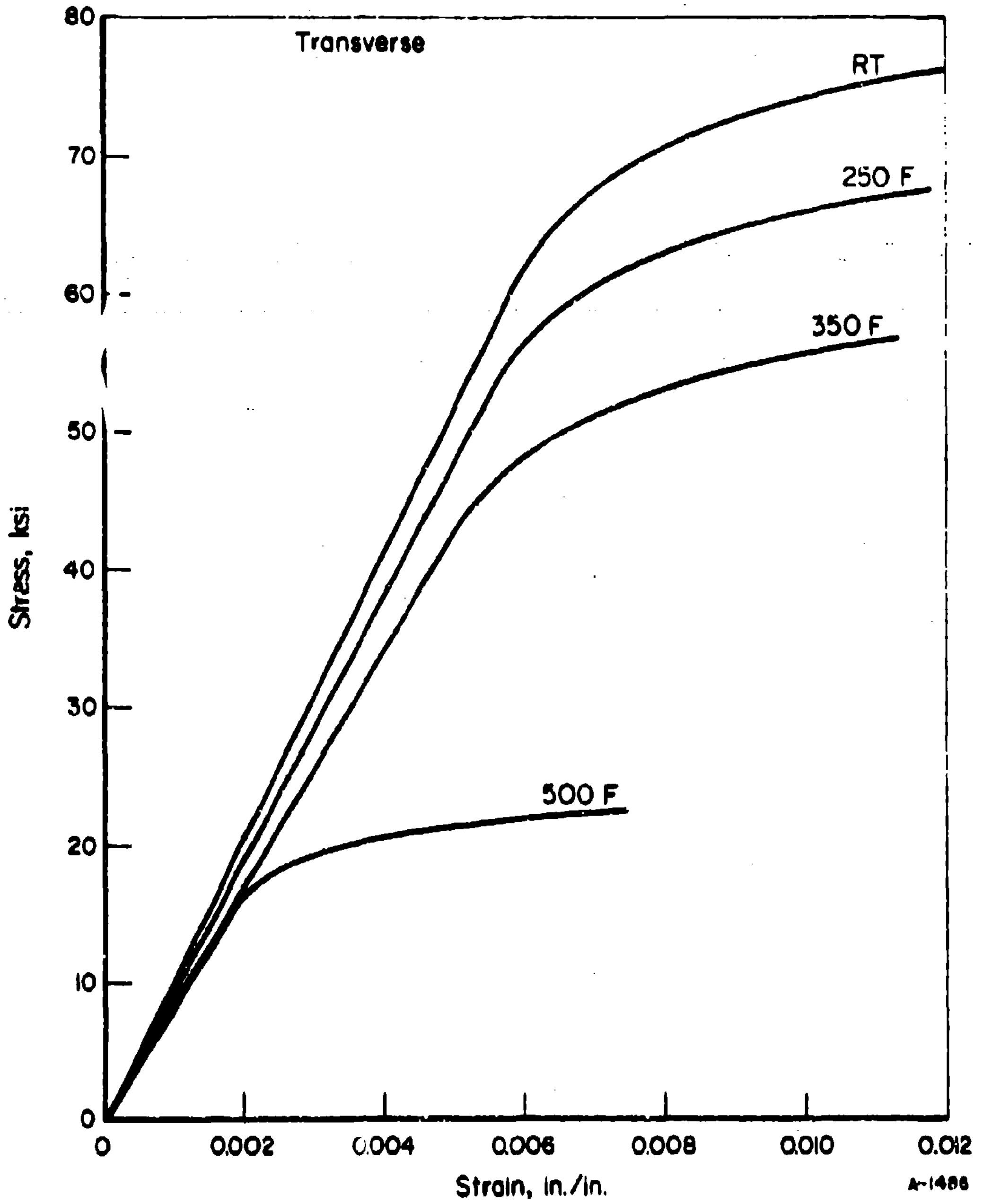



FIGURE 13. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 7050-T73651 PLATE (TRANSVERSE)

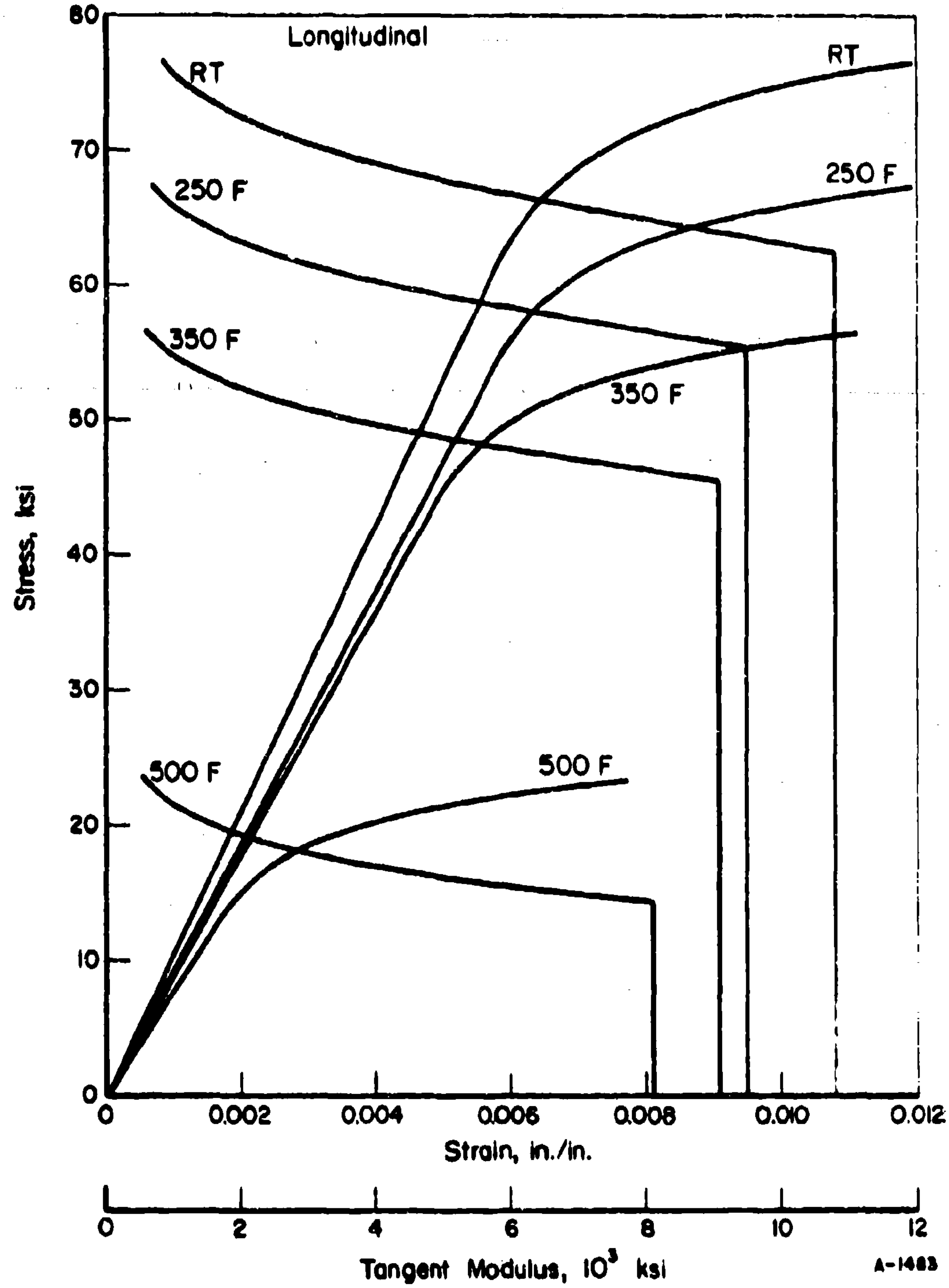



FIGURE 14. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7050-T73651 PLATE (LONGITUDINAL)

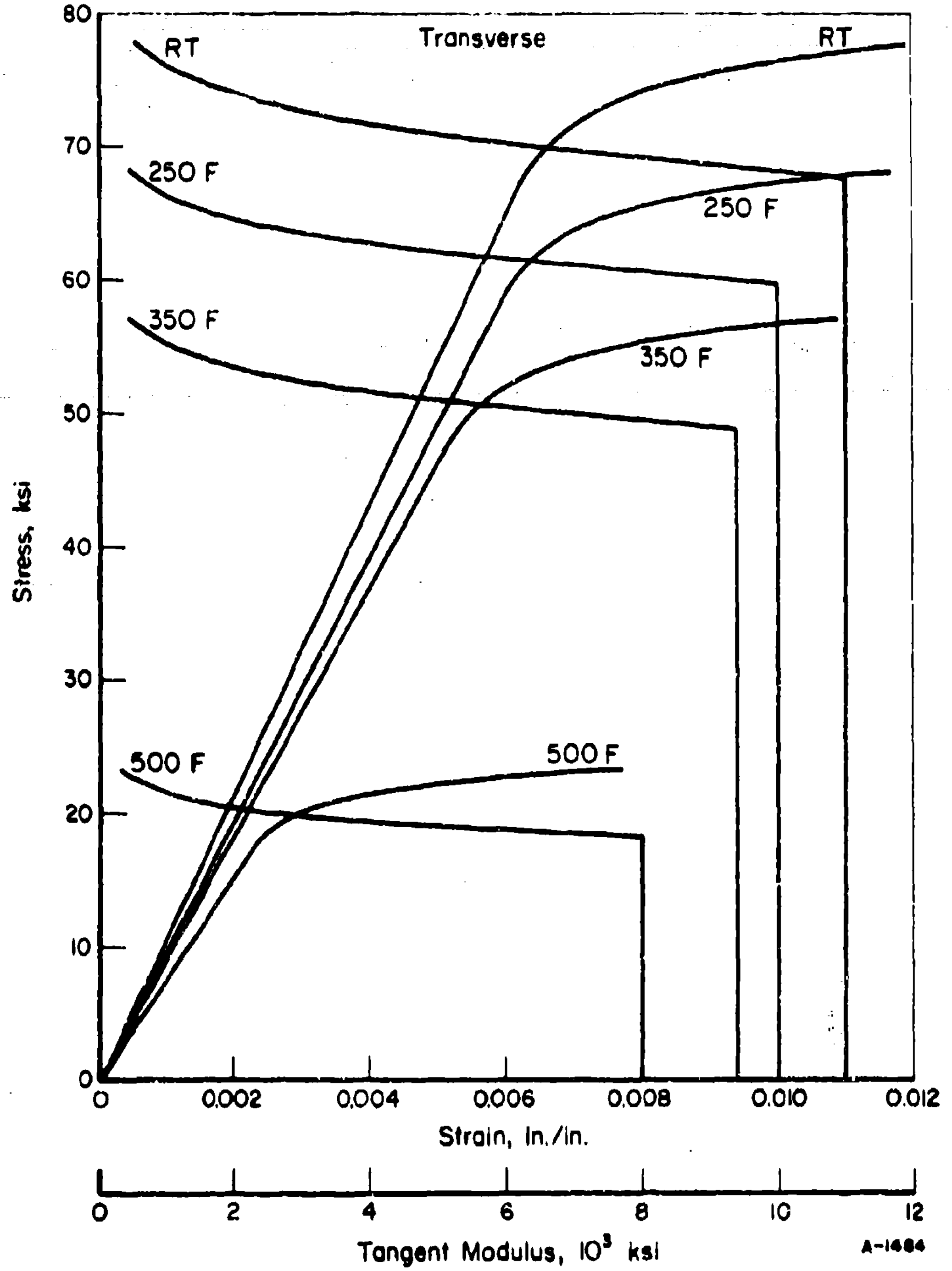



FIGURE 15. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 7050-T73651 PLATE (TRANSVERSE)

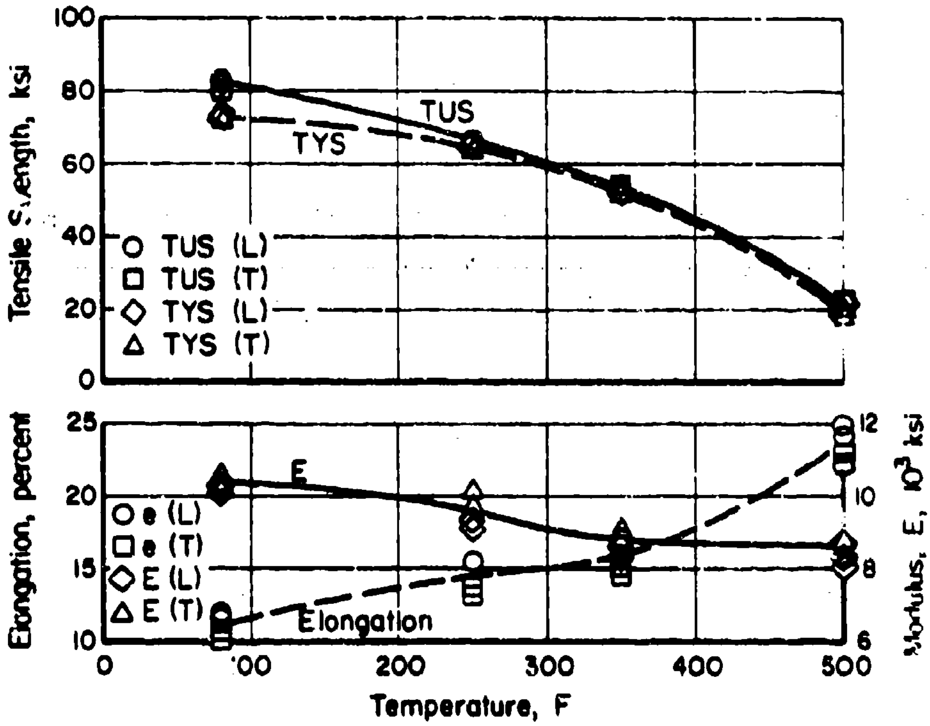



FIGURE 16. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7050-T73651 PLATE

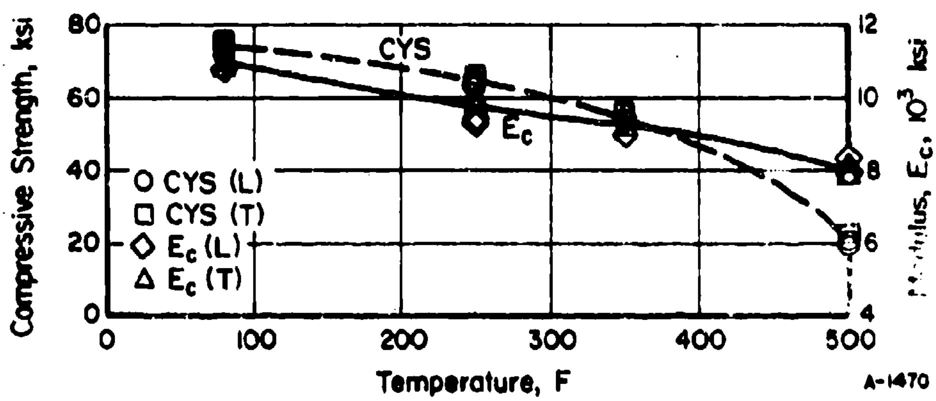



FIGURE 17. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7050-T73651 PLATE

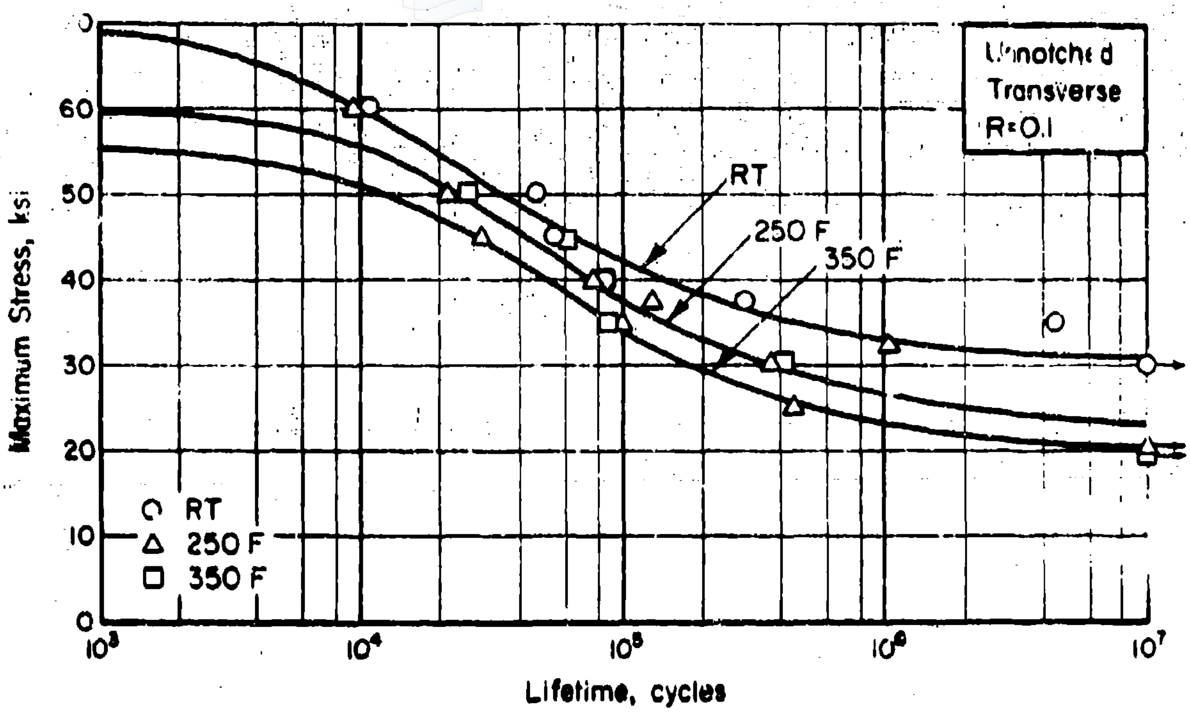



FIGURE 18. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7050-T73651 PLATE (TRANSVERSE)

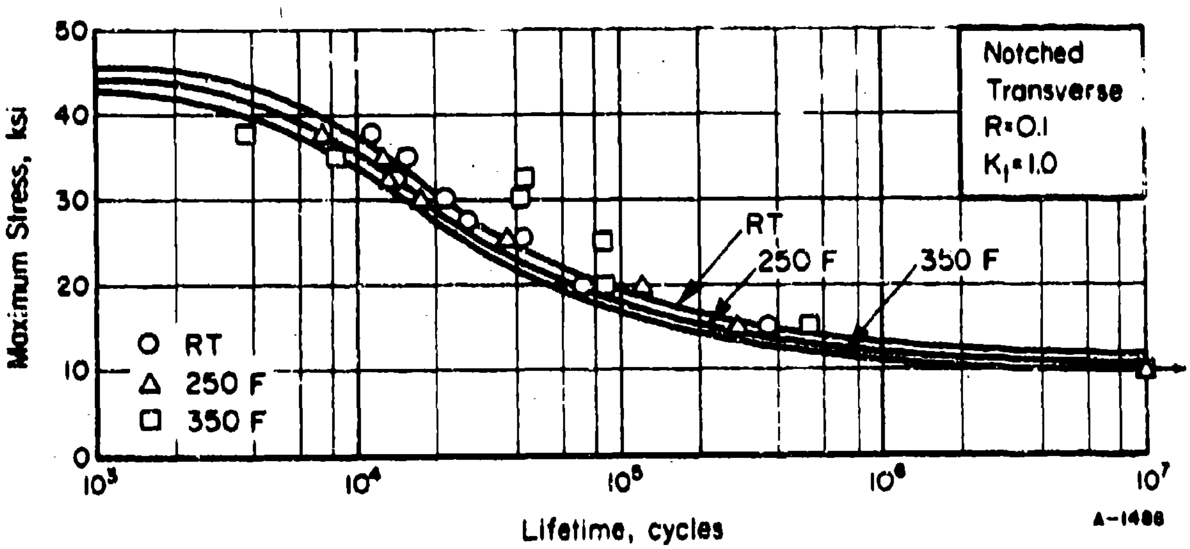



FIGURE 19. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) 7050-T73651 PLATE (TRANSVERSE)

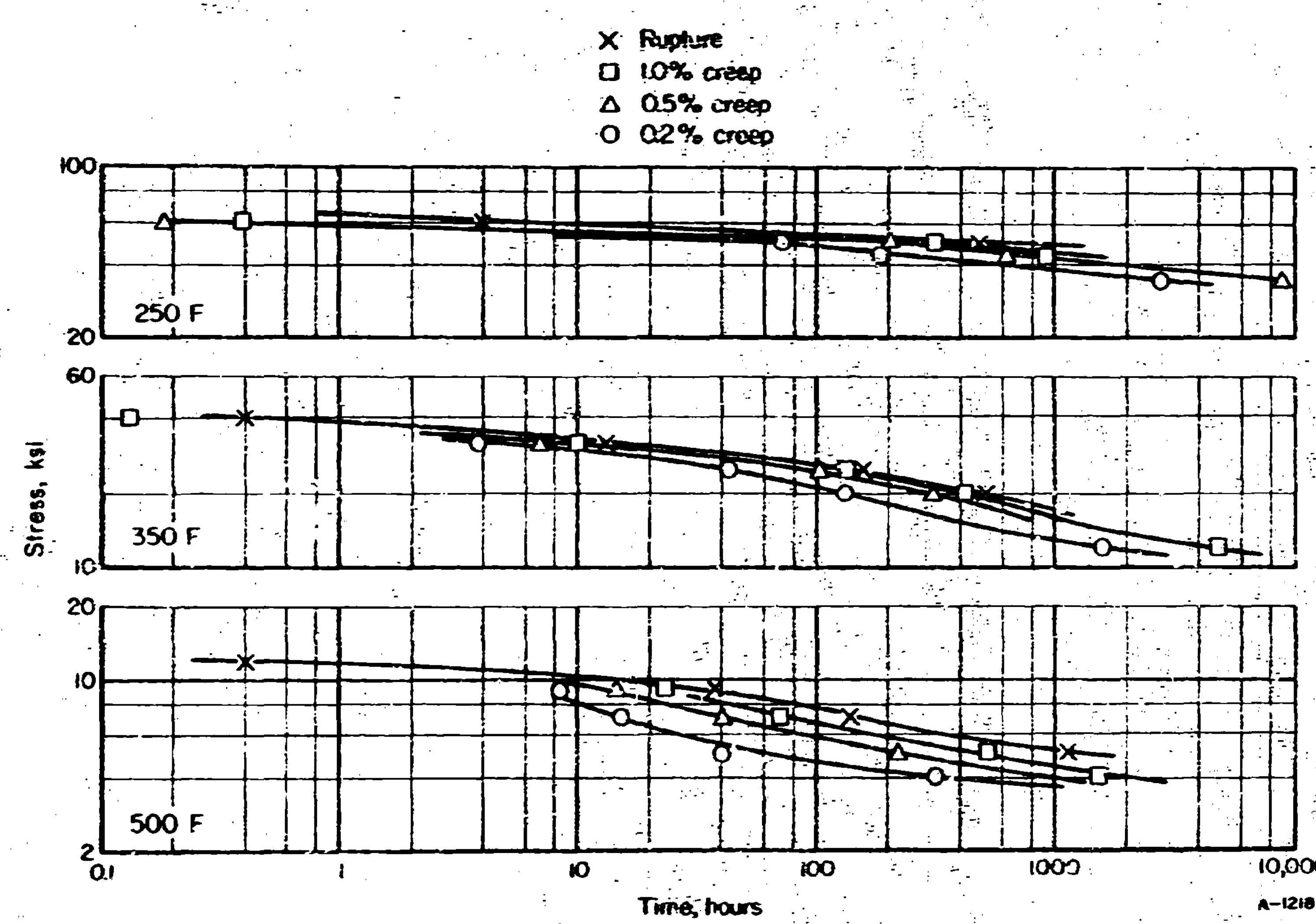



FIGURE 20. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7050-T73651 PLATE (TRANSVERSE)

# 21-6-9 Stainless Steel Alloy

## Material Description

Alloy 21-6-9 is a recent development of the Armco Steel Corporation. It is an austenitic stainless steel, combining high yield strength with good corrosion resistance. The room temperature yield strength of 21-6-9 is superior to Types 304, 321, and 347. It has good elevated temperature properties and retains high strength and toughness at subzero temperatures.

Armco 21-6-9 stainless steel is available in standard finishes in annealed or high tensile temper sheet and strip as well as in bar, wire, forging billets, and plate.

The materials used in this evaluation was an 0.072-inch thick sheet produced within the following composition limits

| | |
|---|---|
| Carbon | 0.08 max |
| Manganese | 8.00 - 10.00 |
| Phosphorus | 0.060 max |
| Sulfur | 0.030 max |
| Silicon | 1.00 max |
| Chromium | 19.00 - 21.50 |
| Nickel | 5.50 - 7.50 |
| Nitrogen | 0.15 - 0.40 |
| Iron | Balance |

## Processing and Heat Treating

The specimen layout is shown in Figure 21. The alloy was evaluated in the as-received annealed condition.

## Test Results

Tension. Results of tests on longitudinal and transverse specimens at room temperature, 400 F, 700 F, and 900 F are given in Table XVII. Typical stress-strain curves at temperature are presented in Figures 22 and 23. Effect-of-temperature curves are shown in Figure 26.

Compression. Test results for longitudinal and transverse specimens at room temperature, 400 F, 700 F, and 900 F are given in Table XVIII. Typical

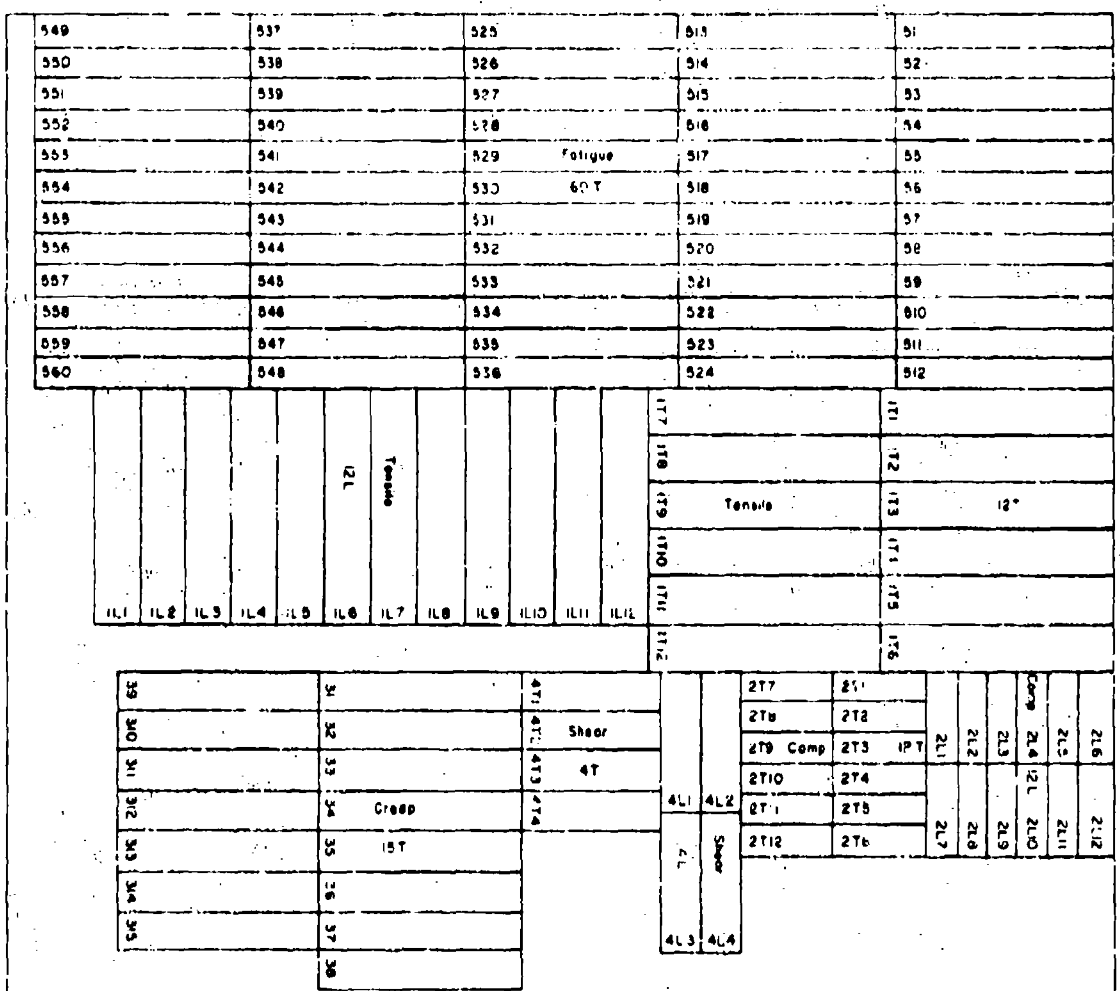


FIGURE 21. SPECIMEN LAYOUT FOR 21-6-9 ANNEALED SHEET

compressive stress-strain and tangent-modulus curves at temperature are presented in Figures 24 and 25. Effect-of-temperature curves are presented in Figure 27.

Shear. Results of sheet-shear type tests for longitudinal and transverse specimens at room temperature are given in Table XIX.

Bend. The minimum bend radius for this material was 1T.

Fracture Toughness. Tests were conducted on transverse (T-L) specimens of full-sheet thickness (0.072-inch) x 18 inches x 36 inches with an EDM flaw in the center. The net section yield stress at fracture was greater than the tensile yield strength of the material; therefore, the K values obtained are considered invalid.

Fatigue. Axial-load test results for transverse specimens at a stress ratio of R = 0.1 are given in Tables XX and XXI. These tests were performed on both unnotched and notched specimens at room temperature, 400 F, and 700 F. S-N curves are presented in Figures 28 and 29.

Creep and Stress Rupture. Tests were conducted for transverse specimens at 400 F, 700 F, and 900 F. Tabular test results are given in Table XXII. Log-stress versus log-time curves are presented in Figure 30.

Stress Corrosion. Tests were conducted as described in the experimental procedures section of this report. No cracks or fractures occurred in the 1000-hour test duration.

Thermal Expansion. The coefficient of expansion for this alloy is $10.6 \times 10^{-6}$ in./in./F from 80 F to 1000 F.

Density. The density of this material is 0.283 lb./in.$^3$.

