ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS

O. L. Deel, et al

Battelle Columbus Laboratories

Prepared for:
Air Force Materials Laboratory

September 1972

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NEW AEROSPACE STRUCTURAL MATERIALS

O. L. DEEL and H. MINDLIN
Battelle
Columbus Laboratories

TECHNICAL REPORT AFML-TR-72-196
VOLUME II

SEPTEMBER 1972

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### Report Title
Engineering Data on New Aerospace Structural Materials

### Abstract
The major objectives of this research program were to evaluate newly developed materials of interest to the Air Force for potential weapons system usage, and then to provide "data sheet" type presentation of engineering data for these materials. The effort covered in this report has concentrated on 15-5 PH (H1025) forged bar, HP 9Ni-4Co-0.20C forged bar, PH 13-8 No (H1060) forged bar, 7049-T76 extrusions, Ti-6Al-2Sn-4Zr-6Mo sheet, Inconel 702 sheet (Aged), and Inconel 706 forged bar (creep-rupture heat treatment).

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

### Related Organizations
- **Sponsoring Military Activity**: Air Force Materials Laboratory
- **Contractor**: Battelle Columbus Laboratories
- **Location**: 505 King Avenue, Columbus, Ohio 43201

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ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS

O. L. Deel and H. Mindlin

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FOREWORD

This report was prepared by Battelle's Columbus Laboratories, Columbus, Ohio, under Contract F33615-71-C-1261. 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/LAE), technical manager.

This final report covers work conducted from April, 1971, to July, 1972. This report was submitted by the authors on August 4, 1972.

This technical report has been reviewed and is approved.

A. Olevitch
Chief, Materials Engineering Branch
Materials Support Division
Air Force Materials Laboratory
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<td>Effect of Temperature on the Compressive Properties of PH 13-8 Mo (H1000) Forged Bar</td>
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INTRODUCTION

The selection of structural 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 information 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 four technical reports, AFML-TR-67-418, AFML-TR-68-211, AFML-TR-70-252, and AFML-TR-71-449.

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. 15-5 PH (H1025) stainless steel forged bar
2. HP 9Ni-4Co-0.20C steel forged bar
3. PH 13-8 Mo (H1000) stainless steel forged bar
4. 7049-T76 aluminum extrusion
5. 6Al-2Sn-4Zr-6Mo titanium sheet
6. Inconel Alloy 702 sheet (Aged)

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. Upon completion of each material evaluation, a "data sheet" was issued to make the data immediately available to potential users rather than defer publication to the end of the contract term and the summary technical report. These data sheets are reproduced in Appendix II.
Detailed information concerning the properties of interest, test techniques, and specimen types are contained in Appendices I and II of this report.
15-5 PH Stainless Steel

Material Description

15-5 PH is a precipitation-hardening stainless steel that offers a combination of high strength and hardness, excellent corrosion resistance, plus good transverse toughness and good forgeability. It is produced by consumable vacuum arc remelting and is virtually "ferrite free".

Fabrication practices for 15-5 PH are generally the same as those established for 17-4 PH. Most techniques are similar to those recommended for the regular grades of stainless steel. Hardening heat treatments require temperatures of only 900 F to 1150 F, depending on the properties desired. Because of the comparatively low hardening temperatures, scaling and distortion difficulties are essentially eliminated.

15-5 PH is available in the form of sheet, strip, plate, bar, and wire. Typical applications include forgings, pump and valve parts for high pressure systems, aircraft components, and hollow bar parts for hydraulic actuators and controls.

The chemical composition of the forging used for this evaluation is as follows:

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<th>Chemical Composition</th>
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<td>Carbon</td>
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<tr>
<td>Manganese</td>
<td>.31</td>
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<td>Phosphorus</td>
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<td>Sulfur</td>
<td>.010</td>
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<td>Silicon</td>
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<td>Columbium</td>
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<tr>
<td>Tantalum</td>
<td>.01</td>
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<tr>
<td>Iron</td>
<td>Balance</td>
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</table>

The material tested was obtained from Armco Heat 4W0370 in the form of 2-1/8 inch x 5-3/4 inch x 8 foot forged bar.

Processing and Heat Treating

The specimen layout for 15-5 PH is shown in Figure 1. Specimens were machined in the as-received Condition A followed by heat treatment for 4 hours at 1025 F to Condition M1025.
FIGURE 1. SPECIMEN LAYOUT FOR 15-5 PH (H1025) FORGED BAR
Test Results

Tension. Results of tests in both the longitudinal and transverse directions at room temperature, 400 F, 700 F, and 900 F are given in Table I. Typical tensile stress-strain curves at temperature are shown in Figures 2 and 3. Effect-of-temperature curves are shown in Figure 6.

Compression. Results of tests in the longitudinal and transverse directions are given in Table II for room temperature, 400 F, 700 F, and 900 F. Typical stress-strain and tangent-modulus curves at temperature are shown in Figures 4 and 5. Effect-of-temperature curves are shown in Figure 7.

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

Impact. Results of room temperature Charpy tests in the longitudinal and transverse direction are given in Table IV.

Fracture Toughness. Six slow-bend type tests were conducted at room temperature. Results are presented in Table V. Since the size ratio, $2.5 \left(K_0 / TYS \right)^2$, was greater than both the specimen thickness and width in all tests, the $K_Q$ value is not a valid $K_{IC}$ value by existing ASTM criteria.

Fatigue. Axial-load tests were conducted at room temperature, 400 F, and 700 F for both unnotched and notched transverse specimens. Test results are given in Tables VI and VII and presented as S-N curves in Figures 8 and 9.

Creep and Stress Rupture. Tests were performed at 700 F, 900 F, and 1100 F. Results are presented in tabular form in Table VIII and as log-stress versus log-time curves in Figure 10.

Stress Corrosion. Specimens were tested as described in the experimental procedure 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 $6.7 \times 10^{-6}$ in/in/F for 70 F to 900 F.

Density. The density value is 0.283 lb/in$^3$. 

5
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<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent</th>
<th>Elongation in 2 Inches, percent</th>
<th>Reduction in Area, percent</th>
<th>Tensile Modulus, psi x 10^6</th>
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<td>Ultimate</td>
<td>Offset Yield Strength, ksi</td>
<td>Elongation in 2 Inches,</td>
<td>Reduction in Area, percent</td>
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|                 |                              | Te
### Table 11. Compression Test Results for 15-5 PH (H1025) Forged Bar

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Compressive Modulus, psi x 10^6</th>
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<td>2L-1</td>
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<tr>
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<td>Transverse at Room Temperature</td>
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<td>2T-1</td>
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<td>29.8</td>
</tr>
<tr>
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<td>30.1</td>
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<tr>
<td>2T-3</td>
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<td>30.9</td>
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<td>Longitudinal at 400 F</td>
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<tr>
<td>2T-4</td>
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<td></td>
<td>Longitudinal at 700 F</td>
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<td>2L-7</td>
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<td>27.7</td>
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<tr>
<td>2L-9</td>
<td>128.0</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>Transverse at 700 F</td>
<td></td>
</tr>
<tr>
<td>2T-7</td>
<td>130.0</td>
<td>27.8</td>
</tr>
<tr>
<td>2T-8</td>
<td>130.0</td>
<td>28.6</td>
</tr>
<tr>
<td>2T-9</td>
<td>130.0</td>
<td>27.8</td>
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<tr>
<td></td>
<td>Longitudinal at 900 F</td>
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<tr>
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<td></td>
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<tr>
<td>2T-12</td>
<td>111.0</td>
<td>24.2</td>
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TABLE III. SHEAR TEST RESULTS FOR
15-5 PH (H1025) FORGED BAR

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Ultimate Shear Strength, ksi</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinal</td>
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</tr>
<tr>
<td>4L-2</td>
<td>106.0</td>
</tr>
<tr>
<td>4L-3</td>
<td>105.0</td>
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<tr>
<td>4L-4</td>
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</tr>
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<td>4T-3</td>
<td>104.0</td>
</tr>
<tr>
<td>4T-4</td>
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TABLE IV. IMPACT TEST RESULTS FOR 15-5 PH (H1025) FORGED BAR

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Energy, ft/lbs</th>
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<tr>
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<td>10L-6</td>
<td>81.5</td>
</tr>
<tr>
<td>Transverse</td>
<td></td>
</tr>
<tr>
<td>10T-1</td>
<td>37.0</td>
</tr>
<tr>
<td>10T-2</td>
<td>38.5</td>
</tr>
<tr>
<td>10T-3</td>
<td>38.5</td>
</tr>
<tr>
<td>10T-4</td>
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</tr>
<tr>
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<tr>
<td>10T-6</td>
<td>43.0</td>
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<tr>
<td>Specimen Number</td>
<td>W, inches</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1L</td>
<td>1.501</td>
</tr>
<tr>
<td>4L</td>
<td>1.500</td>
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<tr>
<td>5L</td>
<td>1.500</td>
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</table>

(a) Candidate fracture toughness values, $K_O$, are invalid as $K_{IC}$ values since $a$, T, $< 2.5 \left( \frac{K_O}{TTS} \right)$.
<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
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</thead>
<tbody>
<tr>
<td>Room Temperature</td>
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<tr>
<td>5-5</td>
<td>170</td>
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<td>5-3</td>
<td>165</td>
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<tr>
<td>5-2</td>
<td>160</td>
<td>120,700</td>
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<tr>
<td>5-4</td>
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<td>5-6</td>
<td>24</td>
<td>273,300</td>
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<tr>
<td>5-7</td>
<td>140</td>
<td>7,934,500</td>
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<tr>
<td>5-8</td>
<td>135</td>
<td>4,167,900</td>
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<tr>
<td>5-9</td>
<td>130</td>
<td>10,000,900(a)</td>
</tr>
<tr>
<td>5-20</td>
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<tr>
<td>5-19</td>
<td>160</td>
<td>14,900</td>
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<tr>
<td>5-18</td>
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<td>5-23</td>
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<td>49,800</td>
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<td>5-24</td>
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<tr>
<td>5-10</td>
<td>140</td>
<td>(b)</td>
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<td>5-11</td>
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<tr>
<td>5-17</td>
<td>115</td>
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<tr>
<td>5-17</td>
<td>110</td>
<td>10,123,000(a)</td>
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</table>

(a) Did not fail.
(b) Failed in first cycle.
<table>
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<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
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<td>16,610</td>
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<td>45,120</td>
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<td>80,250</td>
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<td>5-36</td>
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<td>5-38</td>
<td>50</td>
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<tr>
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<td>400°F</td>
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<td>5-42</td>
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(a) Did not fail.
### TABLE VIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF 15-5 PH (H1025) FORGED BAR (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress, ksi</th>
<th>Temp, °F</th>
<th>Deformation, percent</th>
<th>Hours to Indicated Creep</th>
<th>Initial Strain, percent</th>
<th>Rupture Time, hr</th>
<th>Elongation in 2 in., percent</th>
<th>Minimum Creep Rate, percent/hr</th>
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<tbody>
<tr>
<td>31</td>
<td>134.5</td>
<td>700</td>
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<td>--</td>
<td>--</td>
<td>On loading</td>
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<td>32</td>
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<td>&quot;</td>
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<td>0.03</td>
<td>0.35</td>
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<td>0.539</td>
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<td>85</td>
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<td>65</td>
<td>325</td>
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<td>--</td>
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<td>350</td>
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<td>180</td>
<td>680</td>
<td>1635(b)</td>
<td>--</td>
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</table>

(a) Test discontinued.
(b) Estimate.
FIGURE 2. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 15-5 PH (H1025) FORGED BAR (LONGITUDINAL)
FIGURE 3. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 15-5 PH (H1025) FORGED BAR (TRANSVERSE)
FIGURE 4. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 15-5 PH (H1025) FORGED BAR (LONGITUDINAL)
FIGURE 5. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 15-5 PH (H1025) FORGED BAR (TRANSVERSE)
FIGURE 6. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 15-5 PH (H1025) FORGED BAR

FIGURE 7. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 15-5 PH (H1025) FORGED BAR
**Figure 8.** AXIAL LOAD FATIGUE BEHAVIOR FOR UNNOTCHED 15-5 PH (H1025) FORGED BAR

**Figure 9.** AXIAL LOAD FATIGUE BEHAVIOR FOR NOTCHED ($K_t=3.0$) 15-5 PH (H1025) FORGED BAR
FIGURE 10. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 15-5 PH (H1025) FORGED BAR (TRANSVERSE)
HP 9Ni-4Co-0.20C Alloy Steel

Material Description

HP 9Ni-4Co-0.20C steel was developed specifically to have high hardenability combined with good fracture toughness. It can be welded in the fully heat-treated condition and achieve essentially 100 percent joint efficiency without preheat or postheat treatment. The 0-20C grade is available as sheet, strip, plate, bars, forgings, and tubing.

The material used for this program was consumable electrode vacuum melted and from Republic Steel Heat 3821003. It was obtained as a 2-1/4 inch x 6-inch x 84 inch forged bar and had the following composition:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
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<tbody>
<tr>
<td>Carbon</td>
<td>0.19</td>
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<tr>
<td>Manganese</td>
<td>0.36</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.008</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.007</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.04</td>
</tr>
<tr>
<td>Nickel</td>
<td>9.30</td>
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<tr>
<td>Chromium</td>
<td>0.80</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.04</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.08</td>
</tr>
<tr>
<td>Cobalt</td>
<td>4.70</td>
</tr>
<tr>
<td>Iron</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Processing and Heat Treating

The specimen layout for this alloy is shown in Figure 11. Specimens were rough machined in the as-received annealed condition, heat treated as follows:

1. normalize at 1650 F, 1 hour, air-cool,
2. austenitize at 1500 F, 1 hour, oil quench,
3. single temper at 1025 F, 6 hours, air cool and then finish machined.

Test Results

Tension. Results of tension tests in the longitudinal and transverse directions at room temperature, 500 F, 700 F, and 900 F are given in Table IX.
FIGURE 11. SPECIMEN LAYOUT FOR HP 9Ni-4Cr-0.20C FORGED BAR
Stress-strain curves at temperature are presented in Figures 12 and 13. Effect-of-temperature curves are shown in Figure 16.

Compression. Results of compression tests in the longitudinal and transverse directions at room temperature, 500 F, 700 F, and 900 F are given in Table X. Compressive stress-strain and tangent modulus curves at temperature are presented in Figures 14 and 15. Effect-of-temperature curves are shown in Figure 17.

Shear. Test results for pin shear tests in both the longitudinal and transverse directions at room temperature are given in Table XI.

Impact. Charpy test results at room temperature for longitudinal and transverse specimens are given in Table XII.

Fracture Toughness. Results of six slow-bend type tests are given in Table XIII. The size ratio, 2.5 \( \left( \frac{K_I}{TYS} \right)^2 \), was greater than both the specimen thickness and crack length in all tests, therefore the \( K_I \) value in the table is not a valid \( K_{IC} \) value by existing ASTM criteria.

Fatigue. Axial-load fatigue tests were conducted at room temperature, 500 F, and 700 F for transverse specimens, both unnotched and notched. Results are given in tabular form in Tables XIV and XV. S-N curves are presented in Figures 18 and 19.

Creep and Stress Rupture. Tests were performed at 500 F, 700 F, and 900 F for transverse specimens. Tabular test results are given in Table XVI. Log-stress versus log-time curves are presented in Figure 20.

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

Thermal Expansion. The coefficient of thermal expansion for this steel is \( 6.4 \times 10^{-6} \) in/in/F for 80 F to 900 F.

Density. The density of this alloy is 0.284 lb/in³.
# TABLE IX. TENSILE TEST RESULTS FOR HP 9Ni-4Co-0.20C FORGED BAR

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Elongation in 2 inches, percent</th>
<th>Reduction in Area, percent</th>
<th>Modulus, 10⁵ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate Tensile Strength, ksi</td>
<td>0.2 Percent Offset Yield Strength, ksi</td>
<td>Elongation in 2 inches, percent</td>
<td>Reduction in Area, percent</td>
<td>Modulus, 10⁵ psi</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal at Room Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-1</td>
<td>198.0</td>
<td>181.0</td>
<td>17.5</td>
<td>67.1</td>
<td>28.0</td>
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<tr>
<td>IL-2</td>
<td>196.0</td>
<td>181.0</td>
<td>17.5</td>
<td>68.2</td>
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</tr>
<tr>
<td>IL-3</td>
<td>197.0</td>
<td>180.0</td>
<td>17.5</td>
<td>68.4</td>
<td>26.4</td>
</tr>
<tr>
<td>Transverse at Room Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-1</td>
<td>197.0</td>
<td>180.0</td>
<td>14.5</td>
<td>55.0</td>
<td>27.9</td>
</tr>
<tr>
<td>IT-2</td>
<td>197.0</td>
<td>180.0</td>
<td>14.5</td>
<td>56.3</td>
<td>27.7</td>
</tr>
<tr>
<td>IT-3</td>
<td>197.0</td>
<td>180.0</td>
<td>15.0</td>
<td>57.1</td>
<td>26.4</td>
</tr>
<tr>
<td>Longitudinal at 500 F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-4</td>
<td>178.0</td>
<td>165.0</td>
<td>16.0</td>
<td>66.7</td>
<td>25.4</td>
</tr>
<tr>
<td>IL-5</td>
<td>182.0</td>
<td>165.0</td>
<td>16.0</td>
<td>65.4</td>
<td>26.0</td>
</tr>
<tr>
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<td>165.0</td>
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<td>64.4</td>
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</tr>
<tr>
<td>Transverse at 500 F</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-4</td>
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<td>166.0</td>
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<td>56.0</td>
<td>25.7</td>
</tr>
<tr>
<td>IT-5</td>
<td>179.0</td>
<td>166.0</td>
<td>14.0</td>
<td>55.1</td>
<td>25.8</td>
</tr>
<tr>
<td>IT-6</td>
<td>179.0</td>
<td>166.0</td>
<td>14.0</td>
<td>55.8</td>
<td>26.2</td>
</tr>
<tr>
<td>Longitudinal at 700 F</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>IL-7</td>
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<td>155.0</td>
<td>16.0</td>
<td>64.4</td>
<td>24.0</td>
</tr>
<tr>
<td>IL-8</td>
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<td>155.0</td>
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<td>156.0</td>
<td>16.0</td>
<td>66.4</td>
<td>24.6</td>
</tr>
<tr>
<td>Transverse at 700 F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-7</td>
<td>169.0</td>
<td>151.0</td>
<td>14.5</td>
<td>58.4</td>
<td>24.9</td>
</tr>
<tr>
<td>IT-8</td>
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<td>154.0</td>
<td>14.5</td>
<td>57.4</td>
<td>24.8</td>
</tr>
<tr>
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<td>153.0</td>
<td>14.5</td>
<td>57.7</td>
<td>24.4</td>
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</table>
TABLE IX. (Concluded)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Elongation in 2 inches, percent</th>
<th>Reduction in Area, percent</th>
<th>Tensile Modulus, $10^5$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
<tr>
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<tr>
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<td>128.0</td>
<td>16.0</td>
<td>61.2</td>
<td>25.3</td>
</tr>
<tr>
<td>IT-11</td>
<td>147.0</td>
<td>128.0</td>
<td>16.0</td>
<td>59.5</td>
<td>23.4</td>
</tr>
<tr>
<td>IT-12</td>
<td>147.0</td>
<td>131.0</td>
<td>16.0</td>
<td>60.6</td>
<td>22.7</td>
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TABLE X. COMPRESSION TEST RESULTS FOR HP 9NI-4Co-0.23C FORGED BAR

<table>
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<tr>
<th>Specimen No.</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^6$ psi</th>
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<tr>
<td><strong>Longitudinal at Room Temperature</strong></td>
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<td></td>
</tr>
<tr>
<td>2L-1</td>
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<td>2L-2</td>
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<td>28.0</td>
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<tr>
<td><strong>Transverse at Room Temperature</strong></td>
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<td></td>
</tr>
<tr>
<td>2T-1</td>
<td>194.0</td>
<td>27.1</td>
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<tr>
<td>2T-2</td>
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<td>195.0</td>
<td>28.2</td>
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<tr>
<td><strong>Longitudinal at 500 F</strong></td>
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<td></td>
</tr>
<tr>
<td>2L-4</td>
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</tr>
<tr>
<td>2L-5</td>
<td>173.0</td>
<td>26.5</td>
</tr>
<tr>
<td>2L-6</td>
<td>173.0</td>
<td>26.9</td>
</tr>
<tr>
<td><strong>Transverse at 500 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2T-4</td>
<td>171.0</td>
<td>27.0</td>
</tr>
<tr>
<td>2T-5</td>
<td>171.0</td>
<td>25.9</td>
</tr>
<tr>
<td>2T-6</td>
<td>172.0</td>
<td>25.7</td>
</tr>
<tr>
<td><strong>Longitudinal at 700 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2L-7</td>
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<td>24.8</td>
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<td>2L-8</td>
<td>158.0</td>
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<td>2L-9</td>
<td>157.0</td>
<td>25.0</td>
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<tr>
<td><strong>Transverse at 700 F</strong></td>
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<td>2T-7</td>
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<td>25.1</td>
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<tr>
<td>2T-8</td>
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<tr>
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<td>159.0</td>
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TABLE X. (Concluded)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^6$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Longitudinal at 900 F</td>
</tr>
<tr>
<td>2L-10</td>
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<tr>
<td>2L-11</td>
<td>155.0</td>
<td>24.8</td>
</tr>
<tr>
<td>2L-12</td>
<td>134.0</td>
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<tr>
<td></td>
<td></td>
<td>Transverse at 900 F</td>
</tr>
<tr>
<td>2T-10</td>
<td>136.0</td>
<td>23.2</td>
</tr>
<tr>
<td>2T-11</td>
<td>135.0</td>
<td>24.5</td>
</tr>
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<td>Specimen No.</td>
<td>Ultimate Shear Strength, ksi</td>
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<tr>
<td>--------------</td>
<td>-----------------------------</td>
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</tr>
<tr>
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<td>Longitudinal</td>
<td></td>
</tr>
<tr>
<td>4L-1</td>
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<td></td>
</tr>
<tr>
<td>4L-2</td>
<td>124.0</td>
<td></td>
</tr>
<tr>
<td>4L-3</td>
<td>124.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td></td>
</tr>
<tr>
<td>4T-1</td>
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</tr>
<tr>
<td>4T-2</td>
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<tr>
<td>4T-3</td>
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TABLE XII. IMPACT TEST RESULTS FOR
HP 9N1-4Co-0.20 C FORGED BAR

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Energy, ft/lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal</strong></td>
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<tr>
<td>10L-1</td>
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<tr>
<td>10L-5</td>
<td>77.0</td>
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<td><strong>Transverse</strong></td>
<td></td>
</tr>
<tr>
<td>10T-1</td>
<td>50.0</td>
</tr>
<tr>
<td>10T-2</td>
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<tr>
<td>Specimen Number</td>
<td>W, inches</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------</td>
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<tr>
<td>Transverse</td>
<td></td>
</tr>
<tr>
<td>3T</td>
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<tr>
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</tr>
<tr>
<td>Longitudinal</td>
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</tr>
<tr>
<td>2L</td>
<td>1.504</td>
</tr>
<tr>
<td>3L</td>
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<tr>
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</table>

(a) Candidate fracture toughness values, $K_Q$, are invalid as $K_{IC}$ values since $a, T, < 2.5 (TYS)$.
<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
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<td>5-1</td>
<td>120</td>
<td>26,900</td>
</tr>
<tr>
<td>5-2</td>
<td>110</td>
<td>23,900</td>
</tr>
<tr>
<td>5-3</td>
<td>100</td>
<td>34,000</td>
</tr>
<tr>
<td>5-4</td>
<td>90</td>
<td>58,200</td>
</tr>
<tr>
<td>5-5</td>
<td>80</td>
<td>69,900</td>
</tr>
<tr>
<td>5-6</td>
<td>70</td>
<td>124,100</td>
</tr>
<tr>
<td>5-7</td>
<td>60</td>
<td>5,024,900</td>
</tr>
<tr>
<td>5-8</td>
<td>50</td>
<td>11,920,400(a)</td>
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</tbody>
</table>

**Room Temperature**

<table>
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<th>Specimen Number</th>
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<th>Lifetime, cycles</th>
</tr>
</thead>
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<td>145</td>
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<tr>
<td>5-19</td>
<td>135</td>
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<td>21,100</td>
</tr>
<tr>
<td>5-20</td>
<td>125</td>
<td>17,400</td>
</tr>
<tr>
<td>5-16</td>
<td>120</td>
<td>10,115,000(a)</td>
</tr>
<tr>
<td>5-14</td>
<td>100</td>
<td>109,000</td>
</tr>
<tr>
<td>5-15</td>
<td>100</td>
<td>12,916,000(a)</td>
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</table>

**500 F**

<table>
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<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
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<tr>
<td>5-25</td>
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</tr>
<tr>
<td>5-24</td>
<td>150</td>
<td>360,900</td>
</tr>
<tr>
<td>5-22</td>
<td>140</td>
<td>25,600(b)</td>
</tr>
<tr>
<td>5-23</td>
<td>140</td>
<td>2,052,400</td>
</tr>
<tr>
<td>5-21</td>
<td>130</td>
<td>2,702,000</td>
</tr>
<tr>
<td>5-27</td>
<td>120</td>
<td>50,800</td>
</tr>
<tr>
<td>5-28</td>
<td>120</td>
<td>10,277,000(a)</td>
</tr>
</tbody>
</table>

**700 F**

(a) *Did not fail.*

(b) *Failed at thermocouple.*
## TABLE XV. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (Kt=3.0) HP 9Ni-4Co-0.20C FORGED BAR (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room Temperature</td>
<td></td>
</tr>
<tr>
<td>5-31</td>
<td>90</td>
<td>11,900</td>
</tr>
<tr>
<td>5-37</td>
<td>85</td>
<td>17,900</td>
</tr>
<tr>
<td>5-32</td>
<td>80</td>
<td>21,400</td>
</tr>
<tr>
<td>5-35</td>
<td>75</td>
<td>13,500</td>
</tr>
<tr>
<td>5-33</td>
<td>70</td>
<td>21,600</td>
</tr>
<tr>
<td>5-36</td>
<td>65</td>
<td>50,900</td>
</tr>
<tr>
<td>5-34</td>
<td>60</td>
<td>12,381,800(a)</td>
</tr>
<tr>
<td></td>
<td>500 F</td>
<td></td>
</tr>
<tr>
<td>5-41</td>
<td>90</td>
<td>7,800</td>
</tr>
<tr>
<td>5-42</td>
<td>85</td>
<td>11,600</td>
</tr>
<tr>
<td>5-43</td>
<td>80</td>
<td>27,300</td>
</tr>
<tr>
<td>5-44</td>
<td>75</td>
<td>13,200</td>
</tr>
<tr>
<td>5-45</td>
<td>70</td>
<td>25,200</td>
</tr>
<tr>
<td>5-46</td>
<td>65</td>
<td>34,400</td>
</tr>
<tr>
<td>5-47</td>
<td>60</td>
<td>31,300</td>
</tr>
<tr>
<td>5-48</td>
<td>50</td>
<td>99,000</td>
</tr>
<tr>
<td>5-59</td>
<td>40</td>
<td>60,800</td>
</tr>
<tr>
<td>5-60</td>
<td>40</td>
<td>109,900</td>
</tr>
<tr>
<td>5-61</td>
<td>30</td>
<td>10,850,900(a)</td>
</tr>
<tr>
<td></td>
<td>700 F</td>
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</tr>
<tr>
<td>5-51</td>
<td>90</td>
<td>10,900</td>
</tr>
<tr>
<td>5-52</td>
<td>80</td>
<td>14,400</td>
</tr>
<tr>
<td>5-53</td>
<td>75</td>
<td>32,400</td>
</tr>
<tr>
<td>5-54</td>
<td>70</td>
<td>1,699,300</td>
</tr>
<tr>
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<td>65</td>
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<tr>
<td>5-58</td>
<td>50</td>
<td>12,986,000(a)</td>
</tr>
</tbody>
</table>

(a) Did not fail.
TABLE XVI. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF 9Ni-4Co-0.20 FORGED BAR (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>Stress, ksi</th>
<th>Temperature, F</th>
<th>Hours to Indicated Creep Deformation, percent</th>
<th>Initial Strain, Percent</th>
<th>Rupture Time, hr</th>
<th>Elongation in 2 in., percent</th>
<th>Reduction of Area, percent</th>
<th>Minimum Creep Rate, percent/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-3</td>
<td>168</td>
<td>500</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>8.9</td>
</tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>44.7</td>
</tr>
<tr>
<td>3-5</td>
<td>160</td>
<td>500</td>
<td>0.03</td>
<td>0.10</td>
<td>2750(b)</td>
<td>1.828</td>
<td>816.5(a)</td>
<td>2.245</td>
</tr>
<tr>
<td>3-10</td>
<td>145</td>
<td>500</td>
<td>120</td>
<td>4500(b)</td>
<td>---</td>
<td>0.611</td>
<td>793.9</td>
<td>0.748</td>
</tr>
<tr>
<td>3-1</td>
<td>160</td>
<td>700</td>
<td>0.01</td>
<td>0.02</td>
<td>0.07</td>
<td>0.33</td>
<td>1.5</td>
<td>1.871</td>
</tr>
<tr>
<td>3-4</td>
<td>150</td>
<td>700</td>
<td>0.04</td>
<td>0.13</td>
<td>1.5</td>
<td>17.5</td>
<td>6.5</td>
<td>1.064</td>
</tr>
<tr>
<td>3-7</td>
<td>125</td>
<td>700</td>
<td>1.5</td>
<td>21</td>
<td>360</td>
<td>1370(b)</td>
<td>0.563</td>
<td>431.5(a)</td>
</tr>
<tr>
<td>3-9</td>
<td>105</td>
<td>700</td>
<td>30</td>
<td>350</td>
<td>2650(b)</td>
<td>---</td>
<td>0.564</td>
<td>598.7(a)</td>
</tr>
<tr>
<td>3-2</td>
<td>120</td>
<td>900</td>
<td>0.02</td>
<td>0.04</td>
<td>0.12</td>
<td>0.30</td>
<td>0.67</td>
<td>1.015</td>
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<tr>
<td>3-6</td>
<td>95</td>
<td>900</td>
<td>0.15</td>
<td>0.7</td>
<td>12</td>
<td>49</td>
<td>92</td>
<td>0.552</td>
</tr>
<tr>
<td>3-8</td>
<td>80</td>
<td>900</td>
<td>1.5</td>
<td>13.5</td>
<td>120</td>
<td>278</td>
<td>450</td>
<td>0.478</td>
</tr>
<tr>
<td>3-11</td>
<td>55</td>
<td>900</td>
<td>25</td>
<td>140</td>
<td>640</td>
<td>1650(b)</td>
<td>---</td>
<td>0.300</td>
</tr>
<tr>
<td>3-12</td>
<td>35</td>
<td>900</td>
<td>270</td>
<td>740</td>
<td>1700(b)</td>
<td>4100(b)</td>
<td>---</td>
<td>0.207</td>
</tr>
</tbody>
</table>

(a) Test discontinued.
(b) Estimate.
FIGURE 12. TYPICAL TENSILE STRESS-STRAIN CURVES FOR HP 9Ni-4Co-0.20C FORGED EAR (LONGITUDINAL)
FIGURE 13. TYPICAL TENSILE STRESS-STRAIN CURVES FOR HP 9Ni-4Co-0.20C FORGED BAR (TRANSVERSE)
FIGURE 14. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR HP 9Ni-4Co-0.20C FORGED BAR (LONGITUDINAL)
FIGURE 15. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR HP 9Ni-4Cr-0.20C FORGED BAR (TRANSVERSE)
FIGURE 16. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF HP 9Ni-4Co-0.20C FORGED BAR

FIGURE 17. EFFECT OF TEMPERATURE ON THE COMPRESSION PROPERTIES OF HP 9Ni-4Co-0.20C FORGED BAR
FIGURE 18. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED HP 9Ni-4Co-0.20C FORGED BAR

FIGURE 19. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (Kt = 3.0) HP 9Ni-4Co-0.20C FORGED BAR
PH 13-8 Mo Stainless Steel

Material Description

This alloy is a martensitic precipitation hardenable stainless steel developed by the Armco Steel Corporation. It can be heat treated to high strength levels and exhibits good ductility in the transverse direction. This transverse direction toughness is obtained by composition balance designed to prevent formation of delta ferrite in the structure, low carbon content to minimize grain boundary carbide precipitation, and double vacuum melting to reduce alloy segregation. The alloy reportedly has excellent resistance to stress corrosion cracking in synthetic seawater and excellent resistance to corrosion in a 5 percent salt spray environment.

The material used in this evaluation was obtained as a 4-inch x 5-inch x 5 foot forged bar from Armco Heat IW0241. The composition was as follows:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.035</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.01</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.002</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.003</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.02</td>
</tr>
<tr>
<td>Chromium</td>
<td>12.62</td>
</tr>
<tr>
<td>Nickel</td>
<td>8.24</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.16</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.02</td>
</tr>
<tr>
<td>Iron</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Processing and Heat Treating

The specimen layout for PH 13-8 Mo is shown in Figure 21. Specimens were machined in the as-received condition A and then heat treated at 1000 F for 4 hours to Condition H1 1000.

Test Results

Tension. Results of tests in the longitudinal and transverse directions at room temperature, 500 F, 700 F, and 900 F are given in Table XVII. Tensile stress-strain curves at temperature are shown in Figures 22 and 23. Effect-of-temperature curves are presented in Figure 26.

Compression. Test results are given in Table XVIII for longitudinal and transverse specimens at room temperature, 500 F, 700 F, and 900 F. Compressive stress-strain and tangent modulus curves at temperature are presented in Figures 24 and 25. Effect-of-temperature curves are shown in Figure 27.
<table>
<thead>
<tr>
<th>54</th>
<th>524</th>
<th>544</th>
<th>114</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>529</td>
<td>543</td>
<td>113</td>
</tr>
<tr>
<td>512</td>
<td>552</td>
<td>552</td>
<td>112</td>
</tr>
<tr>
<td>516</td>
<td>556</td>
<td>556</td>
<td>Creep 15</td>
</tr>
<tr>
<td>520</td>
<td>540</td>
<td>560</td>
<td>31-315</td>
</tr>
<tr>
<td>2.0</td>
<td>2.5</td>
<td>2.0</td>
<td>Charpy 61</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>Fracture</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Toughness</td>
</tr>
</tbody>
</table>

**FIGURE 21. SPECIMEN LAYOUT FOR PH 13-8 Mo (Ni1000) FORGED BAR**
Shear. Results of pin shear tests at room temperature for longitudinal and transverse specimens are shown in Table XIX.

Impact. Charpy test results are shown in Table XX.

Fracture Toughness. Results of slow-bend type tests are shown in Table XXI. The size ratio, \(2.5 \left(\frac{K_I}{TYS}\right)^2\), was greater than both the specimen thickness and crack length in all tests, therefore, the \(K_I\) value shown in the table is not a valid \(K_{ic}\) value by existing ASTM criteria.

Fatigue. Axial load fatigue tests were conducted at room temperature, 400 F, and 700 F for transverse specimens, both unnotched and notched. Test results are given in Tables XXII and XXIII. S-N curves are shown in Figures 28 and 29.