TABLE XVII. TENSILE TEST RESULTS FOR ANNEALED 21-6-9 STAINLESS STEEL SHEET

| Specimen Number | | Ultimate Tensile Strength, ksi | 0.2 Percent Offset Yield Strength, ksi | Elongation in 2 Inches, percent | Tensile Modulus, $10^6$ psi |
|---|---|---|---|---|---|
| | | **Longitudinal at Room Temperature** | | | |
| 1L-1 | | 113.0 | 64.3 | 54.0 | 26.7 |
| 1L-2 | | 113.0 | 65.0 | 54.5 | 26.6 |
| 1L-3 | | 113.0 | 65.1 | 56.5 | 26.4 |
| | Average | 113.0 | 64.8 | 55.0 | 26.6 |
| | | **Transverse at Room Temperature** | | | |
| 1T-1 | | 114.0 | 65.3 | 50.0 | 28.6 |
| 1T-2 | | 113.0 | 66.3 | 50.0 | 28.2 |
| 1T-3 | | 113.0 | 66.0 | 50.0 | 28.4 |
| | Average | 113.3 | 65.7 | 50.0 | 28.4 |
| | | **Longitudinal at 400 F** | | | |
| 1L-4 | | 88.4 | 42.3 | 44.0 | 21.2 |
| 1L-5 | | 87.6 | 42.6 | 43.0 | 21.8 |
| 1L-6 | | 88.4 | 42.6 | 43.5 | 20.2 |
| | Average | 88.1 | 42.5 | 43.5 | 21.1 |
| | | **Transverse at 400 F** | | | |
| 1T-4 | | 88.4 | 42.7 | 42.0 | 19.9 |
| 1T-5 | | 88.4 | 42.5 | 42.0 | 20.5 |
| 1T-6 | | 88.4 | 43.0 | 42.0 | 19.3 |
| | Average | 88.4 | 42.7 | 42.0 | 19.9 |
| | | **Longitudinal at 700 F** | | | |
| 1L-7 | | 84.2 | 35.9 | 46.0 | 24.8 |
| 1L-8 | | 83.5 | 35.9 | 45.5 | 18.3 |
| 1L-9 | | 83.5 | 35.9 | 45.5 | 22.0 |
| | Average | 83.7 | 35.9 | 45.7 | 21.7 |
| | | **Transverse at 700 F** | | | |
| 1T-7 | | 82.8 | 35.8 | 41.5 | 19.4 |
| 1T-8 | | 83.4 | 35.9 | 42.0 | 18.4 |
| 1T-9 | | 83.5 | 36.0 | 42.0 | 17.4 |
| | Average | 83.2 | 35.9 | 41.8 | 18.4 |
| | | **Longitudinal at 900 F** | | | |
| 1L-10 | | 76.0 | 33.0 | 43.0 | 20.4 |
| 1L-11 | | 76.6 | 33.2 | 43.0 | 16.9 |
| 1L-12 | | 75.7 | 32.9 | 43.0 | 20.2 |
| | Average | 76.1 | 33.0 | 43.0 | 19.2 |
| | | **Transverse at 900 F** | | | |
| 1T-10 | | 76.4 | 33.3 | 41.5 | 15.9 |
| 1T-11 | | 76.6 | 33.3 | 41.0 | 17.6 |
| 1T-12 | | 76.6 | 33.0 | 41.5 | 15.4 |
| | Average | 76.5 | 33.2 | 41.3 | 16.3 |

TABLE XVIII. COMPRESSION TEST RESULTS FOR ANNEALED 21-6-9 STAINLESS STEEL SHEET

| Specimen Number | | 0.2 Percent Offset Yield Strength, ksi | Compression Modulus, $10^6$ psi |
|---|---|---|---|
| | Longitudinal at Room Temperature | | |
| 2L-1 | | 67.2 | 29.3 |
| 2L-2 | | 67.2 | 28.6 |
| 2L-3 | | 67.2 | 27.8 |
| | Average | 67.2 | 28.5 |
| | Transverse at Room Temperature | | |
| 2T-1 | | 66.3 | 29.1 |
| 2T-2 | | 66.5 | 29.0 |
| 2T-3 | | 66.8 | 29.0 |
| | Average | 66.5 | 29.0 |
| | Longitudinal at 400 F | | |
| 2L-4 | | 44.4 | 26.2 |
| 2L-5 | | 45.6 | 27.4 |
| 2L-6 | | 45.4 | 26.6 |
| | Average | 45.1 | 26.7 |
| | Transverse at 400 F | | |
| 2T-4 | | 47.0 | 29.3 |
| 2T-5 | | 46.7 | 29.0 |
| 2T-6 | | 45.3 | 28.0 |
| | Average | 46.3 | 28.8 |
| | Longitudinal at 700 F | | |
| 2L-7 | | 40.2 | 25.8 |
| 2L-8 | | 39.9 | 25.3 |
| 2L-9 | | 41.4 | 26.4 |
| | Average | 40.5 | 25.8 |
| | Transverse at 700 F | | |
| 2T-7 | | 38.3 | 27.7 |
| 2T-8 | | 37.2 | 25.5 |
| 2T-9 | | 38.3 | 26.4 |
| | Average | 37.9 | 26.5 |
| | Longitudinal at 900 F | | |
| 2L-10 | | 35.5 | 25.8 |
| 2L-11 | | 34.8 | 26.1 |
| 2L-12 | | 33.8 | 24.1 |
| | Average | 34.7 | 25.3 |
| | Transverse at 900 F | | |
| 2T-10 | | 34.0 | 26.1 |
| 2T-11 | | 34.1 | 25.8 |
| 2T-12 | | 34.1 | 25.2 |
| | Average | 34.1 | 25.7 |

TABLE XIX. SHEAR TEST RESULTS FOR ANNEALED 21-6-9 STAINLESS STEEL SHEET AT ROOM TEMPERATURE

| Specimen Number | | Ultimate Shear Strength, ksi |
|---|---|---|
| | Longitudinal | |
| 4L-1 | | 101.0 |
| 4L-2 | | 102.0 |
| 4L-3 | | 103.0 |
| 4L-4 | | 103.0 |
| | Average | 102.3 |
| | Transverse | |
| 4T-1 | | 102.0 |
| 4T-2 | | 102.0 |
| 4T-3 | | 104.0 |
| 4T-4 | | 103.0 |
| | Average | 102.8 |

TABLE XX. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 21-6-9 ANNEALED STAINLESS STEEL SHEET (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-5 | 105.0 | 3,500 |
| 5-4 | 100.0 | 43,500 |
| 5-3 | 95.0 | 83,500 |
| 5-2 | 90.0 | 153,300 |
| 5-1 | 85.0 | 294,600 |
| 5-6 | 80.0 | 344,900 |
| 5-7 | 75.0 | 206,000 |
| 5-8 | 65.0 | 10,000,000(a) |
| | 400 F | |
| 5-9 | 100.0 | (b) |
| 5-14 | 90.0 | 200 |
| 5-10 | 90.0 | 500 |
| 5-16 | 87.5 | 122,700 |
| 5-13 | 85.0 | 63,600 |
| 5-17 | 82.5 | 153,300 |
| 5-12 | 80.0 | 110,500 |
| 5-18 | 77.5 | 258,400 |
| 5-15 | 75.0 | 10,167,000(a) |
| | 700 F | |
| 5-19 | 85.0 | (b) |
| 5-21 | 80.0 | 600 |
| 5-20 | 75.0 | 3,399,200 |
| 5-24 | 72.5 | 4,821,600 |
| 5-22 | 70.0 | 140,400 |
| 5-25 | 70.0 | 4,842,000 |
| 5-23 | 65.0 | 10,029,000(a) |

(a) Did not fail.

(b) Failed on first cycle.

TABLE XXI. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ($K_t$=3.0) 21-6-9 ANNEALED STAINLESS STEEL SHEET (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-11 | 75.0 | 12,240 |
| 5-4 | 70.0 | 38,380 |
| 5-5 | 65.0 | 74,510 |
| 5-3 | 60.0 | 97,190 |
| 5-14 | 55.0 | 186,620 |
| 5-6 | 50.0 | 1,757,000 |
| 5-30 | 40.0 | 10,744,400[a] |
| | 400 F | |
| 5-13 | 75.0 | 10,300 |
| 5-31 | 70.0 | 11,200 |
| 5-22 | 65.0 | 14,000 |
| 5-21 | 55.0 | 26,900 |
| 5-20 | 45.0 | 84,400 |
| 5-32 | 40.0 | 204,600 |
| 5-17 | 35.0 | 10,589,500[a] |
| | 700 F | |
| 5-29 | 75.0 | 3,300 |
| 5-28 | 65.0 | 11,400 |
| 5-24 | 55.0 | 27,200 |
| 5-19 | 50.0 | 116,300 |
| 5-26 | 45.0 | 144,200 |
| 5-18 | 40.0 | 143,700 |
| 5-24 | 35.0 | 10,519,200[a] |

(a) Did not fail.

TABLE XXII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR 21-6-9 STAINLESS STEEL SHEET (TRANSVERSE)

| 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 | Minimum Creep Rate, percent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3-1 | 88 | 500 | -- | -- | -- | -- | -- | -- | On Loading | 41.3 | -- |
| 3-4 | 83 | 500 | 0.01 | 0.20 | 0.45 | 19 | 1,500[a] | 26.68 | 841.4[b] | 28.4 | 0.0005 |
| 3-7 | 70 | 500 | 0.10 | 0.35 | 5.0 | 85 | -- | 13.220 | 169.9[b] | 14.42 | -- |
| 3-9 | 40 | 500 | 5.0 | 70 | 1,455 | 4,800[a] | -- | 0.826 | 650.1[b] | 1.355 | 0.0001 |
| 3-12 | 35 | 500 | -- | 3,000[a] | -- | -- | -- | 0.229 | 715.1[b] | 0.251 | -- |
| 3-2 | 86 | 700 | -- | -- | -- | -- | -- | -- | On Loading | 43.1 | -- |
| 3-5 | 80 | 700 | -- | -- | -- | -- | -- | 28.24 | 813.4[b] | 31.1 | 0.00007 |
| 3-8 | 50 | 700 | -- | 0.05 | 0.3 | 7.0 | -- | 4.920 | 309.7[b] | 5.990 | 0.00002 |
| 3-15 | 40 | 700 | -- | 0.10 | 10 | >1,000 | -- | 1.452 | 498.6[b] | 2.050 | -- |
| 3-14 | 35 | 700 | 0.20 | 0.40 | 5,000[a] | -- | -- | 0.314 | 120.7[b] | 1.051 | -- |
| 3-11 | 30 | 700 | -- | 10,000[a] | -- | -- | -- | 0.180 | 268.5[b] | 0.218 | -- |
| 3-3 | 76.5 | 900 | -- | -- | -- | -- | -- | -- | On Loading | 42.2 | -- |
| 3-10 | 70 | 900 | -- | -- | -- | -- | -- | 20.852 | 438.9 | 27.6 | -- |
| 3-6 | 65 | 900 | -- | -- | -- | -- | -- | 10.8 | 753.7 | 20.9 | 0.0006 |
| 3-17 | 35 | 900 | -- | 0.10 | >1,000 | -- | -- | 1.260 | 480.0( ) | 1.475 | -- |
| 3-16 | 30 | 900 | -- | 5,000[a] | -- | -- | -- | 0.198 | 738.5( ) | 0.222 | -- |
| 3-13 | 25 | 900 | -- | -- | -- | -- | -- | 0.162 | 289.4( ) | 0.167 | -- |

(a) Estimate.

(b) Test discontinued.

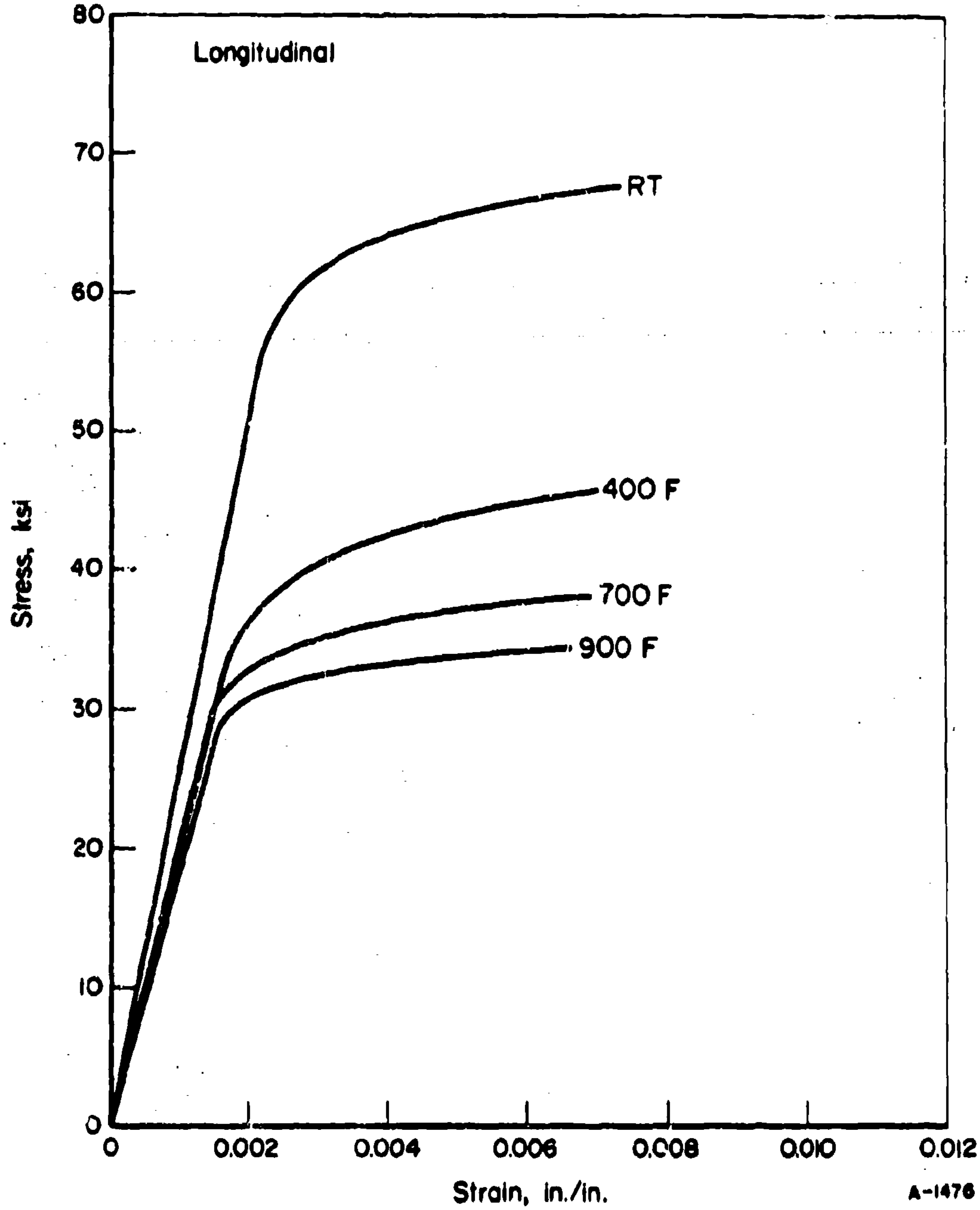



FIGURE 22. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 21-6-9 ANNEALED SHEET (LONGITUDINAL)

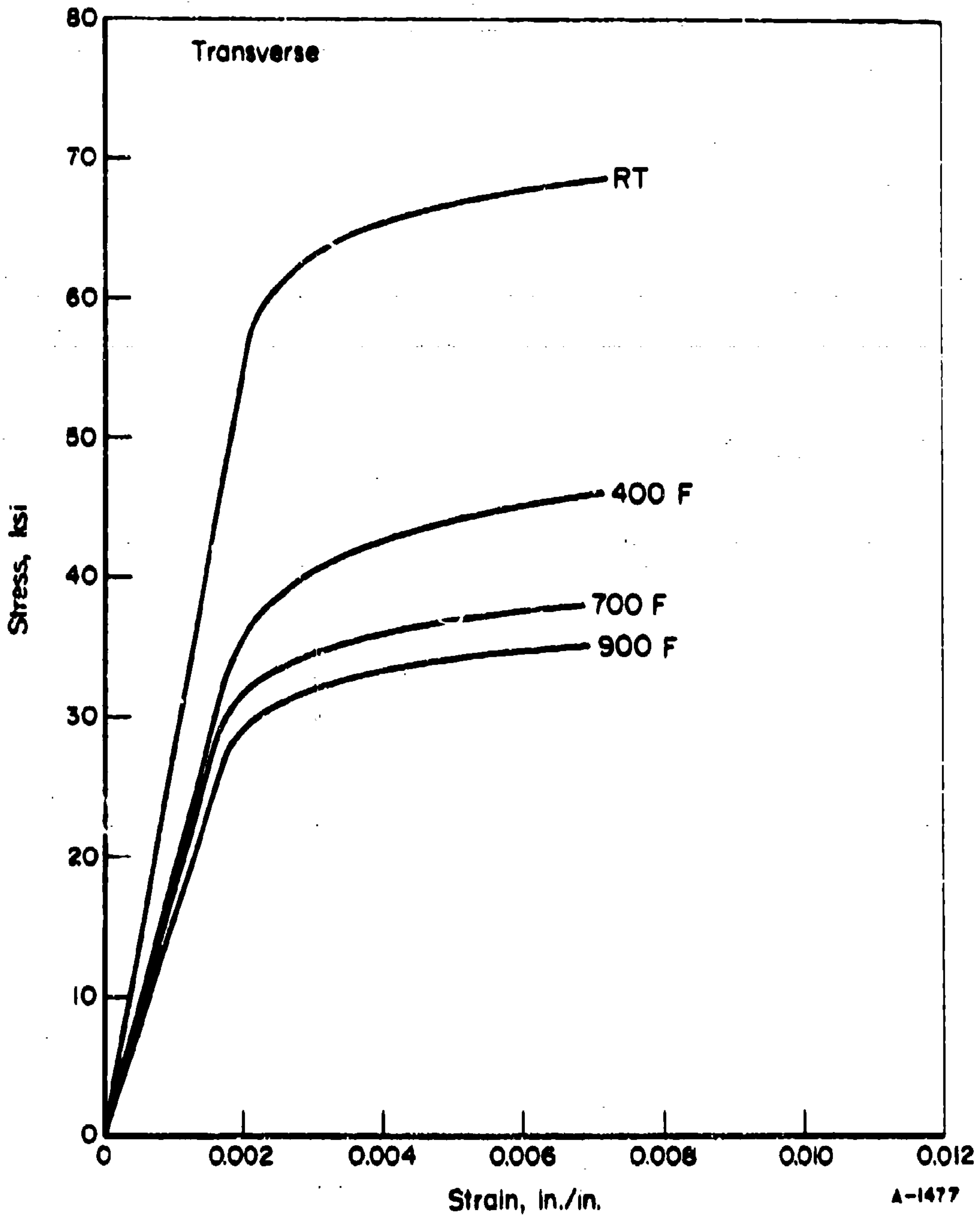



FIGURE 23. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR 21-6-9 ANNEALED SHEET (TRANSVERSE)

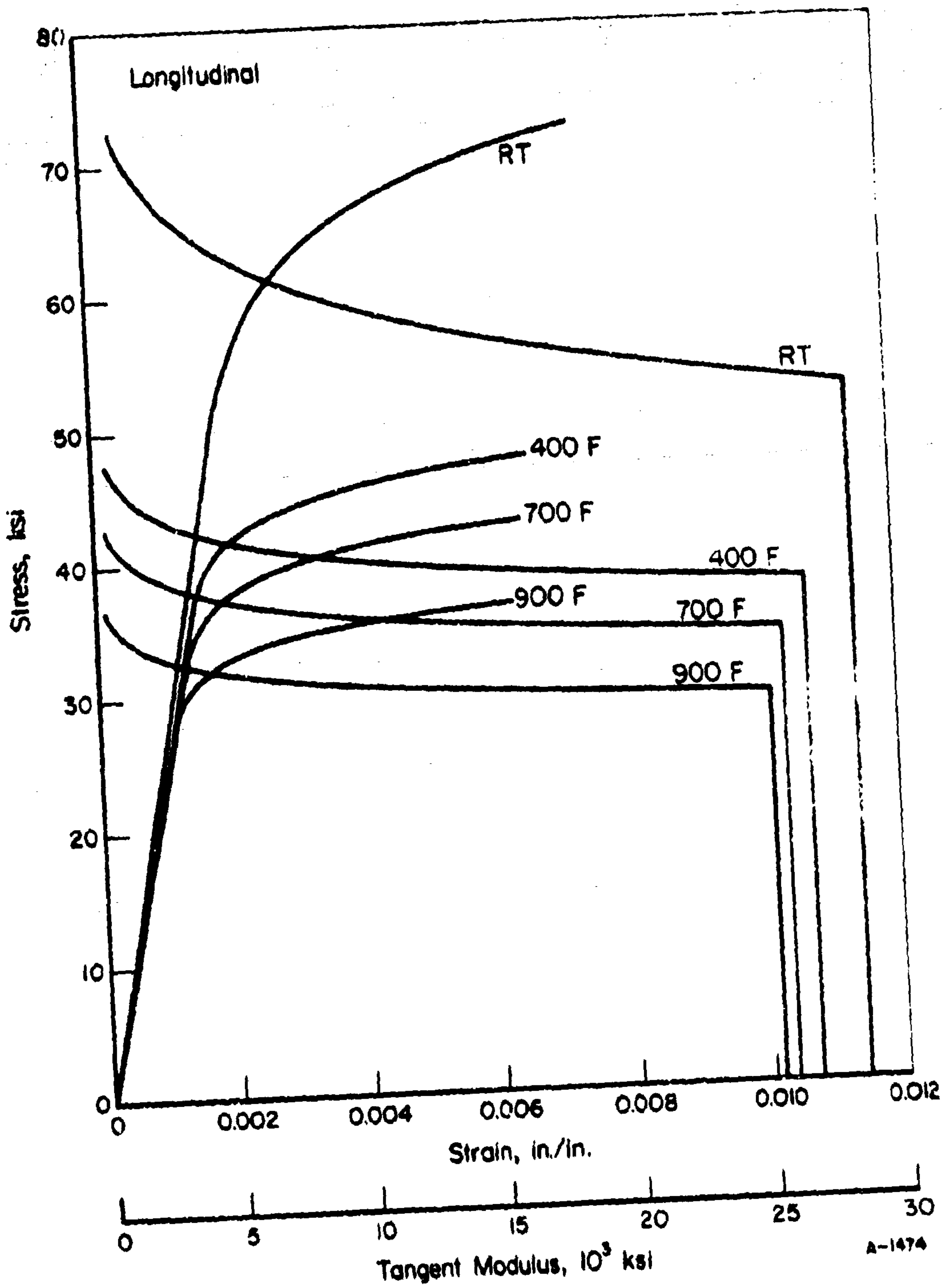



FIGURE 24. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 21-6-9 ANNEALED SHEET (LONGITUDINAL)

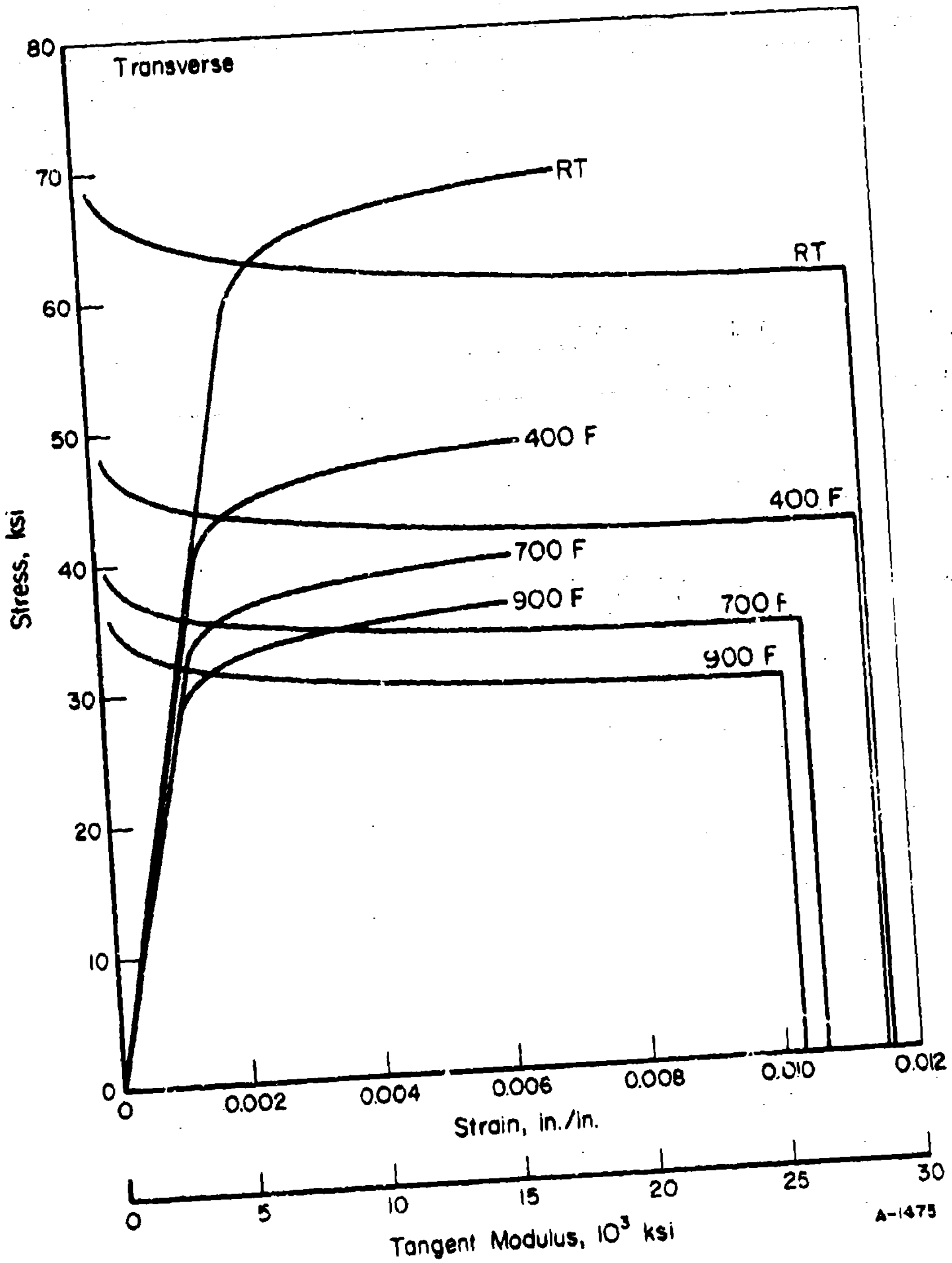



FIGURE 25. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR 21-6-9 ANNEALED SHEET (TRANSVERSE)

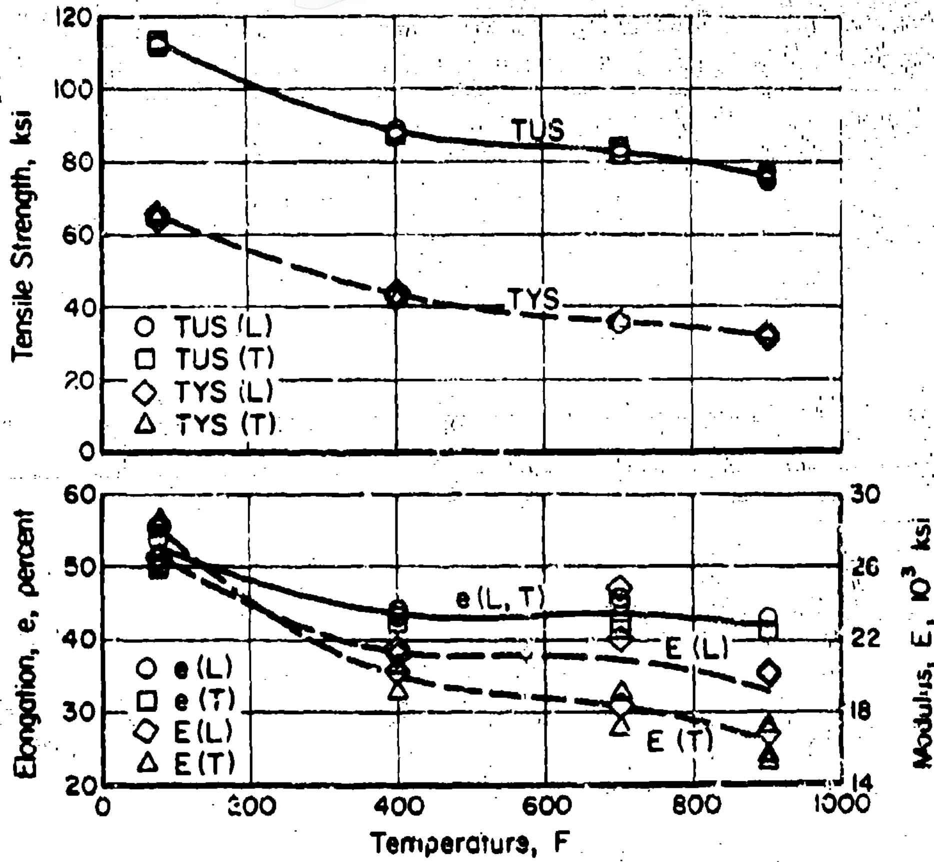



FIGURE 26. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 21-6-9 ANNEALED SHEET

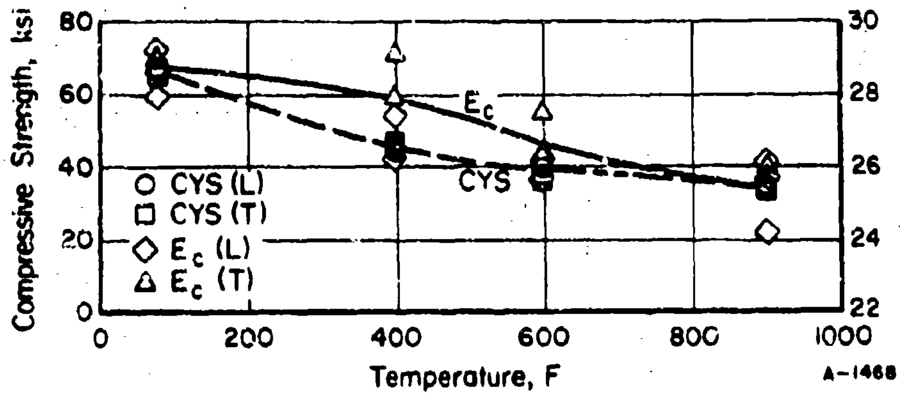



FIGURE 27. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 21-6-9 ANNEALED SHEET

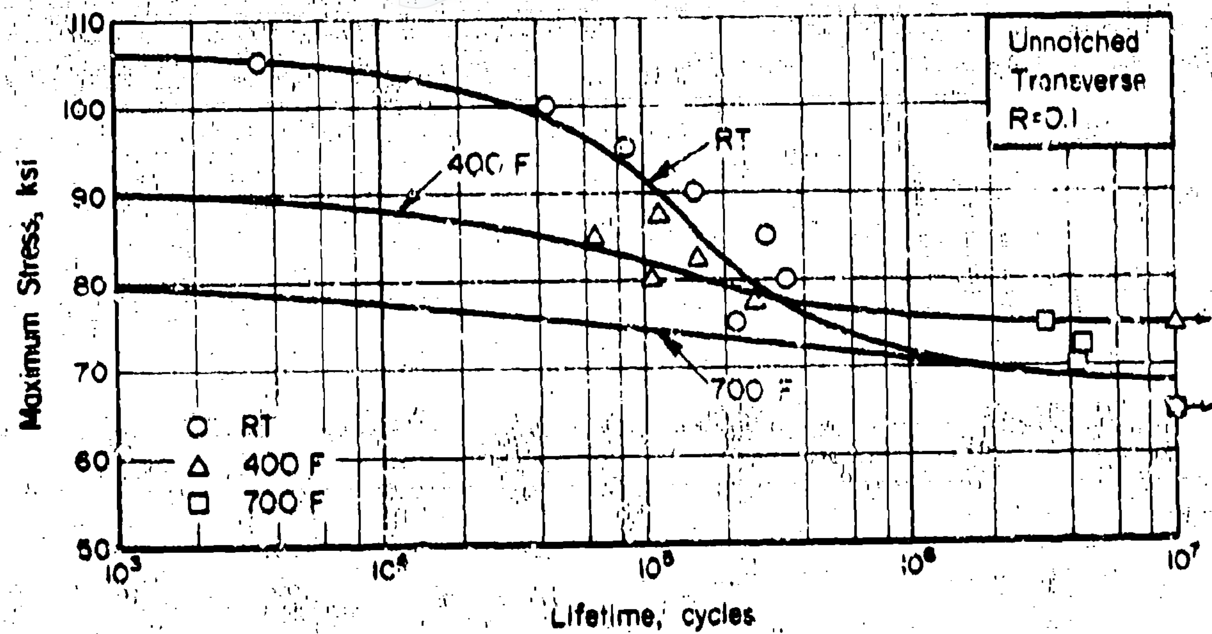



FIGURE 28. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 21-6-9 ANNEALED SHEET (TRANSVERSE)

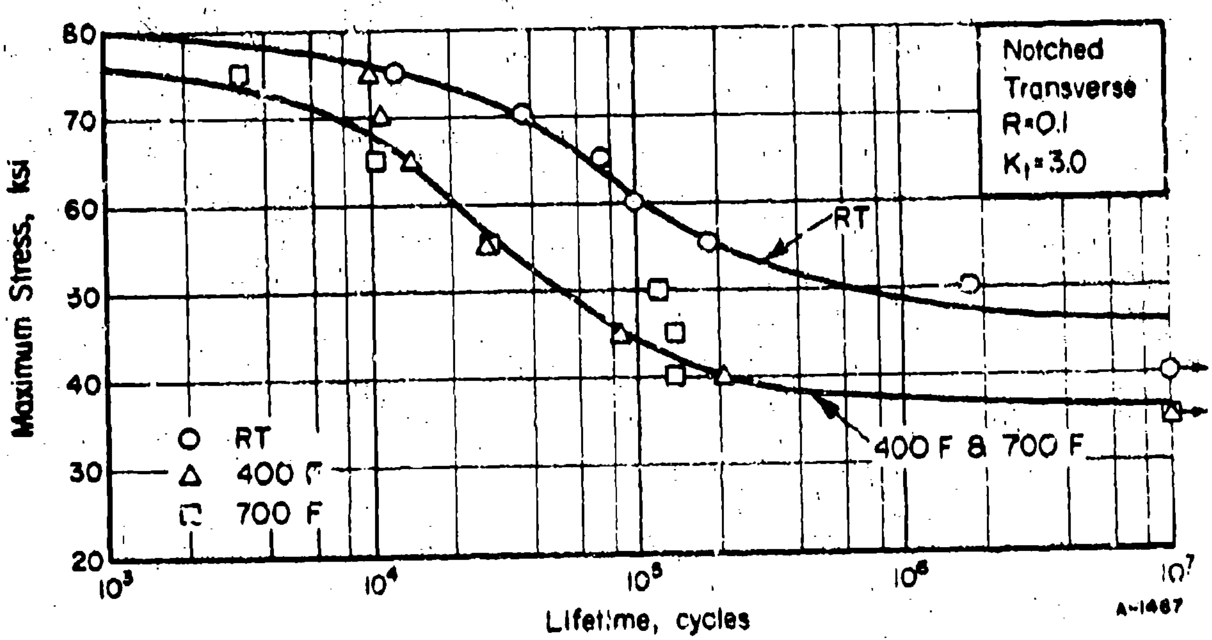



FIGURE 29. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) 21-6-9 ANNEALED SHEET (TRANSVERSE)

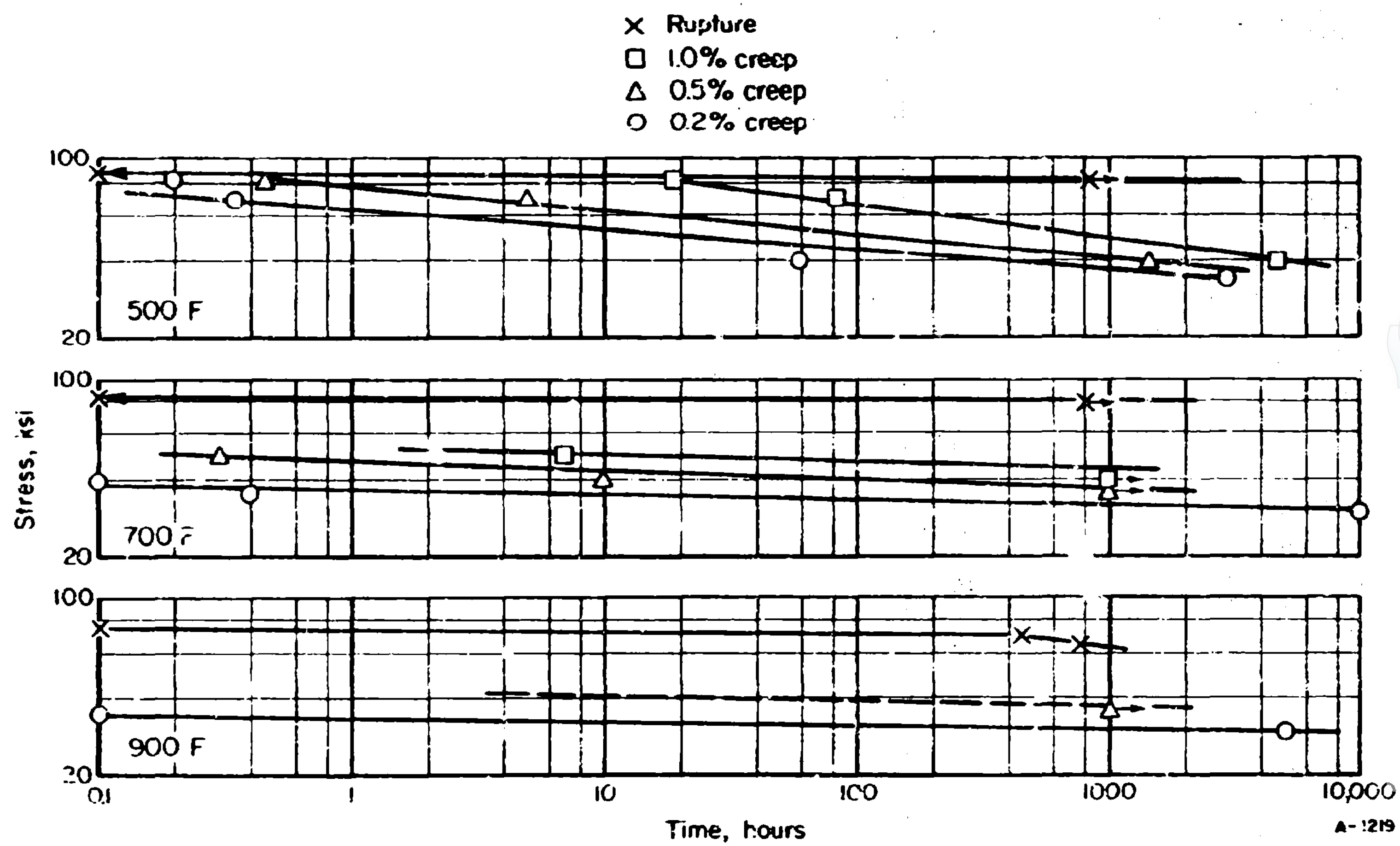



FIGURE 30. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 21-6-9 ANNEALED SHEET (TRANSVERSE)

# Ti-8Mo-8V-2Fe-3Al Alloy

## Material Description

The 8Mo-8V-2Fe-3Al beta titanium alloy is a recent development of TIMET. The alloy was selected for full-scale evaluation after confirming (by TIMET) that it could be melted by the conventional consumable electrode vacuum arc process. It shows producibility and property characteristics that make it suitable for a variety of airframe applications. A variety of heat treatments are available to allow the designer to take advantage of its individual properties or its generally good overall properties.