Creep and Stress Rupture. Tests were performed at 500 F, 700 F, and 900 F for transverse specimens. Tabular test results are given in Table XXIV. Log-stress versus log-time curves are presented in Figure 30.

Stress Corrosion. Specimens were tested as described in the experimental procedure 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 \(6.6 \times 10^{-6}\) in/in/F for 80 F to 900 F.

Density. The density of this material is 0.279 lb/in\(^3\).
### TABLE XVII. TENSILE TEST RESULTS FOR PH 13-8 Mo (H1000) FORGED BAR

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 percent Offset Yield Strength, ksi</th>
<th>Elongation in 2 inches, percent</th>
<th>Reduction in Area, percent</th>
<th>Tensile Modulus, $10^8$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Longitudinal at Room Temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-1</td>
<td>194.0</td>
<td>190.0</td>
<td>13.0</td>
<td>49.5</td>
<td>27.7</td>
</tr>
<tr>
<td>IL-2</td>
<td>193.0</td>
<td>187.0</td>
<td>14.5</td>
<td>58.5</td>
<td>27.6</td>
</tr>
<tr>
<td>IL-3</td>
<td>191.0</td>
<td>185.0</td>
<td>12.5</td>
<td>47.5</td>
<td>27.9</td>
</tr>
<tr>
<td><strong>Long Transverse at Room Temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-1</td>
<td>192.0</td>
<td>187.0</td>
<td>13.0</td>
<td>51.0</td>
<td>27.3</td>
</tr>
<tr>
<td>IT-2</td>
<td>188.0</td>
<td>179.0</td>
<td>14.5</td>
<td>55.5</td>
<td>28.3</td>
</tr>
<tr>
<td>IT-3</td>
<td>191.0</td>
<td>184.0</td>
<td>14.0</td>
<td>56.0</td>
<td>28.4</td>
</tr>
<tr>
<td><strong>Longitudinal at 500 F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-4</td>
<td>170.0</td>
<td>165.0</td>
<td>12.5</td>
<td>58.0</td>
<td>27.4</td>
</tr>
<tr>
<td>IL-5</td>
<td>169.0</td>
<td>164.0</td>
<td>13.0</td>
<td>59.0</td>
<td>27.3</td>
</tr>
<tr>
<td>IL-6</td>
<td>168.0</td>
<td>165.0</td>
<td>12.0</td>
<td>53.0</td>
<td>26.5</td>
</tr>
<tr>
<td><strong>Long Transverse at 500 F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-4</td>
<td>168.0</td>
<td>162.0</td>
<td>11.0</td>
<td>49.5</td>
<td>25.2</td>
</tr>
<tr>
<td>IT-5</td>
<td>166.0</td>
<td>163.0</td>
<td>12.5</td>
<td>56.0</td>
<td>25.5</td>
</tr>
<tr>
<td>IT-6</td>
<td>171.0</td>
<td>166.0</td>
<td>11.0</td>
<td>50.0</td>
<td>25.2</td>
</tr>
<tr>
<td><strong>Longitudinal at 700 F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-7</td>
<td>158.0</td>
<td>148.0</td>
<td>14.0</td>
<td>39.5</td>
<td>24.7</td>
</tr>
<tr>
<td>IL-8</td>
<td>158.0</td>
<td>153.0</td>
<td>11.0</td>
<td>45.0</td>
<td>24.9</td>
</tr>
<tr>
<td>IL-9</td>
<td>157.0</td>
<td>153.0</td>
<td>13.0</td>
<td>55.0</td>
<td>25.8</td>
</tr>
<tr>
<td><strong>Long Transverse at 700 F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-7</td>
<td>159.0</td>
<td>168.0</td>
<td>12.0</td>
<td>51.0</td>
<td>26.2</td>
</tr>
<tr>
<td>IT-8</td>
<td>156.0</td>
<td>150.0</td>
<td>12.5</td>
<td>50.0</td>
<td>24.7</td>
</tr>
<tr>
<td>IT-9</td>
<td>157.0</td>
<td>151.0</td>
<td>13.0</td>
<td>56.0</td>
<td>24.4</td>
</tr>
<tr>
<td><strong>Longitudinal at 900 F</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>IL-10</td>
<td>129.0</td>
<td>119.0</td>
<td>21.0</td>
<td>71.5</td>
<td>22.1</td>
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<tr>
<td>IL-11</td>
<td>129.0</td>
<td>119.0</td>
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<td>69.0</td>
<td>20.7</td>
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<tr>
<td>IL-12</td>
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<td>119.0</td>
<td>21.0</td>
<td>71.0</td>
<td>22.8</td>
</tr>
<tr>
<td><strong>Long Transverse at 900 F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-10</td>
<td>125.0</td>
<td>116.0</td>
<td>22.5</td>
<td>72.0</td>
<td>20.4</td>
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<tr>
<td>IT-11</td>
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<td>120.0</td>
<td>22.0</td>
<td>71.0</td>
<td>22.3</td>
</tr>
<tr>
<td>IT-12</td>
<td>128.0</td>
<td>118.0</td>
<td>20.0</td>
<td>68.5</td>
<td>21.6</td>
</tr>
</tbody>
</table>
TABLE XVII. COMPRESSION TEST RESULTS FOR PH 13-8 Mo (H1000) FORGED BAR

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^6$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>2L-1</td>
<td>183.0</td>
<td>30.9</td>
</tr>
<tr>
<td>2L-2</td>
<td>193.0</td>
<td>30.6</td>
</tr>
<tr>
<td>2L-3</td>
<td>187.0</td>
<td>28.7</td>
</tr>
<tr>
<td>2T-1</td>
<td>199.0</td>
<td>29.9</td>
</tr>
<tr>
<td>2T-2</td>
<td>198.0</td>
<td>30.0</td>
</tr>
<tr>
<td>2T-3</td>
<td>202.0</td>
<td>30.0</td>
</tr>
<tr>
<td>2L-4</td>
<td>160.0</td>
<td>25.9</td>
</tr>
<tr>
<td>2L-5</td>
<td>155.0</td>
<td>26.1</td>
</tr>
<tr>
<td>2L-6</td>
<td>160.0</td>
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<tr>
<td>2T-4</td>
<td>170.0</td>
<td>25.9</td>
</tr>
<tr>
<td>2T-5</td>
<td>170.0</td>
<td>25.8</td>
</tr>
<tr>
<td>2T-6</td>
<td>169.0</td>
<td>25.4</td>
</tr>
<tr>
<td>2L-7</td>
<td>148.0</td>
<td>25.8</td>
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<td>2T-7</td>
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<td>23.6</td>
</tr>
<tr>
<td>2T-8</td>
<td>159.0</td>
<td>25.2</td>
</tr>
<tr>
<td>2T-9</td>
<td>157.0</td>
<td>24.5</td>
</tr>
</tbody>
</table>
### TABLE XVIII. (Concluded)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^5$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2 Percent</td>
<td></td>
</tr>
<tr>
<td>Longitudinal at 900 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2L-10</td>
<td>120.0</td>
<td>22.6</td>
</tr>
<tr>
<td>2L-11</td>
<td>115.0</td>
<td>23.2</td>
</tr>
<tr>
<td>2L-12</td>
<td>120.0</td>
<td>23.7</td>
</tr>
<tr>
<td>Long Transverse at 900 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2T-10</td>
<td>122.0</td>
<td>23.1</td>
</tr>
<tr>
<td>2T-11</td>
<td>119.0</td>
<td>23.0</td>
</tr>
<tr>
<td>2T-12</td>
<td>123.0</td>
<td>23.0</td>
</tr>
</tbody>
</table>
TABLE XIX. SHEAR TEST RESULTS FOR PH 13·8 Mo
\^*(H1000) FORGED BAR

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Ultimate Shear Strength, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td></td>
</tr>
<tr>
<td>4L-1</td>
<td>122.0</td>
</tr>
<tr>
<td>4L-2</td>
<td>122.0</td>
</tr>
<tr>
<td>4L-3</td>
<td>120.0</td>
</tr>
<tr>
<td>Long Transverse</td>
<td></td>
</tr>
<tr>
<td>4T-1</td>
<td>123.0</td>
</tr>
<tr>
<td>4T-2</td>
<td>123.0</td>
</tr>
<tr>
<td>4T-3</td>
<td>123.0</td>
</tr>
</tbody>
</table>
TABLE XX. IMPACT TEST RESULTS FOR PH 13-8 Mo (H1000) FORGED BAR

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Energy, ft/lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal</strong></td>
<td></td>
</tr>
<tr>
<td>10L-1</td>
<td>36.0</td>
</tr>
<tr>
<td>10L-2</td>
<td>35.5</td>
</tr>
<tr>
<td>10L-3</td>
<td>34.5</td>
</tr>
<tr>
<td>10L-4</td>
<td>33.5</td>
</tr>
<tr>
<td>10L-5</td>
<td>31.0</td>
</tr>
<tr>
<td>10L-6</td>
<td>33.5</td>
</tr>
<tr>
<td><strong>Long Transverse</strong></td>
<td></td>
</tr>
<tr>
<td>10T-1</td>
<td>28.0</td>
</tr>
<tr>
<td>10T-2</td>
<td>28.0</td>
</tr>
<tr>
<td>10T-3</td>
<td>26.0</td>
</tr>
<tr>
<td>10T-4</td>
<td>28.0</td>
</tr>
<tr>
<td>10T-5q</td>
<td>29.0</td>
</tr>
<tr>
<td>10T-6</td>
<td>27.0</td>
</tr>
</tbody>
</table>
TABLE XXI. FRACTURE TOUGHNESS TEST RESULTS FOR PH 13-8 Mo (H1000) FORGED BAR (LONGITUDINAL)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>W, inches</th>
<th>a, inches</th>
<th>T, inches</th>
<th>P, lbs</th>
<th>Span, inches</th>
<th>f(a/W)</th>
<th>K_Q (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5L</td>
<td>1.500</td>
<td>.879</td>
<td>.742</td>
<td>10,750</td>
<td>6</td>
<td>3.5</td>
<td>169.0</td>
</tr>
<tr>
<td>4L</td>
<td>1.501</td>
<td>.880</td>
<td>.741</td>
<td>10,500</td>
<td>6</td>
<td>3.6</td>
<td>166.0</td>
</tr>
<tr>
<td>3L</td>
<td>1.499</td>
<td>.868</td>
<td>.741</td>
<td>10,300</td>
<td>6</td>
<td>3.5</td>
<td>158.9</td>
</tr>
<tr>
<td>2L</td>
<td>1.500</td>
<td>.871</td>
<td>.741</td>
<td>9,800</td>
<td>6</td>
<td>3.5</td>
<td>151.9</td>
</tr>
<tr>
<td>1L</td>
<td>1.499</td>
<td>.870</td>
<td>.741</td>
<td>10,500</td>
<td>6</td>
<td>3.5</td>
<td>162.8</td>
</tr>
</tbody>
</table>

(a) Candidate fracture toughness values, K_Q, are invalid as K_Ic values since a, T, < 2.5 (K_Q / TYS).
### TABLE XXII. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED PH 13-8 Mo (H1000) FORGED BAR (LONGITUDINAL)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Room Temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>215.0</td>
<td>14,490</td>
</tr>
<tr>
<td>5-2</td>
<td>210.0</td>
<td>26,120</td>
</tr>
<tr>
<td>5-3</td>
<td>205.0</td>
<td>35,190</td>
</tr>
<tr>
<td>5-4</td>
<td>200.0</td>
<td>61,570</td>
</tr>
<tr>
<td>5-5</td>
<td>195.0</td>
<td>65,470</td>
</tr>
<tr>
<td>5-6</td>
<td>190.0</td>
<td>247,050</td>
</tr>
<tr>
<td>5-7</td>
<td>180.0</td>
<td>333,330</td>
</tr>
<tr>
<td>5-8</td>
<td>175.0</td>
<td>4,404,800</td>
</tr>
<tr>
<td>5-9</td>
<td>170.0</td>
<td>785,900</td>
</tr>
<tr>
<td>5-10</td>
<td>170.0</td>
<td>730,900</td>
</tr>
<tr>
<td>5-11</td>
<td>160.0</td>
<td>458,000</td>
</tr>
<tr>
<td>5-12</td>
<td>150.0</td>
<td>10,010,000(a)</td>
</tr>
<tr>
<td><strong>400 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-15</td>
<td>200.0</td>
<td>100</td>
</tr>
<tr>
<td>5-14</td>
<td>190.0</td>
<td>17,400</td>
</tr>
<tr>
<td>5-12</td>
<td>180.0</td>
<td>151,000</td>
</tr>
<tr>
<td>5-11</td>
<td>170.0</td>
<td>42,900</td>
</tr>
<tr>
<td>5-16</td>
<td>170.0</td>
<td>1,015,600</td>
</tr>
<tr>
<td>5-18</td>
<td>165.0</td>
<td>10,329,900(a)</td>
</tr>
<tr>
<td>5-17</td>
<td>160.0</td>
<td>10,407,300(a)</td>
</tr>
<tr>
<td><strong>700 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-22</td>
<td>170.0</td>
<td>(b)</td>
</tr>
<tr>
<td>5-26</td>
<td>165.0</td>
<td>200</td>
</tr>
<tr>
<td>5-24</td>
<td>160.0</td>
<td>33,960</td>
</tr>
<tr>
<td>5-21</td>
<td>155.0</td>
<td>28,900</td>
</tr>
<tr>
<td>5-29</td>
<td>150.0</td>
<td>945,500(a)</td>
</tr>
<tr>
<td>5-23</td>
<td>150.0</td>
<td>10,090,700(a)</td>
</tr>
</tbody>
</table>

(a) Did not fail.

(b) Failed on loading.
TABLE XXIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED \( K_t = 3.0 \) PH 13-8 Mo (H1000) FORGED BAR (LONGITUDINAL)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Room Temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>180.0</td>
<td>1,410</td>
</tr>
<tr>
<td>5-2</td>
<td>160.0</td>
<td>1,900</td>
</tr>
<tr>
<td>5-3</td>
<td>140.0</td>
<td>3,800</td>
</tr>
<tr>
<td>5-5</td>
<td>120.0</td>
<td>7,910</td>
</tr>
<tr>
<td>5-6</td>
<td>100.0</td>
<td>32,830</td>
</tr>
<tr>
<td>5-7</td>
<td>80.0</td>
<td>72,800</td>
</tr>
<tr>
<td>5-8</td>
<td>60.0</td>
<td>210,000</td>
</tr>
<tr>
<td>5-9</td>
<td>50.0</td>
<td>17,555,500(a)</td>
</tr>
<tr>
<td></td>
<td><strong>400 F</strong></td>
<td></td>
</tr>
<tr>
<td>5-11</td>
<td>180.0</td>
<td>1,100</td>
</tr>
<tr>
<td>5-12</td>
<td>170.0</td>
<td>1,700</td>
</tr>
<tr>
<td>5-13</td>
<td>160.0</td>
<td>1,800</td>
</tr>
<tr>
<td>5-14</td>
<td>140.0</td>
<td>1,350</td>
</tr>
<tr>
<td>5-15</td>
<td>120.0</td>
<td>1,500</td>
</tr>
<tr>
<td>5-16</td>
<td>100.0</td>
<td>8,100</td>
</tr>
<tr>
<td>5-17</td>
<td>90.0</td>
<td>26,400</td>
</tr>
<tr>
<td>5-18</td>
<td>80.0</td>
<td>60,500</td>
</tr>
<tr>
<td>5-19</td>
<td>70.0</td>
<td>14,754,700(a)</td>
</tr>
<tr>
<td>5-20</td>
<td>60.0</td>
<td>10,192,200(a)</td>
</tr>
<tr>
<td></td>
<td><strong>700 F</strong></td>
<td></td>
</tr>
<tr>
<td>5-21</td>
<td>100.0</td>
<td>3,900</td>
</tr>
<tr>
<td>5-23</td>
<td>90.0</td>
<td>18,300</td>
</tr>
<tr>
<td>5-26</td>
<td>85.0</td>
<td>16,900</td>
</tr>
<tr>
<td>5-22</td>
<td>80.0</td>
<td>599,800</td>
</tr>
<tr>
<td>5-27</td>
<td>75.0</td>
<td>1,344,700</td>
</tr>
<tr>
<td>5-24</td>
<td>70.0</td>
<td>5,358,700</td>
</tr>
<tr>
<td>5-25</td>
<td>60.0</td>
<td>14,928,700(a)</td>
</tr>
</tbody>
</table>

(a) Did not fail.
### TABLE XXIV. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF PH 13-8 Mo (H1000) FORGED BAR (LONGITUDINAL)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress, ksi</th>
<th>Temp, F</th>
<th>Hours to Indicated Creep Deformation, percent</th>
<th>Initial Strain, percent</th>
<th>Rupture Time, hr</th>
<th>Elongation in 2 in., percent</th>
<th>Reduction of Area, percent</th>
<th>Minimum Creep Rate, percent/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-3</td>
<td>171.5</td>
<td>500</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>On Loading</td>
<td>9.6</td>
<td>44.2</td>
</tr>
<tr>
<td>3-4</td>
<td>165</td>
<td>500</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.01</td>
<td>9.6</td>
<td>54.7</td>
</tr>
<tr>
<td>3-5</td>
<td>160</td>
<td>500</td>
<td>0.14</td>
<td>2.6</td>
<td>107</td>
<td>1100</td>
<td>0.904</td>
<td>1078.0 (a)</td>
</tr>
<tr>
<td>3-10</td>
<td>140</td>
<td>500</td>
<td>2900 (b)</td>
<td>4800 (b)</td>
<td>---</td>
<td>---</td>
<td>0.763</td>
<td>1027.5 (a)</td>
</tr>
<tr>
<td>3-8</td>
<td>140</td>
<td>700</td>
<td>0.07</td>
<td>0.25</td>
<td>1.1</td>
<td>3.6</td>
<td>0.804</td>
<td>29.4</td>
</tr>
<tr>
<td>3-2</td>
<td>120</td>
<td>700</td>
<td>3</td>
<td>15</td>
<td>130</td>
<td>716</td>
<td>0.571</td>
<td>836.9 (a)</td>
</tr>
<tr>
<td>3-9</td>
<td>100</td>
<td>700</td>
<td>70</td>
<td>620</td>
<td>3600 (b)</td>
<td>---</td>
<td>0.507</td>
<td>667.6 (a)</td>
</tr>
<tr>
<td>3-6</td>
<td>100</td>
<td>300</td>
<td>---</td>
<td>0.08</td>
<td>0.15</td>
<td>0.4</td>
<td>0.637</td>
<td>21.5</td>
</tr>
<tr>
<td>3-1</td>
<td>70</td>
<td>900</td>
<td>0.2</td>
<td>0.6</td>
<td>3.5</td>
<td>9.5</td>
<td>0.362</td>
<td>196.3</td>
</tr>
<tr>
<td>3-7</td>
<td>53</td>
<td>900</td>
<td>1.0</td>
<td>3.3</td>
<td>30</td>
<td>175</td>
<td>0.277</td>
<td>201.2 (a)</td>
</tr>
<tr>
<td>3-313</td>
<td>30</td>
<td>900</td>
<td>95</td>
<td>625</td>
<td>2600 (b)</td>
<td>---</td>
<td>0.033</td>
<td>524.8 (a)</td>
</tr>
</tbody>
</table>

(a) Test discontinued.
(b) Estimate.
FIGURE 22. TYPICAL TENSILE STRESS-STRAIN CURVES FOR PH 13-8 Mo (H1000) FORGED BAR (LONGITUDINAL)
FIGURE 23. TYPICAL TENSILE STRESS-STRAIN CURVES FOR PH 13-8 Mo (H1000) FORGED BAR (LONG TRANSVERSE)
FIGURE 24. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR PH 13-8 Mo (H1000) FORCED BAR (LONGITUDINAL)
FIGURE 25. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR PH 13-8 Mo (H1000) FORGED BAR (LONG TRANSVERSE)
FIGURE 26. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF PH 13-8 Mo (H1000) FORGED BAR

FIGURE 27. EFFECT OF TEMPERATURE ON THE COMPRESSION PROPERTIES OF PH 13-8 Mo (H1000) FORGED BAR
FIGURE 28. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED PH 13-8 Mo (H1000) FORGED BAR

FIGURE 29. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) PH 13-8 Mo (H1000) FORGED BAR
FIGURE 30. STRESS-RUPTURE AND CREEP DEFORMATION CURVES FOR PH 13-8 Mo (H1000) FORGED BAR (LONGITUDINAL.)
Material Description

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

The material evaluated was a 4-inch x 4-inch extrusion supplied by Kaiser with the following composition:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>7.6</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.5</td>
</tr>
<tr>
<td>Copper</td>
<td>1.5</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.15</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.25 max</td>
</tr>
<tr>
<td>Iron</td>
<td>0.35 max</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.10 max</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.20 max</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Processing and Heat Treating

The specimen layout for 7049 is shown in Figure 31. Specimens were tested in the as-received -T76 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 XXV. Room temperature short transverse tensile test results are also given in Table XXV. 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, 250 F, 350 F, and 500 F are given in Table XXVI. Compressive stress-strain and tangent modulus curves at temperature are presented in Figures 34 and 35. Effect-of-temperature curves are presented in Figure 37.

Shear. Pin shear test results for longitudinal and transverse specimens at room temperature are shown in Table XXVII.
Impact. Charpy test results for longitudinal and transverse specimens at room temperature are shown in Table XXVII.

Fracture Toughness. Slow-bend type tests were performed for six longitudinal specimens. Results are shown in Table XXIX. Since the size ratio, $2.5 \left(\frac{K_Q}{TYS}\right)^2$, was greater than both the specimen thickness and crack length in all tests, the $K_Q$ values are not valid $K_{IC}$ values by existing ASTM criteria.

Fatigue. Axial-load fatigue tests were conducted on transverse specimens at room temperature, 250°F, and 350°F. Tabular test results are presented in Tables XXX and XXXI. S-N curves are shown in Figures 38 and 39.

Creep and Stress-Rupture. Results for transverse tests at 250°F, 350°F, and 500°F are shown in Table XXXII. Log-stress versus log-time curves are presented in Figure 40.

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. Coefficient of thermal expansion for this alloy is $12.9 \times 10^{-6}$ in/in/°F for 80°F to 212°F.

Density. The density for this material is 0.099 lb/in³.
<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Elongation in 1 Inch, percent</th>
<th>Reduction in Area, percent</th>
<th>Tensile Modulus, $10^3$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal at Room Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-1</td>
<td>81.1</td>
<td>72.2</td>
<td>13.0</td>
<td>35.9</td>
<td>10.6</td>
</tr>
<tr>
<td>IL-2</td>
<td>82.1</td>
<td>74.6</td>
<td>13.0</td>
<td>34.7</td>
<td>11.0</td>
</tr>
<tr>
<td>IL-3</td>
<td>86.9</td>
<td>81.0</td>
<td>12.0</td>
<td>36.3</td>
<td>10.5</td>
</tr>
<tr>
<td>Transverse at Room Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT-1</td>
<td>76.2</td>
<td>67.2</td>
<td>11.5</td>
<td>23.3</td>
<td>9.5</td>
</tr>
<tr>
<td>IT-2</td>
<td>76.2</td>
<td>67.7</td>
<td>11.0</td>
<td>23.2</td>
<td>9.9</td>
</tr>
<tr>
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</tr>
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<td>10.4</td>
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<tr>
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<td>93.0</td>
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<td>15.9</td>
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TABLE XXVI. COMPRESSION TEST RESULTS FOR 7049-T76 EXTRUSIONS

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^5$ psi</th>
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<tbody>
<tr>
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<td>2L-2</td>
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<td>11.0</td>
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<td>2L-3</td>
<td>79.6</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transverse at Room Temperature</td>
</tr>
<tr>
<td>2T-1</td>
<td>75.0</td>
<td>10.8</td>
</tr>
<tr>
<td>2T-2</td>
<td>73.0</td>
<td>9.9</td>
</tr>
<tr>
<td>2T-3</td>
<td>76.2</td>
<td>10.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal at 250 F</td>
</tr>
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<td>2L-4</td>
<td>66.4</td>
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</tr>
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<td>Transverse at 250 F</td>
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<td>2T-4</td>
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<td>10.4</td>
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<td>2T-5</td>
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<td></td>
<td></td>
<td>Longitudinal at 350 F</td>
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<td>2L-8</td>
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<td>9.1</td>
</tr>
<tr>
<td>2L-9</td>
<td>50.4</td>
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<td>9.2</td>
</tr>
<tr>
<td>2T-9</td>
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<td>Longitudinal at 500 F</td>
</tr>
<tr>
<td>2L-10</td>
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<td>6.6</td>
</tr>
<tr>
<td>2L-11</td>
<td>19.4</td>
<td>6.3</td>
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<td>2L-12</td>
<td>19.0</td>
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<td></td>
<td></td>
<td>Transverse at 500 F</td>
</tr>
<tr>
<td>2T-10</td>
<td>17.6</td>
<td>8.0</td>
</tr>
<tr>
<td>2T-11</td>
<td>17.8</td>
<td>7.4</td>
</tr>
<tr>
<td>2T-12</td>
<td>17.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Specimen Number</td>
<td>Ultimate Shear Strength, ksi</td>
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</tr>
<tr>
<td>-----------------</td>
<td>-----------------------------</td>
<td></td>
</tr>
<tr>
<td>4L-1</td>
<td>45.1</td>
<td></td>
</tr>
<tr>
<td>4L-2</td>
<td>45.6</td>
<td></td>
</tr>
<tr>
<td>4L-3</td>
<td>44.6</td>
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<td>4T-2</td>
<td>44.9</td>
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<tr>
<td>4T-4</td>
<td>41.8</td>
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</table>

**Longitudinal**

**Transverse**
TABLE XXVIII. IMPACT TEST RESULTS FOR 7049-T76 EXTRUSIONS AT ROOM TEMPERATURE

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Energy, ft/lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal</strong></td>
<td></td>
</tr>
<tr>
<td>10L-1</td>
<td>6.5</td>
</tr>
<tr>
<td>10L-2</td>
<td>5.0</td>
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<tr>
<td>10L-3</td>
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<tr>
<td>10L-4</td>
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<td>10L-5</td>
<td>7.0</td>
</tr>
<tr>
<td>10L-6</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Transverse</strong></td>
<td></td>
</tr>
<tr>
<td>10T-1</td>
<td>1.5</td>
</tr>
<tr>
<td>10T-2</td>
<td>2.0</td>
</tr>
<tr>
<td>10T-3</td>
<td>1.5</td>
</tr>
<tr>
<td>10T-4</td>
<td>2.0</td>
</tr>
<tr>
<td>10T-5</td>
<td>1.0</td>
</tr>
<tr>
<td>10T-6</td>
<td>1.5</td>
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</tbody>
</table>
TABLE XXIX. FRACTURE TOUGHNESS TEST RESULTS FOR 7049-T76 EXTRUSIONS (LONGITUDINAL)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>W, inches</th>
<th>a, inches</th>
<th>T, inches</th>
<th>P, lb</th>
<th>Span, inches</th>
<th>$\frac{f(a)}{W}$</th>
<th>$\overline{\cal{K}}_Q$ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6L</td>
<td>1.500</td>
<td>.830</td>
<td>.750</td>
<td>3,440</td>
<td>6</td>
<td>3.1</td>
<td>47.7</td>
</tr>
<tr>
<td>5L</td>
<td>1.500</td>
<td>.848</td>
<td>.7</td>
<td>3,870</td>
<td>6</td>
<td>3.2</td>
<td>55.3</td>
</tr>
<tr>
<td>1L</td>
<td>1.501</td>
<td>.866</td>
<td>.751</td>
<td>3,720</td>
<td>6</td>
<td>3.4</td>
<td>56.0</td>
</tr>
<tr>
<td>3L</td>
<td>1.501</td>
<td>.850</td>
<td>.750</td>
<td>3,850</td>
<td>6</td>
<td>3.3</td>
<td>55.9</td>
</tr>
<tr>
<td>2L</td>
<td>1.502</td>
<td>.859</td>
<td>.750</td>
<td>3,650</td>
<td>6</td>
<td>3.4</td>
<td>54.0</td>
</tr>
<tr>
<td>4L</td>
<td>1.509</td>
<td>.854</td>
<td>.750</td>
<td>3,800</td>
<td>6</td>
<td>3.3</td>
<td>55.8</td>
</tr>
</tbody>
</table>

(a) Candidate fracture toughness values, $\overline{\cal{K}}_Q$, are invalid as $K_{IC}$ values since $a, T, \frac{f(a)}{W} < 2.5 \left( \frac{\cal{K}}{\cal{K}_{YS}} \right)$. 
TABLE XXX. AXIAL-LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 7049-T76 EXTRUSIONS (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Room Temperature</td>
</tr>
<tr>
<td>5-4</td>
<td>65.0</td>
<td>9,300</td>
</tr>
<tr>
<td>5-3</td>
<td>60.0</td>
<td>68,340</td>
</tr>
<tr>
<td>5-2</td>
<td>55.0</td>
<td>86,030</td>
</tr>
<tr>
<td>5-1</td>
<td>50.0</td>
<td>177,220</td>
</tr>
<tr>
<td>5-5</td>
<td>45.0</td>
<td>7,075,410</td>
</tr>
<tr>
<td>5-6</td>
<td>40.0</td>
<td>9,717,860</td>
</tr>
<tr>
<td></td>
<td></td>
<td>250 F</td>
</tr>
<tr>
<td>5-17</td>
<td>65.0</td>
<td>11,950</td>
</tr>
<tr>
<td>5-19</td>
<td>62.5</td>
<td>26,240</td>
</tr>
<tr>
<td>5-15</td>
<td>66.0</td>
<td>29,530</td>
</tr>
<tr>
<td>5-20</td>
<td>57.5</td>
<td>84,050</td>
</tr>
<tr>
<td>5-16</td>
<td>55.0</td>
<td>289,210</td>
</tr>
<tr>
<td>5-21</td>
<td>52.5</td>
<td>540,560</td>
</tr>
<tr>
<td>5-18</td>
<td>50.0</td>
<td>10,199,430</td>
</tr>
<tr>
<td></td>
<td></td>
<td>350 F</td>
</tr>
<tr>
<td>5-7</td>
<td>60.0</td>
<td>19,790</td>
</tr>
<tr>
<td>5-10</td>
<td>55.0</td>
<td>54,760</td>
</tr>
<tr>
<td>5-8</td>
<td>55.0</td>
<td>217,850</td>
</tr>
<tr>
<td>5-12</td>
<td>52.5</td>
<td>49,11G</td>
</tr>
<tr>
<td>5-11</td>
<td>50.0</td>
<td>1,457,64J</td>
</tr>
<tr>
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<td>47.5</td>
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<td>5-9</td>
<td>45.0</td>
<td>6,006,900</td>
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<tr>
<td>5-22</td>
<td>40.0</td>
<td>11,429,780</td>
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</table>

(a) Did not fail.
# TABLE XXXI. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED \((K_t = 3.0)\) 7049-T76 EXTRUSIONS (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-19</td>
<td>40.0</td>
<td>6,840</td>
</tr>
<tr>
<td>5-1</td>
<td>35.0</td>
<td>15,410</td>
</tr>
<tr>
<td>5-2</td>
<td>30.0</td>
<td>19,030</td>
</tr>
<tr>
<td>5-3</td>
<td>25.0</td>
<td>31,270</td>
</tr>
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<td>5-4</td>
<td>20.0</td>
<td>144,750</td>
</tr>
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<td>5-5</td>
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<tr>
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<td>558,590</td>
</tr>
<tr>
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<td>13.5</td>
<td>331,080</td>
</tr>
<tr>
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<td>10.0</td>
<td>15,146,300(^{(a)})</td>
</tr>
<tr>
<td>250 F</td>
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<tr>
<td>5-16</td>
<td>35.0</td>
<td>7,640</td>
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<td>32.5</td>
<td>9,690</td>
</tr>
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<td>20,040</td>
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<td>27.5</td>
<td>23,810</td>
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<td>25.0</td>
<td>19,860</td>
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<td>5-18</td>
<td>25.0</td>
<td>934,090</td>
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<tr>
<td>5-24</td>
<td>20.0</td>
<td>841,400</td>
</tr>
<tr>
<td>5-25</td>
<td>10.0</td>
<td>843,100</td>
</tr>
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<td>5-26</td>
<td>5.0</td>
<td>10,016,090(^{(a)})</td>
</tr>
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<td></td>
</tr>
<tr>
<td>5-9</td>
<td>35.0</td>
<td>9,350</td>
</tr>
<tr>
<td>5-10</td>
<td>30.0</td>
<td>20,760</td>
</tr>
<tr>
<td>5-11</td>
<td>25.0</td>
<td>19,620</td>
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<td>5-14</td>
<td>10.0</td>
<td>652,300(^{(a)})</td>
</tr>
<tr>
<td>5-15</td>
<td>5.0</td>
<td>10,062,800(^{(a)})</td>
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</table>

\(^{(a)}\) Did not fail.
TABLE XXXII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF 7046-T76 ALUMINUM EXTRUSIONS (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress, ksi</th>
<th>Temp, F</th>
<th>Hours to Indicated Creep Deformation, percent</th>
<th>Initial Strain, percent</th>
<th>Rupture Time, hr</th>
<th>Elongation in 2 in., percent</th>
<th>Reduction of Area, percent</th>
<th>Minimum Creep Rate, percent/hr</th>
</tr>
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<tbody>
<tr>
<td>7046-31</td>
<td>50</td>
<td>250</td>
<td>0.2</td>
<td>0.7</td>
<td>2.7</td>
<td>6.4</td>
<td>---</td>
<td>0.592</td>
</tr>
<tr>
<td>7049-33</td>
<td>60</td>
<td>250</td>
<td>10</td>
<td>50</td>
<td>183</td>
<td>322</td>
<td>450</td>
<td>0.489</td>
</tr>
<tr>
<td>7049-36</td>
<td>35</td>
<td>250</td>
<td>40</td>
<td>165</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>0.459</td>
</tr>
<tr>
<td>7049-39</td>
<td>30</td>
<td>250</td>
<td>50</td>
<td>350</td>
<td>1670 (b)</td>
<td>---</td>
<td>---</td>
<td>0.315</td>
</tr>
<tr>
<td>7049-32</td>
<td>25</td>
<td>350</td>
<td>0.8</td>
<td>2.4</td>
<td>6.5</td>
<td>9</td>
<td>---</td>
<td>0.377</td>
</tr>
<tr>
<td>7049-34</td>
<td>15</td>
<td>350</td>
<td>22</td>
<td>52</td>
<td>125</td>
<td>200</td>
<td>270</td>
<td>0.263</td>
</tr>
<tr>
<td>7049-35</td>
<td>9.5</td>
<td>350</td>
<td>145</td>
<td>390</td>
<td>1160 (b)</td>
<td>---</td>
<td>---</td>
<td>0.104</td>
</tr>
<tr>
<td>7049-37</td>
<td>7</td>
<td>500</td>
<td>0.4</td>
<td>1.0</td>
<td>2.6</td>
<td>4.5</td>
<td>7.1</td>
<td>0.113</td>
</tr>
<tr>
<td>7049-38</td>
<td>5</td>
<td>500</td>
<td>1.7</td>
<td>5.0</td>
<td>12</td>
<td>25</td>
<td>43</td>
<td>0.037</td>
</tr>
<tr>
<td>7049-310</td>
<td>3.5</td>
<td>500</td>
<td>5</td>
<td>25</td>
<td>60</td>
<td>160</td>
<td>220</td>
<td>0.033</td>
</tr>
<tr>
<td>7049-311</td>
<td>1.9</td>
<td>500</td>
<td>60</td>
<td>425</td>
<td>2100 (b)</td>
<td>---</td>
<td>---</td>
<td>0.070</td>
</tr>
</tbody>
</table>

(a) Test discontinued.
(b) Estimate.
FIGURE 32. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 7049-T76 EXTRUSIONS (LONGITUDINAL)
FIGURE 33. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 7049-T76 EXTRUSIONS (TRANSVERSE)
FIGURE 34. TYPICAL COMpressive STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 7049-T76 EXTRUSION (LONCITUDINAL.)
FIGURE 35. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 7049-176 EXTRUSION (TRANSVERSE)
FIGURE 36. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T76 EXTRUSION

FIGURE 37. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T76 EXTRUSION
FIGURE 38. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED 7079-T76 EXTRUSIONS

FIGURE 39. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED \( K_L = 3.0 \) 7049-T76 EXTRUSIONS
FIGURE 40. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7049-T76 EXTRUSIONS (TRANSVERSE)
Ti-6Al-2Sn-4Zr-6Mo Alloy

Material Description

Initially, this alloy was developed by the Titanium Metals Corporation as an off-shoot of the Ti-6Al-2Sn-4Zr-2Mo high temperature alloy. Studies had shown that increasing the molybdenum content beyond the 2 percent level resulted in an alloy having improved room and elevated temperature strength with good creep resistance. During early development, investigations were limited to the evaluation of the alloy as a heavy section forging alloy. Promising high temperature properties achieved in heat-treated sections up to 3 inches suggested the alloy might also be useful as a sheet alloy since it should be air hardenable at sheet gages.