The material used in this evaluation was an 0.040-inch-thick sheet from TIMET Heat K-5055 with the following composition

| | |
|---|---|
| Molybdenum | 8.0 |
| Vandaium | 8.2 |
| Iron | 2.0 |
| Aluminum | 3.0 |
| Oxygen | 0.14 |
| Nitrogen | 0.011 |
| Titanium | Balance |

## Processing and Heat Treating

The specimen layout is shown in Figure 31. The material was received in the solution-treated condition. Specimens were aged at 900 F for 6 hours. This condition is called the high strength, fully-aged condition.

## Test Results

Tension. Test results for longitudinal and transverse specimens at room temperature, 400 F, 600 F, and 800 F are given in Table XXIII. Stress-strain curves at temperature are presented in Figures 32 and 33. Effect-of-temperature curves are shown in Figure 36.

Compression. Test results for longitudinal and transverse specimens at room temperature, 400 F, 600 F, and 800 F are given in Table XXIV. Typical stress-strain and tangent moudlus curves at temperature are presented in Figures 34 and 35. Effect-of-temperature curves are presented in Figure 37.

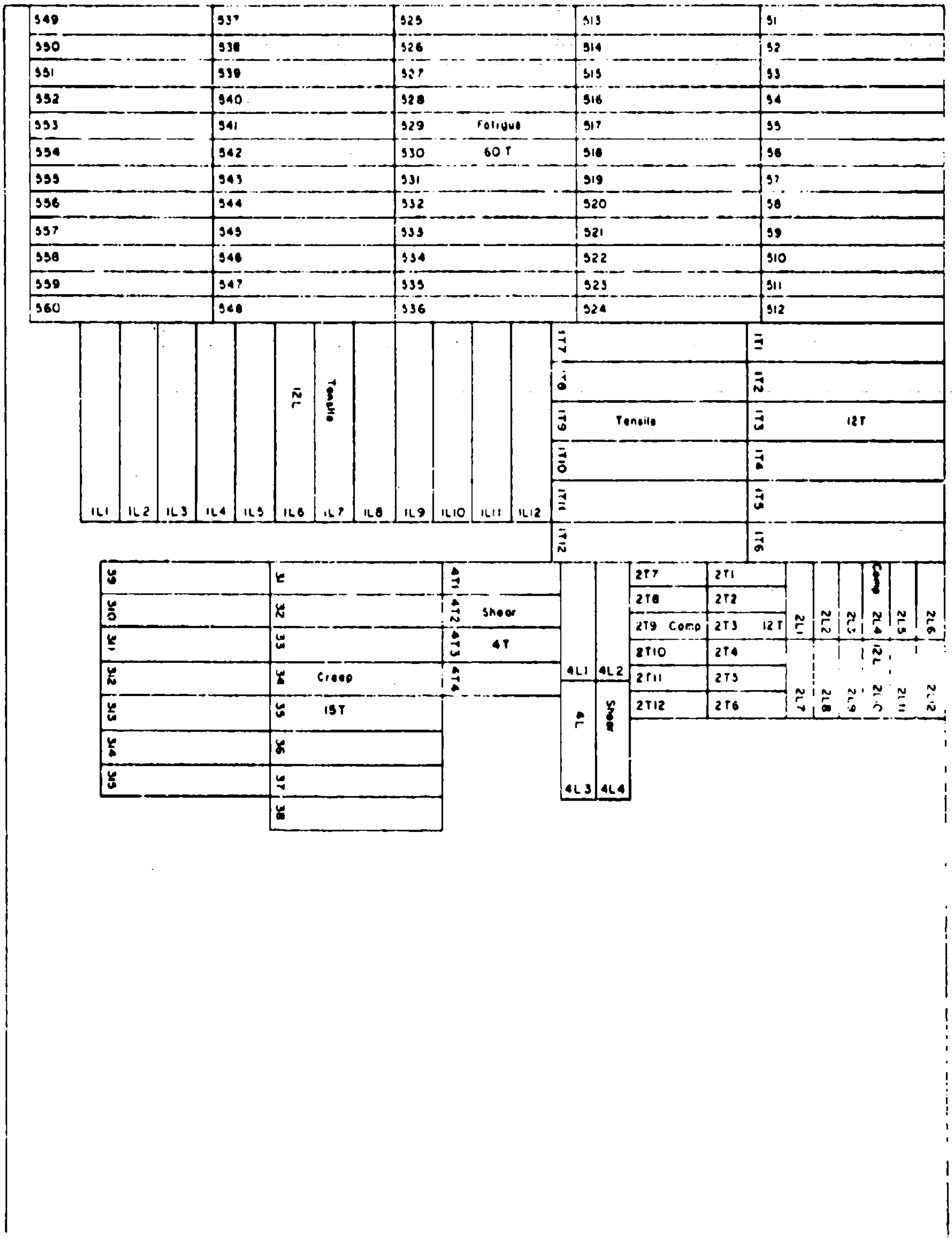



FIGURE 31. SPECI... LAYOUT FOR Ti-8Mo-8V-2Fe-3Al SHEET

Shear. Test results for longitudinal and transverse specimens at room temperature are given in Table XXV.

Fracture Toughness. Specimens were full-sheet thickness (0.040-inch) by 18 inches wide by 36 inches long with an EDM flaw in the center. The average $K_Q$ obtained from four transverse (T-L) specimens was 50 ksi $\sqrt{\text{in.}}$ By existing ASTM criteria, this is considered a valid $K_c$ value.

Fatigue. Axial load tests were conducted on transverse specimens, both unnotched and notched, at a stress ratio of $R = 0.1$. Test temperatures were room temperature, 400 F, and 600 F. Tabular test results are given in Tables XXVI and XXVII. S-N curves are presented in Figures 38 and 39.

Creep and Stress-Rupture. Tests were performed at 550 F, 700 F, and 900 F. Tabular test results are given in Table XXVIII. Log-stress versus log-time curves are presented in Figure 40.

Stress-Corrosion. Tests were performed 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 $5.0 \times 10^{-6}$ in./in./F from 68 F to 800 F.

Density. The density of this alloy is 0.175 lb./in.$^3$.

TABLE XXIII. TENSILE TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET

| Specimen Number | | Ultimate Tensile Strength, ksi | 0.2 Percent Offset Yield Strength, ksi | Elongation in 2 Inches, percent | Tensile Modulus, $10^6$ psi |
|---|---|---|---|---|---|
| | | **Longitudinal at Room Temperature** | | | |
| 1L-1 | | 160.0 | 143.0 | 12.0 | 13.6 |
| 1L-2 | | 162.0 | 147.0 | 12.0 | 13.6 |
| 1L-3 | | 159.0 | 144.0 | 11.0 | 13.7 |
| | Average | 160.3 | 144.7 | 11.7 | 13.6 |
| | | **Transverse at Room Temperature** | | | |
| 1T-1 | | 176.0 | 160.0 | 9.0 | 15.4 |
| 1T-2 | | 175.0 | 157.0 | 10.0 | 14.9 |
| 1T-3 | | 173.0 | 157.0 | 9.5 | 14.5 |
| | Average | 174.7 | 158.0 | 9.5 | 14.9 |
| | | **Longitudinal at 400 F** | | | |
| 1L-4 | | 148.0 | 123.0 | 9.5 | 13.2 |
| 1L-5 | | 149.0 | 124.0 | 9.0 | 13.5 |
| 1L-6 | | 149.0 | 123.0 | 8.5 | 13.2 |
| | Average | 148.7 | 123.3 | 9.0 | 13.3 |
| | | **Transverse at 400 F** | | | |
| 1T-4 | | 153.0 | 135.0 | 7.0 | 14.4 |
| 1T-5 | | 158.0 | 133.0 | 6.5 | 13.8 |
| 1T-6 | | 155.0 | 132.0 | 7.0 | 14.1 |
| | Average | 155.3 | 133.3 | 6.8 | 14.1 |
| | | **Longitudinal at 600 F** | | | |
| 1L-7 | | 144.0 | 116.0 | 7.5 | 12.3 |
| 1L-8 | | 147.0 | 118.0 | 7.5 | 12.4 |
| 1L-9 | | 147.0 | 119.0 | 7.0 | 12.5 |
| | Average | 146.[illegible] | 117.7 | 7.3 | 12.4 |
| | | **Transverse at 600 F** | | | |
| 1T-7 | | 152.0 | 123.0 | 6.[illegible] | 13.2 |
| 1T-8 | | 153.0 | 124.0 | 6.5 | 13.5 |
| 1T-9 | | 152.0 | 125.0 | 7.0 | 13.0 |
| | Average | 152.3 | 124.0 | 6.7 | 13.2 |
| | | **Longitudinal at 800 F** | | | |
| 1L-10 | | 139.0 | 102.0 | 21.0 | 12.1 |
| 1L-11 | | 140.0 | 110.0 | 19.0 | 11.8 |
| 1L-12 | | 134.0 | 105.0 | 16.0 | 11.4 |
| | Average | 137.7 | 105.7 | 18.7 | 11.8 |
| | | **Transverse at 800 F** | | | |
| 1T-10 | | 139.0 | 112.0 | 16.5 | 12.3 |
| 1T-11 | | 146.0 | 118.0 | 16.0 | 12.4 |
| 1T-12 | | 138.0 | 108.0 | 16.0 | 12.2 |
| | Average | 141.0 | 112.7 | 16.2 | 12.3 |

TABLE XXIV. COMPRESSION TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET

| Specimen Number | | 0.2 Percent Offset Yield Strength, ksi | Compression Modulus, $10^6$ psi |
|---|---|---|---|
| | Longitudinal at Room Temperature | | |
| 2L-1 | | 177.0 | 15.9 |
| 2L-2 | | 177.0 | 15.8 |
| 2L-3 | | 179.0 | 16.0 |
| | Average | 177.7 | 15.9 |
| | Transverse at Room Temperature | | |
| 2T-1 | | 190.0 | 16.8 |
| 2T-2 | | 192.0 | 16.8 |
| 2T-3 | | 193.0 | 17.1 |
| | Average | 191.7 | 16.9 |
| | Longitudinal at 400 F | | |
| 2L-4 | | 138.0 | 14.4 |
| 2L-5 | | 164.0 | 15.9 |
| 2L-6 | | 142.0 | 14.7 |
| | Average | 140.7 | 14.5 |
| | Transverse at 400 F | | |
| 2T-4 | | 164.0 | 16.1 |
| 2T-5 | | 164.0 | 15.9 |
| 2T-6 | | 163.0 | 16.2 |
| | Average | 163.7 | 16.1 |
| | Longitudinal at 600 F | | |
| 2L-7 | | 141.0 | 14.5 |
| 2L-8 | | 137.0 | 13.9 |
| 2L-9 | | 138.0 | 14.1 |
| | Average | 138.7 | 14.2 |
| | Transverse at 600 F | | |
| 2T-7 | | 152.0 | 14.9 |
| 2T-8 | | 154.0 | 14.9 |
| 2T-9 | | 149.0 | 14.7 |
| | Average | 151.7 | 14.8 |
| | Longitudinal at 800 F | | |
| 2L-10 | | 134.0 | 12.7 |
| 2L-11 | | 136.0 | 12.5 |
| 2L-12 | | 134.0 | 12.9 |
| | Average | 134.7 | 12.7 |
| | Transverse at 800 F | | |
| 2T-10 | | 140.0 | 13.5 |
| 2T-11 | | 139.0 | 13.7 |
| 2T-12 | | 137.0 | 13.5 |
| | Average | 138.7 | 13.6 |

TABLE XXV. SHEAR TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET AT ROOM TEMPERATURE

| Specimen Number | | Ultimate Shear Strength, ksi |
|---|---|---|
| | Longitudinal | |
| 4L-1 | | 92.9 |
| 4L-2 | | 102.0 |
| 4L-3 | | 102.0 |
| 4L-4 | | 100.5 |
| | Average | 100.5 |
| | Transverse | |
| 4T-1 | | 103.0 |
| 4T-2 | | 106.0 |
| 4T-3 | | 109.0 |
| 4T-4 | | 109.0 |
| | Average | 106.8 |

TABLE XXVI. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED, SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-2 | 110.0 | 8,200 |
| 5-1 | 100.0 | 16,800 |
| 5-3 | 90.0 | 24,000 |
| 5-4 | 80.0 | 34,800 |
| 5-5 | 70.0 | 61,400[a] |
| 5-25 | 70.0 | 324,000[b] |
| 5-6 | 65.0 | 11,153,000[b] |
| 5-7 | 60.0 | 11,053,400 |
| | 400 F | |
| 5-11 | 110.0 | 12,100 |
| 5-12 | 100.0 | 13,500 |
| 5-13 | 90.0 | 22,400 |
| 5-15 | 85.0 | 40,600 |
| 5-14 | 80.0 | 33,900 |
| 5-16 | 75.0 | 36,500[c] |
| 5-9 | 70.0 | 290,000[b] |
| 5-10 | 70.0 | 10,940,500[b] |
| 5-8 | 60.0 | 10,245,100 |
| | 700 F | |
| 5-17 | 110.0 | 4,010 |
| 5-18 | 100.0 | 4,870 |
| 5-19 | 90.0 | 7,650 |
| 5-20 | 80.0 | 12,500 |
| 5-21 | 70.0 | 100,380[b] |
| 5-22 | 60.0 | 10,352,900 |

(a) Failed in grip.

(b) Did not fail.

(c) Failed at thermocouple.

TABLE XXVII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ($K_t$=3.0) SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-31 | 80.0 | 3,700 |
| 5-32 | 70.0 | 4,300 |
| 5-35 | 60.0 | 6,600 |
| 5-33 | 50.0 | 12,500 |
| 5-36 | 40.0 | 17,000 |
| 5-34 | 30.0 | 911,500 |
| 5-37 | 20.0 | 10,001,300(a) |
| | 400 F | |
| 5-39 | 80.0 | 4,700 |
| 5-40 | 70.0 | 5,500 |
| 5-41 | 60.0 | 6,700 |
| 5-42 | 50.0 | 11,400 |
| 5-43 | 40.0 | 21,100 |
| 5-44 | 30.0 | 10,329,900 |
| 5-38 | 20.0 | 10,001,700(a) |
| | 700 F | |
| 5-45 | 80.0 | 2,900 |
| 5-46 | 70.0 | 3,200 |
| 5-47 | 60.0 | 5,100 |
| 5-48 | 50.0 | 8,200 |
| 5-49 | 40.0 | 26,500 |
| 5-50 | 30.0 | 33,400 |
| 5-51 | 25.0 | 16,537,900(a) |

(a) Did not fail.

TABLE XXVIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR Ti-8Mo-8V-2Fe-3Al ALLOY SHEET (TRANSVERSE)

| 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 | 156 | 700 | -- | -- | -- | -- | -- | -- | On Loading | 5.3 | -- |
| 3-2 | 150 | 700 | -- | -- | -- | -- | -- | -- | 0.1 | 3.6 | -- |
| 3-3 | 140 | 700 | 0.05 | 0.20 | 1.3 | 4.2 | 13 | 1.187 | 162.3 | 12.0 | 0.047 |
| 3-8 | 100 | 700 | 1.6 | 4 | 11 | 23 | 75 | 0.751 | 989.7 | 7.1 | 0.0025 |
| 3-10 | 60 | 700 | 4 | 8 | 27 | 95 | 500(a) | 0.491 | 114.6(b) | 1.578 | -- |
| 3-11 | 30 | 700 | 20 | 55 | 450(a) | 2000(a) | -- | 0.082 | 313.3(b) | 0.529 | 0.00036 |
| 3-4 | 75 | 900 | -- | 0.1 | 0.3 | 0.65 | 1.7 | 0.545 | 8.1 | 31.1 | 1.2 |
| 3-5 | 50 | 900 | 0.05 | 0.15 | 0.6 | 2.0 | 6.7 | 0.264 | 59.4 | 50.2 | 0.22 |
| 3-7 | 25 | 900 | 0.50 | 2.5 | 10 | 40 | 155 | 0.135 | 1406.2 | 57.3 | 0.008 |
| 3-13 | 12 | 900 | 4.3 | 20 | 153 | 450(a) | -- | 0.109 | 172.8(b) | 0.647 | 0.0018 |
| 3-6 | 155 | 550 | -- | -- | -- | -- | -- | -- | On Loading | 8.9 | -- |
| 3-9 | 145 | 550 | 0.3 | 2.8 | 30 | 105 | 1200(a) | 2.538 | 1104.6(b) | 4.50 | 0.0003 |
| 3-12 | 110 | 550 | 8.0 | 26 | 98 | 3500(a) | -- | 0.968 | 173.9(b) | 1.682 | -- |
| 3-16 | 70 | 550 | 30 | 103 | 360(a) | -- | -- | 0.422 | 234.6(b) | 0.780 | -- |

(a) Estimate.

(b) Test discontinued.

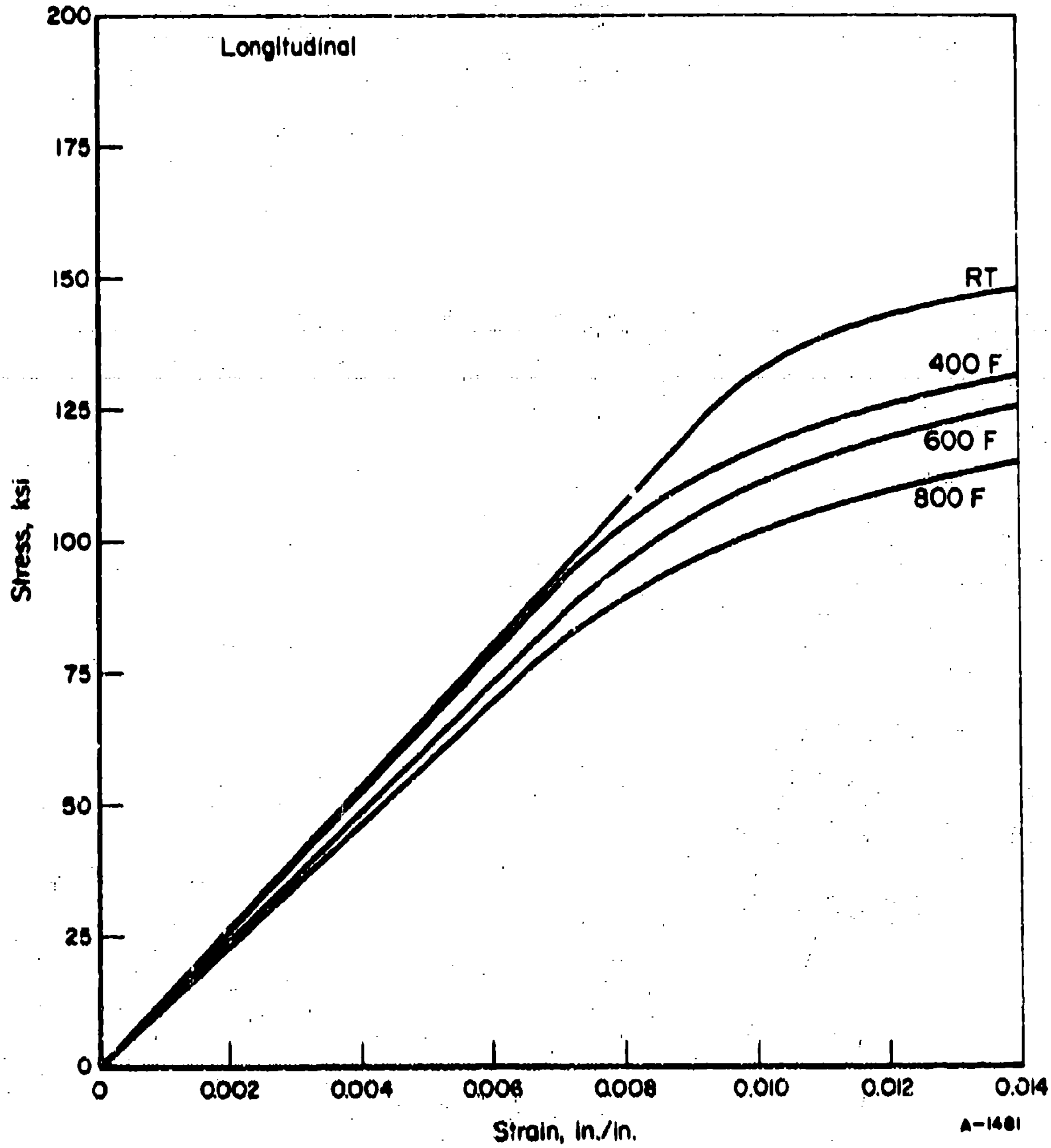



FIGURE 32. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET (LONGITUDINAL)

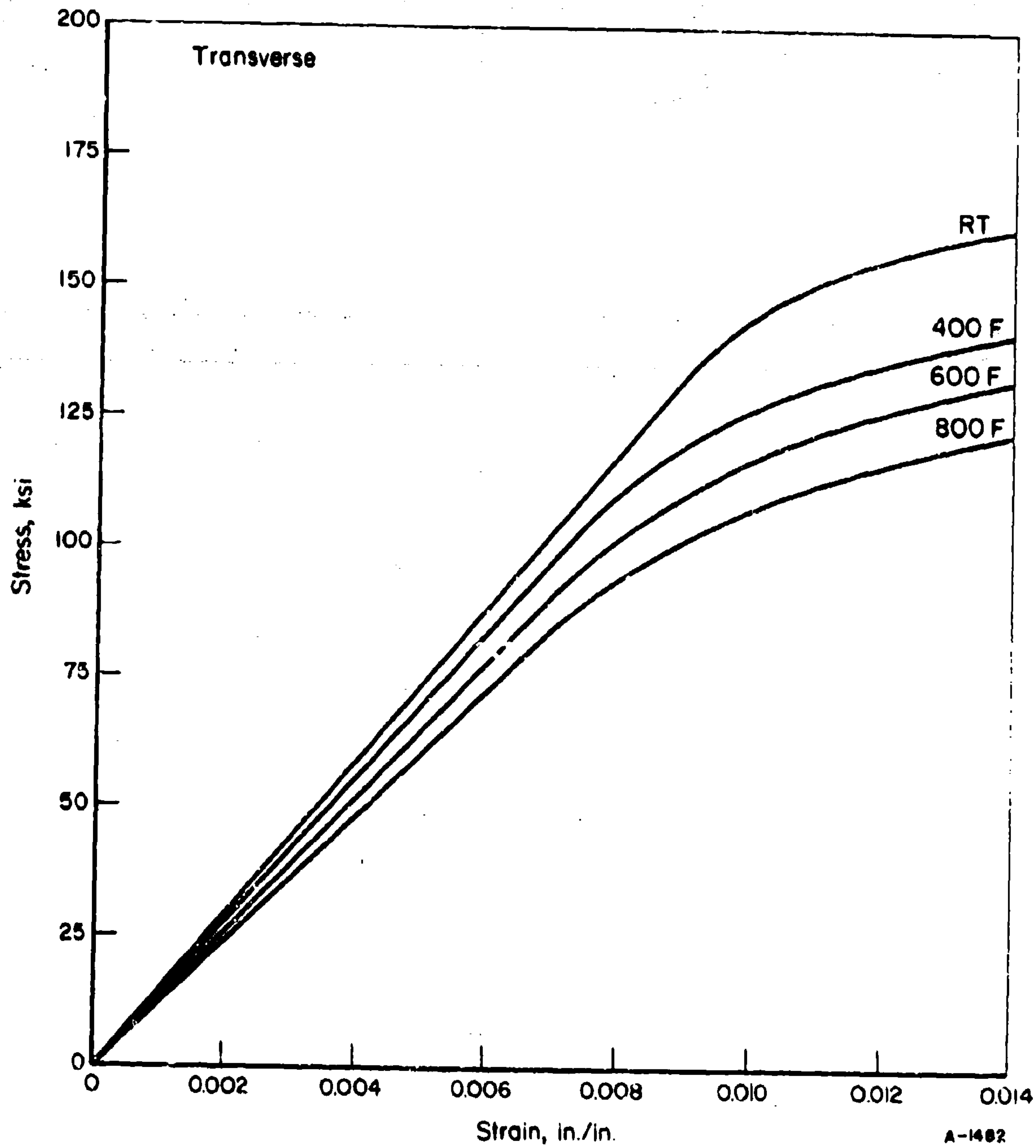



FIGURE 33. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET (TRANSVERSE)

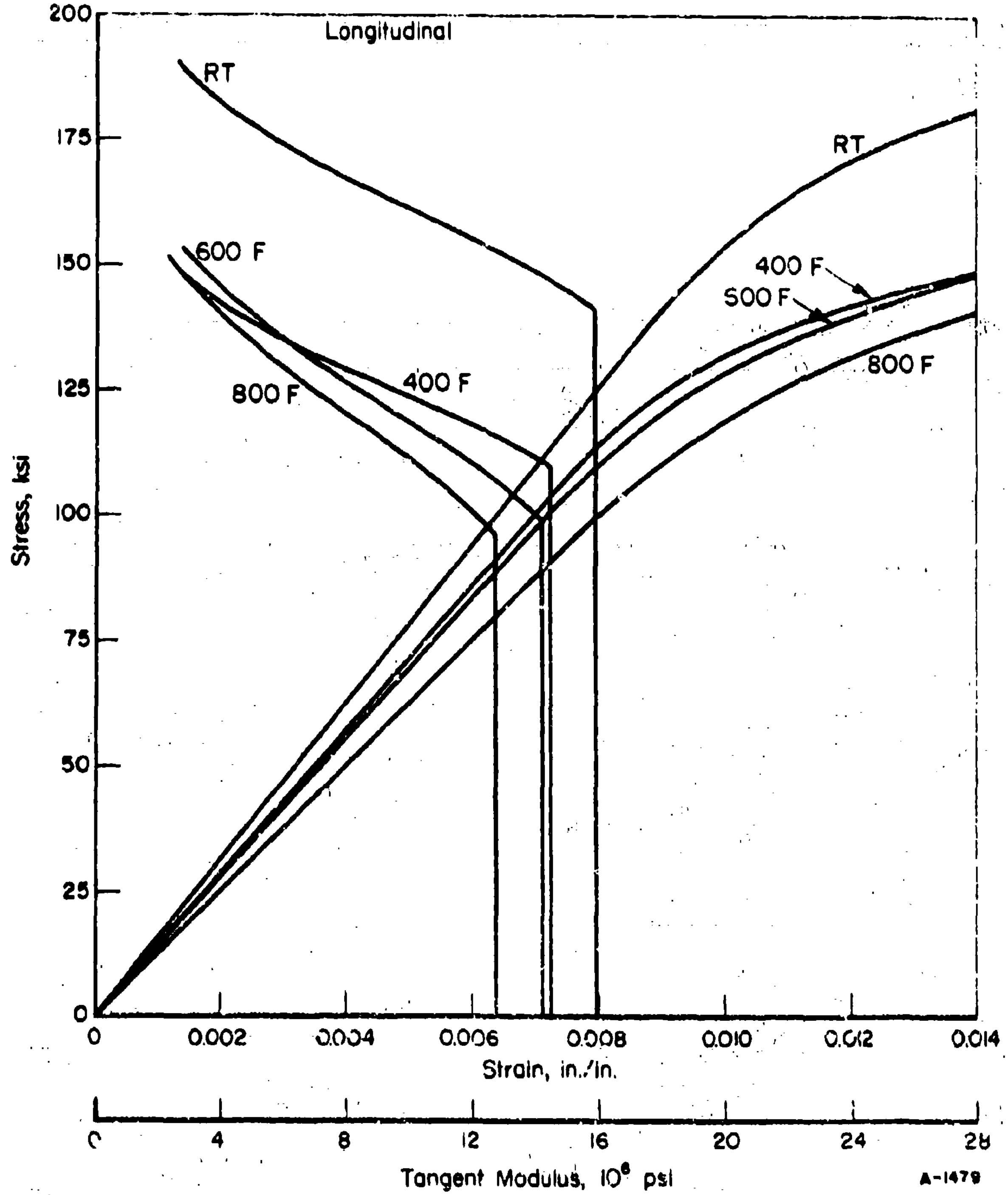



FIGURE 34. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET (LONGITUDINAL)

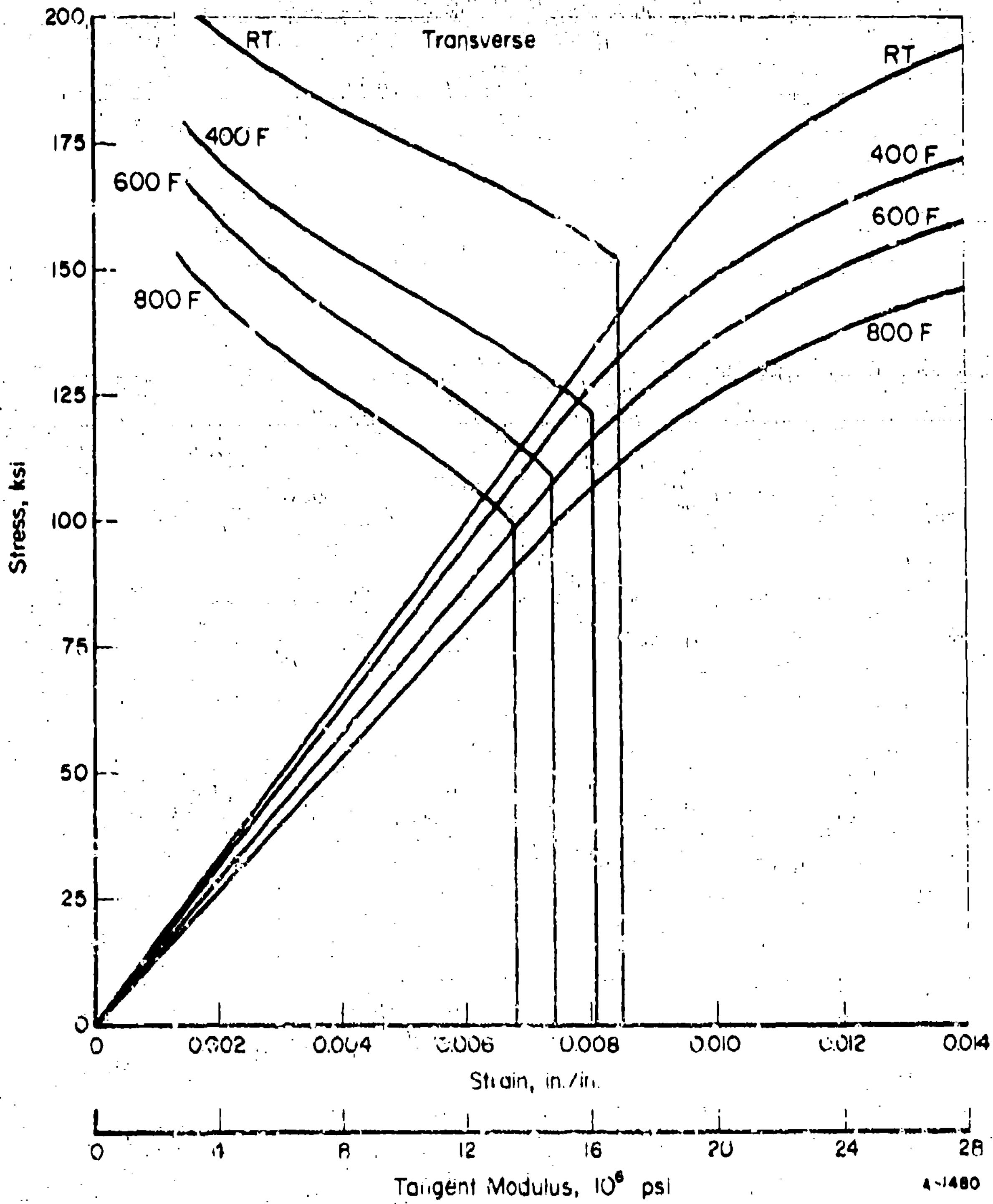



FIGURE 35. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES AT TEMPERATURE FOR SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET (TRANSVERSE)

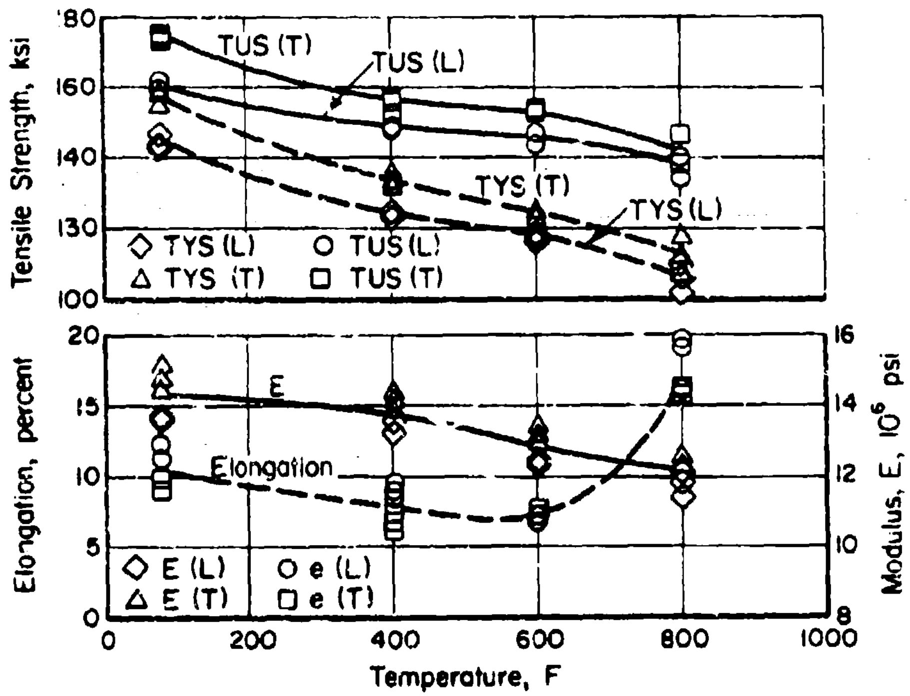



FIGURE 36. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET

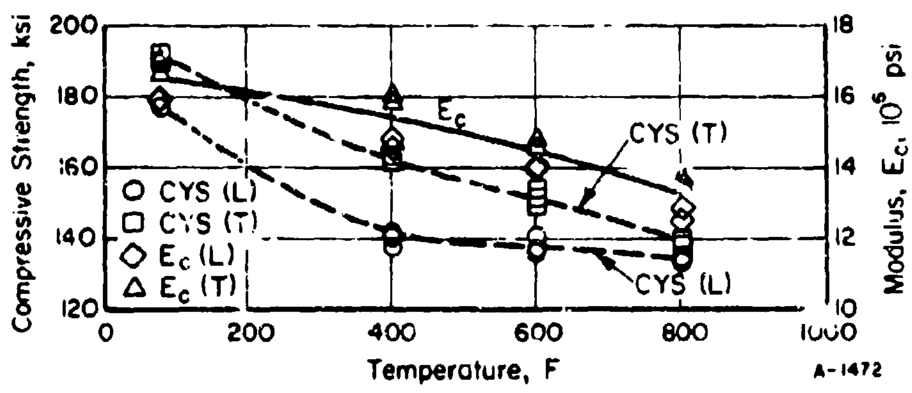



FIGURE 37. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET

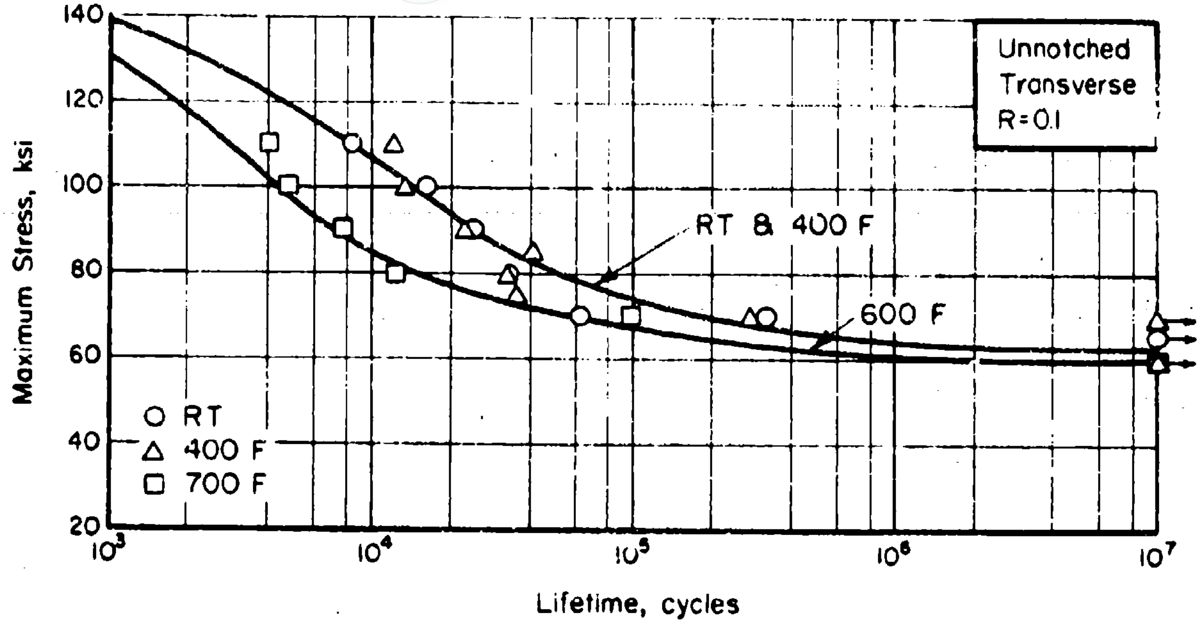



FIGURE 38. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET (TRANSVERSE)

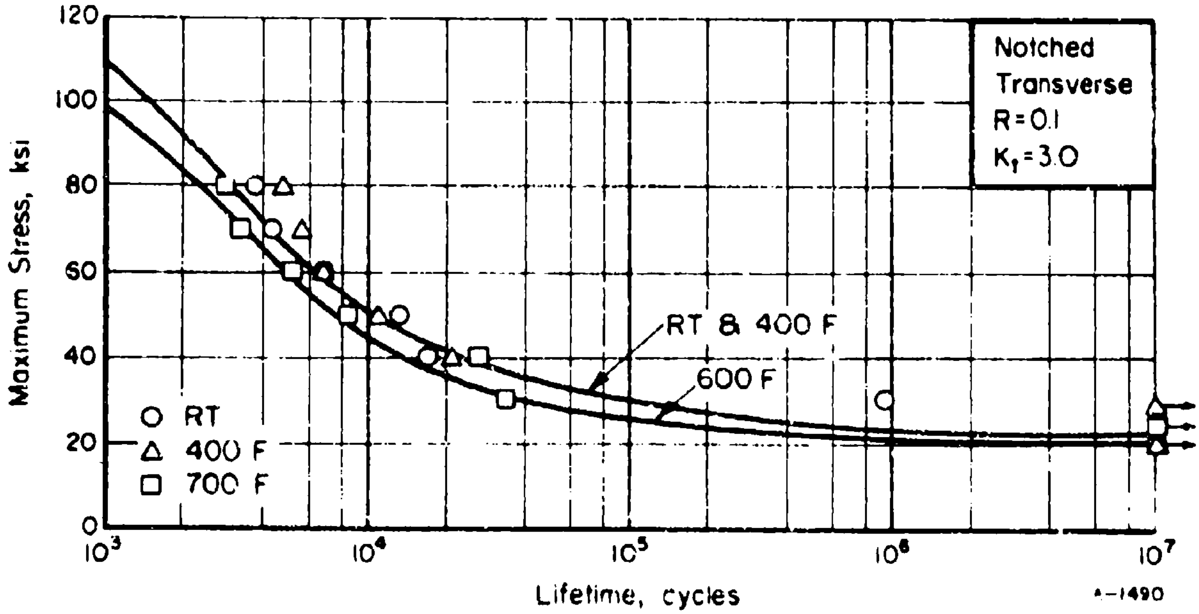
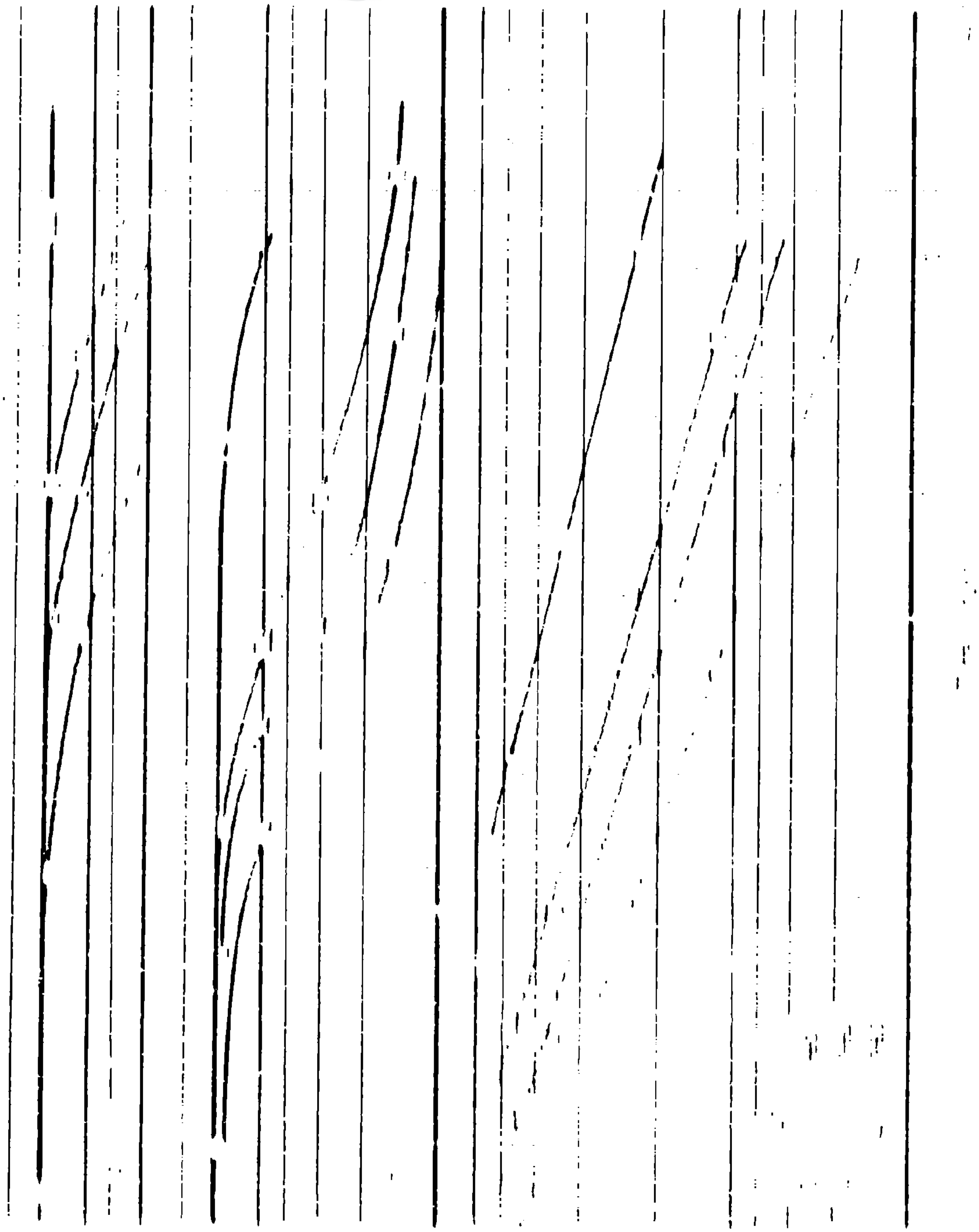



FIGURE 39. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) SOLUTION-TREATED AND AGED Ti-8Mo-8V-2Fe-3Al SHEET (TRANSVERSE)



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

## Material Description

This alloy is a recent development of RMI Company. It is an alpha-beta type alloy designed for deep hardenability. Preliminary information shows the material 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 1 1/2-inch-thick plate from RMI ingot number 890180.

## Processing and Heat Treating

The specimen layout is shown in Figure 41. The material was received in the solution-treated (1740 F, 1 hour, AC) condition and specimens were aged at 1000 F for 8 hours.

## 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 XXIX. Typical stress-strain curves at temperature are shown in Figures 42 and 43. Effect-of-temperature curves are presented in Figure 46.

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 XXX. Typical stress-strain and tangent-modulus curves at temperature are shown in Figures 44 and 45. Effect-of-temperature curves are shown in Figure 47.

Shear. Results of pin shear tests at room temperature for longitudinal and transverse specimens are given in Table XXXI.

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

Fracture Toughness. Results of slow-bend type tests in both the longitudinal (L-T) and transverse (T-L) directions are given in Table XXXIII. Even though the candidate $K_Q$ values do not meet the rigorous a, T, $< 2.5 \left(\frac{K_Q}{TYS}\right)^2$ criteria they are above $2.2\left(\frac{K_Q}{TYS}\right)^2$ and should be considered good indicative $K_{Ic}$ values.

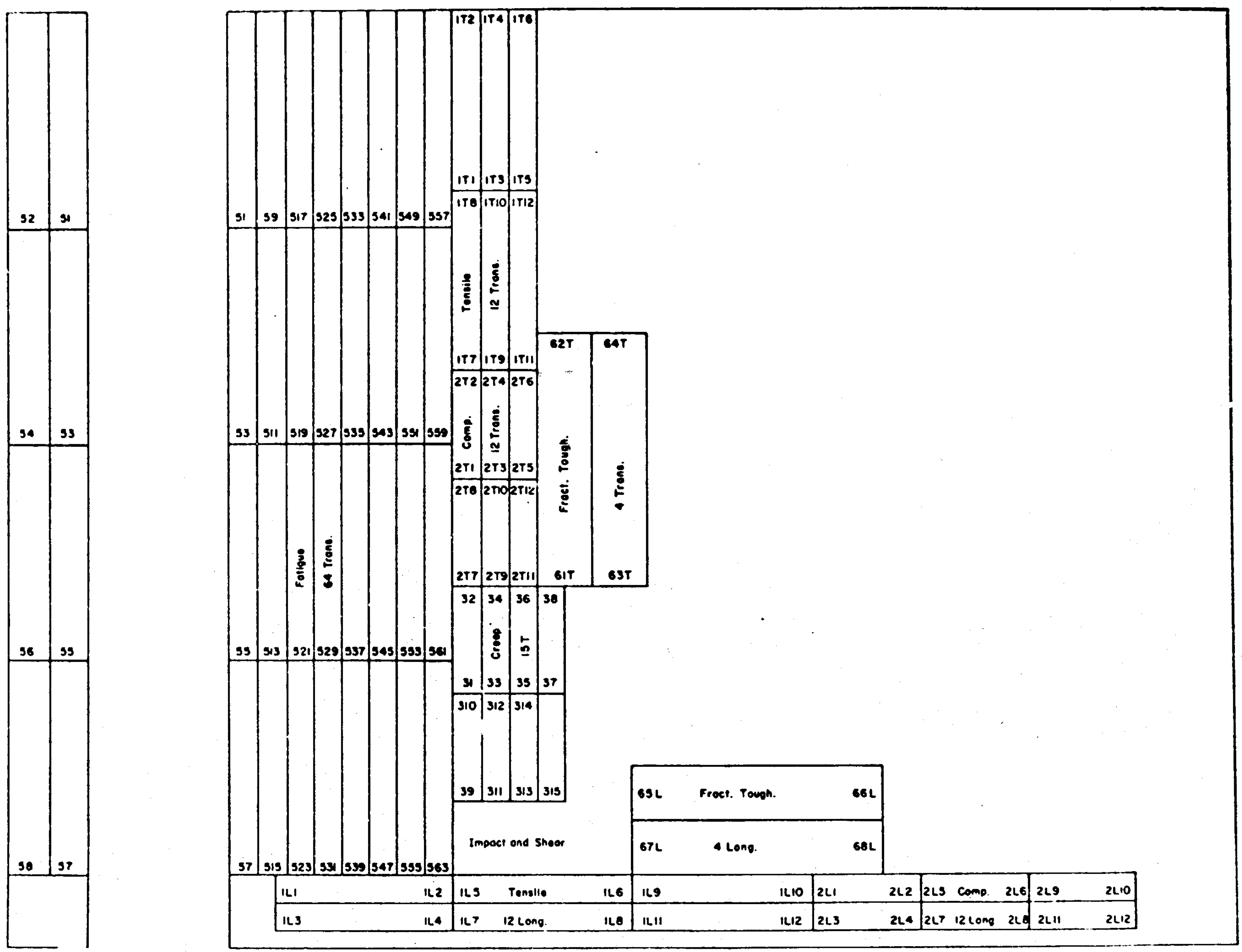



FIGURE 41. SPECIMEN LAYOUT FOR Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

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

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 XXXVI. 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 $5.1 \times 10^{-6}$ in./in./F for 70 to 800 F.

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

TABLE XXIX. TENSILE TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY PLATE

| Specimen Number | | Ultimate Tensile Strength, ksi | 0.2 Percent Offset Yield Strength, ksi | Elongation in 1-inch, percent | Reduction in Area, percent | Tensile Modulus, $10^6$ psi |
|---|---|---|---|---|---|---|
| | | Longitudinal at Room Temperature | | | | |
| 1L-1 | | 169.0 | 155.0 | 18.0 | 25.0 | 17.9 |
| 1L-2 | | 168.0 | 156.0 | 18.0 | 24.8 | 17.9 |
| 1L-3 | | 168.0 | 156.0 | 18.0 | 24.6 | 17.8 |
| | Average | 168.3 | 155.6 | 18.0 | 24.8 | 17.9 |
| | | Transverse at Room Temperature | | | | |
| 1T-1 | | 168.0 | 157.0 | 18.0 | 24.0 | 17.5 |
| 1T-2 | | 169.0 | 156.0 | 17.5 | 27.3 | 17.7 |
| 1T-3 | | 169.0 | 157.0 | 17.5 | 27.4 | 18.3 |
| | Average | 168.7 | 156.6 | 17.7 | 26.2 | 17.8 |
| | | Longitudinal at 400 F | | | | |
| 1L-4 | | 144.0 | 111.0 | 17.5 | 29.8 | 15.4 |
| 1L-5 | | 147.0 | 120.0 | 20.5 | 34.6 | 17.0 |
| 1L-6 | | 145.0 | 117.0 | 20.5 | 35.3 | 15.2 |
| | Average | 145.3 | 116.0 | 19.5 | 33.2 | 15.9 |
| | | Transverse at 400 F | | | | |
| 1T-4 | | 145.0 | 120.0 | 19.0 | 34.5 | 15.9 |
| 1T-5 | | 147.0 | 120.0 | 20.0 | 33.5 | 16.1 |
| 1T-6 | | 146.0 | 119.0 | 20.0 | 33.0 | 16.7 |
| | Average | 146.0 | 119.7 | 19.7 | 33.7 | 16.2 |
| | | Longitudinal at 600 F | | | | |
| 1L-7 | | 138.0 | 107.0 | 18.5 | 34.5 | 14.8 |
| 1L-8 | | 139.0 | 107.0 | 20.0 | 36.0 | 16.2 |
| 1L-9 | | 140.0 | 107.0 | 17.0 | 34.2 | 15.8 |
| | Average | 139.0 | 107.0 | 18.5 | 34.9 | 15.6 |
| | | Transverse at 600 F | | | | |
| 1T-7 | | 139.0 | 108.0 | 18.5 | 30.4 | 16.0 |
| 1T-8 | | 140.0 | 109.0 | 18.0 | 35.0 | 16.0 |
| 1T-9 | | 140.0 | 109.0 | 18.0 | 34.6 | 16.0 |
| | Average | 139.7 | 108.7 | 18.2 | 33.3 | 16.0 |
| | | Longitudinal at 800 F | | | | |
| 1L-10 | | 131.0 | 99.5 | 22.0 | 41.3 | 13.8 |
| 1L-11 | | 132.0 | 102.0 | 22.0 | 44.0 | 14.5 |
| 1L-12 | | 133.0 | 102.0 | 20.0 | 40.9 | 14.9 |
| | Average | 132.0 | 101.2 | 21.3 | 42.1 | 14.4 |
| | | Transverse at 800 F | | | | |
| 1T-10 | | 133.0 | 106.0 | 21.0 | 44.7 | 13.9 |
| 1T-11 | | 131.0 | 102.0 | 21.0 | 37.4 | 14.4 |
| 1T-12 | | 132.0 | 104.0 | 21.0 | 42.0 | 15.5 |
| | Average | 132.0 | 104.0 | 21.0 | 41.4 | 14.6 |

TABLE XXX. COMPRESSION TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY PLATE

| Specimen Number | | 0.2 Percent Offset Yield Strength, ksi | Compressive Modulus, $10^6$ psi |
|---|---|---|---|
| | Longitudinal at Room Temperature | | |
| 2L-1 | | 168.0 | 17.8 |
| 2L-2 | | 170.0 | 18.5 |
| 2L-3 | | 171.0 | 18.0 |
| | Average | 169.7 | 18.1 |
| | Transverse at Room Temperature | | |
| 2T-1 | | 172.0 | 18.3 |
| 2T-2 | | 174.0 | 18.5 |
| 2T-3 | | 174.0 | 18.6 |
| | Average | 173.3 | 18.5 |
| | Longitudinal at 400 F | | |
| 2L-4 | | 132.0 | 16.5 |
| 2L-5 | | 125.0 | 17.2 |
| 2L-6 | | 128.0 | 16.5 |
| | Average | 128.3 | 16.7 |
| | Transverse at 400 F | | |
| 2T-4 | | 130.0 | 16.3 |
| 2T-5 | | 130.0 | 16.5 |
| 2T-6 | | 128.0 | 16.2 |
| | Average | 129.3 | 16.3 |
| | Longitudinal at 600 F | | |
| 2L-7 | | 113.0 | 15.7 |
| 2L-8 | | 113.0 | 16.4 |
| 2L-9 | | 111.0 | 15.4 |
| | Average | 112.3 | 15.8 |
| | Transverse at 600 F | | |
| 2T-7 | | 114.0 | 15.9 |
| 2T-8 | | 116.0 | 15.6 |
| 2T-9 | | 115.0 | 15.9 |
| | Average | 115.0 | 15.8 |
| | Longitudinal at 800 F | | |
| 2L-10 | | 107.0 | 14.4 |
| 2L-11 | | 105.0 | 14.7 |
| 2L-12 | | 105.0 | 14.7 |
| | Average | 105.7 | 14.6 |
| | Transverse at 800 F | | |
| 2T-10 | | 106.0 | 14.7 |
| 2T-11 | | 106.0 | 14.7 |
| 2T-12 | | 107.0 | 14.4 |
| | Average | 106.3 | 14.6 |

TABLE XXXI. SHEAR TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY PLATE AT ROOM TEMPERATURE

| Specimen Number | | Ultimate Shear Strength, ksi |
|---|---|---|
| | Longitudinal | |
| 4L-1 | | 103.0 |
| 4L-2 | | 114.0 |
| 4L-3 | | 107.0 |
| 4L-4 | | 109.0 |
| | Average | 108.3 |
| | Transverse | |
| 4T-1 | | 108.0 |
| 4T-2 | | 109.0 |
| 4T-3 | | 109.0 |
| 4T-4 | | 106.0 |
| | Average | 108.0 |

TABLE XXXII. IMPACT TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY PLATE AT ROOM TEMPERATURE

| Specimen Number | | Energy, ft./lbs. |
|---|---|---|
| | Longitudinal | |
| 10L-1 | | 14.0 |
| 10L-2 | | 13.0 |
| 10L-3 | | 13.0 |
| 10L-4 | | 15.0 |
| 10L-5 | | 15.0 |
| 10L-6 | | 13.0 |
| | Average | 13.9 |
| | Transverse | |
| 10T-1 | | 16.0 |
| 10T-2 | | 15.0 |
| 10T-3 | | 16.5 |
| 10T-4 | | 17.0 |
| 10T-5 | | 16.0 |
| 10T-6 | | 17.0 |
| | Average | 16.3 |

TABLE XXXIII. RESULTS OF SLOW-BEND TYPE FRACTURE TOUGHNESS TESTS ON SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

| 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 |
| | | | 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, $< 2.5 \left(\frac{K_Q}{TYS}\right)^2$. However, they do exceed a $2.2 \left(\frac{K_Q}{TYS}\right)^2$ and as such should be considered marginally valid.

TABLE XXXIV. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED SOLUTION-TREATED AND AGED Ti-6Al-2Sn-2Mo-2Cr ALLOY PLATE (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-6 | 160.0 | 7,600 |
| 5-5 | 150.0 | 23,300 |
| 5-4 | 140.0 | 189,600 |
| 5-3 | 130.0 | 208,900 |
| 5-2 | 120.0 | 302,400 |
| 5-7 | 115.0 | 424,400 |
| 5-8 | 110.0 | 1,087,800 |
| 5-9 | 105.0 | 818,800 |
| 5-10 | 100.0 | 1,767,200 |
| 5-1 | 90.0 | 1,616,800 |
| 5-11 | 80.0 | 5,855,600 |
| 5-27 | 70.0 | 13,625,400(a) |
| | 400 F | |
| 5-12 | 150.0 | 7,100 |
| 5-13 | 140.0 | 12,000 |
| 5-14 | 130.0 | 21,400 |
| 5-15 | 120.0 | 178,500 |
| 5-16 | 110.0 | 369,000 |
| 5-17 | 100.0 | 829,500 |
| 5-18 | 90.0 | 2,142,600 |
| 5-19 | 80.0 | 3,059,600 |
| 5-24 | 70.0 | 10,144,000(a) |
| | 600 F | |
| 5-28 | 140.0 | (b) |
| 5-29 | 130.0 | 9,000 |
| 5-20 | 120.0 | 16,700 |
| 5-21 | 110.0 | 458,800 |
| 5-22 | 100.0 | 1,341,600 |
| 5-23 | 90.0 | 2,653,700 |
| 5-25 | 80.0 | 4,227,400 |
| 5-26 | 70.0 | 10,305,400(a) |

(a) Did not fail.

(b) Failed on loading.

TABLE XXXV. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ($K_t$=3.0) SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY PLATE (TRANSVERSE)

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-31 | 120.0 | 1,590 |
| 5-32 | 100.0 | 5,780 |
| 5-33 | 90.0 | 7,700 |
| 5-34 | 80.0 | 11,100 |
| 5-38 | 75.0 | 24,800 |
| 5-35 | 70.0 | 133,400 |
| 5-36 | 60.0 | 400,250 |
| 5-37 | 50.0 | 813,600 |
| 5-41 | 45.0 | 1,135,800 |
| 5-40 | 40.0 | 10,624,900[a] |
| | 400 F | |
| 5-46 | 75.0 | 9,500 |
| 5-47 | 70.0 | 27,600 |
| 5-48 | 65.0 | 39,900 |
| 5-49 | 60.0 | 67,000 |
| 5-50 | 55.0 | 124,000 |
| 5-51 | 50.0 | 1,846,000 |
| 5-53 | 40.0 | 1,568,200 |
| 5-54 | 30.0 | 16,000,000[a] |
| | 600 F | |
| 5-39 | 80.0 | 2,530 |
| 5-40 | 70.0 | 9,100 |
| 5-42 | 60.0 | 25,480 |
| 5-45 | 55.0 | 361,150 |
| 5-43 | 50.0 | 366,120 |
| 5-53 | 40.0 | 1,417,600 |
| 5-55 | 30.0 | 14,718,600[a] |

(a) Did not fail.

TABLE XXXVI. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY PLATE (TRANSVERSE)

| 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 | | | | | |
| 3-4 | 142 | 400 | -- | -- | -- | -- | -- | -- | On Loading | 13.6 | 47.7 | -- |
| 3-5 | 137 | 400 | 0.01 | 0.03 | 0.7 | -- | -- | 3.725 | 353.7(b) | 4.302 | -- | 0.00005 |
| 3-6 | 120 | 400 | 0.10 | 550 | -- | -- | -- | 1.180 | 574.5(b) | 1.400 | -- | 0.00004 |
| 3-2 | 133 | 600 | -- | -- | -- | -- | -- | -- | On Loading | -- | -- | -- |
| 3-3 | 128 | 600 | 0.05 | 10 | 4000(a) | -- | -- | 2.980 | 643.9(b) | 3.280 | -- | 0.000055 |
| 3-10 | 120 | 600 | 3.5 | 100 | -- | -- | -- | 1.940 | 382.3(b) | 2.168 | -- | -- |
| 3-7 | 110 | 600 | 1350(a) | -- | -- | -- | -- | 1.260 | 365.7(b) | 1.332 | -- | -- |
| 3-11 | 130 | 800 | -- | -- | -- | -- | -- | -- | On Loading | 13.6 | 48.3 | -- |
| 3-9 | 120 | 800 | 0.1 | 0.3 | 1.5 | 6.2 | 21 | 2.408 | 504.9 | 11.2 | 21.5 | -- |
| 3-8 | 100 | 800 | 6 | 10 | 175 | 2200(a) | -- | 0.992 | 504.4(b) | 1.731 | -- | 0.0004 |
| 3-1 | 50 | 800 | 320 | 2200(a) | 7500(a) | -- | -- | 0.456 | 841.0(b) | 0.584 | -- | 0.000056 |

(a) Estimate.

(b) Test discontinued.