The material used in this evaluation was 0.075 inch sheet obtained from TMCA. It had the following composition:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>5.98</td>
</tr>
<tr>
<td>Tin</td>
<td>1.99</td>
</tr>
<tr>
<td>Zirconium</td>
<td>3.94</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>5.86</td>
</tr>
<tr>
<td>Iron</td>
<td>0.057</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.10</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.004</td>
</tr>
<tr>
<td>Titanium</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Processing and Heat Treating

The specimen layout for this alloy is shown in Figure 41. Specimens were machined in the as-received condition and heat-treated as follows:

(1) 1600 F, 15 minutes, air cooled,
(2) 1325 F, 15 minutes, air cooled,
(3) 1100 F, 2 hours, air cooled.

This was suggested by TMCA and is called the "strengthened and heat-treated" condition.

Test Results

Tension. Results of tests in the longitudinal and transverse directions at room temperature, 400 F, 700 F, and 1000 F are given in Table XXXIII.
strain curves at temperature are presented in Figures 42 and 43. Effect-of-
temperature curves are shown in Figure 46.

**Compression.** Test results for longitudinal and transverse specimens
at room temperature, 400 F, 700 F, and 1000 F are shown in Table XXXIV. Stress-
strain and tangent modulus curves at temperature are presented in Figures 44
and 45. Effect-of-temperature curves are presented in Figure 47.

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

**Fracture Toughness.** Test specimens were the full sheet thickness (0.075-
inches) x 18 inches x 36 inches with an EDM flaw in the center. The 36 inch specimen
dimension was parallel to longitudinal grain direction of sheets. The average $K_c$
value obtained was 132 ksi $\sqrt{\text{in}}$. The net section yield stress at fracture was
less than the tensile yield strength of the material. Therefore, the $K_c$ value is
considered valid.

**Fatigue.** Results of axial-load fatigue tests for transverse specimens,
both unnotched and notched, at room temperature, 400 F, and 700 F are given in
Tables XXXVI and XXXVII. S-N curves are presented in Figures 48 and 49.

**Creep and Stress-Rupture.** Tests were conducted at 700 F, 900 F, and
1100 F. Tabular results are given in Table XXXVIII. Log-stress versus log-
time curves are presented in Figure 50.

**Stress Corrosion.** Testing was conducted as described in the experi-
mental procedure 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 $5.5 \times 10^{-5}$ in/in/F for 80 F to 1000 F.

**Density.** The density of this alloy is 0.165 lb/in$^3$. 


TABLE XXXIII. TENSILE TEST RESULTS FOR Ti-6Al-2Sn-4Zr-6Y SHEET

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Elongation in 2 inches, percent</th>
<th>Tensile Modulus, 10^6 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinal at Room Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-1</td>
<td>168.0</td>
<td>160.0</td>
<td>16.0</td>
<td>17.5</td>
</tr>
<tr>
<td>L1-2</td>
<td>168.0</td>
<td>160.0</td>
<td>10.0</td>
<td>17.7</td>
</tr>
<tr>
<td>L1-3</td>
<td>168.0</td>
<td>160.0</td>
<td>11.0</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>Transverse at Room Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-1</td>
<td>169.0</td>
<td>163.0</td>
<td>10.0</td>
<td>17.2</td>
</tr>
<tr>
<td>L1-2</td>
<td>170.0</td>
<td>163.0</td>
<td>11.0</td>
<td>17.2</td>
</tr>
<tr>
<td>L1-3</td>
<td>169.0</td>
<td>163.0</td>
<td>14.0</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>Longitudinal at 400 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-4</td>
<td>149.0</td>
<td>129.0</td>
<td>14.5</td>
<td>16.4</td>
</tr>
<tr>
<td>L1-5</td>
<td>148.0</td>
<td>127.0</td>
<td>15.0</td>
<td>16.2</td>
</tr>
<tr>
<td>L1-6</td>
<td>148.0</td>
<td>127.0</td>
<td>15.0</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>Transverse at 400 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-4</td>
<td>150.0</td>
<td>130.0</td>
<td>14.0</td>
<td>15.4</td>
</tr>
<tr>
<td>L1-5</td>
<td>150.0</td>
<td>131.0</td>
<td>14.5</td>
<td>15.7</td>
</tr>
<tr>
<td>L1-6</td>
<td>150.0</td>
<td>131.0</td>
<td>14.0</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>Longitudinal at 700 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-7</td>
<td>141.0</td>
<td>114.0</td>
<td>14.0</td>
<td>14.9</td>
</tr>
<tr>
<td>L1-8</td>
<td>141.0</td>
<td>115.0</td>
<td>14.0</td>
<td>15.4</td>
</tr>
<tr>
<td>L1-9</td>
<td>140.0</td>
<td>114.0</td>
<td>15.5</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Transverse at 700 F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1-7</td>
<td>141.0</td>
<td>117.0</td>
<td>15.0</td>
<td>14.7</td>
</tr>
<tr>
<td>L1-8</td>
<td>142.0</td>
<td>117.0</td>
<td>14.0</td>
<td>14.5</td>
</tr>
<tr>
<td>L1-9</td>
<td>143.0</td>
<td>117.0</td>
<td>14.0</td>
<td>14.7</td>
</tr>
</tbody>
</table>
TABLE XXXIII. (Concluded)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Longation in 2 inches, percent</th>
<th>Tensile Modulus, $10^6$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal at 1000 F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1L-10</td>
<td>107.0</td>
<td>98.2</td>
<td>29.0</td>
<td>13.1</td>
</tr>
<tr>
<td>1L-11</td>
<td>104.0</td>
<td>96.0</td>
<td>41.0</td>
<td>12.6</td>
</tr>
<tr>
<td>1L-12</td>
<td>105.0</td>
<td>97.8</td>
<td>39.0</td>
<td>12.6</td>
</tr>
<tr>
<td><strong>Transverse at 1000 F</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1T-10</td>
<td>106.0</td>
<td>98.5</td>
<td>35.0</td>
<td>12.6</td>
</tr>
<tr>
<td>1T-11</td>
<td>108.0</td>
<td>99.5</td>
<td>35.0</td>
<td>12.8</td>
</tr>
<tr>
<td>1T-12</td>
<td>106.0</td>
<td>98.8</td>
<td>36.0</td>
<td>13.0</td>
</tr>
</tbody>
</table>
TABLE XXXIV. COMPRESSION TEST RESULTS FOR Ti-6Al-2Sn-4Zr-6Mo SHEET

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^5$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Longitudinal at Room Temperature</td>
</tr>
<tr>
<td>2L-1</td>
<td>167.0</td>
<td>19.1</td>
</tr>
<tr>
<td>2L-2</td>
<td>167.0</td>
<td>19.6</td>
</tr>
<tr>
<td>2L-3</td>
<td>168.0</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transverse at Room Temperature</td>
</tr>
<tr>
<td>2T-1</td>
<td>169.0</td>
<td>18.8</td>
</tr>
<tr>
<td>2T-2</td>
<td>171.0</td>
<td>18.9</td>
</tr>
<tr>
<td>2T-3</td>
<td>172.0</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal at 400 F</td>
</tr>
<tr>
<td>2L-4</td>
<td>133.0</td>
<td>17.9</td>
</tr>
<tr>
<td>2L-5</td>
<td>133.0</td>
<td>17.9</td>
</tr>
<tr>
<td>2L-6</td>
<td>134.0</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transverse at 400 F</td>
</tr>
<tr>
<td>T-4</td>
<td>136.0</td>
<td>17.5</td>
</tr>
<tr>
<td>2T-5</td>
<td>138.0</td>
<td>17.8</td>
</tr>
<tr>
<td>2T-6</td>
<td>138.0</td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal at 700 F</td>
</tr>
<tr>
<td>2L-7</td>
<td>123.0</td>
<td>16.2</td>
</tr>
<tr>
<td>2L-8</td>
<td>124.0</td>
<td>16.4</td>
</tr>
<tr>
<td>2L-9</td>
<td>123.0</td>
<td>16.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transverse at 700 F</td>
</tr>
<tr>
<td>2T-7</td>
<td>127.0</td>
<td>16.1</td>
</tr>
<tr>
<td>2T-8</td>
<td>127.0</td>
<td>16.1</td>
</tr>
<tr>
<td>2T-9</td>
<td>126.0</td>
<td>16.1</td>
</tr>
</tbody>
</table>

83
<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Longitudinal at 1000 F</th>
<th>Transverse at 1900 F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C.2 Percent Offset Yield Strength, ksi</td>
<td>Compression Modulus, $10^6$ psi</td>
</tr>
<tr>
<td>L-10</td>
<td>110.0</td>
<td>13.8</td>
</tr>
<tr>
<td>L-11</td>
<td>113.0</td>
<td>14.1</td>
</tr>
<tr>
<td>L-12</td>
<td>109.6</td>
<td>13.7</td>
</tr>
<tr>
<td>T-10</td>
<td>112.0</td>
<td>13.4</td>
</tr>
<tr>
<td>T-11</td>
<td>113.0</td>
<td>13.7</td>
</tr>
<tr>
<td>T-12</td>
<td>113.6</td>
<td>13.7</td>
</tr>
</tbody>
</table>
TABLE XXXV  SHEAR TEST RESULTS FOR Ti-6Al-2Sn-4Zr-6Mo
SHEET AT ROOM TEMPERATURE

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Shear Strength, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td></td>
</tr>
<tr>
<td>4L1</td>
<td>97.3</td>
</tr>
<tr>
<td>4L2</td>
<td>96.4</td>
</tr>
<tr>
<td>4L3</td>
<td>(a)</td>
</tr>
<tr>
<td>4L4</td>
<td>96.8</td>
</tr>
<tr>
<td>Transverse</td>
<td></td>
</tr>
<tr>
<td>4T1</td>
<td>(a)</td>
</tr>
<tr>
<td>4T2</td>
<td>98.2</td>
</tr>
<tr>
<td>4T3</td>
<td>98.1</td>
</tr>
<tr>
<td>4T4</td>
<td>98.0</td>
</tr>
</tbody>
</table>

(a) Did not fail in shear.
<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Room Temperature</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-7</td>
<td>120.0</td>
<td>102,620</td>
</tr>
<tr>
<td>5-1</td>
<td>115.0</td>
<td>43,920</td>
</tr>
<tr>
<td>5-5</td>
<td>112.5</td>
<td>1,864,250</td>
</tr>
<tr>
<td>5-2</td>
<td>110.0</td>
<td>59,270</td>
</tr>
<tr>
<td>5-4</td>
<td>107.5</td>
<td>6,079,870</td>
</tr>
<tr>
<td>5-6</td>
<td>105.0</td>
<td>495,200</td>
</tr>
<tr>
<td>5-8</td>
<td>90.0</td>
<td>12,007,080       (a)</td>
</tr>
<tr>
<td><strong>400 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-19</td>
<td>125.0</td>
<td>28,600</td>
</tr>
<tr>
<td>5-20</td>
<td>122.5</td>
<td>17,100</td>
</tr>
<tr>
<td>5-18</td>
<td>120.0</td>
<td>1,666,400</td>
</tr>
<tr>
<td>5-22</td>
<td>117.5</td>
<td>68,700</td>
</tr>
<tr>
<td>5-21</td>
<td>115.0</td>
<td>5,420,300</td>
</tr>
<tr>
<td>5-23</td>
<td>110.0</td>
<td>64,300</td>
</tr>
<tr>
<td>5-24</td>
<td>100.0</td>
<td>573,000          (a)</td>
</tr>
<tr>
<td>5-25</td>
<td>90.0</td>
<td>12,837,230       (a)</td>
</tr>
<tr>
<td><strong>700 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-9</td>
<td>120.0</td>
<td>9,300</td>
</tr>
<tr>
<td>5-10</td>
<td>115.0</td>
<td>14,800</td>
</tr>
<tr>
<td>5-11</td>
<td>110.0</td>
<td>14,700</td>
</tr>
<tr>
<td>5-12</td>
<td>105.0</td>
<td>17,000</td>
</tr>
<tr>
<td>5-13</td>
<td>100.0</td>
<td>192,200</td>
</tr>
<tr>
<td>5-17</td>
<td>100.0</td>
<td>10,796,000       (a)</td>
</tr>
<tr>
<td>5-18</td>
<td>90.0</td>
<td>11,032,000       (a)</td>
</tr>
</tbody>
</table>

(a) Did not fail.
TABLE XXXVII. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED 
\((K_t = 3.0)\) Ti-6Al-2Sn-4Zr-6Mo 
SHEET (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Room Temperature</td>
</tr>
<tr>
<td>5-1</td>
<td>100.0</td>
<td>1,130</td>
</tr>
<tr>
<td>5-2</td>
<td>90.0</td>
<td>2,510</td>
</tr>
<tr>
<td>5-3</td>
<td>70.0</td>
<td>1,510</td>
</tr>
<tr>
<td>5-4</td>
<td>50.0</td>
<td>6,310</td>
</tr>
<tr>
<td>5-5</td>
<td>40.0</td>
<td>17,500</td>
</tr>
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<td>35.0</td>
<td>10,119,850 (a)</td>
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<td></td>
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<td>25.0</td>
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(a) Did not fail.
### TABLE XXXVIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES OF Ti-6Al-25-4Zr-6Mo SHEET (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Stress, ksi</th>
<th>Temperature, °F</th>
<th>Hours to Indicated Creep Deformation, percent</th>
<th>Initial Strain, percent</th>
<th>Rupture Time, hr</th>
<th>Elongation in 2 inches, percent</th>
<th>Minimum Creep Rate, percent/ hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-16</td>
<td>149</td>
<td>700</td>
<td>23.8</td>
<td>112 (b)</td>
<td>0.800</td>
<td>746.0 (a)</td>
<td>1.472</td>
</tr>
<tr>
<td>3-15</td>
<td>135</td>
<td>700</td>
<td>33.7</td>
<td>120 (b)</td>
<td>0.233</td>
<td>672.5 (a)</td>
<td>3.36</td>
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<td>120</td>
<td>700</td>
<td>27.7</td>
<td>505</td>
<td>0.800</td>
<td>746.0 (a)</td>
<td>1.472</td>
</tr>
<tr>
<td>3-5</td>
<td>110</td>
<td>700</td>
<td>67.1</td>
<td>112 (b)</td>
<td>0.800</td>
<td>746.0 (a)</td>
<td>1.472</td>
</tr>
<tr>
<td>3-8</td>
<td>120</td>
<td>700</td>
<td>27.7</td>
<td>120 (b)</td>
<td>0.800</td>
<td>746.0 (a)</td>
<td>1.472</td>
</tr>
<tr>
<td>3-10</td>
<td>60</td>
<td>900</td>
<td>14.9</td>
<td>120 (b)</td>
<td>0.800</td>
<td>746.0 (a)</td>
<td>1.472</td>
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<td>900</td>
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<td>428 (b)</td>
<td>0.144</td>
<td>143.7 (a)</td>
<td>0.391</td>
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<td>0.200</td>
<td>792.0 (a)</td>
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<td>10.04</td>
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<td>35</td>
<td>1100</td>
<td>0.09</td>
<td>0.22</td>
<td>0.34</td>
<td>0.67</td>
<td>0.324</td>
</tr>
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<td>3-3</td>
<td>35</td>
<td>1100</td>
<td>0.09</td>
<td>0.22</td>
<td>0.34</td>
<td>0.67</td>
<td>0.324</td>
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<td>1100</td>
<td>0.09</td>
<td>0.22</td>
<td>0.34</td>
<td>0.67</td>
<td>0.324</td>
</tr>
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<td>10</td>
<td>28</td>
<td>114</td>
<td>260 (b)</td>
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<td>95.4 (a)</td>
<td>0.498</td>
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<td>1</td>
<td>1100</td>
<td>425</td>
<td>1300 (b)</td>
<td>0.066</td>
<td>95.4 (a)</td>
<td>0.498</td>
</tr>
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</table>

(a) Test discontinued.
(b) Estimate
FIGURE 42. TYPICAL TENSILE STRESS-STRAIN CURVES FOR Ti-6Al-2Sn-4Zr-6Mo SHEET (LONGITUDINAL)
FIGURE 43. TYPICAL TENSILE STRESS-STRAIN CURVES FOR Ti-6Al-2Sn-4Zr-6Mo SHEET (TRANSVERSE)
FIGURE 44. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR Ti-6Al-2Sn-4Zr-6Mo SHEET (LONGITUDINAL)
FIGURE 45. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR TI-6Al-2Sn-4Zr-6Mo SHEET (TRANSVERSE)
FIGURE 46. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-2Sn-4Zr-6Mo SHEET

FIGURE 47. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-2Sn-4Zr-6Mo SHEET
FIGURE 48. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED Ti-6Al-2Sn-4Zr-6Mo SHEET

FIGURE 49. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) Ti-6Al-2Sn-4Zr-6Mo SHEET
Inconel 702 Alloy

Material Description

Inconel alloy 702 contains high aluminum content for excellent resistance to oxidation at temperatures up to 2400 F. At elevated temperatures, the surface of a nickel-rich, nickel-chromium alloy becomes covered with a compact layer of uniformly thick oxide; the aluminum content of alloy 702 improves the protective action of the oxide. Alloy 702 has good mechanical strength at high temperatures; age hardening improves the strength of the alloy up to about 1500 F.