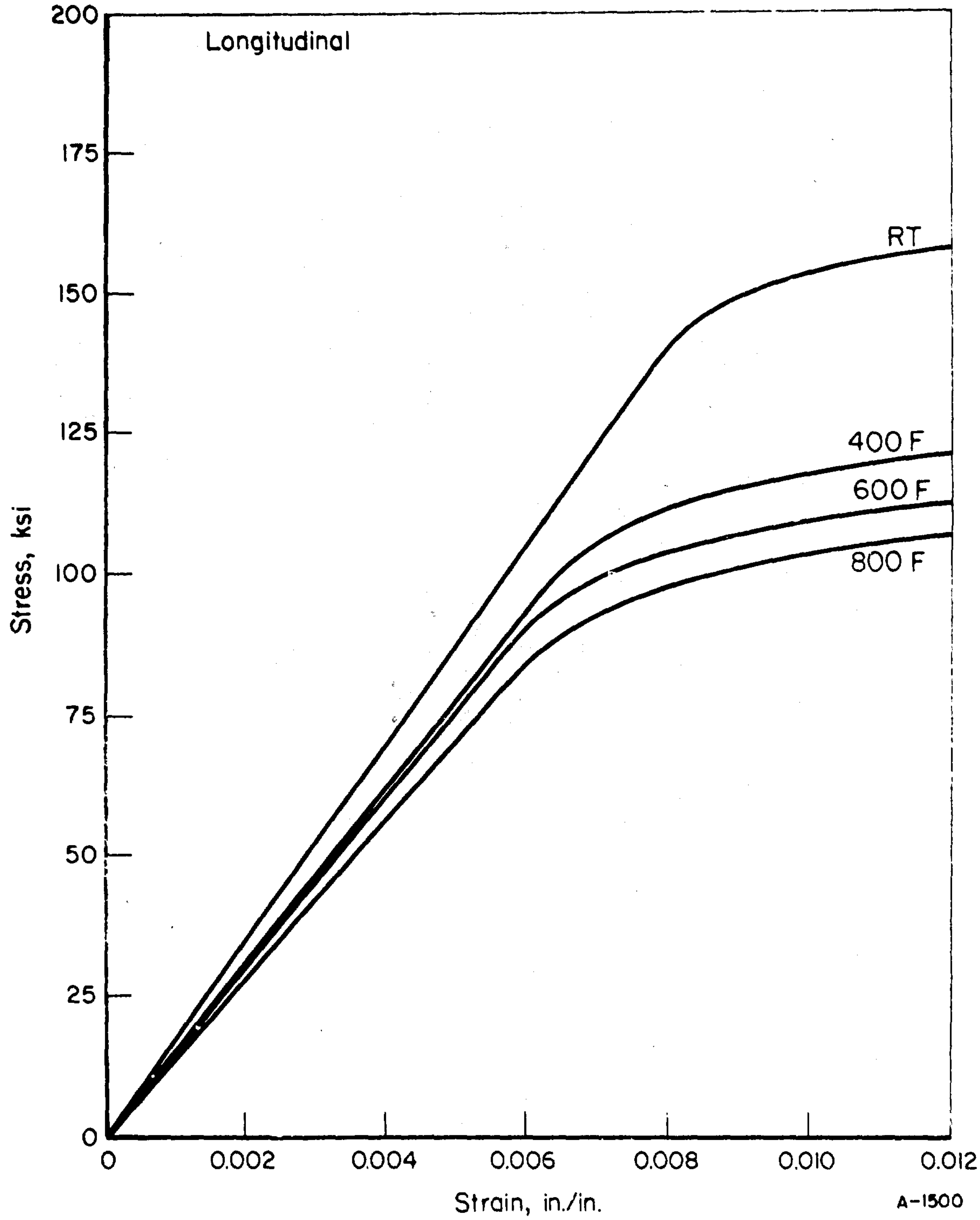



FIGURE 42. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURE FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (LONGITUDINAL)

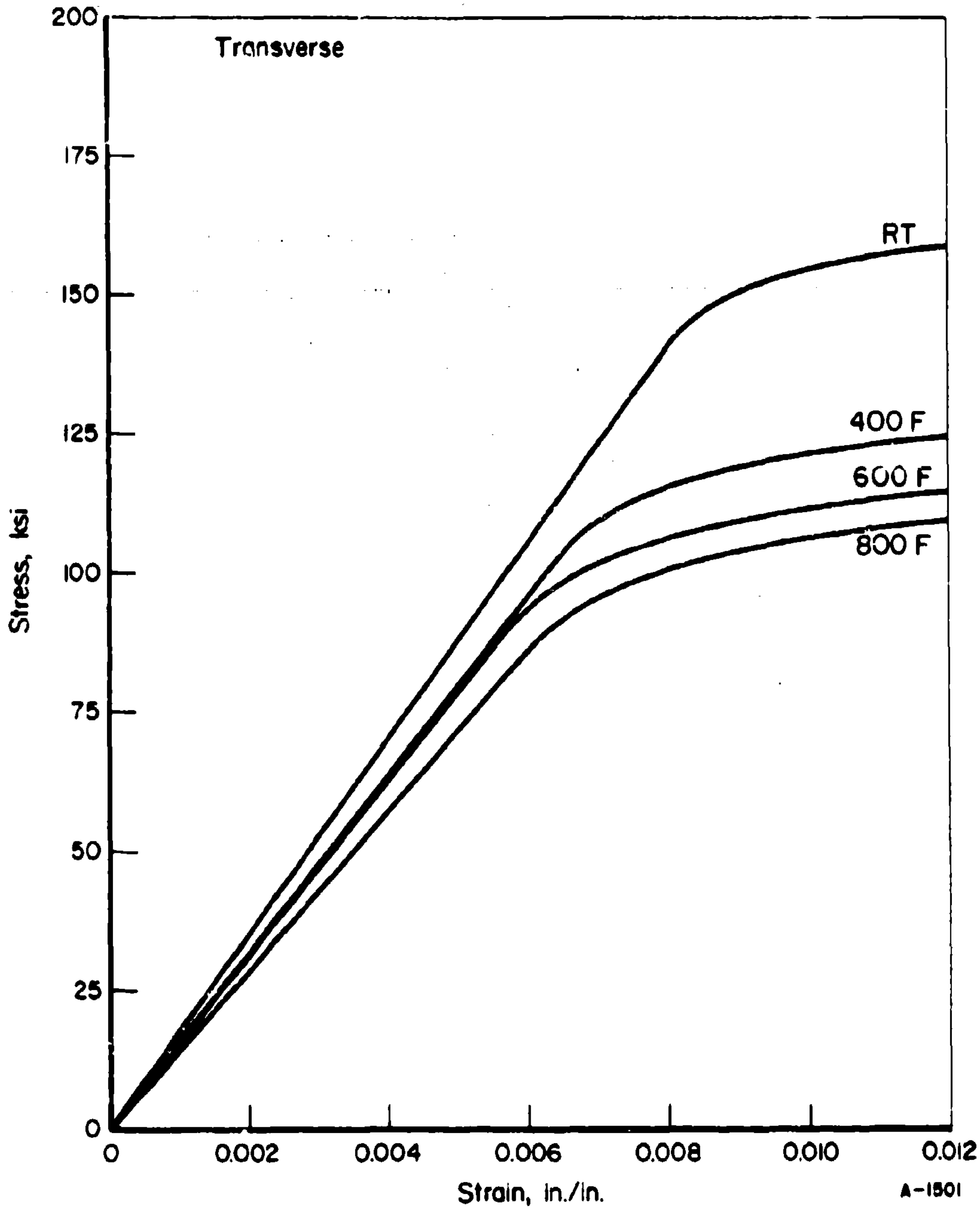



FIGURE 43. TYPICAL TENSILE STRESS-STRAIN CURVES AT TEMPERATURES FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (TRANSVERSE)

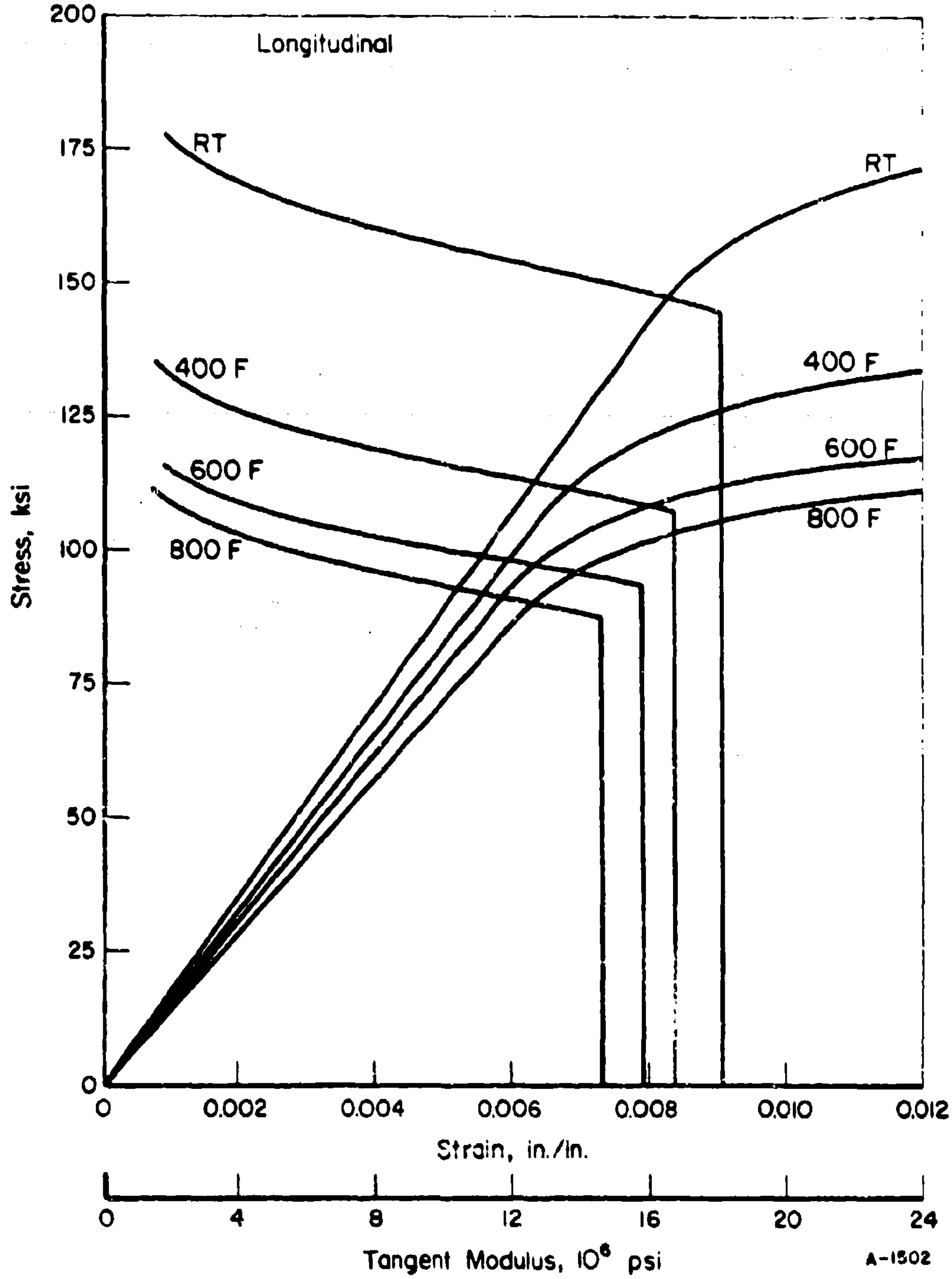



FIGURE 44. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (LONGITUDINAL)

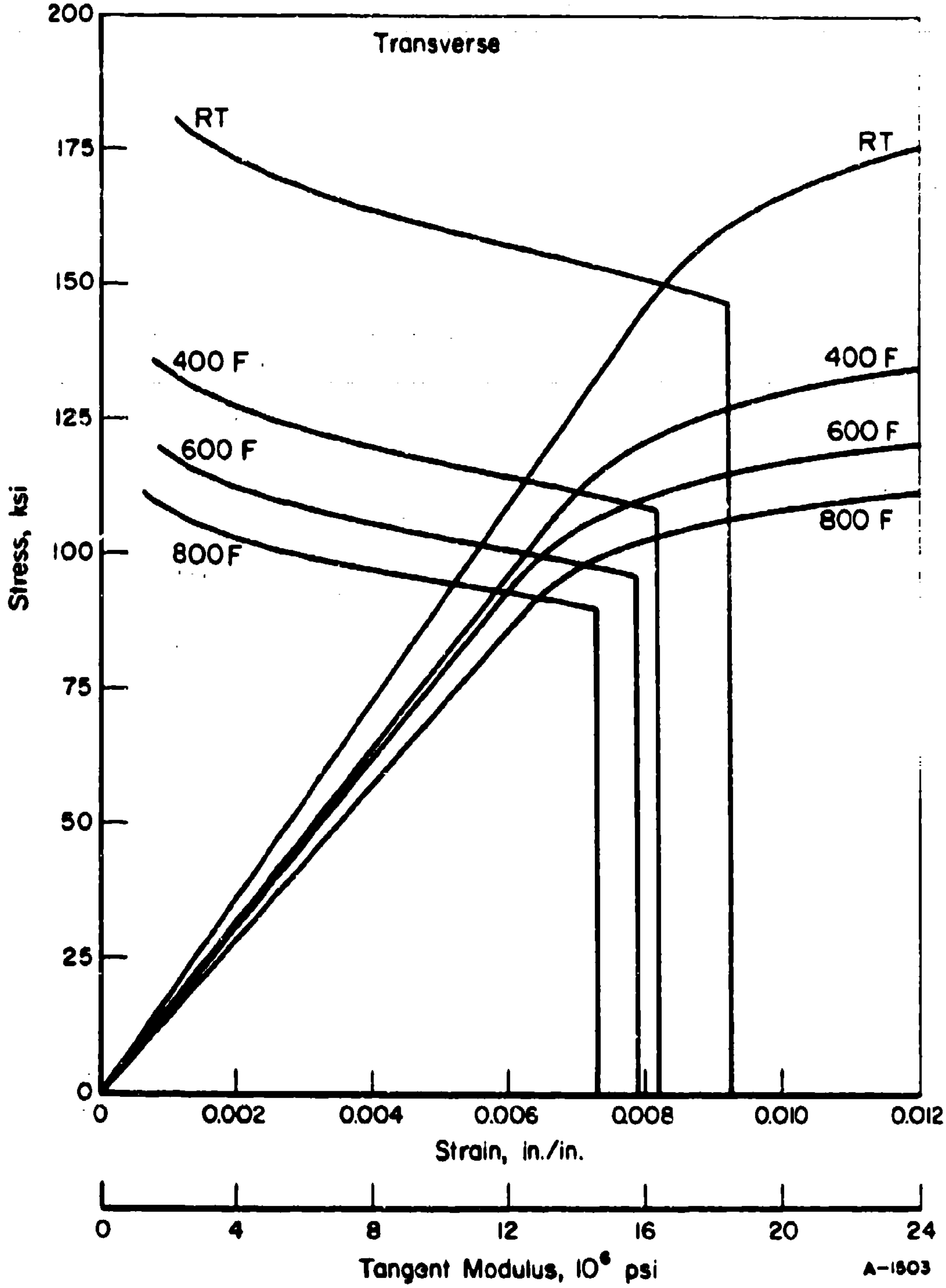



FIGURE 45. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (TRANSVERSE)

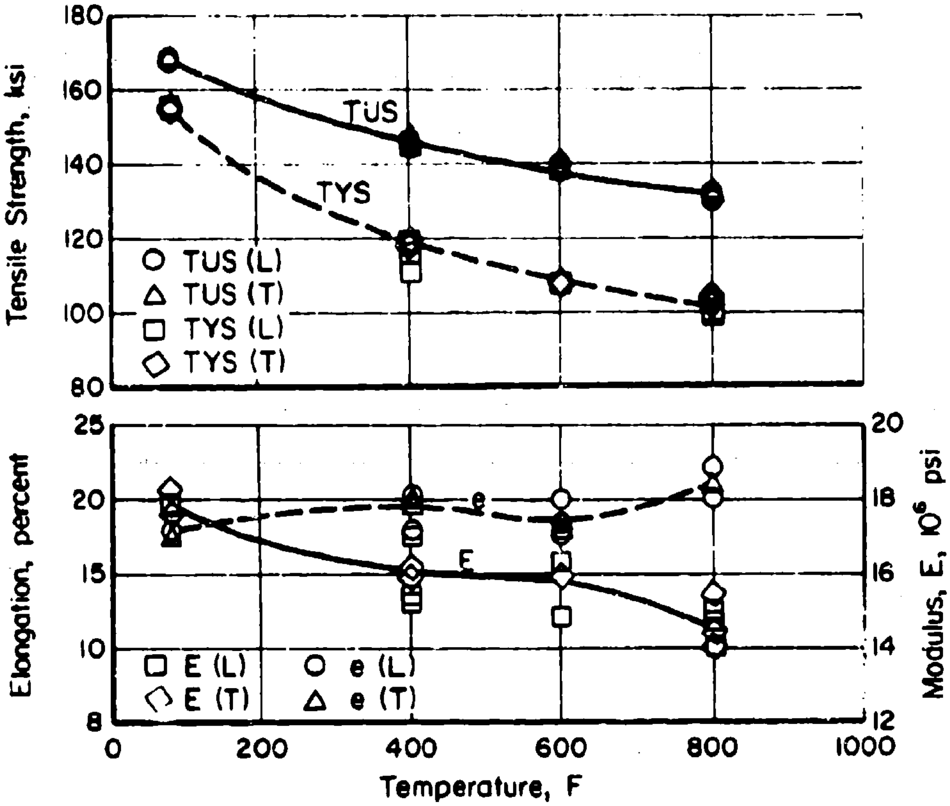



FIGURE 46. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

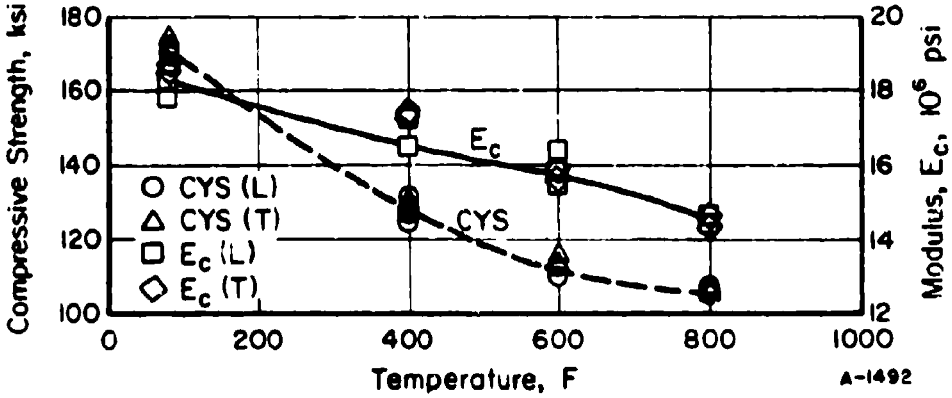



FIGURE 47. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

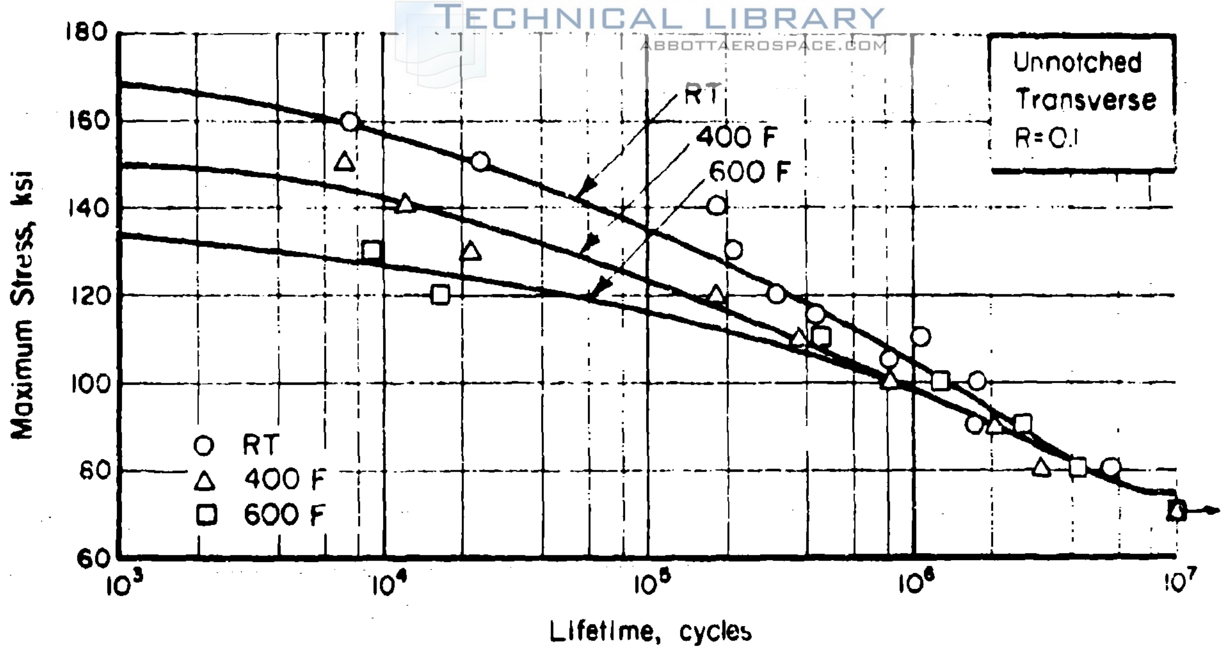



FIGURE 48. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (TRANSVERSE)

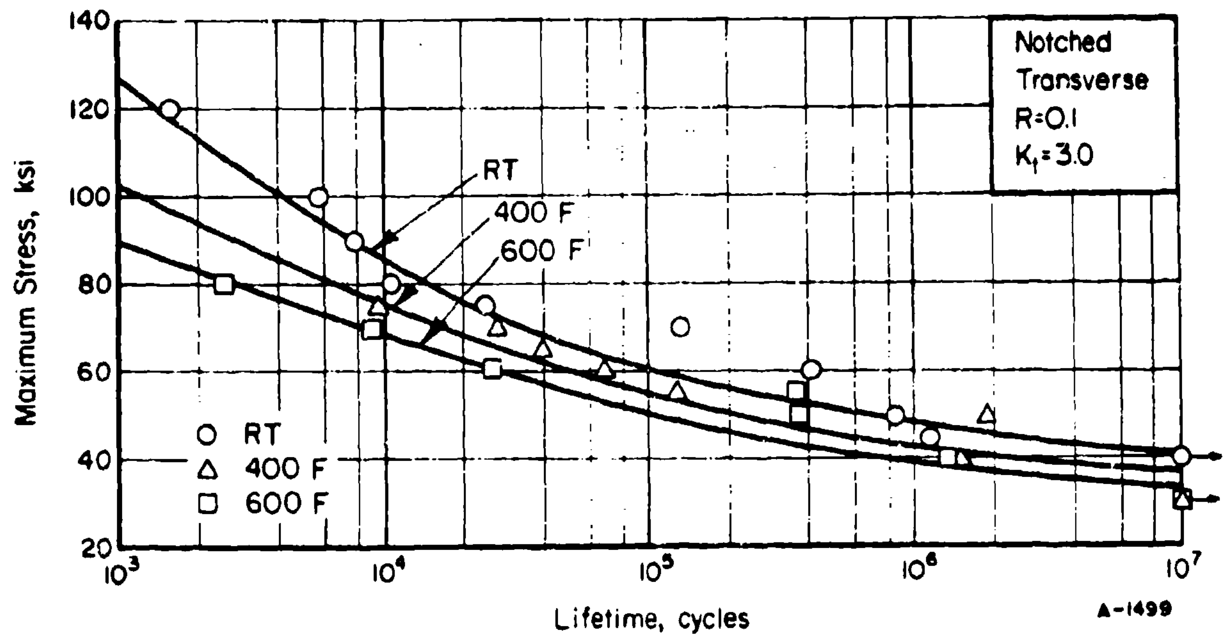



FIGURE 49. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) SOLUTION-TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (TRANSVERSE)

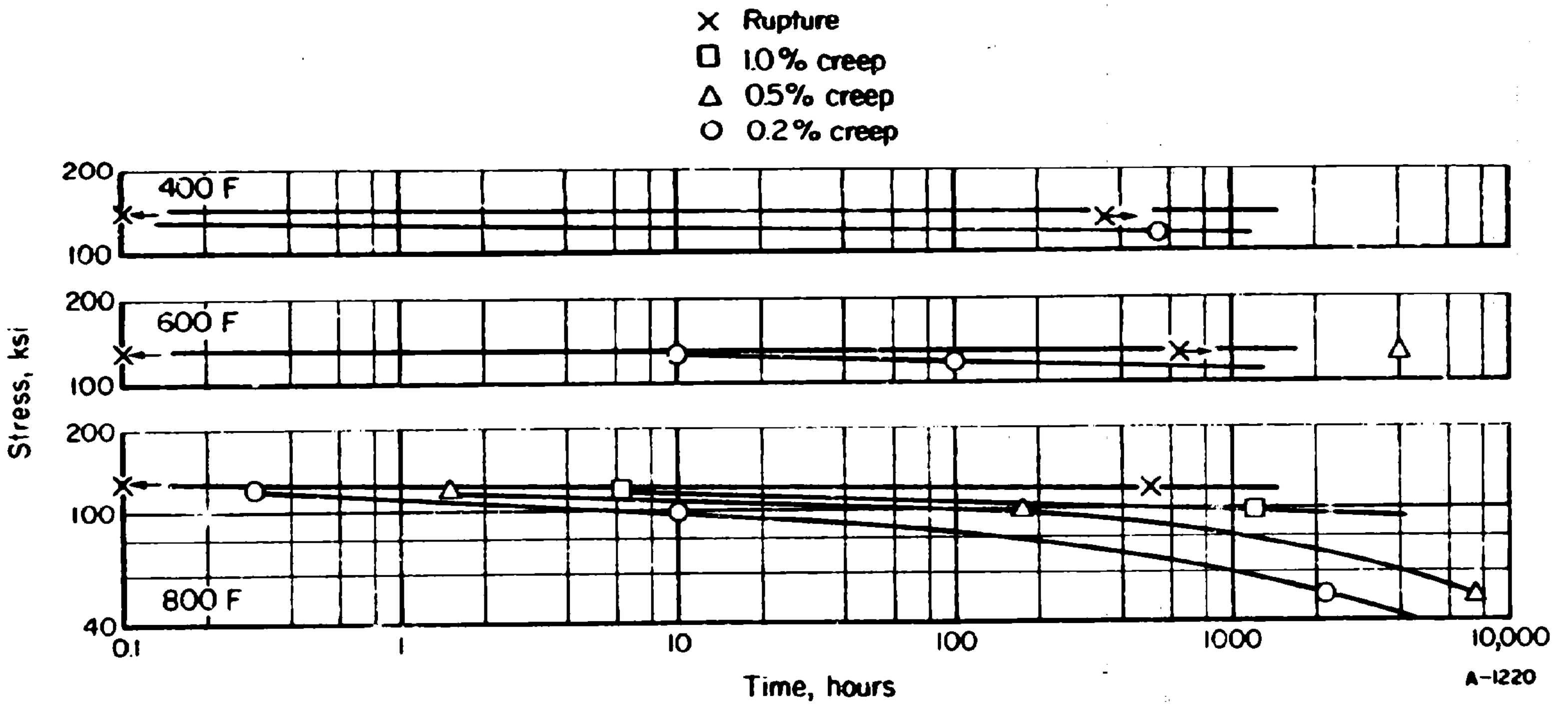



FIGURE 50. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR SOLUTION TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (TRANSVERSE)

## Ti-6Al-6V-2Sn Isothermal Die Forgings

### Material Description

This is a heat-treatable alpha-beta type alloy similar in many respects to Ti-6Al-4V, but containing increased content of beta-stabilizing elements which provide higher strength potential.

The material used for this evaluation was made by IIT Research Institute under Air Force Contract F33615-67-C-1722. It consisted of structural shapes and nose wheels that were isothermally creep (slow speed) forged from flat preforms machined from conventionally forged Ti-6Al-6V-2Sn alloy billets.

### Processing and Heat Treating

The material was received with no heat treatment after forging. Specimens were solution treated at 1650 F for 1/2 hour, water quenched, and aged at 1050 F for 4 hours and air cooled as suggested by IIT Research Institute. Other heat treatments designed for lower UTS and higher toughness should be considered for other applications.

Since the material was of complex shapes, it was necessary to cut specimens from various positions and no specimen layout drawing is shown.

### Test Results

Tension. Test results for transverse specimens at room temperature, 400 F, 700 F, and 900 F are given in Table XXXVII. Typical stress-strain curves at temperature are presented in Figure 51. Effect of temperature curves are shown in Figure 53.

Compression. Results of tests on transverse specimens at room temperature, 400 F, 700 F, and 900 F are given in Table XXXVIII. Typical stress-strain and tangent-modulus curves at temperature are shown in Figure 52. Effect of temperature curves are shown in Figure 54.

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

Impact. Test results for longitudinal and transverse specimens at room temperature are given in Table XL.

Fracture Toughness. Slow-bend tests were attempted, but the material thickness was not sufficient to obtain large specimens. The candidate $K_Q$ values did not meet ASTM criteria and are not reported. Results of tests on compact tension specimens at AFML are reported in the data sheet in Appendix III.

Fatigue. Axial load tests were conducted at room temperature, 400 F, and 700 F for both unnotched and notched transverse specimens at a stress ratio of R = 0.1. Tabular test results are given in Tables XLI and XLII. S-N curves are presented in Figures 55 and 56.

Creep and Stress Rupture. Test results for transverse specimens at 700 F and 900 F are given in Table XLIII. Tests were attempted at 400 F and 550 F, but no appreciable creep occurred. Log-stress versus log-time curves are presented in Figure 57.

Stress Corrosion. Tests were conducted 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 $5.3 \times 10^{-6}$ in./in./F from 70 F to 900 F.

Density. The density value for this alloy is 0.164 lb./in.$^3$.

TABLE XXXVII. TENSION TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGING (TRANSVERSE)

| Specimen Number | | Ultimate Tensile Strength, ksi | 0.2 Percent Offset Yield Strength, ksi | Elongation, in 1 Inch, percent | Tensile Modulus, $10^6$ psi |
|---|---|---|---|---|---|
| | | | Room Temperature | | |
| 5 | | 203.3 | 194.1 | 3.0 | 14.9 |
| 6 | | 199.6 | 188.6 | 7.0 | 16.0 |
| 13 | | 204.5 | 196.1 | 4.0 | 17.0 |
| | Average | 202.5 | 192.9 | 4.7 | 16.0 |
| | | | 400 F | | |
| 7 | | 171.6 | 154.8 | 7.0 | 15.4 |
| 8 | | 174.0 | 152.0 | 9.0 | 14.1 |
| 9 | | 165.5 | 152.7 | 7.0 | 14.7 |
| | Average | 170.4 | 153.2 | 7.7 | 14.7 |
| | | | 700 F | | |
| 10 | | 154.7 | 134.4 | 12.0 | 13.0 |
| 11 | | 155.7 | 132.8 | 8.0 | 13.3 |
| 12 | | 164.8 | 128.2 | 5.0 | 13.0 |
| | Average | 158.4 | 131.8 | 8.3 | 13.1 |
| | | | 900 F | | |
| 15 | | 137.4 | 82.4 | 23.0 | 11.5 |
| 16 | | 143.6 | 87.5 | 20.0 | 12.4 |
| 17 | | 119.7 | 70.9 | 23.0 | 12.4 |
| | Average | 133.6 | 80.3 | 22.0 | 12.1 |

TABLE XXXVIII. COMPRESSION TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS (TRANSVERSE)

| Specimen Number | | 0.2 Percent Offset Yield Strength, ksi | | Compression Modulus, $10^6$ psi |
|---|---|---|---|---|
| | | **Room Temperature** | | |
| 2T-1 | | 202.6 | | 18.0 |
| 2T-2 | | 200.1 | | 18.5 |
| 2T-3 | | 195.2 | | 17.6 |
| | Average | 199.3 | Average | 18.0 |
| | | **400 F** | | |
| 2T-4 | | 170.6 | | 16.6 |
| 2T-5 | | 172.2 | | 16.0 |
| 2T-6 | | 180.0 | | 15.7 |
| | Average | 174.3 | Average | 16.1 |
| | | **700 F** | | |
| 2T-7 | | 156.6 | | 12.0 |
| 2T-8 | | 150.0 | | 13.6 |
| 2T-9 | | 152.3 | | 14.0 |
| | Average | 152.9 | Average | 13.2 |
| | | **900 F** | | |
| 2T-10 | | 101.2 | | 12.0 |
| 2T-11 | | 110.0 | | 12.2 |
| 2T-12 | | 112.0 | | 11.6 |
| | Average | 107.7 | Average | 11.9 |

TABLE XXXIX. SHEAR TEST RESULTS AT ROOM TEMPERATURE FOR SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

| Specimen Number | | Ultimate Shear Strength, ksi |
|---|---|---|
| | Longitudinal | |
| 4L-1 | | 131.0 |
| 4L-2 | | 132.0 |
| 4L-3 | | 131.7 |
| 4L-4 | | 131.6 |
| | Average | 131.6 |
| | Transverse | |
| 4T-1 | | 130.0 |
| 4T-2 | | 130.0 |
| 4T-3 | | 130.1 |
| 4T-4 | | 130.0 |
| | Average | 130.0 |

TABLE XL. IMPACT TEST RESULTS FOR SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

| Specimen Number | | Energy, ft. lbs. |
|---|---|---|
| | Longitudinal | |
| 10L-1 | | 12.0 |
| 10L-2 | | 11.0 |
| 10L-3 | | 11.0 |
| 10L-4 | | 11.7 |
| | Average | 11.7 |
| | Transverse | |
| 10T-1 | | 8.5 |
| 10T-2 | | 9.0 |
| 10T-3 | | 8.0 |
| 10T-4 | | 8.5 |
| | Average | 8.5 |

TABLE XLI. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-1 | 100.0 | 4,700 |
| 5-2 | 100.0 | 15,300 |
| 5-3 | 90.0 | 15,500 |
| 5-4 | 80.0 | 15,300 |
| 5-6 | 70.0 | 19,900 |
| 5-5 | 60.0 | 25,800 |
| 5-7 | 50.0 | 35,990 |
| 5-17 | 40.0 | 12,679,200[a] |
| | 400 F | |
| 5-8 | 80.0 | 15,900 |
| 5-9 | 70.0 | 19,900 |
| 5-10 | 60.0 | 100,400 |
| 5-11 | 50.0 | 30,700 |
| 5-18 | 40.0 | 100,700 |
| 5-19 | 30.0 | 10,452,600[a] |
| | 700 F | |
| 5-12 | 80.0 | 18,000 |
| 5-13 | 70.0 | 30,200 |
| 5-14 | 60.0 | 27,500 |
| 5-15 | 60.0 | 38,900 |
| 5-16 | 50.0 | 3,161,100[b] |
| 5-20 | 40.0 | 11,436,800[a] |

(a) Did not fail.

(b) Grip failure.

TABLE XLII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ($K_t$ = 3.0) SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

| Specimen Number | Maximum Stress, ksi | Lifetime, cycles |
|---|---|---|
| | Room Temperature | |
| 5-35 | 70.0 | 3,900 |
| 5-31 | 60.0 | 16,200 |
| 5-32 | 50.0 | 26,300 |
| 5-33 | 40.0 | 244,000 |
| 5-34 | 30.0 | 8,134,400 |
| 5-21 | 25.0 | 10,189,800[a] |
| | 400 F | |
| 5-37 | 70.0 | 9,400 |
| 5-38 | 60.0 | 18,200 |
| 5-40 | 55.0 | 26,600 |
| 5-39 | 50.0 | 662,200 |
| 5-41 | 45.0 | 61,200 |
| 5-36 | 40.0 | 4,784,900 |
| 5-20 | 35.0 | 10,160,400[a] |
| | 700 F | |
| 5-42 | 65.0 | 6,100 |
| 5-43 | 60.0 | 7,800 |
| 5-44 | 55.0 | 19,700 |
| 5-45 | 50.0 | 56,400 |
| 5-46 | 45.0 | 120,700 |
| 5-47 | 40.0 | 86,[illegible]00 |
| 5-48 | 35.0 | 1,110,500 |
| 5-49 | 30.0 | 14,219,800[a] |

(a) Did not fail.

TABLE XLIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS (TRANSVERSE)

| 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 | 153.3 | 700 | -- | -- | -- | -- | -- | -- | On Loading | 8.9 | 24.8 | -- |
| 3-4 | 145 | 700 | -- | -- | 0.07 | 0.25 | 0.70 | 4.133 | 2.6 | 13.8 | 32.6 | 1.5 |
| 3-5 | 135 | 700 | 0.08 | 0.2 | 0.8 | 2.5 | 11.0 | 1.680 | 59.8 | 18.5 | 45.3 | 0.13 |
| 3-6 | 110 | 700 | 0.3 | 1.0 | 12 | 47 | 180 | 0.781 | 1007.8(b) | 6.96 | -- | 0.0050 |
| 3-8 | 50 | 700 | 17 | 75 | 1000(a) | -- | -- | 0.242 | 122.8(b) | 0.465 | -- | -- |
| 3-9 | 25 | 700 | 120 | 1450 | 7500(a) | -- | -- | 0.073 | 935.5(b) | 0.246 | -- | 0.000050 |
| 3-2 | 60 | 900 | 0.07 | 0.15 | 0.7 | 2.0 | 5.2 | 0.446 | 27.6 | 33.9 | 73.2 | 0.31 |
| 3-7 | 30 | 900 | 0.30 | 1.0 | 6.0 | 28 | 77 | 0.350 | 624.3 | 48.5 | 81.0 | 0.020 |
| 3-10 | 8 | 900 | 5.5 | 25 | -- | -- | -- | 0.138 | 119.8(b) | 0.469 | -- | -- |
| 3-11 | 3 | 900 | 100 | 125 | 5000(a) | -- | -- | 0.173 | 937.6(b) | 0.377 | -- | 0.000075 |

(a) Estimate.

(b) Test discontinued.

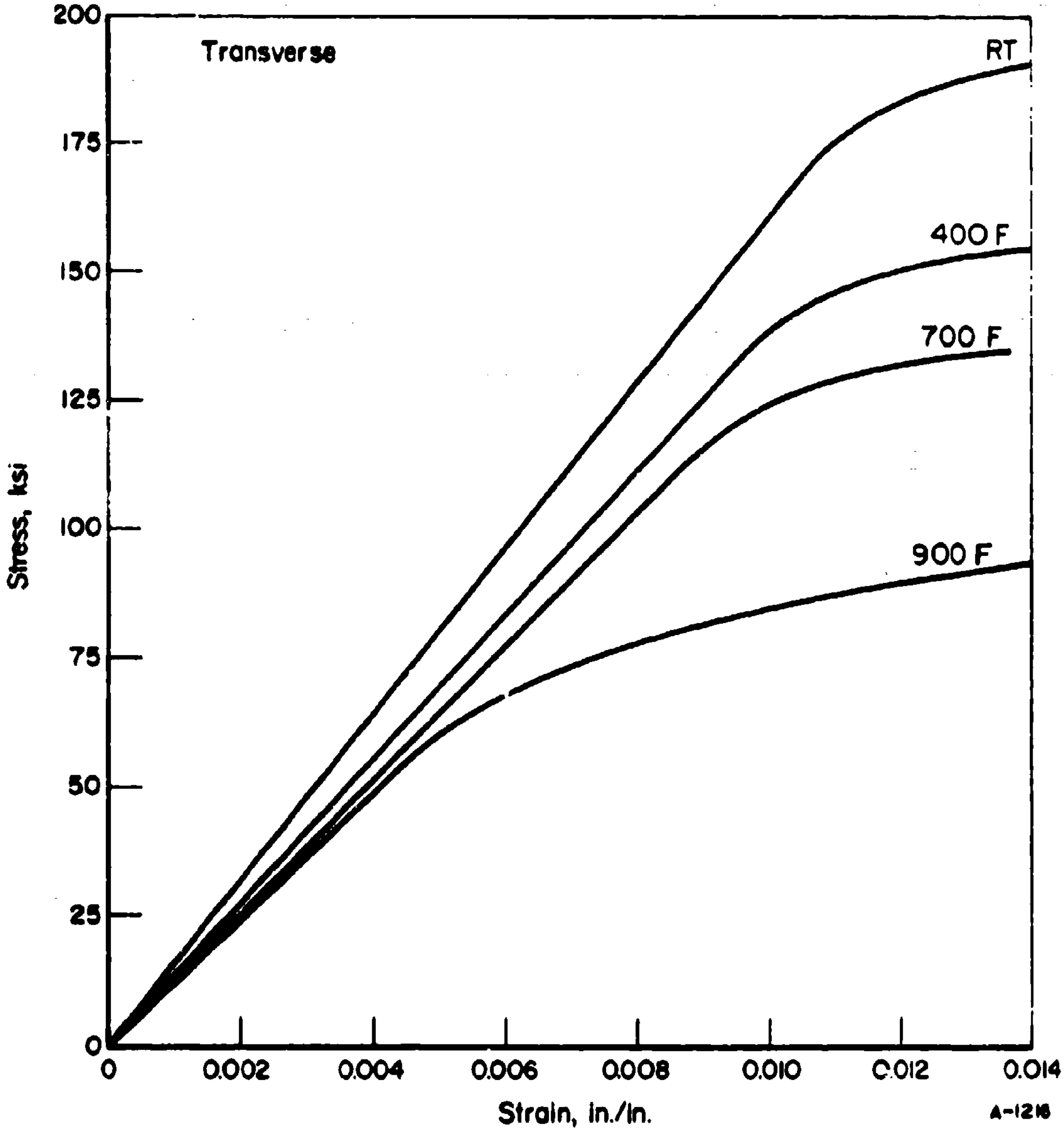



FIGURE 51. TYPICAL TENSILE STRESS-STRAIN CURVES FOR SOLUTION TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

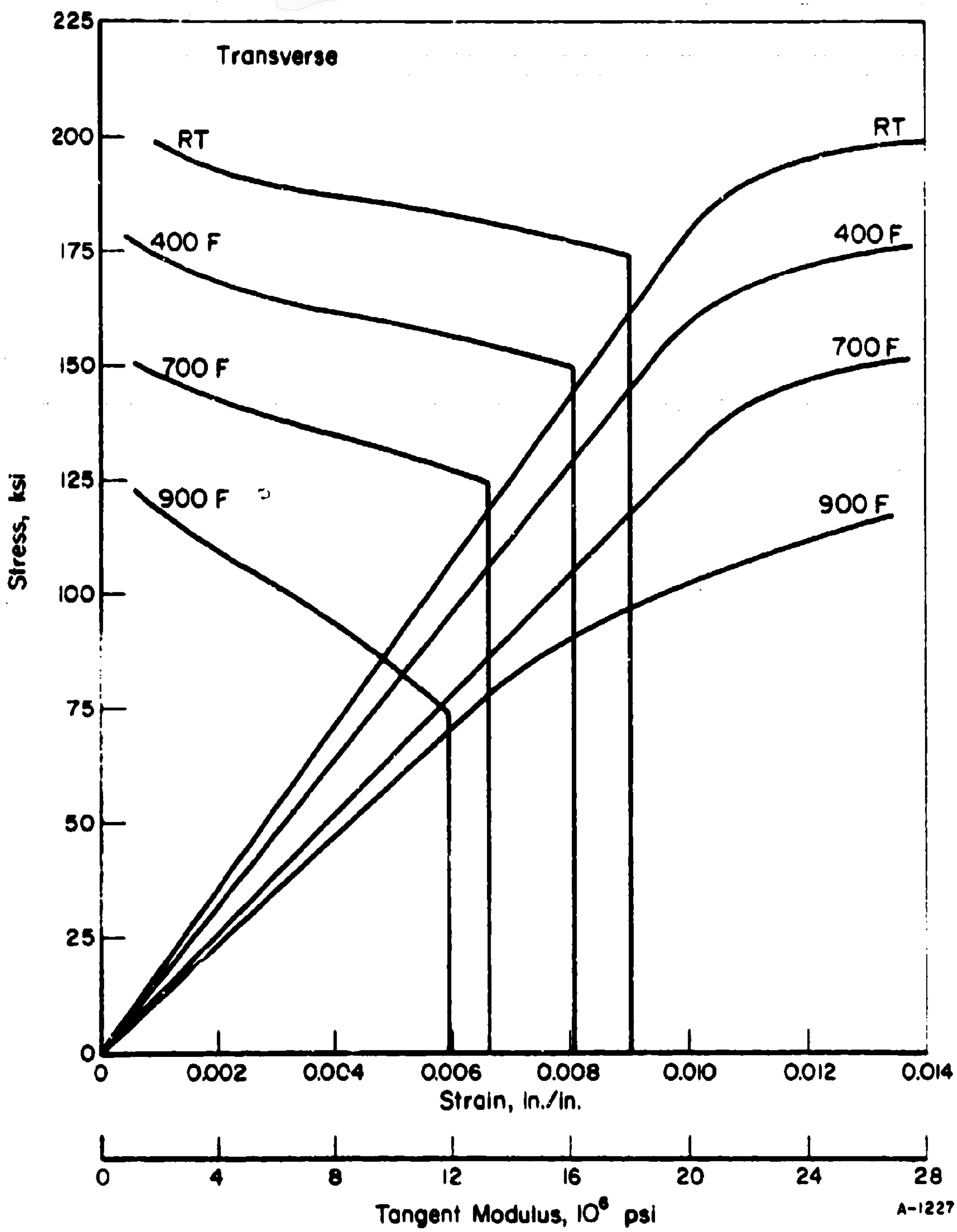



FIGURE 52. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR SOLUTION TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

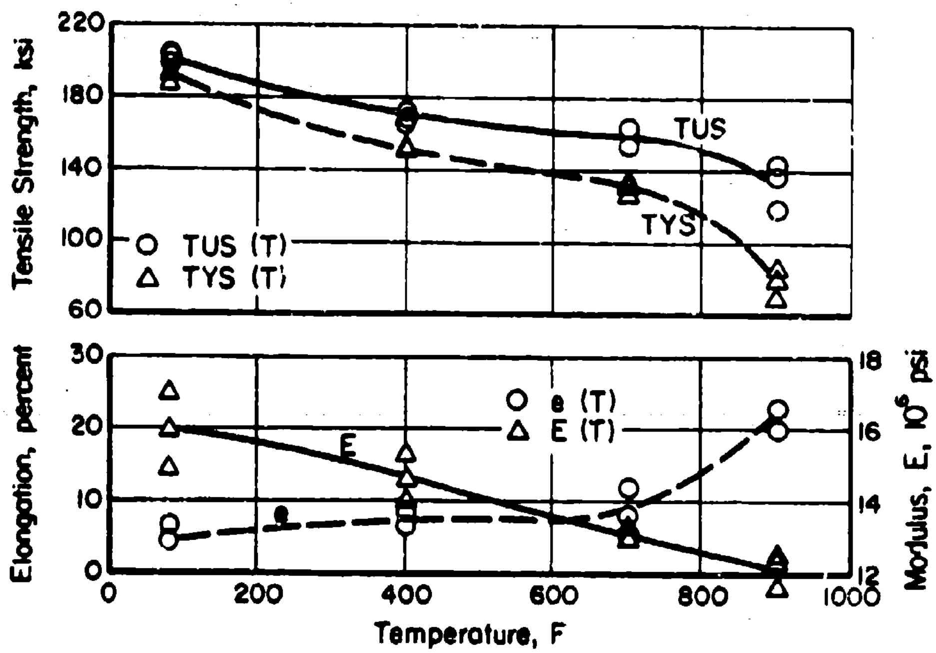



FIGURE 53. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

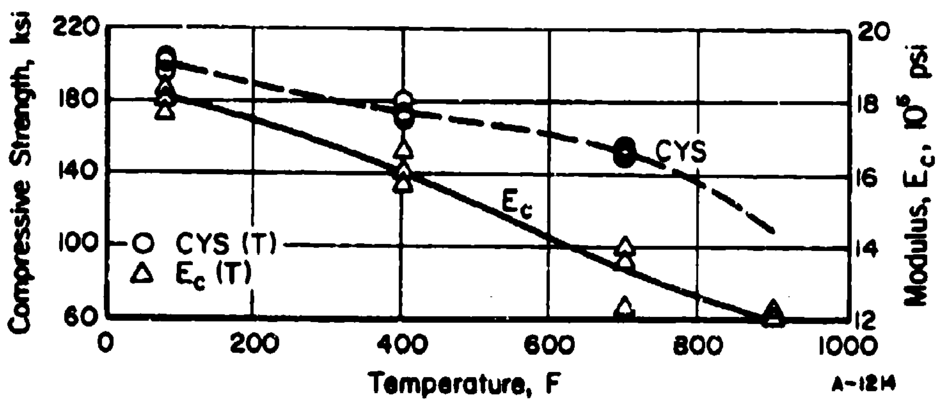



FIGURE 54. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF SOLUTION TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

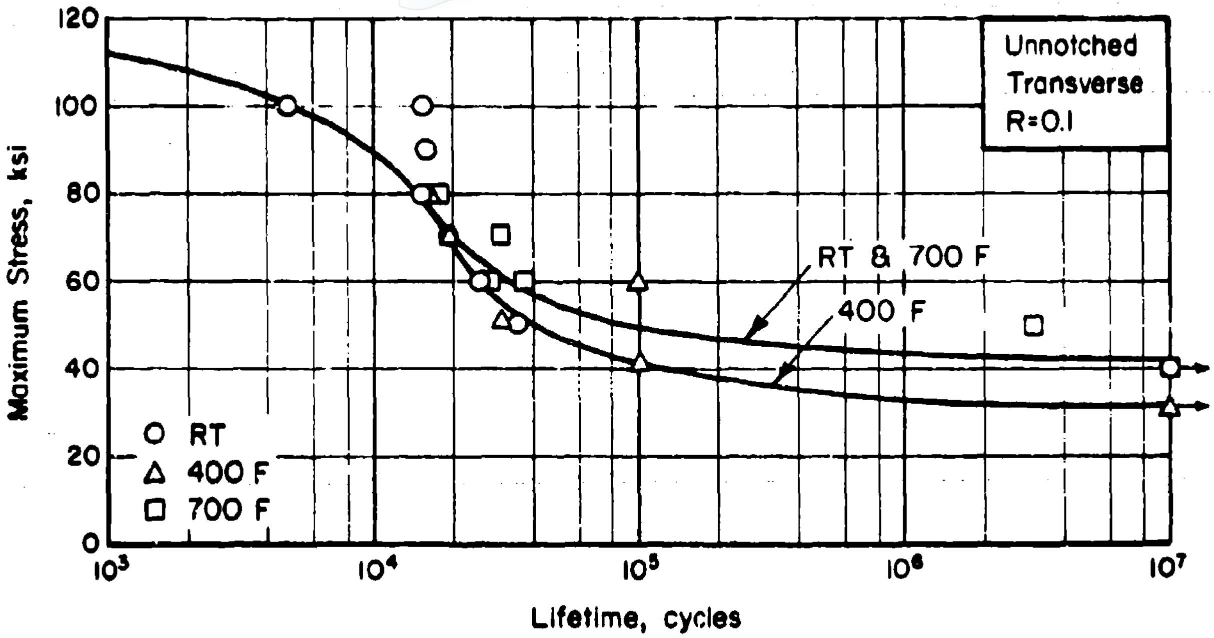



FIGURE 55. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS (TRANSVERSE)

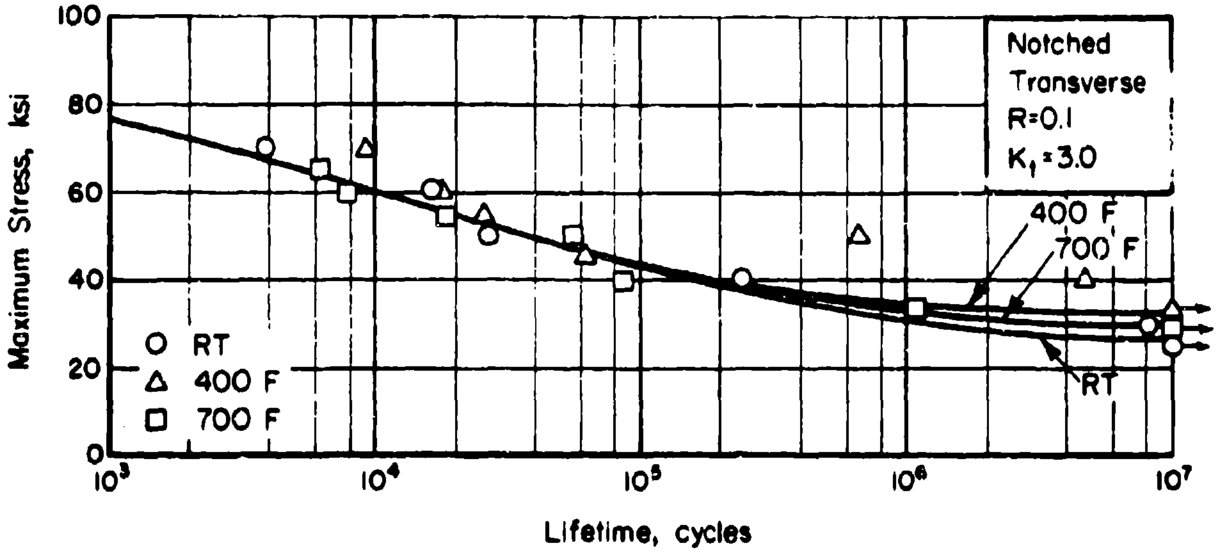



FIGURE 56. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) SOLUTION-TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS (TRANSVERSE)

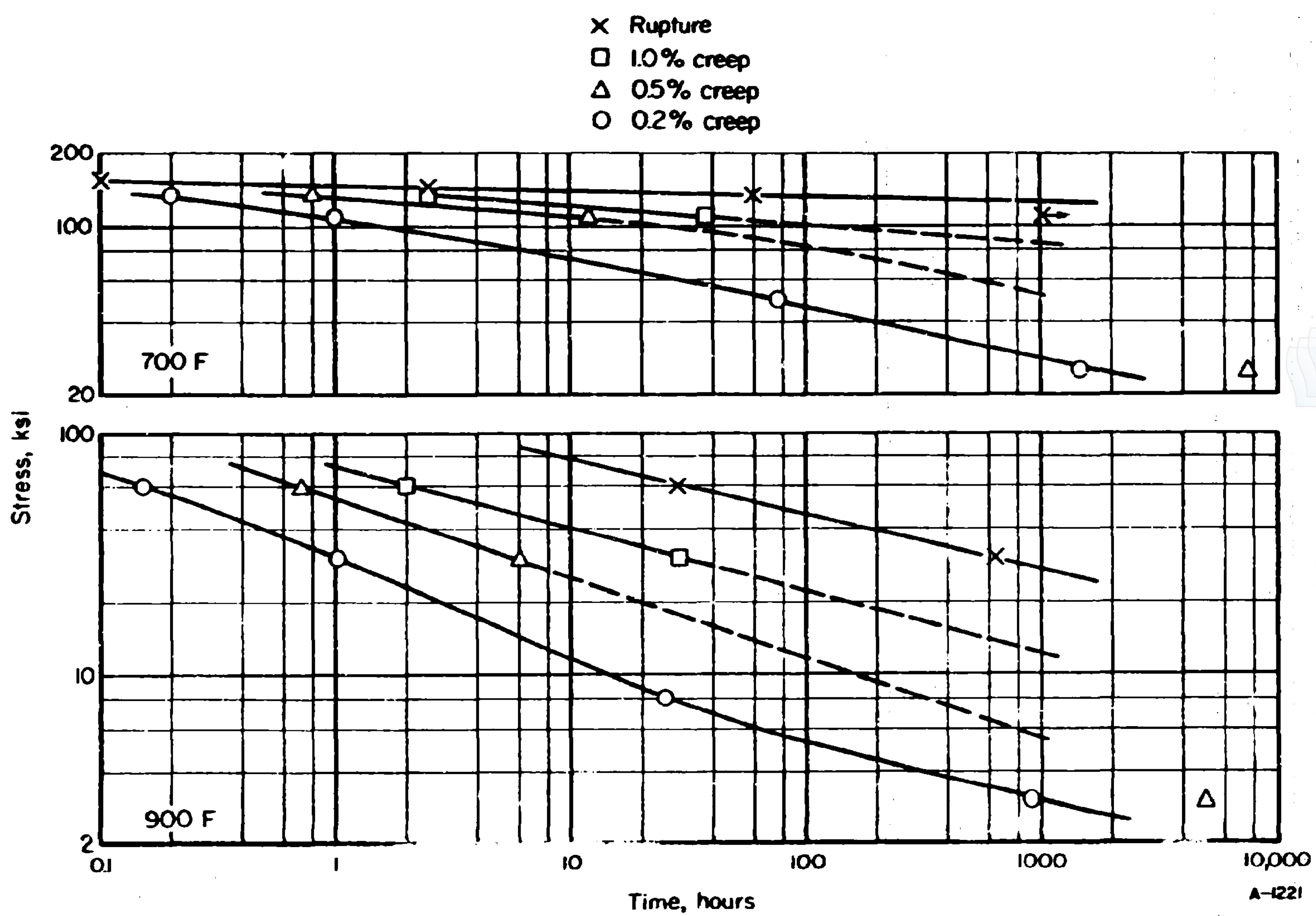



FIGURE 57. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR SOLUTION TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

## 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, weldability, oxidation resistance, etc., can be of particular importance 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 data generated on this program are compared to information for similar alloys. Figures 58 and 59 are effect-of-temperature curves concerned with these properties.

## 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) X2048-T851 Plate

(2) 7050-T73651 Plate

(3) 21-6-9 Annealed Sheet

(4) Ti-8Mo-8V-2Fe-3Al (STA) Sheet

(5) Ti-6Al-2Zr-2Sn-2Mo-2Cr (STA) Plate

(6) Ti-6Al-6V-2Sn STA Isothermal Die Forgings.

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

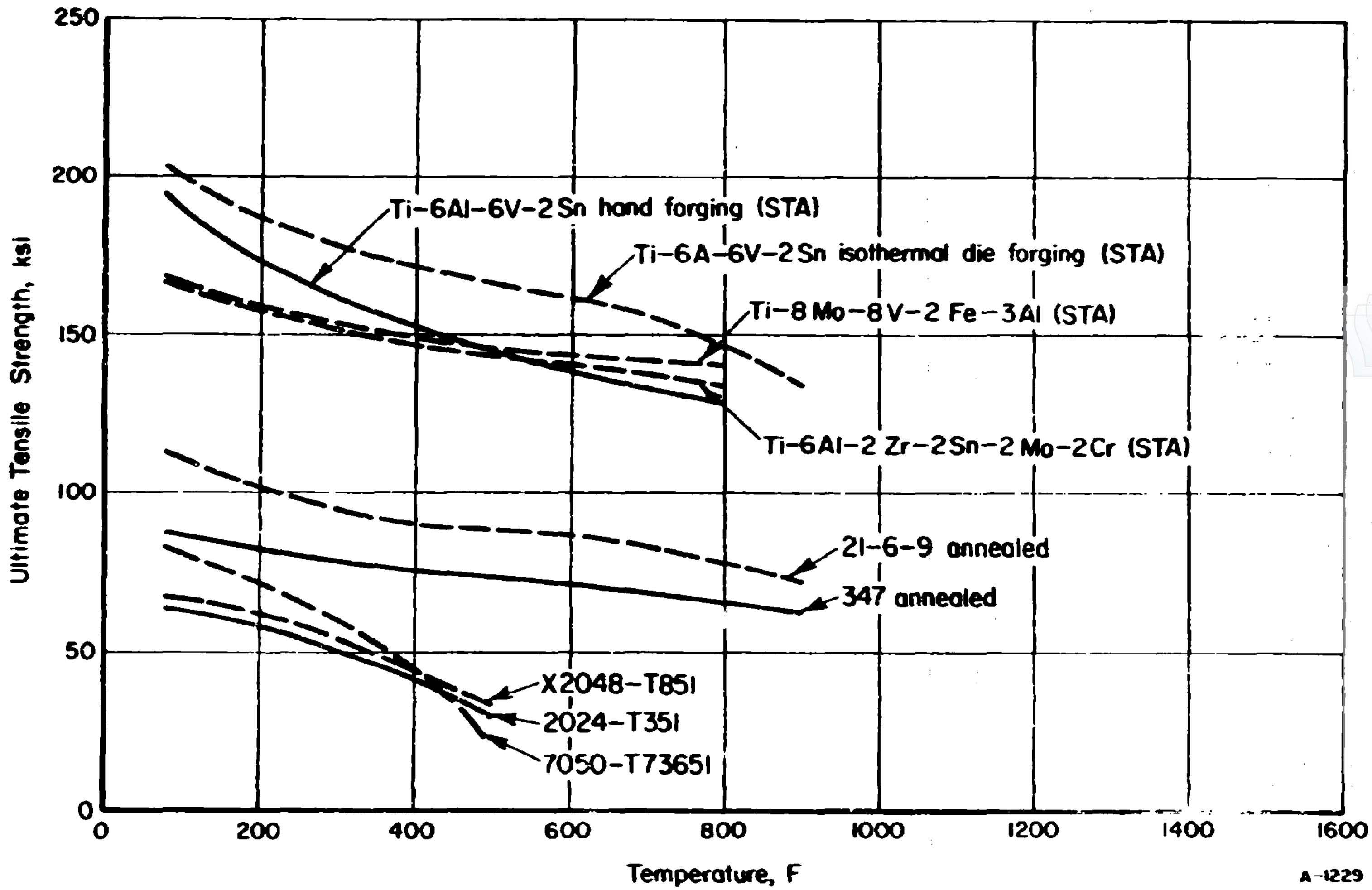



FIGURE 58. TENSILE ULTIMATE STRENGTH AS A FUNCTION OF TEMPERATURE

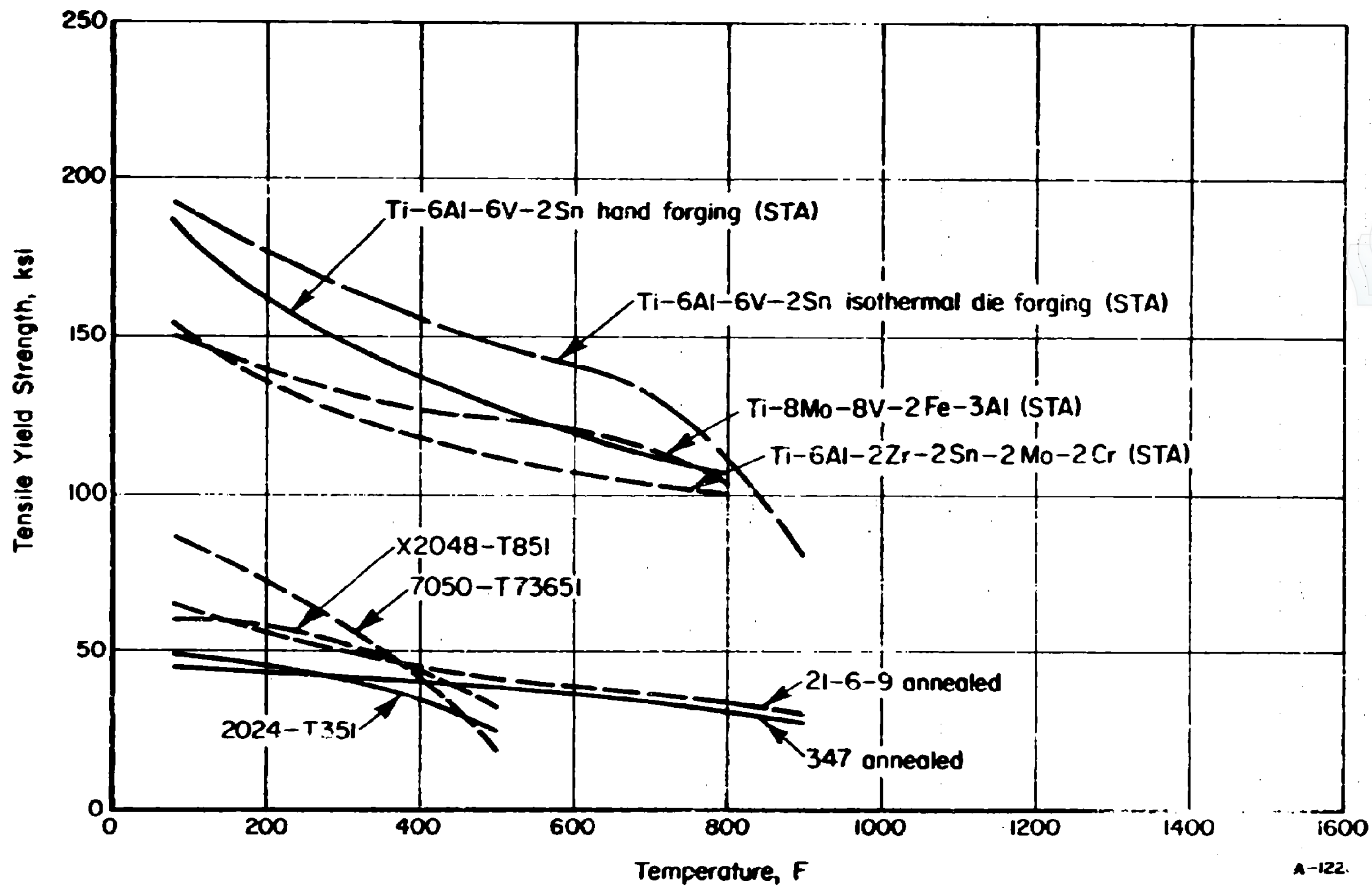



FIGURE 59. TENSILE YIELD STRENGTH AS A FUNCTION OF TEMPERATURE

# 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 E8-68 and E21-66T as well as in Federal Test Method standard No. 151a (method 211.1). 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 E4-64 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 E3-64T 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 E9-67 along with temperature control provisions of E21-66T. 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 2. Specimen heating was accomplished by a forced-air furnace for temperatures up to 1000 F. Specimen temperature was maintained by means of a Wheelco pyrometer. Three Chromel-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 E9-67 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 E139-66T.

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 $\pm$ 2 F by Foxboro controllers in response to signals from the centrally located thermocouple. The temperature of a specimen under test was stabilized for at least 1/2 hour prior to loading.

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

## Stress Corrosion

Seven specimens of each alloy were tested for susceptibility to 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

$\sigma$ = maximum fiber stress

$\ell$ = 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

Two types of fracture toughness tests were used. For heavy section materials, the chevron-notched, slow bend test specimen of ASTM Method E-399-72 was selected. For thinner section sheet materials, center through-cracked tension panels were used as test specimens. All specimens were precracked in fatigue and subsequently fractured in a servocontrolled electrohydraulic testing system of appropriate load capacity.