The material used in this evaluation was 0.050 inch sheet from Huntington Alloy Products Division, Heat HT38C3DS. The composition was as follows:

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<th>Chemical Composition</th>
<th>Percent</th>
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<tr>
<td>Manganese</td>
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<tr>
<td>Iron</td>
<td>0.32</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.007</td>
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<tr>
<td>Silicon</td>
<td>0.11</td>
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<tr>
<td>Copper</td>
<td>0.01</td>
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<td>Chromium</td>
<td>16.34</td>
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<td>Aluminum</td>
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<td>Titanium</td>
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<tr>
<td>Nickel</td>
<td>79.50</td>
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</table>

Processing and Heat Treating

The specimen layout for Inconel 702 sheet is shown in Figure 51. Specimens were machined in the as-received annealed condition and then aged at 1400 F for 5 hours.

Test Results

Tension. Results of tests in longitudinal and transverse specimens at room temperature, 600 F, 1000 F, and 1400 F are given in Table XXXIX. Tensile stress-strain curves at temperature are shown in Figures 52 and 53. Effect-of-temperature curves are presented in Figure 56.

Compression. Compression test results at room temperature, 600 F, 1000 F, and 1400 F for longitudinal and transverse specimens are given in Table XL. Stress-strain and tangent modulus curves at temperature are presented in Figures 54 and 55. Effect-of-temperature curves are presented in Figure 57.
Shear. Test results for longitudinal and transverse specimens at room temperature are given in Table XLI.

Fracture Toughness. Tests were conducted on specimens of full sheet thickness (0.050-inch) by 18 inches by 36 inches with EDM flaw in center. The net section yield stress at fracture was greater than the tensile yield strength of the materials; therefore, the K values are considered not valid.

Fatigue. Axial-load fatigue test results for unnotched and notched transverse specimens at room temperature, 600 F, and 1000 F are given in Tables XLII and XLIII. S-N curves are presented in Figures 58 and 59.

Creep and Stress-Rupture. Tests were conducted at 800 F, 1100 F, and 1400 F for transverse specimens. Tabular results are given in Table XLIV. Log-stress versus log-time curves are presented in Figure 60.

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

Thermal Expansion. Coefficient of thermal expansion value for this alloy is \(8.7 \times 10^{-6}\ \text{in/in/F}\) for 70 F to 1500 F.

Density. The density of this material is 0.305 lb/in\(^3\).
<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Elongation in 2 inches, percent</th>
<th>Tensile Modulus, $10^6$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal at Room Temperature</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>IL-1</td>
<td>152.0</td>
<td>94.6</td>
<td>34.5</td>
<td>34.8</td>
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<td>IL-2</td>
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<td>94.8</td>
<td>35.0</td>
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</tr>
<tr>
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<td>94.8</td>
<td>35.0</td>
<td>33.5</td>
</tr>
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<td>Transverse at Room Temperature</td>
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<tr>
<td>IT-1</td>
<td>151.0</td>
<td>94.5</td>
<td>34.0</td>
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<tr>
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<td>95.3</td>
<td>34.0</td>
<td>32.9</td>
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<td>138.0</td>
<td>86.4</td>
<td>37.5</td>
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</tr>
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<td>IL-7</td>
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<td>36.0</td>
<td>28.3</td>
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<td>131.0</td>
<td>84.1</td>
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<td>30.6</td>
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<td>84.0</td>
<td>37.0</td>
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<tr>
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TABLE XXXIX. (Concluded)

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<th>Specimen No.</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Elongation in 2 inches, percent</th>
<th>Tensile Modulus, (10^8) psi</th>
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<tr>
<td>4L3</td>
<td>117.0</td>
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<tr>
<td>4L4</td>
<td>116.0</td>
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</tr>
<tr>
<td></td>
<td><strong>Transverse</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4T1</td>
<td>117.0</td>
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</tr>
<tr>
<td>4T2</td>
<td>116.0</td>
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<tr>
<td>4T3</td>
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<td>4T4</td>
<td>117.0</td>
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TABLE XLII. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED INCONEL 702 SHEET (AGED) (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Room Temperature</td>
</tr>
<tr>
<td>5-4</td>
<td>75.0</td>
<td>98,300</td>
</tr>
<tr>
<td>5-3</td>
<td>65.0</td>
<td>209,900</td>
</tr>
<tr>
<td>5-2</td>
<td>55.0</td>
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</tr>
<tr>
<td>5-1</td>
<td>45.0</td>
<td>1,594,800</td>
</tr>
<tr>
<td>5-8</td>
<td>40.0</td>
<td>7,086,400</td>
</tr>
<tr>
<td>5-5</td>
<td>35.0</td>
<td>3,403,100</td>
</tr>
<tr>
<td>5-7</td>
<td>30.0</td>
<td>10,138,000 (a)</td>
</tr>
<tr>
<td>5-6</td>
<td>25.0</td>
<td>10,130,000 (a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600 F</td>
</tr>
<tr>
<td>5-11</td>
<td>75.0</td>
<td>117,500</td>
</tr>
<tr>
<td>5-12</td>
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<td>184,400</td>
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<td>5-13</td>
<td>55.0</td>
<td>584,200</td>
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<td>5-14</td>
<td>45.0</td>
<td>4,809,000 (a)</td>
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<td>40.0</td>
<td>10,226,700 (a)</td>
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<td>35.0</td>
<td>12,376,900 (a)</td>
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<td></td>
<td></td>
<td>1000 F</td>
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<td>10,097,700 (a)</td>
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<tr>
<td>5-27</td>
<td>45.0</td>
<td>10,331,300 (a)</td>
</tr>
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</table>

(a) Did not fail.
### TABLE XLIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED ($K=3.0$) INCONEL 702 SHEET (AGED) (TRANSVERSE)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
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<tbody>
<tr>
<td></td>
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</tr>
<tr>
<td><strong>Room Temperature</strong></td>
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<td></td>
</tr>
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<td>5-4</td>
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<td>31,900</td>
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<td>5-3</td>
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<td>111,100</td>
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<td>45.0</td>
<td>336,200</td>
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<td>782,400</td>
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<td>10,537,500(a)</td>
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<tr>
<td><strong>600 F</strong></td>
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<tr>
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<td>50.0</td>
<td>821,200</td>
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<td>35.0</td>
<td>10,069,500(a)</td>
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<td><strong>1000 F</strong></td>
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<td>5-21</td>
<td>65.0</td>
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<td>1,774,800</td>
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<tr>
<td>5-34</td>
<td>35.0</td>
<td>10,549,600(a)</td>
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</table>

(a) Did not fail.
<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Stress, ksi</th>
<th>Temperature, F</th>
<th>Hours to Indicated Creep Deformation, percent</th>
<th>Initial Strain, %</th>
<th>Rupture Time, hr</th>
<th>Elongation in 2 in., percent</th>
<th>Minimum Creep Rate, percent/hr</th>
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<tbody>
<tr>
<td>3-13</td>
<td>132</td>
<td>800</td>
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<td>3-10</td>
<td>130</td>
<td>800</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
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<td>120</td>
<td>800</td>
<td>12</td>
<td>50</td>
<td>380</td>
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<tr>
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<td>110</td>
<td>800</td>
<td>50</td>
<td>280</td>
<td>1150(b)</td>
<td>--</td>
<td>9.204</td>
</tr>
<tr>
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<td>100</td>
<td>800</td>
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<td>1100</td>
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<td>5</td>
<td>12.8</td>
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<td>10</td>
<td>38</td>
<td>75</td>
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</tr>
<tr>
<td>3-5</td>
<td>65</td>
<td>1100</td>
<td>15</td>
<td>43</td>
<td>137</td>
<td>220</td>
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</tr>
<tr>
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<td>50</td>
<td>1100</td>
<td>70</td>
<td>323</td>
<td>935</td>
<td>1225</td>
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<tr>
<td>3-3</td>
<td>30</td>
<td>1400</td>
<td>0.8</td>
<td>1.7</td>
<td>6.5</td>
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<td>1400</td>
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<td>12.0</td>
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<td>255</td>
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<td>315</td>
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<td>6</td>
<td>1400</td>
<td>435</td>
<td>655</td>
<td>1100(b)</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

(a) Test discontinued.
(b) Estimate.
FIGURE 52. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 702 SHEET (AGE) (LONGITUDINAL)
FIGURE 53. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 702 SHEET (AGED) (TRANSVERSE)
FIGURE 54. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCOHEL 702 SHEET (AGED) (LONGITUDINAL)
FIGURE 55. TYPICAL COMpressive STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCONEL 702 SHEET (AGED) (TRANSVERSE)
FIGURE 56. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 702 SHEET (AGED)

FIGURE 57. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 702 SHEET (AGED)
FIGURE 58. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED INCONEL 702 SHEET (AGED)

FIGURE 59. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_e = 3.0$) INCONEL 702 SHEET (AGED)
Figure 60. Stress-Rupture and Plastic Deformation Curves for Inconel 702 Sheet (Aged) (Transverse)
Inconel 706 Alloy

Material Description

Inconel alloy 706 is a precipitation-hardenable, nickel-iron-chromium alloy with characteristics similar to those of Inconel 718, except that 706 has improved machinability. It has high strength at temperatures ranging from cryogenic to 1300°F. It also has good resistance to oxidation and corrosion over a broad range of temperatures and environments.

Fabrication of the alloy is enhanced by its good formability and weldability. Alloy 706 has excellent resistance to postweld strain-age cracking.

The material used in this evaluation was obtained as a 6-inch-square forging from INCO, Heat No. 50C3H5. The composition was as follows:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
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<tbody>
<tr>
<td>Carbon</td>
<td>0.03</td>
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<tr>
<td>Manganese</td>
<td>0.12</td>
</tr>
<tr>
<td>Iron</td>
<td>36.37</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.007</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.13</td>
</tr>
<tr>
<td>Copper</td>
<td>0.02</td>
</tr>
<tr>
<td>Chromium</td>
<td>16.32</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.28</td>
</tr>
<tr>
<td>Titanium</td>
<td>1.62</td>
</tr>
<tr>
<td>Columbium plus</td>
<td>2.96</td>
</tr>
<tr>
<td>Tantalum</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>42.12</td>
</tr>
</tbody>
</table>

Processing and Heat Treating

The 6-inch-square material was press forged to a 2 inch x 6 inch bar to make specimen blanks easier to obtain. The specimen layout is shown in Figure 61. After machining, specimens were heat treated as follows for optimum creep-rupture strength:

1. 1900°F, 2 hours, air cool,
2. 1850°F, 3 hours, air cool,
3. 1325°F, 8 hours, furnace cool to 1150°F, hold for 18 hours, air cool.

Test Results

Tensile. Results of longitudinal and transverse tests at room temperature, 800°F, 1000°F, and 1200°F are given in Table XLV. Stress-strain curves at
**FIGURE 61. SPECIMEN LAYOUT FOR INCONEL 706 FORGED BAR**
temperature are shown in Figures 62 and 63. Effect-of-temperature curves are
shown in Figure 66.

Compression. Results of longitudinal and transverse tests at room
temperature, 800 °F, 1000 °F, and 1200 °F are given in Table XLVI. Stress-strain
and tangent-modulus curves at temperature are shown in Figures 64 and 65.
Effect-of-temperature curves are presented in Figure 67.

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

Impact. Charpy test results for room temperature longitudinal
and transverse specimens are given in Table XLVIII.

Fracture Toughness. Results of slow bend tests at room temperature
are given in Table XLIX. The size ratio, 2.5 \((KQ/TYS)^2\), was greater than both
the specimen thickness and crack length in all tests, therefore the \(K_Q\) value in
the table is not a valid \(K_{IC}\) value by existing ASTM criteria.

Fatigue. Axial-load fatigue tests were performed on transverse speci-
mens, both notched and unnotched, at room temperature, 600 °F, and 1000 °F. Test
results are given in Tables L and LI. S-N curves are presented in Figures 68 and 69.

Creep and Stress-Rupture. Tests were conducted at 800 °F, 1000 °F, and
1200 °F. Results are given in Table LII. Log-stress versus log-time curves are
presented in Figure 70.

Stress Corrosion. No failures or cracks occurred in the 1000 hour
test duration as described in the experimental procedure section of this report.

Thermal Expansion. The coefficient of thermal expansion for Inconel
706 is \(9.8 \times 10^{-6}\) in/in/°F for 70 °F to 1500 °F.