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

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

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

# APPENDIX II

## SPECIMEN DRAWINGS

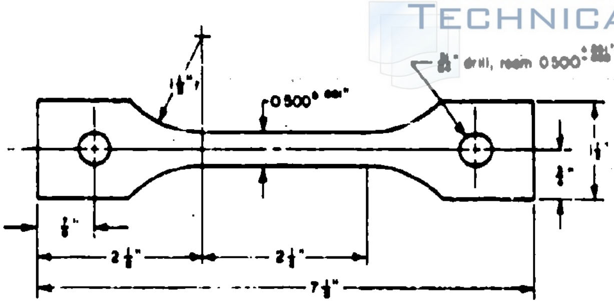


FIGURE 60. SHEET AND THIN-PLATE TENSILE SPECIMEN

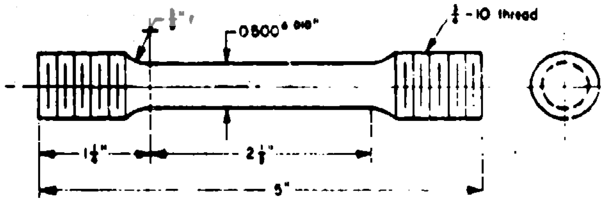



FIGURE 61. ROUND TENSILE SPECIMEN

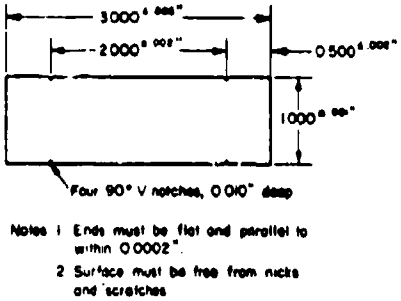



FIGURE 62. SHEET COMPRESSION SPECIMEN

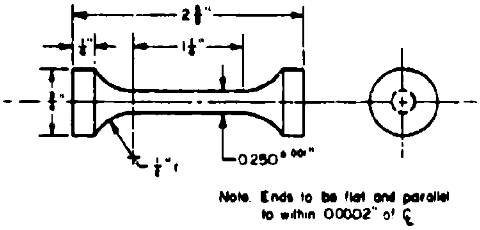



FIGURE 63. ROUND COMPRESSION SPECIMEN

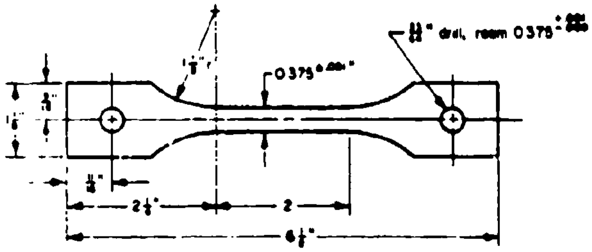
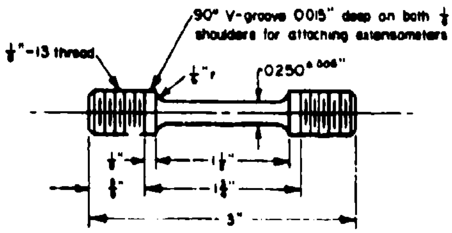


FIGURE 64. SHEET CREEP- AND STRESS-RUPTURE SPECIMEN




A-1363

FIGURE 65. ROUND CREEP - AND STRESS-RUPTURE SPECIMEN

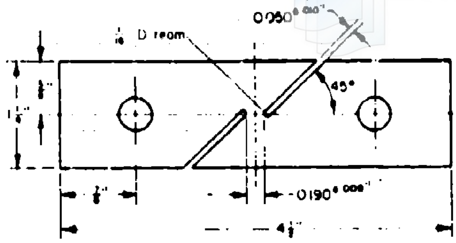



FIGURE 66. SHEET SHEAR TEST SPECIMEN

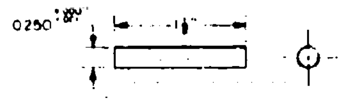


FIGURE 67. PIN SHEAR SPECIMEN

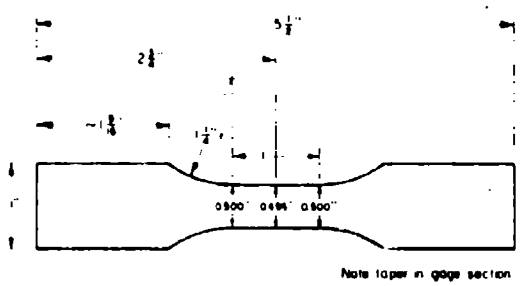



FIGURE 68. UNNOTCHED SHEET FATIGUE SPECIMEN

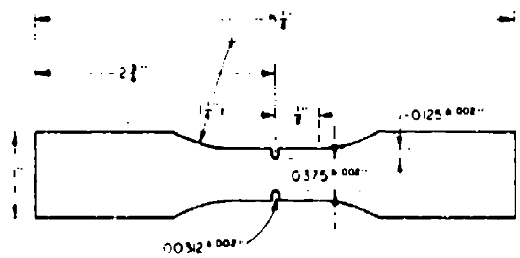


FIGURE 69. NOTCHED SHEET FATIGUE SPECIMEN

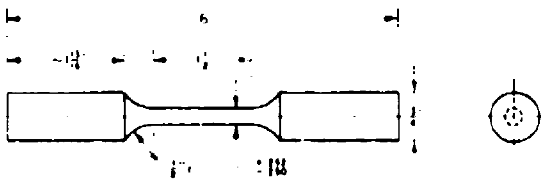


FIGURE 70. UNNOTCHED ROUND FATIGUE SPECIMEN

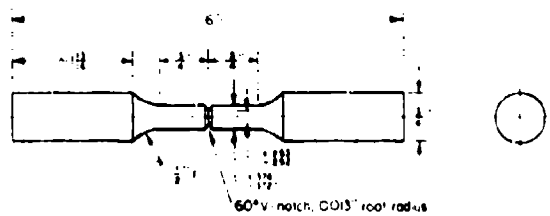



FIGURE 71. NOTCHED ROUND FATIGUE SPECIMEN

A-1226

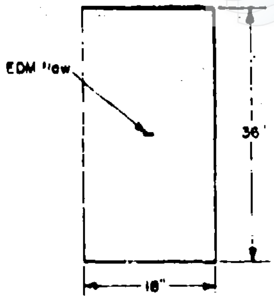



FIGURE 72. SHEET FRACTURE TOUGHNESS SPECIMEN

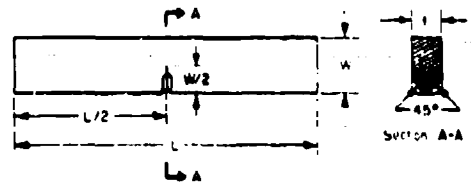



FIGURE 73. SLOW BEND FRACTURE TOUGHNESS SPECIMEN

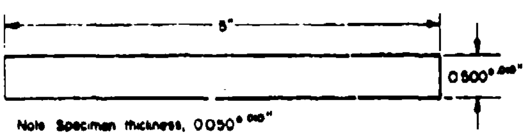



FIGURE 74. STRESS-CORROSION SPECIMEN

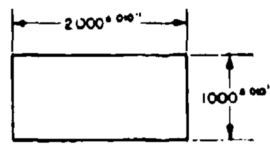


FIGURE 75. THERMAL-EXPANSION SPECIMEN

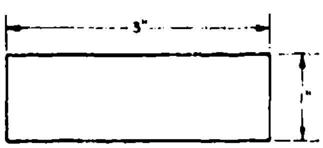



FIGURE 76. SHEET BEND SPECIMEN

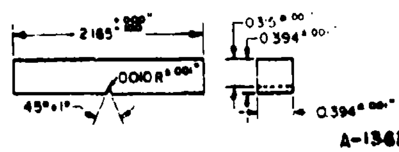



FIGURE 77. NOTCHED IMPACT SPECIMEN

# APPENDIX III

## DATA SHEETS

## X2048-T851 Aluminum Alloy

### Material Description

Alloy X2048-T851 is a recent development of the Reynolds Metals Company. The development aim was a thick section alloy with high toughness and stability at moderate temperatures. The goal was to achieve the strength, fatigue resistance, corrosion resistance, and thermal stability of 2024-T851 or 2124-T851 and the toughness of 2219.

The material used for this evaluation was 3-inch plate produced within the following composition limits:

| | |
|---|---|
| Copper | 2.8 to 3.8 |
| Manganese | 0.20 to 0.60 |
| Magnesium | 1.2 to 1.8 |
| Zinc | 0.25 max |
| Titanium | 0.10 max |
| Silicon | 0.15 max |
| Iron | 0.20 max |
| Others total | 0.15 max |
| Aluminum | Balance . |

### Processing and Heat Treating

The specimens were tested in the as-received -T851 temper.

## X2048-T851 Aluminum Alloy Data[a]

Thickness: 3-inch plate

| Properties | Temperature, F | | | |
|---|---|---|---|---|
| | RT | 250 | 350 | 500 |
| **Tension** | | | | |
| TUS (longitudinal), ksi | 66.3 | 60.1 | 51.4 | 34.0 |
| TUS (transverse), ksi | 67.4 | 60.0 | 50.3 | 33.4 |
| TUS (short transverse), ksi | 67.1 | U | U | U |
| TYS (longitudinal), ksi | 60.4 | 56.8 | 49.1 | 31.7 |
| TYS (transverse), ksi | 60.9 | 56.3 | 48.8 | 31.6 |
| TYS (short transverse), ksi | 58.9 | U | U | U |
| e (longitudinal), percent in 2 in. | 8.3 | 12.7 | 14.2 | 9.5 |
| e (transverse), percent in 2 in. | 7.2 | 12.7 | 16.5 | 8.2 |
| e (short transverse), percent in 2 in. | 6.3 | U | U | U |
| RA (longitudinal), percent | 15.7 | 31.6 | 37.3 | 23.4 |
| RA (transverse), percent | 11.7 | 27.7 | 34.2 | 15.0 |
| RA (short transverse), percent | 9.4 | U | U | U |
| E (longitudinal), $10^6$ psi | 10.2 | 9.9 | 9.3 | 8.3 |
| E (transverse), $10^6$ psi | 10.5 | 9.8 | 9.3 | 7.7 |
| E (short transverse), $10^6$ psi | 11.1 | U | U | U |
| **Compression** | | | | |
| CYS (longitudinal), ksi | 60.9 | 56.7 | 50.6 | 35.2 |
| CYS (transverse), ksi | 60.6 | 56.0 | 51.1 | [illegible] |
| $E_c$ (longitudinal), $10^6$ psi | 11.3 | 10.2 | 9.6 | 9.4 |
| $E_c$ (transverse), $10^6$ psi | 11.1 | 10.3 | 9.7 | 9.6 |
| **Shear**[b] | | | | |
| SUS (longitudinal), ksi | 39.3 | U[c] | U | U |
| SUS (transverse), ksi | 39.2 | U | U | U |
| **Impact**[d] | | | | |
| V-notch Charpy, ft. lb. | | | | |
| (longitudinal) | 7.6 | U | U | U |
| (transverse) | 4.5 | U | U | U |
| **Fracture Toughness**[e] | | | | |
| $K_{Ic}$, crack direction LT, ksi $\sqrt{in.}$ | 32.0 | U | U | U |
| $K_{Ic}$, crack direction TL, ksi $\sqrt{in.}$ | 29.1 | U | U | U |

X2048-T851 Aluminum Alloy
(continued)

| Properties | RT | 250 | 350 | 500 |
|---|---|---|---|---|
| | Temperature, F | | | |
| **Axial Fatigue (longitudinal)(f)** | | | | |
| Unnotched, R = 0.1 | | | | |
| $10^5$ cycles, ksi | 63 | 63 | 63 | U |
| $10^6$ cycles, ksi | 38 | 37 | 35 | U |
| $10^7$ cycles, ksi | 32 | 28 | 25 | U |
| Notched, $K_t$ = 3.0, R = 0.1 | | | | |
| $10^5$ cycles, ksi | 54 | 54 | 50 | U |
| $10^6$ cycles, ksi | 22 | 21 | 19 | U |
| $10^7$ cycles, ksi | 16 | 14 | 12 | U |
| **Creep (longitudinal)** | | | | |
| 0.2% plastic deformation, 100 hr, ksi | NA(c) | 44 | 35 | 8.5 |
| 0.2% plastic deformation, 1000 hr, ksi | NA | 41 | 19 | 4.5 |
| **Stress-Rupture (longitudinal)** | | | | |
| Rupture, 100 hr, ksi | NA | 50 | 39 | 13 |
| Rupture, 1000 hr, ksi | NA | 47 | 32 | 8.5 |
| **Stress Corrosion(g)** | | | | |
| 80% TYS, 1000 hr maximum | no cracks | | | |
| **Coefficient of Thermal Expansion** | U | | | |
| **Density** | | | | |
| .0994 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) Values are average of 6 tests in each direction.

(e) Values are average of 6 slow-bend type tests in each direction. Specimen size was 1.000-inch thick by 2.000 inches wide with a span of 8 inches. (Higher $K_{Ic}$ values may be achieved with larger specimens. Reference J. G. Kaufman, "Notes for E-24.01 Meeting", held at Battelle's Columbus Laboratories on October 4, 1972.

(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.

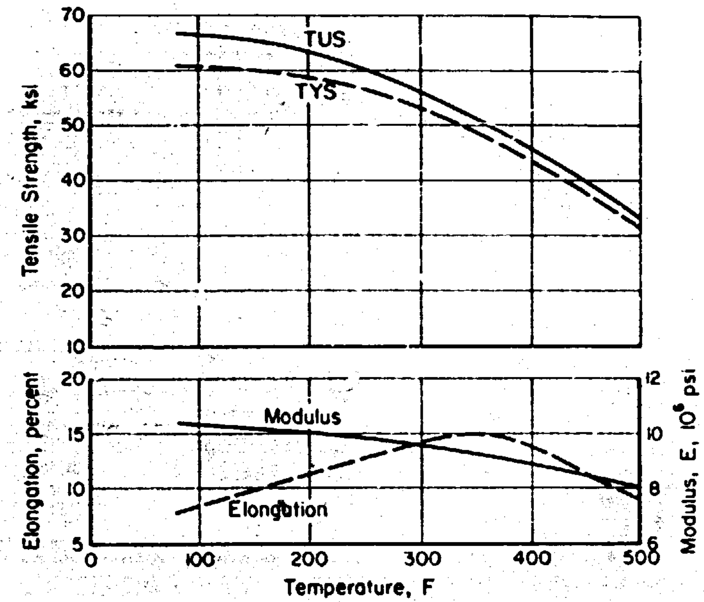



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF X2048-T851 PLATE

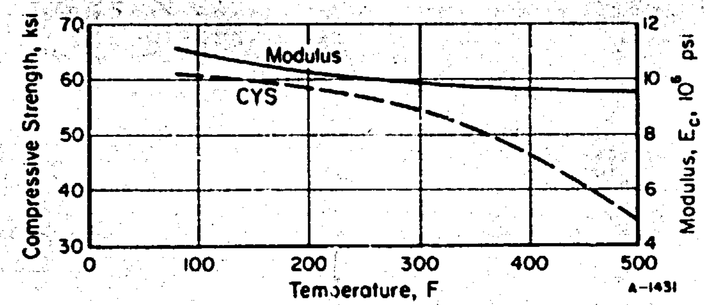



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF X2048-T851 PLATE

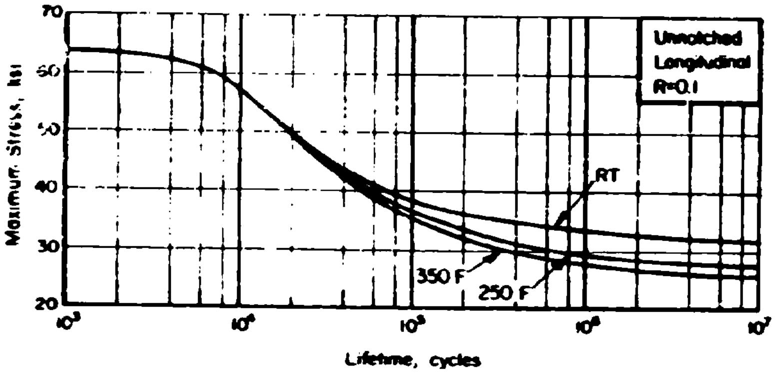



FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED X2048-T851 PLATE

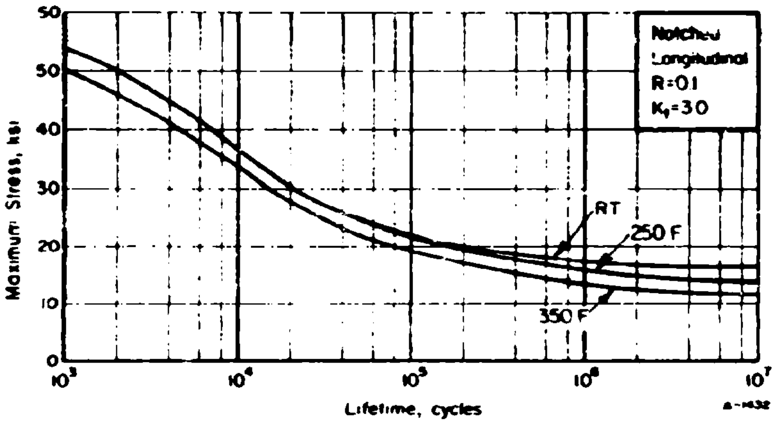



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) X2048-T851 PLATE

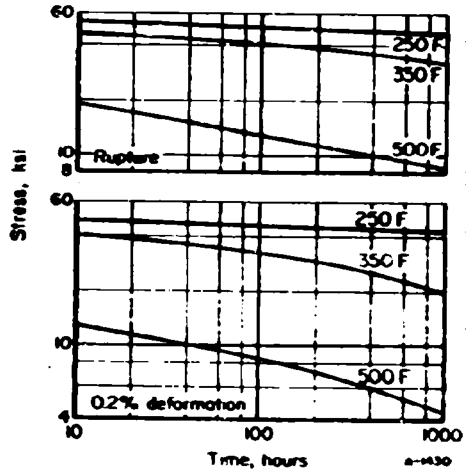



FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR X2048-T851 PLATE (LONGITUDINAL)

## 7050-T73651 Aluminum Alloy

### Material Description

Alloy 7050 is an Al-Zn-Mg-Cu alloy developed by the Alcoa Research Laboratories supported by the Naval Air Systems Command and the Air Force Materials Laboratory. When heat treated and aged to the -T73 temper, thick 7050 plate and hand forgings exhibit strengths equal to or exceeding those of 7079-T6XX products combined with improved fracture toughness and a high resistance to exfoliation and stress-corrosion cracking. The alloy differs from conventional 7XXX series aluminum alloys in that zirconium is added and chromium and manganese are restricted in order to minimize quench sensitivity.

The material used in this evaluation was 1-inch plate from Heat S-416420 produced within the following composition limits:

| | |
|---|---|
| Copper | 2.0 to 2.8 |
| Iron | 0.15 max |
| Silicon | 0.12 max |
| Manganese | 0.10 max |
| Magnesium | 1.9 to 2.6 |
| Zinc | 5.7 to 6.7 |
| Chromium | 0.04 max |
| Titanium | 0.06 max |
| Aluminum | Balance |

### Processing and Heat Treating

Specimens were tested in the as-received -T73651 temper.



## 7050-T73651 Aluminum Alloy Data[a]

Thickness: 1-inch plate

| Properties | Temperature, F RT | 250 | 350 | 500 |
|---|---|---|---|---|
| **Tension** | | | | |
| TUS (longitudinal), ksi | 82.6 | 65.0 | 53.7 | 21.2 |
| TUS (transverse), ksi | 81.5 | 64.5 | 53.5 | 20.9 |
| TYS (longitudinal), ksi | 73.8 | 64.9 | 53.5 | 20.9 |
| TYS (transverse), ksi | 72.5 | 64.1 | 53.3 | 20.8 |
| e (longitudinal), percent in 2 in. | 11.7 | 15.5 | 16.8 | 23.8 |
| e (transverse), percent in 2 in. | 10.5 | 13.3 | 14.7 | 23.5 |
| RA (longitudinal), percent | 30.2 | 48.1 | 58.1 | 81.0 |
| RA (transverse), percent | 24.5 | 38.7 | 47.8 | 79.8 |
| E (longitudinal), $10^3$ psi | 10.3 | 9.4 | 8.7 | 8.4 |
| E (transverse), $10^3$ psi | 10.5 | 9.7 | 8.7 | 8.7 |
| **Compression** | | | | |
| CYS (longitudinal), ksi | 73.0 | 64.3 | 53.7 | 20.9 |
| CYS (transverse), ksi | 75.3 | 66.1 | 55.1 | 22.0 |
| $E_c$ (longitudinal), $10^3$ psi | 10.8 | 9.5 | 9.1 | 8.1 |
| $E_c$ (transverse), $10^3$ psi | 11.0 | 10.0 | 9.4 | 8.0 |
| **Shear**[b] | | | | |
| SUS (longitudinal), ksi | 48.7 | U[c] | U | U |
| SUS (transverse), ksi | 47.9 | U | U | U |
| **Impact**[d] | | | | |
| V-notch Charpy, ft. lb. | | | | |
| (longitudinal) | 34.7 | U | U | U |
| (transverse) | 5.7 | U | U | U |
| **Fracture Toughness**[e] | | | | |
| $K_{Ic}$, L-T, ksi $\sqrt{in.}$ | 27.7 | U | U | U |
| $K_{Ic}$, L-T, ksi $\sqrt{in.}$ | 34.9 | U | U | U |
| **Axial Fatigue (transverse)**[f] | | | | |
| Unnotched, R = 0.1 | | | | |
| $10^5$ cycles, ksi | [illegible] | 60 | 56 | U |
| $10^6$ cycles, ksi | 42 | 37 | 34 | U |
| $10^7$ cycles, ksi | 31 | 23 | 20 | U |
| Notched, $K_t$ = 3.0, R = 0.1 | | | | |
| $10^5$ cycles, ksi | [illegible] | 44 | 43 | U |
| $10^6$ cycles, ksi | 19 | 18 | 16 | U |
| $10^7$ cycles, ksi | 12 | 11 | 10 | U |

7050-T73651 Aluminum Alloy Data
(continued)

| Properties | RT | Temperature, F 250 | 350 | 500 |
|---|---|---|---|---|
| **Creep (transverse)** | | | | |
| 0.2% plastic deformation, 100 hr, ksi | NA(c) | 49 | 21 | 5 |
| 0.2% plastic deformation, 1000 hr, ksi | NA | 35 | 13.5 | 3.5 |
| **Stress-Rupture (transverse)** | | | | |
| Rupture, 100 hr, ksi | NA | 53 | 26 | 7.5 |
| Rupture, 1000 hr, ksi | NA | 47 | 17 | 4.5 |
| **Stress Corrosion(g)** | | | | |
| 80% TYS, 1000 hr maximum | no cracks | | | |
| **Coefficient of Thermal Expansion** | | | | |
| $12.8 \times 10^{-6}$ in/in/F (68 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) Values are average of 6 slo.-bend type tests in each direction. Specimen size was 1.000-inch thick by 2.000 inches wide with a span of 8 inches.

(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.

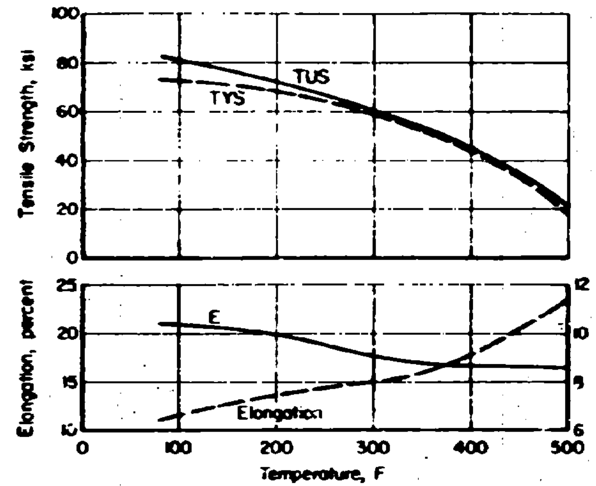



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7050-T73651 ALUMINUM ALLOY PLATE

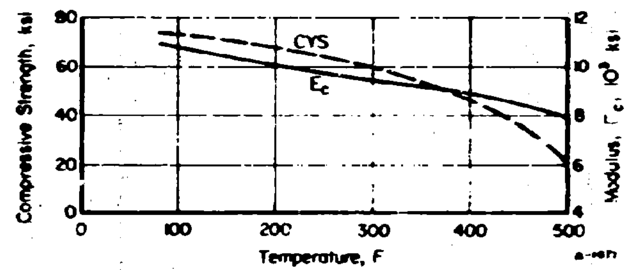



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7050-T73651 ALUMINUM ALLOY PLATE

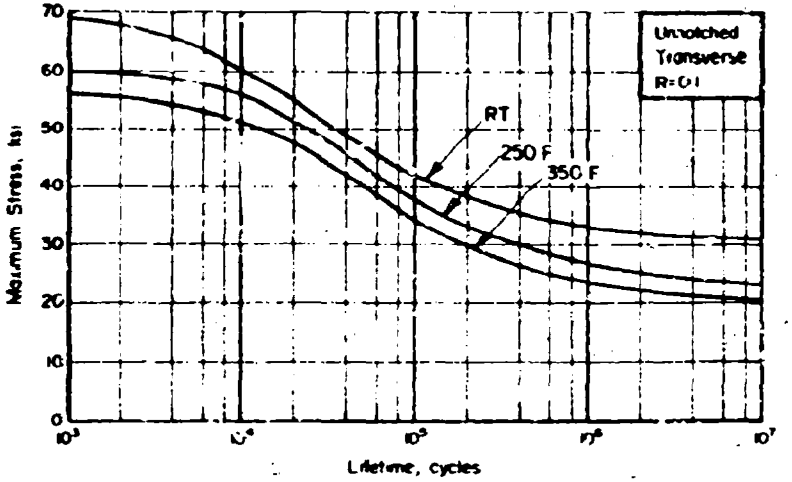



FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED 7050-T73651 ALUMINUM PLATE (TRANSVERSE)

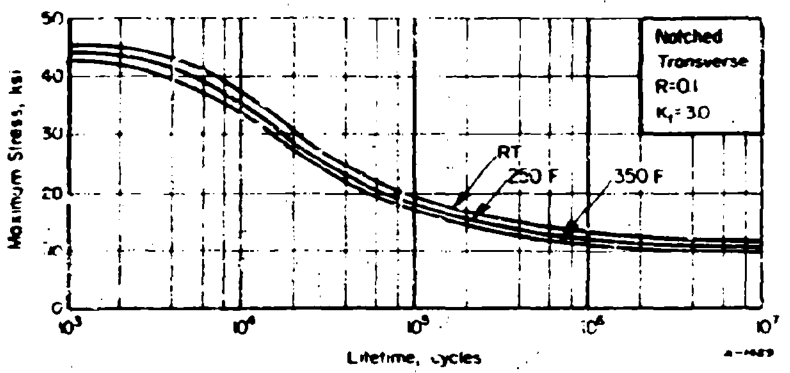



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$=3.0) 7050-T73651 ALUMINUM PLATE (TRANSVERSE)

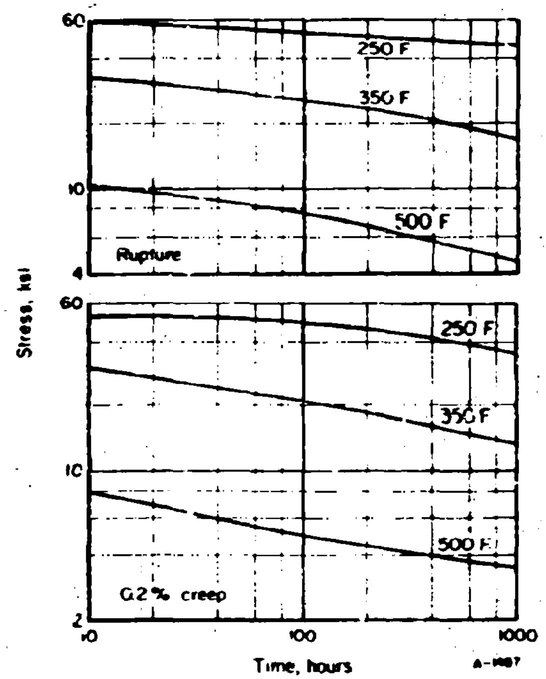



FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7050-T73651 ALUMINUM ALLOY PLATE (TRANSVERSE)

## 21-6-9 Stainless Steel Alloy

### Material Description

Alloy 21-6-9 is a recent development of the Armco Steel Corporation. It is an austenitic stainless steel, combining high yield strength with good corrosion resistance. The room temperature yield strength of 21-6-9 is superior to Types 304, 321, and 347. It has good elevated temperature properties and retains high strength and toughness at subzero temperatures.

Armco 21-6-9 stainless steel is available in standard finishes in annealed or high tensile temper sheet and strip as well as in bar, wire, forging billets, and plate.

The material used in this evaluation was an 0.072-inch thick sheet produced within the following composition limits:

| | |
|---|---|
| Carbon | 0.08 max |
| Manganese | 8.00 - 10.00 |
| Phosphorus | 0.060 max |
| Sulfur | 0.030 max |
| Silicon | 1.00 max |
| Chromium | 19.00 - 21.50 |
| Nickel | 5.50 - 7.50 |
| Nitrogen | 0.15 - 0.40 |
| Iron | Balance |

### Processing and Heat Treating

The alloy was evaluated in the as-received annealed condition.



## 21-6-9 Stainless Steel Data[a]

Condition: Annealed
Thickness: 0.072-inch sheet

| Properties | Temperature, F: RT | 400 | 700 | 900 |
|---|---|---|---|---|
| **Tension** | | | | |
| TUS (longitudinal), ksi | 113.0 | 88.1 | 83.7 | 76.1 |
| TUS (transverse), ksi | 113.3 | 88.4 | 83.2 | 76.5 |
| TYS (longitudinal), ksi | 64.8 | 42.5 | 35.9 | 33.0 |
| TYS (transverse), ksi | 65.7 | 42.7 | 35.9 | 33.2 |
| e (longitudinal), percent in 2 in. | 55.0 | 43.5 | 45.6 | [illegible] |
| e (transverse), percent in 2 in. | 50.0 | 42.0 | 41.8 | 41.3 |
| E (longitudinal), $10^6$ psi | 26.6 | 21.1 | 21.7 | 19.2 |
| E (transverse), $10^6$ psi | 28.4 | 19.9 | 18.4 | [illegible] |
| **Compression** | | | | |
| CYS (longitudinal), ksi | 67.2 | 45.1 | 40.5 | [illegible] |
| CYS (transverse), ksi | 66.5 | 46.3 | 37.9 | [illegible] |
| $E_c$ (longitudinal), $10^6$ psi | 28.5 | 26.7 | 25.8 | [illegible] |
| $E_c$ (transverse), $10^6$ psi | 29.0 | 28.8 | 26.5 | [illegible] |
| **Shear**[b] | | | | |
| SUS (longitudinal), ksi | 102.3 | U[c] | U | U |
| SUS (transverse), ksi | 102.8 | U | U | U |
| **Bend**[d] | | | | |
| Minimum Radius | 1T | U | U | U |
| **Fracture Toughness** | | | | |
| $K_c$, T-L, ksi $\sqrt{\text{in.}}$ | (e) | U | U | U |
| **Axial Fatigue (transverse)**[f] | | | | |
| Unnotched, R = 0.1 | | | | |
| $10^5$ cycles, ksi | 106 | 90 | 80 | U |
| $10^6$ cycles, ksi | 92 | 82 | 74 | U |
| $10^7$ cycles, ksi | [illegible] | 75 | 68 | U |

21-6-9 Stainless Steel Data
(continued)

| Properties | Temperature, F | | | |
|---|---|---|---|---|
| | RT | 400 | 700 | 900 |
| Axial Fatigue (transverse) (continued) | | | | |
| Notched, $K_t$ = 3.0, R = 0.1 | | | | |
| $10^5$ cycles, ksi | 80 | 75 | 75 | U |
| $10^6$ cycles, ksi | 61 | 44 | 44 | U |
| $10^7$ cycles, ksi | 46 | 35 | 36 | U |
| Creep (transverse) | | | | |
| 0.2% plastic deformation, 100 hr, ksi | NA(c) | 40 | 33 | 31 |
| 0.2% plastic deformation, 1000 hr, ksi | NA | 35 | 32 | 30 |
| Stress Rupture (transverse) | | | | |
| Rupture, 100 hr, ksi | NA | 85 | 83 | 72 |
| Rupture, 1000 hr, ksi | NA | 84 | 82 | 6[illegible] |
| Stress Corrosion(g) | | | | |
| 80% TYS, 1000 hr maximum | no cracks | | | |
| Coefficient of Thermal Expansion | | | | |
| $10.6 \times 10^{-6}$ in/in/F (80-1000 F) | | | | |
| Density | | | | |
| 0.283 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 4 tests in each direction.

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

(d) Specimens tested from RT to 440 F. No cracks.

(e) Transverse specimens were full sheet thickness by 18 inches wide by 36 inches long with an EDM flaw in the center. The net section yield stress was greater than the tensile yield strength of the material; therefore, the K values obtained are considered not valid.