Density. The density of this material is 0.291 lb/in\(^3\).
TABLE XLV. TENSILE TEST RESULTS FOR
INCONEL 705 FORGED BAR
(STRESS-ROUPTURE HEAT TREATMENT)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Ultimate Tensile Strength, ksi</th>
<th>0.2 percent Offset Yield Strength, ksi</th>
<th>Elongation in 2 inches, percent</th>
<th>Reduction in Area, percent</th>
<th>Tensile Modulus, $10^8$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal at Room Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-1</td>
<td>177.0</td>
<td>138.0</td>
<td>22.0</td>
<td>32.5</td>
<td>30.9</td>
</tr>
<tr>
<td>IL-2</td>
<td>178.0</td>
<td>139.0</td>
<td>22.5</td>
<td>33.5</td>
<td>28.9</td>
</tr>
<tr>
<td>IL-3</td>
<td>178.0</td>
<td>139.0</td>
<td>22.0</td>
<td>32.5</td>
<td>27.9</td>
</tr>
<tr>
<td>Transverse at Room Temperature</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>30.0</td>
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<td>22.0</td>
<td>31.5</td>
<td>28.6</td>
</tr>
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<td>176.0</td>
<td>140.0</td>
<td>22.5</td>
<td>31.5</td>
<td>31.6</td>
</tr>
<tr>
<td>Longitudinal at 800 F</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<tr>
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<td>21.0</td>
<td>39.0</td>
<td>23.9</td>
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<td>21.0</td>
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<td>33.5</td>
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<td>123.0</td>
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<td>34.5</td>
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<td></td>
</tr>
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<td>119.0</td>
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<td>38.0</td>
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<td>120.0</td>
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<td>40.0</td>
<td>20.4</td>
</tr>
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<td>19.0</td>
<td>33.5</td>
<td>22.0</td>
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<tr>
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<td>19.5</td>
<td>35.5</td>
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<td>122.0</td>
<td>18.0</td>
<td>35.0</td>
<td>21.3</td>
</tr>
<tr>
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</tr>
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<td>21.4</td>
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<td>116.0</td>
<td>23.5</td>
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<td>116.0</td>
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<td>40.0</td>
<td>20.1</td>
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<td>117.0</td>
<td>24.0</td>
<td>36.0</td>
<td>20.7</td>
</tr>
<tr>
<td>IT-12</td>
<td>139.0</td>
<td>118.0</td>
<td>21.5</td>
<td>37.5</td>
<td>20.9</td>
</tr>
</tbody>
</table>
TABLE XLVI. COMPRESSION TEST RESULTS FOR INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^6$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Longitudinal at Room Temperature</td>
</tr>
<tr>
<td>2L-1</td>
<td>149.0</td>
<td>31.8</td>
</tr>
<tr>
<td>2L-2</td>
<td>150.0</td>
<td>30.9</td>
</tr>
<tr>
<td>2L-3</td>
<td>150.0</td>
<td>30.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transverse at Room Temperature</td>
</tr>
<tr>
<td>2T-1</td>
<td>149.0</td>
<td>30.8</td>
</tr>
<tr>
<td>2T-2</td>
<td>149.0</td>
<td>31.1</td>
</tr>
<tr>
<td>2T-3</td>
<td>149.0</td>
<td>32.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal at 800 F</td>
</tr>
<tr>
<td>2L-4</td>
<td>127.0</td>
<td>23.9</td>
</tr>
<tr>
<td>2L-5</td>
<td>124.0</td>
<td>25.2</td>
</tr>
<tr>
<td>2L-6</td>
<td>129.0</td>
<td>23.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transverse at 800 F</td>
</tr>
<tr>
<td>2T-4</td>
<td>129.0</td>
<td>24.6</td>
</tr>
<tr>
<td>2T-5</td>
<td>131.0</td>
<td>24.0</td>
</tr>
<tr>
<td>2T-6</td>
<td>128.0</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal at 1000 F</td>
</tr>
<tr>
<td>2L-7</td>
<td>123.0</td>
<td>23.2</td>
</tr>
<tr>
<td>2L-8</td>
<td>123.0</td>
<td>23.0</td>
</tr>
<tr>
<td>2L-9</td>
<td>124.0</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transverse at 1000 F</td>
</tr>
<tr>
<td>2T-7</td>
<td>125.0</td>
<td>24.5</td>
</tr>
<tr>
<td>2T-8</td>
<td>125.0</td>
<td>23.4</td>
</tr>
<tr>
<td>2T-9</td>
<td>124.0</td>
<td>24.0</td>
</tr>
</tbody>
</table>
TABLE XLVI  (Concluded)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>0.2 Percent Offset Yield Strength, ksi</th>
<th>Compression Modulus, $10^5$ psi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal at 1200 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2L-10</td>
<td>118.0</td>
<td>23.3</td>
</tr>
<tr>
<td>2L-11</td>
<td>120.0</td>
<td>22.0</td>
</tr>
<tr>
<td>2L-12</td>
<td>122.0</td>
<td>22.1</td>
</tr>
<tr>
<td><strong>Transverse at 1200 F</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2T-10</td>
<td>120.0</td>
<td>22.2</td>
</tr>
<tr>
<td>2T-11</td>
<td>120.0</td>
<td>22.2</td>
</tr>
<tr>
<td>2T-12</td>
<td>124.0</td>
<td>22.2</td>
</tr>
</tbody>
</table>
TABLE XLVII. SHEAR TEST RESULTS FOR INCONEL 706 FORGED BAR  
(STRESS-RUPTURE HEAT TREATMENT)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Ultimate Shear Strength, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>4L-1</td>
<td>117.0</td>
</tr>
<tr>
<td>4L-2</td>
<td>117.0</td>
</tr>
<tr>
<td>4L-3</td>
<td>117.0</td>
</tr>
<tr>
<td>4L-4</td>
<td>118.0</td>
</tr>
<tr>
<td>4T-1</td>
<td>117.0</td>
</tr>
<tr>
<td>4T-2</td>
<td>117.0</td>
</tr>
<tr>
<td>4T-3</td>
<td>117.0</td>
</tr>
<tr>
<td>4T-4</td>
<td>117.0</td>
</tr>
<tr>
<td>4T-5</td>
<td>117.5</td>
</tr>
</tbody>
</table>
TABLE XLVII. IMPACT TEST RESULTS FOR INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Energy, ft/lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinal</td>
</tr>
<tr>
<td>10L-1</td>
<td>29.5</td>
</tr>
<tr>
<td>10L-2</td>
<td>32.0</td>
</tr>
<tr>
<td>10L-3</td>
<td>33.0</td>
</tr>
<tr>
<td>10L-4</td>
<td>31.5</td>
</tr>
<tr>
<td>10L-5</td>
<td>33.0</td>
</tr>
<tr>
<td>10L-6</td>
<td>32.0</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
</tr>
<tr>
<td>10T-1</td>
<td>28.0</td>
</tr>
<tr>
<td>10T-2</td>
<td>26.0</td>
</tr>
<tr>
<td>10T-3</td>
<td>28.0</td>
</tr>
<tr>
<td>10T-4</td>
<td>26.5</td>
</tr>
<tr>
<td>10T-5</td>
<td>25.0</td>
</tr>
<tr>
<td>10T-6</td>
<td>27.0</td>
</tr>
</tbody>
</table>
TABLE XLIX. FRACTURE TOUGHNESS TEST RESULTS FOR INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>W, inches</th>
<th>a, inches</th>
<th>l, inches</th>
<th>P, lbs</th>
<th>Span, inches</th>
<th>( f(\psi) )</th>
<th>( K_Q ) (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1L</td>
<td>1.498</td>
<td>.737</td>
<td>.750</td>
<td>9,800</td>
<td>4.5</td>
<td>2.6</td>
<td>83.3</td>
</tr>
<tr>
<td>2L</td>
<td>1.499</td>
<td>.754</td>
<td>.751</td>
<td>9,900</td>
<td>4.5</td>
<td>2.5</td>
<td>86.9</td>
</tr>
<tr>
<td>3L</td>
<td>1.500</td>
<td>.760</td>
<td>.750</td>
<td>10,250</td>
<td>4.5</td>
<td>2.7</td>
<td>91.1</td>
</tr>
<tr>
<td><strong>Transverse</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1T</td>
<td>1.497</td>
<td>.747</td>
<td>.750</td>
<td>10,150</td>
<td>4.5</td>
<td>2.6</td>
<td>88.3</td>
</tr>
<tr>
<td>2T</td>
<td>1.490</td>
<td>.749</td>
<td>.747</td>
<td>9,850</td>
<td>4.5</td>
<td>2.6</td>
<td>84.3</td>
</tr>
<tr>
<td>3T</td>
<td>1.497</td>
<td>.735</td>
<td>.749</td>
<td>10,750</td>
<td>4.5</td>
<td>2.6</td>
<td>91.3</td>
</tr>
</tbody>
</table>

(a) Candidate fracture toughness values, \( K_Q \), are invalid as \( K_{ic} \) values since \( a, l < 2.5 \left( \frac{W}{W_{ig}} \right)^{0.5} \).

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<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-3</td>
<td>125.0</td>
<td>88,100</td>
</tr>
<tr>
<td>5-4</td>
<td>115.0</td>
<td>150,300</td>
</tr>
<tr>
<td>5-2</td>
<td>105.0</td>
<td>227,500</td>
</tr>
<tr>
<td>5-1</td>
<td>95.0</td>
<td>364,400</td>
</tr>
<tr>
<td>5-5</td>
<td>85.0</td>
<td>679,000</td>
</tr>
<tr>
<td>5-6</td>
<td>125.0</td>
<td>8,446,000</td>
</tr>
<tr>
<td>5-7</td>
<td>65.0</td>
<td>8,000,000</td>
</tr>
<tr>
<td>5-8</td>
<td>60.0</td>
<td>10,000,000</td>
</tr>
<tr>
<td>600 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-17</td>
<td>125.0</td>
<td>25,220</td>
</tr>
<tr>
<td>5-18</td>
<td>115.0</td>
<td>42,700</td>
</tr>
<tr>
<td>5-19</td>
<td>105.0</td>
<td>82,100</td>
</tr>
<tr>
<td>5-20</td>
<td>95.0</td>
<td>139,900</td>
</tr>
<tr>
<td>5-21</td>
<td>85.0</td>
<td>164,300</td>
</tr>
<tr>
<td>5-22</td>
<td>75.0</td>
<td>422,300</td>
</tr>
<tr>
<td>5-23</td>
<td>65.0</td>
<td>6,226,100</td>
</tr>
<tr>
<td>5-24</td>
<td>55.0</td>
<td>10,792,700</td>
</tr>
<tr>
<td>1000 F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-9</td>
<td>125.0</td>
<td>14,000</td>
</tr>
<tr>
<td>5-10</td>
<td>115.0</td>
<td>42,700</td>
</tr>
<tr>
<td>5-11</td>
<td>105.0</td>
<td>31,300</td>
</tr>
<tr>
<td>5-12</td>
<td>95.0</td>
<td>163,600</td>
</tr>
<tr>
<td>5-13</td>
<td>85.0</td>
<td>165,300</td>
</tr>
<tr>
<td>5-14</td>
<td>75.0</td>
<td>722,300</td>
</tr>
<tr>
<td>5-15</td>
<td>65.0</td>
<td>2,232,100</td>
</tr>
<tr>
<td>5-16</td>
<td>55.0</td>
<td>5,557,700</td>
</tr>
<tr>
<td>5-25</td>
<td>45.0</td>
<td>12,239,200(a)</td>
</tr>
</tbody>
</table>

(a) Did not fail.
**TABLE LI. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (Kt = 3.0) INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT) (TRANSVERSE)**

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Maximum Stress, ksi</th>
<th>Lifetime, cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Room Temperature</td>
</tr>
<tr>
<td>5-1</td>
<td>105.0</td>
<td>9,900</td>
</tr>
<tr>
<td>5-2</td>
<td>95.0</td>
<td>14,100</td>
</tr>
<tr>
<td>5-3</td>
<td>85.0</td>
<td>32,000</td>
</tr>
<tr>
<td>5-4</td>
<td>75.0</td>
<td>29,000</td>
</tr>
<tr>
<td>5-5</td>
<td>65.0</td>
<td>47,200</td>
</tr>
<tr>
<td>5-6</td>
<td>55.0</td>
<td>88,300</td>
</tr>
<tr>
<td>5-7</td>
<td>45.0</td>
<td>150,000</td>
</tr>
<tr>
<td>5-8</td>
<td>35.0</td>
<td>445,900</td>
</tr>
<tr>
<td>5-23</td>
<td>30.0</td>
<td>475,000</td>
</tr>
<tr>
<td>5-9</td>
<td>25.0</td>
<td>4,770,490</td>
</tr>
<tr>
<td>5-10</td>
<td>20.0</td>
<td>11,953,000&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600 F</td>
</tr>
<tr>
<td>5-11</td>
<td>75.0</td>
<td>25,300</td>
</tr>
<tr>
<td>5-12</td>
<td>65.0</td>
<td>44,900</td>
</tr>
<tr>
<td>5-13</td>
<td>55.0</td>
<td>74,000</td>
</tr>
<tr>
<td>5-14</td>
<td>45.0</td>
<td>204,700</td>
</tr>
<tr>
<td>5-15</td>
<td>40.0</td>
<td>255,100</td>
</tr>
<tr>
<td>5-25</td>
<td>35.0</td>
<td>529,500</td>
</tr>
<tr>
<td>5-26</td>
<td>30.0</td>
<td>10,012,000&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>5-16</td>
<td>25.0</td>
<td>13,091,900&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000 F</td>
</tr>
<tr>
<td>5-17</td>
<td>75.0</td>
<td>12,200</td>
</tr>
<tr>
<td>5-18</td>
<td>65.0</td>
<td>25,700</td>
</tr>
<tr>
<td>5-19</td>
<td>55.0</td>
<td>46,900</td>
</tr>
<tr>
<td>5-20</td>
<td>45.0</td>
<td>116,300</td>
</tr>
<tr>
<td>5-21</td>
<td>40.0</td>
<td>17,555,700&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>5-22</td>
<td>35.0</td>
<td>7,421,600</td>
</tr>
<tr>
<td>5-23</td>
<td>30.0</td>
<td>11,685,000&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Did not fail.
<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Stress, ksi</th>
<th>Temp., F</th>
<th>Hours to Indicated Creep Deformation, percent</th>
<th>Initial Strain, percent</th>
<th>Rupture Time, hr</th>
<th>Elongation in 2 in., percent</th>
<th>Reduction of Area, percent</th>
<th>Minimum Creep Rate, percent/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>158</td>
<td>800</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3-2</td>
<td>155</td>
<td>800</td>
<td>95</td>
<td>75 (b)</td>
<td>16.346</td>
<td>476.8 (a)</td>
<td>14.520</td>
<td>0.00010</td>
</tr>
<tr>
<td>3-10</td>
<td>150</td>
<td>800</td>
<td>---</td>
<td>---</td>
<td>6.404</td>
<td>144.7 (a)</td>
<td>6.410</td>
<td>---</td>
</tr>
<tr>
<td>3-3</td>
<td>150</td>
<td>1000</td>
<td>0.02</td>
<td>0.04</td>
<td>0.1</td>
<td>0.22</td>
<td>0.51</td>
<td>12.288</td>
</tr>
<tr>
<td>3-7</td>
<td>160</td>
<td>1000</td>
<td>0.5</td>
<td>2.0</td>
<td>10</td>
<td>35</td>
<td>100 (b)</td>
<td>3.41</td>
</tr>
<tr>
<td>3-4</td>
<td>130</td>
<td>1000</td>
<td>8</td>
<td>45</td>
<td>280</td>
<td>300</td>
<td>1800 (b)</td>
<td>1.625</td>
</tr>
<tr>
<td>3-6</td>
<td>120</td>
<td>1000</td>
<td>420</td>
<td>1600 (b)</td>
<td>---</td>
<td>0.839</td>
<td>791.2 (a)</td>
<td>0.962</td>
</tr>
<tr>
<td>3-5</td>
<td>110</td>
<td>1200</td>
<td>0.15</td>
<td>0.4</td>
<td>1.1</td>
<td>3.1</td>
<td>7.7</td>
<td>0.681</td>
</tr>
<tr>
<td>3-5</td>
<td>100</td>
<td>1200</td>
<td>1.6</td>
<td>6.0</td>
<td>31</td>
<td>50</td>
<td>76</td>
<td>0.496</td>
</tr>
<tr>
<td>3-6</td>
<td>80</td>
<td>1200</td>
<td>300</td>
<td>570</td>
<td>1000 (b)</td>
<td>---</td>
<td>0.550</td>
<td>719.5 (a)</td>
</tr>
</tbody>
</table>

(a) Test discontinued.
(b) Estimate.
FIGURE 62. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 706 FORGED BAR (LONGITUDINAL) (STRESS-RUPTURE HEAT TREATMENT)
FIGURE 63. TYPICAL TENSILE STRESS-STRAIN CURVES FOR INCONEL 706 FORGED BAR (TRANSVERSE) (STRESS-RUPTURE HEAT TREATMENT)
FIGURE 64. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCONEL 706 FORGED BAR (LONGITUDINAL) (STRESS-RUPTURE HEAT TREATMENT)
FIGURE 65. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR INCONEL 706 FORGED BAR (TRANSVERSE) (STRESS-RUPTURE HEAT TREATMENT)
FIGURE 66. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

FIGURE 67. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)
FIGURE 68. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)

FIGURE 69. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_t = 3.0$) INCONEL 706 FORGED BAR (STRESS-RUPTURE HEAT TREATMENT)
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 almost always 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 in Figures 71 and 72.

CONCLUSIONS

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

(1) 15-5 PH (H1025) stainless steel forged bar
(2) HP 9Ni-4Co-0.20C steel forged bar
(3) PH 13-8 Mo (H1000) stainless steel forged bar
(4) 7049-T76 aluminum extrusion
(5) 6Al-2Sn-4Zr-6Mo titanium sheet
(6) Inconel Alloy 702 sheet (Aged)
(7) Inconel Alloy 706 forged bar (Creep-rupture heat treatment).

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

EXPERIMENTAL PROCEDURE
APPENDIX I

EXPERIMENTAL PROCEDURE

Mechanical Properties

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

(1) Tension
   (a) Tensile ultimate strength, TUS
   (b) Tensile yield strength, TYS
   (c) Elongation, $e_t$
   (d) Reduction in area, RA
   (e) Modulus of elasticity, $E_t$

(2) Compression
   (a) Compressive yield strength, CYS
   (b) Modulus of elasticity, $E_c$

(3) Creep and stress-rupture
   (a) Stress for 0.2 or 0.5 percent deformation in 100 hours and 1000 hours
   (b) Stress for rupture in 100 hours and 1000 hours.

(4) Shear
   (a) Shear ultimate strength, SUS

(5) Axial fatigue
   (a) Unnotched, $R = 0.1$, lifetime: $10^3$ through $10^7$ cycles

*"R" represents the algebraic ratio of the minimum stress to the maximum stress in one cycle; that is, $R = \frac{S_{\text{min}}}{S_{\text{max}}}$. "$k_t$" represents the Neuber-Peterson theoretical stress concentration factor.
(b) Notched \( (K_c = 3.0), R = 0.1 \), lifetime: \( 10^5 \) 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:

<table>
<thead>
<tr>
<th>Assigned Number</th>
<th>Test Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tension</td>
</tr>
<tr>
<td>2</td>
<td>Compression</td>
</tr>
<tr>
<td>3</td>
<td>Creep and stress-rupture</td>
</tr>
<tr>
<td>4</td>
<td>Shear</td>
</tr>
<tr>
<td>5</td>
<td>Fatigue</td>
</tr>
<tr>
<td>6</td>
<td>Fracture toughness</td>
</tr>
</tbody>
</table>

137
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 A|SM 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 cups 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 ± 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:

\[ y = \frac{\sigma(3l^2-4a^2)}{12de} \]

where:

- \( y \) = deflection
- \( \sigma \) = maximum fiber stress
- \( l \) = distance between outer load points
- \( a \) = distance between outer and inner load points
- \( d \) = specimen thickness
- \( E \) = modulus of specimen material.
Each stressed specimen was suspended on an alternate immersion unit. This unit alternately immersed specimens in the 3.5 percent sodium chloride solution for ten minutes and held them above the solution to dry for 50 minutes. Tests were continued to the first sign of cracking or for 1000 hours, whichever occurred first.

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

Thermal Expansion

Linear-thermal-expansion measurements were performed in a recording dilatometer with specimens protected by a vacuum of about $2 \times 10^{-6}$ mm of mercury. In this apparatus a sheet-type specimen is supported between two graphite structures inside a tantalum-tube heater element. On heating, the differential movement of the two structures caused by specimen expansion results in the displacement of the core of a linear-variable differential transformer. The output of the transformer is recorded continuously as a function of specimen temperature. The entire assembly is enclosed in a vacuum chamber.