(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.



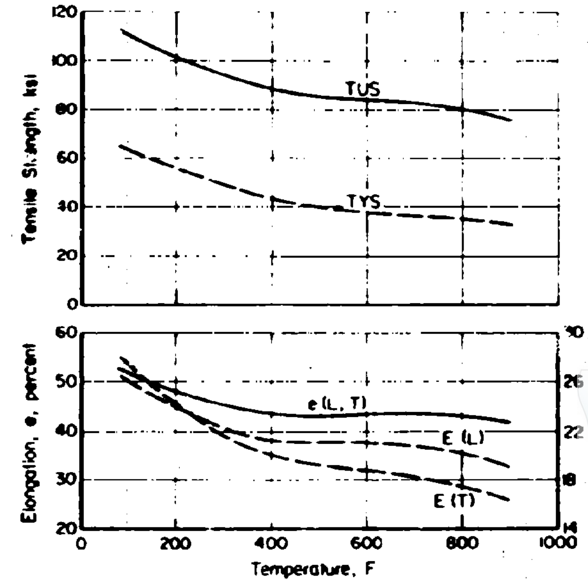



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF ANNEALED 21-6-9 STAINLESS STEEL SHEET

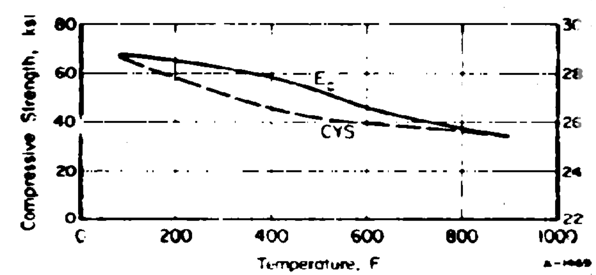



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF ANNEALED 21-6-9 STAINLESS STEEL SHEET

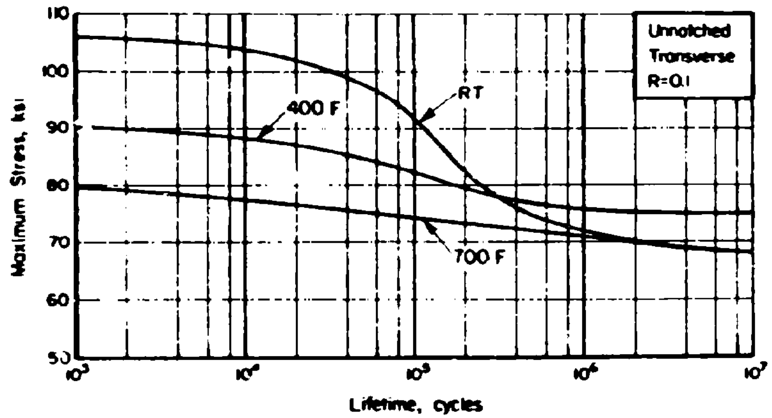



FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED ANNEALED 21-6-9 STAINLESS STEEL SHEET

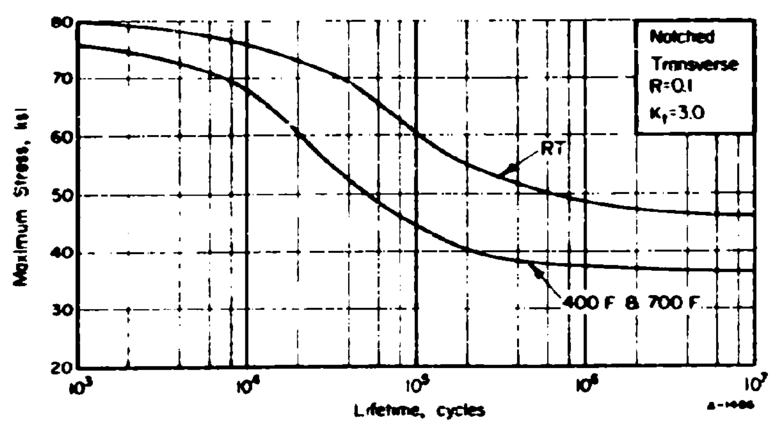



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) ANNEALED 21-6-9 STAINLESS STEEL SHEET

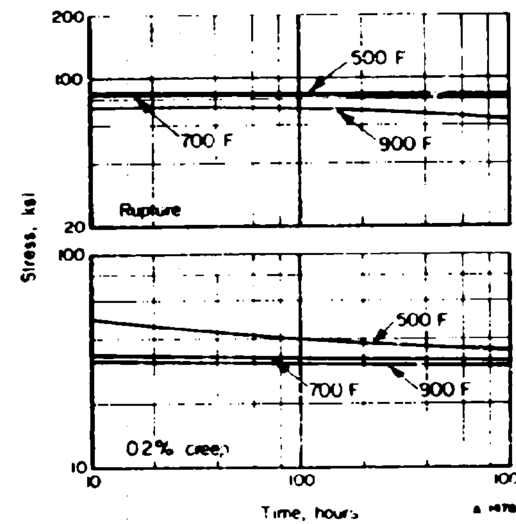



FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR ANNEALED 21-6-9 STAINLESS STEEL SHEET

## Ti-8Mo-8V-2Fe-3Al Alloy

### Material Description

The 8Mo-8V-2Fe-3Al beta titanium alloy is a recent development of TIMET. The alloy was selected for full-scale evaluation after confirming (by TIMET) that it could be melted by the conventional consumable electrode vacuum arc process. It shows producibility and property characteristics that make it suitable for a variety of airframe applications. A variety of heat treatments are available to allow the designer to take advantage of its individual properties or its generally good overall properties. Its short aging times and low density make it particularly desirable for some applications.

The material used in this evaluation was from TIMET Heat K-5055 and was analyzed as follows:

| | |
|---|---|
| Molybdenum | 8.0 |
| Vanadium | 8.2 |
| Iron | 2.0 |
| Aluminum | 3.0 |
| Oxygen | 0.16 |
| Nitrogen | 0.011 |
| Titanium | Balance |

### Processing and Heat Treating

The material was received in the solution treated condition. Specimens were aged at 900 F for 6 hours. This condition is called the high strength, fully-aged condition.

### Ti-8Mo-8V-2Fe-3Al Alloy Data[a]

Condition: Solution treated and aged 900 F)
Thickness: 0.040-inch sheet

| Properties | Temperature, F RT | 400 | 600 | 800 |
|---|---|---|---|---|
| **Tension** | | | | |
| TUS (longitudinal), ksi | 160.3 | 148.7 | 146.0 | 137.7 |
| TUS (transverse), ksi | 174.7 | 155.3 | 152.3 | 141.0 |
| TYS (longitudinal), ksi | 144.7 | 123.3 | 117.7 | 105.7 |
| TYS (transverse), ksi | 158.0 | 133.3 | 124.0 | 1.5 |
| e (longitudinal), percent in 2 in. | 11.7 | 9.0 | 7.3 | 18.7 |
| e (transverse), percent in 2 in. | 9.5 | 6.8 | 6.7 | 16.2 |
| E (longitudinal), 10 psi | 13.6 | 13.3 | 12.4 | 11.8 |
| E (transverse), 10 psi | 14.9 | 14.1 | 13.2 | 12.3 |
| **Compression** | | | | |
| CYS (longitudinal), ksi | 177.7 | 140.7 | 138.7 | 134.7 |
| CYS (transverse), ksi | 191.7 | 163.7 | 151.7 | 138.7 |
| $E_c$ (longitudinal), 10 psi | 15.9 | 14.5 | 14.2 | 12.7 |
| $E_c$ (transverse), 10 psi | 16.9 | 16.1 | 14.8 | 13.6 |
| **Shear**[b] | | | | |
| SUS (longitudinal), ksi | 100.5 | U[c] | U | U |
| SUS (transverse), ksi | 105.6 | U | U | U |
| **Fracture Toughness**[d] | | | | |
| $K_c$, T-L, ksi$\sqrt{in.}$ | 46 | U | U | |
| **Axial Fatigue (Transverse)**[e] | | | | |
| Unnotched, R = 0.1 | | | | |
| 10 cycles, ksi | 138 | 138 | 130 | [illegible] |
| 10 cycles, ksi | 74 | 74 | 67 | |
| 10 cycles, ksi | 63 | 63 | 60 | |
| Notched, $K_t$ = 3.0, R = 0.1 | | | | |
| 10 cycles, ksi | 109 | 109 | 98 | U |
| 10 cycles, ksi | 30 | 30 | 26 | U |
| 10 cycles, ksi | 22 | 22 | 20 | U |

Ti-8Mo-8V-2Fe-3Al Alloy Data
(Continued)

| Properties | RT | Temperature, F 550 | 700 | 900 |
|---|---|---|---|---|
| Creep (Transverse) | | | | |
| 0.2% plastic deformation, 100 hr, ksi | NA | 70 | 27 | 7 |
| 0.2% plastic deformation, 1000 hr, ksi | NA | 40 | 20 | 3 |
| Stress Rupture (Transverse) | | | | |
| Rupture 100 hr, ksi | NA | 149 | 144 | 43 |
| Rupture 1000 hr, ksi | NA | 147 | 100 | 26 |
| Stress Corrosion (f) | | | | |
| 60 TYS, 1000 hr maximum | no cracks | | | |

Coefficient of Thermal Expansion

5.0 x 10$^{-6}$ in./in./F (RT to 800 F)

Density

0.175 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 4 tests in each direction.

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

(d) Transverse specimens were full sheet thickness by 18 inches wide by 36 inches long with an EDM flaw in the center.

(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.

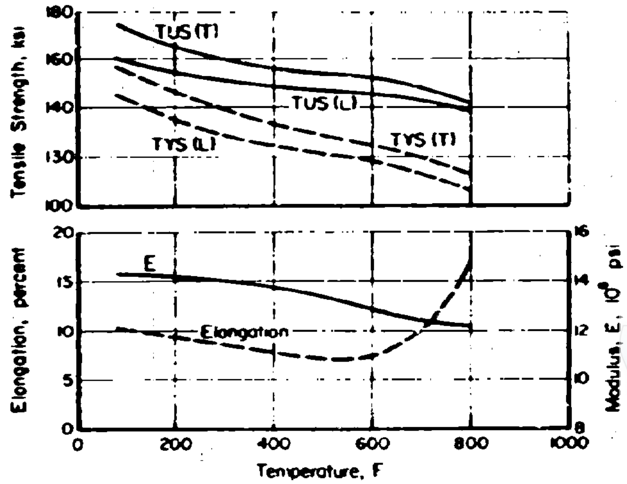



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET

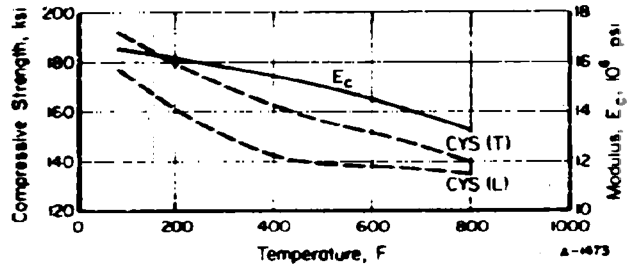



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF SOLUTION TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET

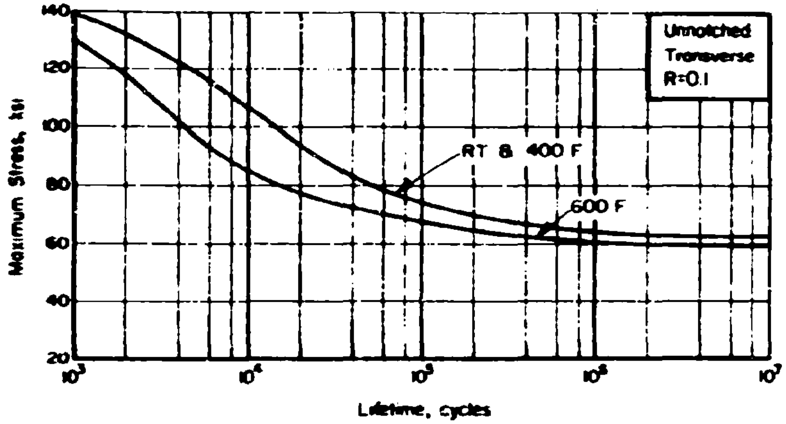



FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED SOLUTION TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET

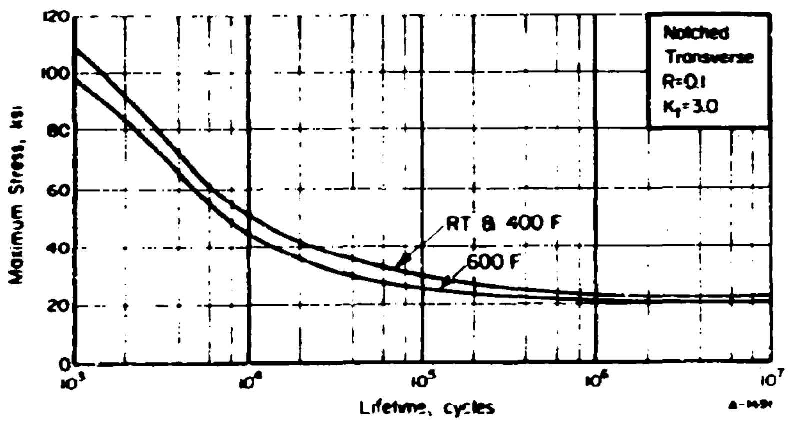



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) SOLUTION TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET

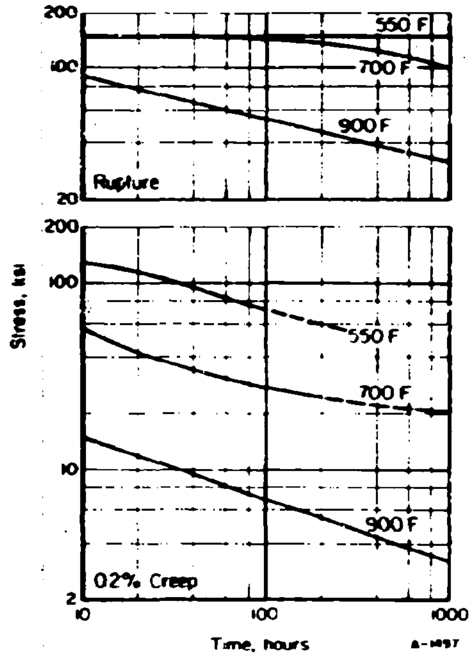



FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR SOLUTION TREATED AND AGED Ti-8Mo-8V-2Fe-3Al ALLOY SHEET

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

### Material Description

This alloy is a recent development of RMI Company. It is an alpha-beta type alloy designed for deep hardenability. Preliminary information shows the material 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 1 1/2-inch thick plate from RMI ingot number 890180 which had the following chemistry:

| | |
|---|---|
| Al | 5.8 |
| Sn | 2.1 |
| Zr | 1.8 |
| Mo | 2.0 |
| Cr | 1.9 |
| Si | 0.21 |
| Fe | 0.06 |
| C | 0.02 |
| $N_2$ | 0.010 |
| $O_2$ | 0.011 |

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

### Processing and Heat Treating

The plate product evaluated was alpha beta processed to develop a refined microstructure. The plate was received in the solution-treated condition (1740 F, 1 hour, Air Cooled) condition. Specimens were then aged at 1000 F for 8 hours. It should be noted that heavier sections require oil or water quench to effectively solution treat the product.



### Ti-6Al-2Zr-2Sn-2Mo-2Cr ALLOY DATA[a]

Condition: solution treated and aged
Thickness: 1 1/2 inch plate

| Properties | Temperature, F: RT | 400 | 600 | 800 |
|---|---|---|---|---|
| **Tension** | | | | |
| TUS (longitudinal), ksi | 168.3 | 145.3 | 139.0 | 132.0 |
| TUS (transverse), ksi | 168.7 | 146.0 | 139.7 | 132.0 |
| TYS (longitudinal), ksi | 155.6 | 116.0 | 107.0 | 101.2 |
| TYS (transverse), ksi | 156.6 | 119.7 | 108.7 | 104.0 |
| e (longitudinal), percent in 1 in. | 18.0 | 19.5 | 18.5 | 21.3 |
| e (transverse), percent in 1 in. | 17.7 | 19.7 | 18.2 | 21.0 |
| RA (longitudinal), percent | 24.8 | 33.2 | 34.9 | 42.1 |
| RA (transverse), percent | 26.2 | 33.7 | 33.3 | 41.4 |
| E (longitudinal), $10^3$ psi | 17.9 | 15.9 | 15.6 | 14[illegible] |
| E (transverse), $10^3$ psi | 17.8 | 16.2 | 16.0 | 14[illegible] |
| **Compression** | | | | |
| CYS (longitudinal), ksi | 169.7 | 128.3 | 112.0 | 105[illegible] |
| CYS (transverse), ksi | 173.3 | 129.3 | 115.0 | 10[illegible] |
| $E_c$ (longitudinal), $10^3$ | 18.1 | 16.7 | 15.8 | [illegible] |
| $E_c$ (transverse), $10^3$ psi | 18.5 | 16.3 | 15.8 | 1[illegible] |
| **Shear**[b] | | | | |
| SUS (longitudinal), ksi | 108.3 | [illegible](c) | [illegible] | [illegible] |
| SUS (transverse), ksi | 108.0 | [illegible] | [illegible] | |
| **Impact**[d] | | | | |
| V-notch Charpy, Ft. lb. | | | | |
| (longitudinal) | 13.9 | [illegible] | [illegible] | |
| (transverse) | 15.3 | [illegible] | [illegible] | |
| **Fracture Toughness**[e] | | | | |
| $K_{Ic}$, L-T, ksi √in. | 55.0 | [illegible] | [illegible] | |
| $K_{Ic}$, T-L, ksi √in. | 93.0 | [illegible] | [illegible] | |
| **Axial Fatigue (transverse)**[f] | | | | |
| Unnotched, R=0.1 | | | | |
| $10^3$ cycles, ksi | 155 | 150 | 134 | [illegible] |
| $10^5$ cycles, ksi | 135 | 123 | 115 | [illegible] |
| $10^7$ cycles, ksi | 75 | 75 | 75 | [illegible] |
| Notched, $K_t$=3.0, R=0.1 | | | | |
| $10^3$ cycles, ksi | 12[illegible] | 112 | 99 | [illegible] |
| $10^5$ cycles, ksi | 6[illegible] | 55 | 50 | [illegible] |
| $10^7$ cycles, ksi | 42 | 37 | 37 | [illegible] |

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

| Properties | RT | 400 | 600 | 800 |
|---|---|---|---|---|
| | Temperature, F | | | |
| **Creep (transverse)** | | | | |
| 0.2% plastic deformation, 100 hr., ksi | NA | 122 | 120 | 83 |
| 0.2% plastic deformation, 1000 hr., ksi | NA | 118 | 115 | 60 |
| **Stress-Rupture (transverse)** | | | | |
| Rupture, 100 hr., ksi | NA | 142 | 132 | 122 |
| Rupture, 1000 hr., ksi | NA | 141 | 131 | 119 |
| **Stress Corrosion**(g) | | | | |
| 80% TYS, 1000 hr. maximum | no cracks | | | |
| **Coefficient of Thermal Expansion** | | | | |
| 5.1 x $10^{-6}$ 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) Values are average of 6 tests in each direction.

(e) These values do not meet the rigorous A.T. $< 2.5\left(\frac{K_Q}{TYS}\right)^2$ criteria. However, they are over $2.2\left(\frac{K_Q}{TYS}\right)^2$ and should be considered good indicative $K_{Ic}$ 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 3-1/2% NaCl.

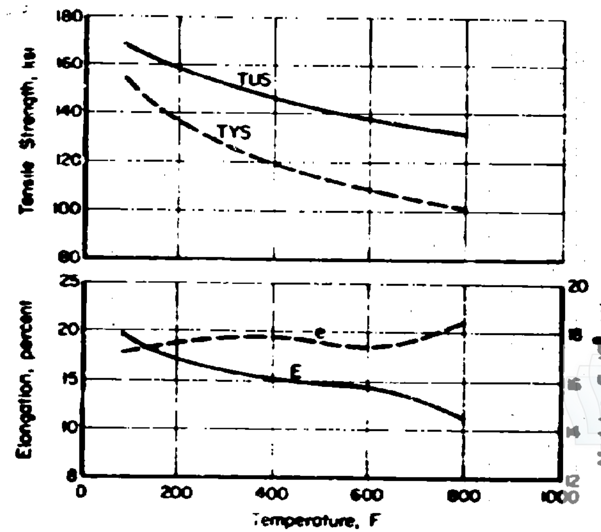



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

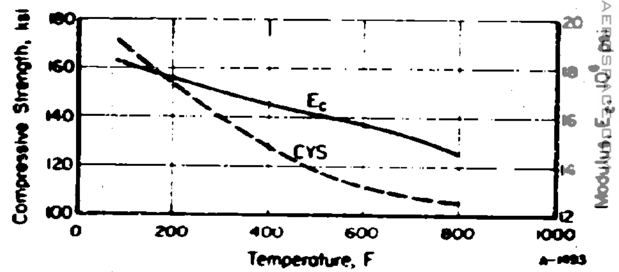



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF SOLUTION TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

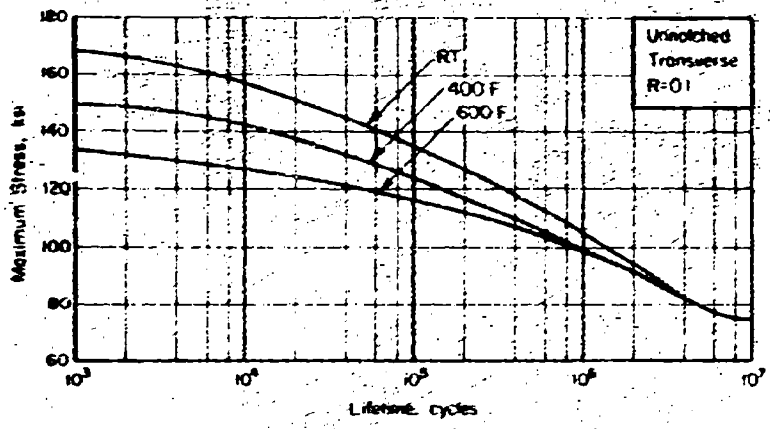



FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED SOLUTION TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

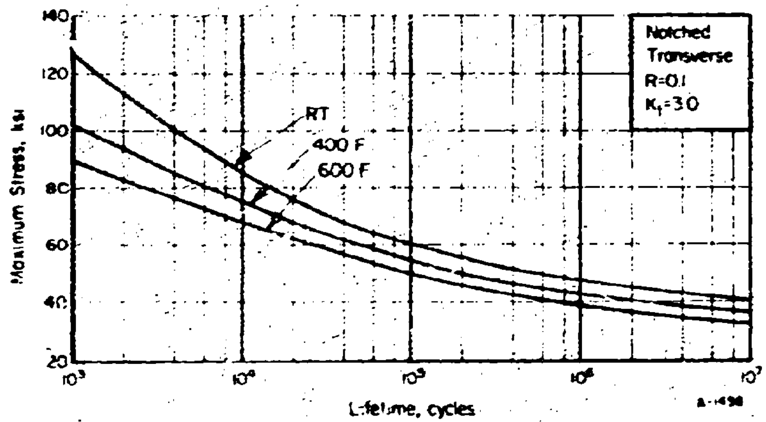



FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR OF NOTCHED ($K_t$ = 3.0) SOLUTION TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE

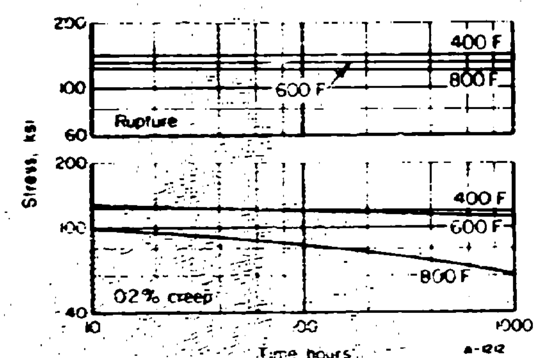



FIGURE 5. STRESS RUPTURE AND PLASTIC DEFORMATION CURVES FOR SOLUTION TREATED AND AGED Ti-6Al-2Zr-2Sn-2Mo-2Cr PLATE (TRANSVERSE)

## Ti-6Al-6V-2Sn Isothermal Die Forgings

### Material Description

This is a heat-treatable alpha beta type alloy similar in many respects to Ti-6Al-4V, but containing increased content of beta stabilizing elements which provide higher strength potential.

The material used for this evaluation was made by IIT Research Institute under Air Force Contract F33615-67-C-1722. It consisted of structural shapes and nose wheels that were isothermally creep (slow speed) forged from flat preforms machined from conventionally forged Ti-6Al-6V-2Sn alloy billets.

### Processing and Heat Treating

The material was received with no heat treatment after forging. Specimens were solution treated at 1650 F for 1/2 hour, water quenched, and aged at 1050 F for 4 hours and air cooled. This treatment was as suggested by IIT Research Institute.

### Ti-6Al-6V-2Sn Alloy Data[a]

Condition: Solution treated and aged
Thickness: Die forging of varying thickness

| Properties | Temperature, F RT | 400 | 700 | 900 |
|---|---|---|---|---|
| **Tension** | | | | |
| TUS (transverse), ksi | 202.5 | 170.4 | 158.4 | 133.6 |
| TYS (transverse), ksi | 192.9 | 153.2 | 131.8 | 80.5 |
| e (transverse), percent in 1 in. | 4.7 | 7.7 | 8.3 | 22.0 |
| E (transverse), $10^3$ psi | 16.0 | 14.7 | 13.1 | 12.1 |
| **Compression** | | | | |
| CYS (transverse), ksi | 199.3 | 174.3 | 152.9 | 107.7 |
| $E_c$ (transverse), $10^3$ psi | 18.0 | 16.1 | 13.2 | 11.9 |
| **Shear**[b] | | | | |
| SUS (longitudinal), ksi | 131.6 | U[c] | U | U |
| SUS (transverse), ksi | 130.0 | U | U | U |
| **Impact**[d] | | | | |
| V-notch Charpy, ft. lbs. | | | | |
| (longitudinal) | 11.7 | U | U | U |
| (transverse) | 9.5 | U | U | U |
| **Fracture Toughness**[e] | | | | |
| $K_{Ic}$, L-T, ksi$\sqrt{in.}$ | 25.0 | U | U | U |
| $K_{Ic}$, T-L, ksi$\sqrt{in.}$ | 26.7 | U | U | U |
| **Axial Fatigue (transverse)**[f] | | | | |
| Unnotched, R = 0.1 | | | | |
| $10^5$ cycles, ksi | 112 | 112 | 112 | U |
| $10^6$ cycles, ksi | 50 | 42 | 50 | U |
| $10^7$ cycles, ksi | 42 | 32 | 42 | U |
| Notched, $K_t$ = 3.0, R = 0.1 | | | | |
| $10^5$ cycles, ksi | 76 | 76 | 76 | U |
| $10^6$ cycles, ksi | 43 | 43 | 43 | U |
| $10^7$ cycles, ksi | 26 | 30 | 32 | U |
| **Creep (transverse)** | | | | |
| 0.2 plastic deformation, 100 hr., ksi | NA[c] | NA | 45 | [illegible] |
| 0.2 plastic deformation, 1000 hr., ksi | NA | NA | 27 | [illegible] |

Ti-6Al-6V-2Sn Alloy Data
(Continued)

| Properties | RT | 400 | 700 | 900 |
|---|---|---|---|---|
| | Temperature, F | | | |
| **Stress-Rupture (transverse)** | | | | |
| Rupture, 100 hr., ksi | NA | NA | 130 | 45 |
| Rupture, 1000 hr., ksi | NA | NA | 115 | 36 |
| **Stress Corrosion**(g) | | | | |
| 80 TYS, 1000 hr. maximum | no cracks | | | |
| **Coefficient of Thermal Expansion** | | | | |
| $5.3 \times 10^{-6}$ in./in./F (68 F to 900 F) | | | | |
| **Density** | | | | |
| 0.164 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 4 tests in each direction.

(e) Results of tests at AFML on compact tension 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 3-1/2 NaCl.

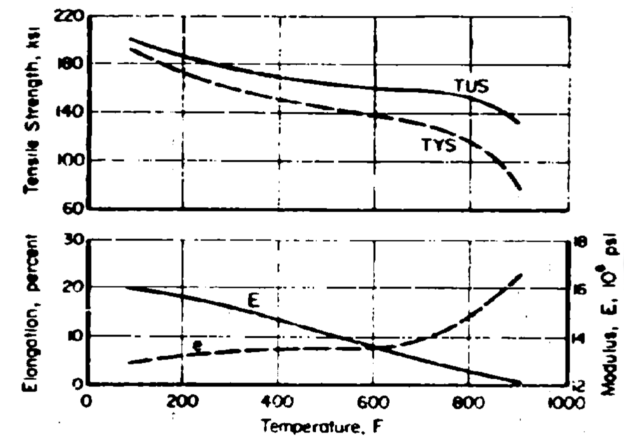



FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF SOLUTION TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

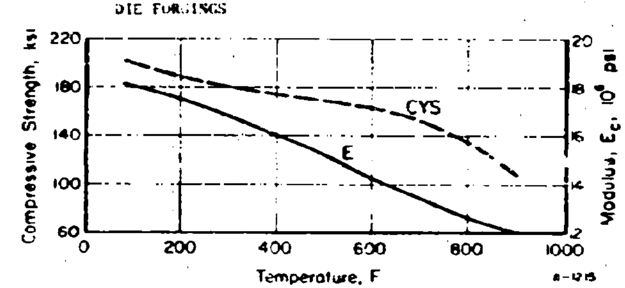



FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF SOLUTION TREATED AND AGED Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS

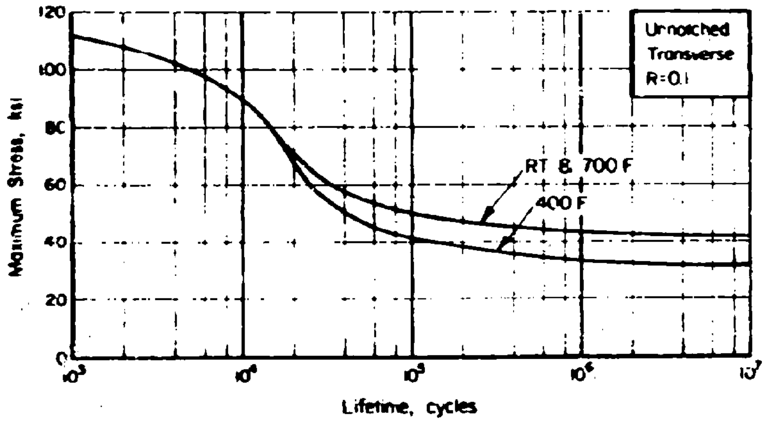
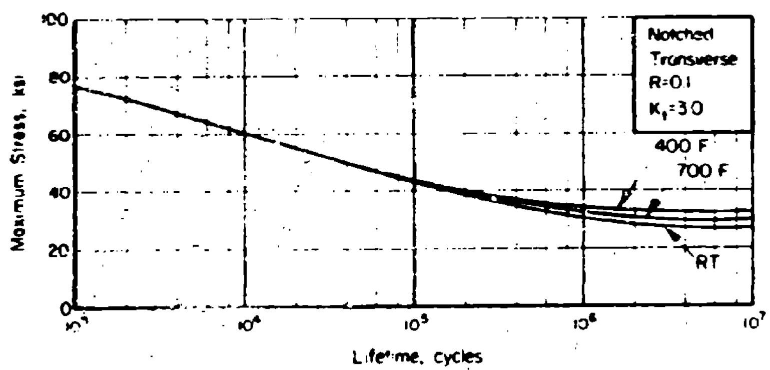
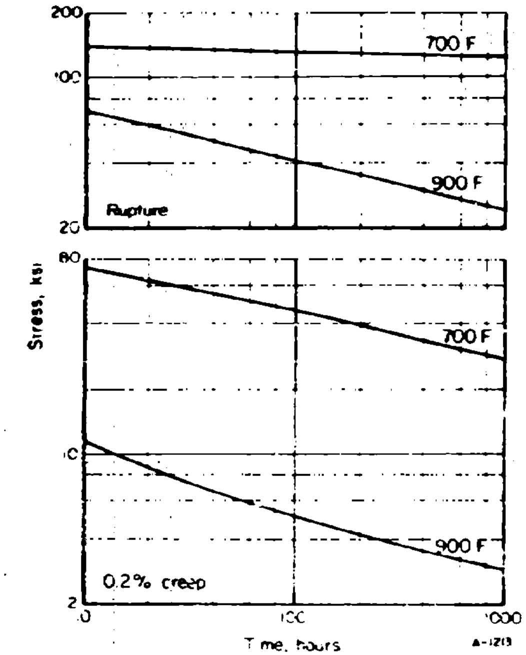



FIGURE 3. AXIAL LOAD FATIGUE BEHAVIOR OF UNNOTCHED SOLUTION TREATED AND [illegible] Ti-6Al-6V-2Sn ISOTHERMAL DIE FORGINGS




[illegible]




[illegible]