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

Fatigue

Fatigue tests were conducted using MTS electrohydraulic-servocontrolled testing machines. The frequency of cycling of these machines is variable to beyond 2,000 cpm depending on specimen rigidity. These machines operate with closed-loop deflection, strain or load control. Under load control used in this program, cyclic loads were automatically maintained (regardless of the required amount of ram travel) by means of load-cell feedback signals. The calibration and alignment of each machine are checked periodically. In each case, the dynamic load-control accuracy is better than ±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 ±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 \( 1 \times 10^3 \) and \( 1 \times 10^7 \) 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

\[ 0.002 \text{ ksi} < \Delta S < 0.005 \text{ ksi/min} \]

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

SPECIMEN DRAWINGS
FIGURE 79. SHEET SHEAR TEST SPECIMEN

FIGURE 80. PIN SHEAR SPECIMEN

FIGURE 81. UNNOTCHED SHEET FATIGUE SPECIMEN

FIGURE 82. NOTCHED SHEET FATIGUE SPECIMEN

FIGURE 83. UNNOTCHED ROUND FATIGUE SPECIMEN

FIGURE 84. NOTCHED ROUND FATIGUE SPECIMEN
FIGURE 85. SHEET FRACTURE TOUGHNESS SPECIMEN

FIGURE 86. SLOW BEND FRACTURE TOUGHNESS SPECIMEN

FIGURE 87. STRESS-CORROSION SPECIMEN

FIGURE 88. THERMAL-EXPANSION SPECIMEN

FIGURE 89. SHEET BEND SPECIMEN

FIGURE 90. NOTCHED IMPACT SPECIMEN
APPENDIX III

DATA SHEETS
15-5 PH Stainless Steel

15-5 PH is a precipitation-hardening stainless steel that offers a combination of high strength and hardness, excellent corrosion resistance plus good transverse toughness and good forgeability. It is produced by consumable vacuum arc remelting and is virtually "ferrite free".

Fabrication practices for 15-5 PH are generally the same as those established for 17-4 PH. Most techniques are similar to those recommended for the regular grades of stainless steel. Hardening treatments require temperatures of only 900°F to 1150°F, depending on the properties desired. Because of the comparatively low hardening temperatures scaling and distortion difficulties are essentially eliminated.

15-5 PH is available in the form of billets, plates, bars, and wire. Typical applications include forgings, pump and valve parts for high pressure systems, aircraft components, and hollow bar parts for hydraulic actuators and controls.

The chemical composition of the forging used for this evaluation is as follows:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>.037</td>
</tr>
<tr>
<td>Manganese</td>
<td>.31</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>.018</td>
</tr>
<tr>
<td>Sulfur</td>
<td>.010</td>
</tr>
<tr>
<td>Silicon</td>
<td>.30</td>
</tr>
<tr>
<td>Chromium</td>
<td>15.14</td>
</tr>
<tr>
<td>Nickel</td>
<td>4.55</td>
</tr>
<tr>
<td>Copper</td>
<td>3.32</td>
</tr>
<tr>
<td>Tantalum</td>
<td>.26</td>
</tr>
<tr>
<td>Iron</td>
<td>.01</td>
</tr>
<tr>
<td>Balance</td>
<td></td>
</tr>
</tbody>
</table>

The material tested was obtained from Armo Heat 400370 in the form of 2-1/8 inch x 5-3/4 inch x 8 foot forged bar.

**Processing and Heat Treatment**

Specimens were machined in the as-received Condition A followed by heat treatment for 4 hours at 1025°F to Condition H1025.

<table>
<thead>
<tr>
<th>15-5 PH Stainless Steel Data (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition: H 1025</td>
</tr>
<tr>
<td>Thickness: 2 inch x 6 inch forged bar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Tension</td>
</tr>
<tr>
<td>TUS (longitudinal), ksi</td>
</tr>
<tr>
<td>TUS (transverse), ksi</td>
</tr>
<tr>
<td>TTS (longitudinal), ksi</td>
</tr>
<tr>
<td>TTS (transverse), ksi</td>
</tr>
<tr>
<td>% (longitudinal), percent in 2 in.</td>
</tr>
<tr>
<td>% (transverse), percent in 2 in.</td>
</tr>
<tr>
<td>EA (longitudinal), percent</td>
</tr>
<tr>
<td>EA (transverse), percent</td>
</tr>
<tr>
<td>E (longitudinal), 10^6 psi</td>
</tr>
<tr>
<td>E (transverse), 10^6 psi</td>
</tr>
<tr>
<td>Compression</td>
</tr>
<tr>
<td>CTS (longitudinal), ksi</td>
</tr>
<tr>
<td>CTS (transverse), ksi</td>
</tr>
<tr>
<td>Kc (longitudinal), 10^6 psi</td>
</tr>
<tr>
<td>Kc (transverse), 10^6 psi</td>
</tr>
<tr>
<td>Fracture Toughness</td>
</tr>
<tr>
<td>Etc, ksi</td>
</tr>
<tr>
<td>Fatigue (transverse)</td>
</tr>
<tr>
<td>Unnotched, R = 0.1</td>
</tr>
<tr>
<td>10^7 cycles, ksi</td>
</tr>
<tr>
<td>10^8 cycles, ksi</td>
</tr>
<tr>
<td>10^9 cycles, ksi</td>
</tr>
<tr>
<td>Notched, E, R = 3.0, R = 0.1</td>
</tr>
<tr>
<td>10^7 cycles, ksi</td>
</tr>
<tr>
<td>10^8 cycles, ksi</td>
</tr>
<tr>
<td>10^9 cycles, ksi</td>
</tr>
</tbody>
</table>
18-8 PH Stainless Steel Data (continued)

<table>
<thead>
<tr>
<th>Property</th>
<th>Temperature °F</th>
<th>Temperature °C</th>
<th>E' (GPa)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress-Tensile</td>
<td>70</td>
<td>37.2</td>
<td>120</td>
<td>59</td>
</tr>
<tr>
<td>Plastic Deformation, 1499 MPa, psi</td>
<td>70</td>
<td>37.2</td>
<td>57</td>
<td>41</td>
</tr>
<tr>
<td>Stress - Ultimate Tensile Strength</td>
<td>1000 MPa, psi</td>
<td>70</td>
<td>37.2</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>1000 MPa, psi</td>
<td>70</td>
<td>37.2</td>
<td>132</td>
</tr>
<tr>
<td>Stress Concentration</td>
<td>80% TTS, 100% max tension</td>
<td>No cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>6.7 x 10^-6 in/in/F (20 to 400°F)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.7 x 10^-6 in/in/F (70 to 900°F)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>0.285 lb/in^3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Values are average of duplicate tests conducted at-rate under the subject condition on a series of specimens. Data are from tests conducted using the results of a greater number of tests.

(b) Double-shear plug-type specimen; average of 4 tests.

(c) N. unattainable; NA, not applicable.

(d) Average of 5 tests.

(e) Six longitudinal stress-free specimens were tested. Specimen size was 0.750-inch thick by 1.500 inches wide with a slab of 1.75 inches. The average K_0 obtained was 191.0 psi. Since the slab ratio, 2.2 (2.5/1.125), was greater than both the specimen thickness and crack length in all tests, this K_0 value is a valid K_0 value by existing criteria.

(f) M'' represents the algebraic rate of maximum stress to minimum stress in one cycle; that is, M'' = K''/K_0. M'' represents the Soderberg theoretical stress concentration factor.

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

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 15-5 PH (X155) FORGED BAR

FIGURE 2. EFFECT OF TEMPERATURE OF THE COMPOSITE PROPERTIES OF 15-5 PH (X152) FORGED BAR
FIGURE 4. AXIAL LOAD FATIGUE BEHAVIOR FOR NOTCHED (\(R = 3.0\)) 15-5 PH (X1025) FORGED BAR

FIGURE 5. AXIAL LOAD FATIGUE BEHAVIOR FOR UNNOTCHED 15-5 PH (X1025) FORGED BAR

---

FIGURE 3. STRESS-rupture AND PLASTIC DEFORMATION CURVES FOR 15-5 PH (X1025) FORGED BAR (TRANSVERSE)
Material Description

HP 98/6-Cr-0.20C steel was developed specifically to have high hardensibility combined with good fracture toughness. It can be welded in the fully heat-treated condition and achieve essentially 100 percent joint efficiency without preheat or postheat treatment. The 0-20C grade is available as sheet, strip, plate, bars, forgings, and tubing.

The material used for this program was consumable electrode vacuum melted and from Republic Steel Heat 3871015. It was obtained as a 3-1/4 inch x 6-inch x 6 inch forged bar and had the following composition:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.18</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.36</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.0002</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.007</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.04</td>
</tr>
<tr>
<td>Nickel</td>
<td>9.30</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.80</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.04</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.08</td>
</tr>
<tr>
<td>Cobalt</td>
<td>4.70</td>
</tr>
<tr>
<td>Iron</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Processing and Heat Treatment

Specimens were rough machined in the as-received annealed condition, heat treated as follows:

1. Normalize at 1650°F, 1 hour, air cool,
2. Acestemize at 1900°F, 1 hour, oil quench,
3. Single temper at 1035°F, 6 hours, air cool and then finish machined.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Temperature, F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NT</td>
</tr>
<tr>
<td>Tensile</td>
<td></td>
</tr>
<tr>
<td>TS (longitudinal), psi</td>
<td></td>
</tr>
<tr>
<td>TS (transverse), psi</td>
<td></td>
</tr>
<tr>
<td>TVS (longitudinal), psi</td>
<td></td>
</tr>
<tr>
<td>TVS (transverse), psi</td>
<td></td>
</tr>
<tr>
<td>Elong (longitudinal), %</td>
<td></td>
</tr>
<tr>
<td>Elong (transverse), %</td>
<td></td>
</tr>
<tr>
<td>RA (longitudinal), %</td>
<td></td>
</tr>
<tr>
<td>RA (transverse), %</td>
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</table>

Compression

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NT</td>
</tr>
<tr>
<td>CYT (longitudinal), psi</td>
<td></td>
</tr>
<tr>
<td>CYT (transverse), psi</td>
<td></td>
</tr>
<tr>
<td>EC (longitudinal), psi</td>
<td></td>
</tr>
<tr>
<td>EC (transverse), psi</td>
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</tr>
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</table>

Impact (d)

<table>
<thead>
<tr>
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<th>Temperature, F</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>NT</td>
</tr>
<tr>
<td>V-notch Charpy, ft-lb.</td>
<td></td>
</tr>
<tr>
<td>(longitudinal)</td>
<td></td>
</tr>
<tr>
<td>(transverse)</td>
<td></td>
</tr>
</tbody>
</table>

Fracture Toughness

<table>
<thead>
<tr>
<th>Properties</th>
<th>Temperature, F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NT</td>
</tr>
<tr>
<td>E (longitudinal), psi</td>
<td></td>
</tr>
<tr>
<td>E (transverse), psi</td>
<td></td>
</tr>
</tbody>
</table>

Axial Fatigue (transverse)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Temperature, F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NT</td>
</tr>
<tr>
<td>Continuous, N = 0.1</td>
<td></td>
</tr>
<tr>
<td>10^6 cycles, psi</td>
<td></td>
</tr>
<tr>
<td>10^8 cycles, psi</td>
<td></td>
</tr>
<tr>
<td>10^10 cycles, psi</td>
<td></td>
</tr>
<tr>
<td>Notched, N = 3.0, R = 0.1</td>
<td></td>
</tr>
<tr>
<td>10^6 cycles, psi</td>
<td></td>
</tr>
<tr>
<td>10^8 cycles, psi</td>
<td></td>
</tr>
<tr>
<td>10^10 cycles, psi</td>
<td></td>
</tr>
</tbody>
</table>
HP 991-4Co-0.2GC Data (continued)

<table>
<thead>
<tr>
<th>Properties</th>
<th>RT</th>
<th>350</th>
<th>700</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Creep (transverse)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2% plastic deformation, 100 hr, ksl</td>
<td>HA</td>
<td>150</td>
<td>115</td>
<td>60</td>
</tr>
<tr>
<td>0.2% plastic deformation, 1900 hr, ksl</td>
<td>HA</td>
<td>149</td>
<td>95</td>
<td>31</td>
</tr>
<tr>
<td><strong>Stress Rupture (transverse)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rupture, 100 hr, ksl</td>
<td>HA</td>
<td>162</td>
<td>111</td>
<td>95</td>
</tr>
<tr>
<td>Rupture, 1900 hr, ksl</td>
<td>HA</td>
<td>159</td>
<td>149</td>
<td>70</td>
</tr>
<tr>
<td><strong>Stress corrosion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80% TYS, 1000 hr maximum</td>
<td>no cracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Coefficient of Thermal Expansion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6.4 \times 10^{-6}$ in./in./F (80 to 900 F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.294 lb./in.³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Values are averages of triplicate tests conducted at intervals under the subject stress unless otherwise indicated. Fatigue, creep, and stress-corrosion values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 3 tests.

(c) U, tensile; RA, not applicable.

(d) Average of 5 tests.

(e) Three longitudinal and 3 transverse slow-bend specimens were tested. Specimen size was 0.750-inch by 1.250 inches wide with a span of 6 inches. Average $K_I$ obtained was 101.3 ksi√in. in the longitudinal direction and 123.9 ksi√in. in the transverse direction. Since the size ratio, $i = l/a$, was greater than both the specimen thickness and crack length in all cases, these values are the valid $K_I$ values by existing ASTM criteria.

(f) $K_I$ represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $K = \sigma_N\sqrt{a}/F_{max}$. $K_I$ represents the Sneddon-Petersen theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternating immersion in 3-1/2% BaCl.
**PM 11-3 No Stainless Steel**

**Material Description**

This alloy is a martensitic precipitation hardenable stainless steel developed by the Arevo Steel Corporation. It can be heat treated to high strength levels and exhibits good ductility in the transverse direction. This transverse direction toughness is obtained by compositional balance designed to prevent formation of delta ferrite in the structure, low carbon content to minimize grain boundary carbide precipitation, and double vacuum melting to reduce alloy segregation. The alloy reportedly has excellent resistance to stress corrosion cracking in synthetic seawater and excellent resistance to corrosion in a 5 percent salt spray environment.

The material used in this evaluation was obtained as a 4-inch x 3-inch x 3-foot forged bar from Arevo Steel (BLOOM). The composition was as follows:

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.015</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.01</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.002</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.003</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.02</td>
</tr>
<tr>
<td>Chromium</td>
<td>12.61</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.36</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.14</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.01</td>
</tr>
<tr>
<td>Iron</td>
<td>Balance</td>
</tr>
</tbody>
</table>

**Processing and Heat Treating**

Specimens were machined in the as-received Condition A and then heat treated at 1000°F for 4 hours + condition B 1100.

**PM 13-2 No Stainless Steel Data**

**Condition:** B1000

**Thickness:** 4-inch x 6-inch forged bar

<table>
<thead>
<tr>
<th>Property</th>
<th>RT</th>
<th>600</th>
<th>900</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTS (longitudinal), ksi</td>
<td>192.7</td>
<td>169.0</td>
<td>157.7</td>
<td>132.9</td>
</tr>
<tr>
<td>TTS (transverse), ksi</td>
<td>190.3</td>
<td>164.3</td>
<td>157.2</td>
<td>137.0</td>
</tr>
<tr>
<td>TTS (longitudinal), ksi</td>
<td>187.3</td>
<td>164.7</td>
<td>151.3</td>
<td>139.0</td>
</tr>
<tr>
<td>TTS (transverse), ksi</td>
<td>183.3</td>
<td>163.7</td>
<td>149.7</td>
<td>118.0</td>
</tr>
<tr>
<td>e (longitudinal), percent in 2 in.</td>
<td>15.3</td>
<td>12.5</td>
<td>12.7</td>
<td>21.2</td>
</tr>
<tr>
<td>e (transverse), percent in 2 in.</td>
<td>15.0</td>
<td>11.5</td>
<td>12.5</td>
<td>21.5</td>
</tr>
<tr>
<td>RA (longitudinal), percent</td>
<td>51.8</td>
<td>54.7</td>
<td>55.2</td>
<td>70.3</td>
</tr>
<tr>
<td>RA (transverse), percent</td>
<td>56.2</td>
<td>51.8</td>
<td>52.3</td>
<td>70.3</td>
</tr>
<tr>
<td>E (longitudinal), 10^6 psi</td>
<td>27.7</td>
<td>27.1</td>
<td>25.1</td>
<td>21.9</td>
</tr>
<tr>
<td>E (transverse), 10^6 psi</td>
<td>28.0</td>
<td>25.3</td>
<td>25.1</td>
<td>21.4</td>
</tr>
</tbody>
</table>

| **Compressive**                 |    |     |     |      |
| CTS (longitudinal), ksi         | 187.7 | 158.3 | 150.7 | 118.3 |
| CTS (transverse), ksi           | 199.7 | 159.7 | 150.7 | 131.5 |
| E_c (longitudinal), 10^6 psi    | 30.0 | 26.2 | 25.8 | 23.2 |
| E_c (transverse), 10^6 psi      | 30.0 | 23.7 | 24.4 | 23.0 |

| **Impact**                      |    |     |     |      |
| UTS (longitudinal), ksi         | 121.5 | U  | U   | U    |
| UTS (transverse), ksi           | 123.0 | U  | U   | U    |

| **Fracture Toughness**          |    |     |     |      |
| E_k1 (longitudinal), ksi/ft^2   | (a) | U  | U   | U    |
| E_k (transverse), ksi/ft^2       | (a) | U  | U   | U    |

| **Axial Fatigue**               |    |     |     |      |
| E_k (longitudinal), ksi          | (c) | U  | U   | U    |
| E_k_c (transverse), ksi          | (c) | U  | U   | U    |

**Horned, R = 0.1**

| 10^6 cycles, ksi | 115 | 200 | 163 | U |
| 10^6 cycles, ksi | 187 | 170 | 153 | U |
| 10^6 cycles, ksi | 155 | 162 | 146 | U |

**Horned, R = 3.0, R = 0.1**

| 10^6 cycles, ksi | 189 | 167 | 113 | U |
| 10^6 cycles, ksi | 70  | 80  | 74  | U |
| 10^6 cycles, ksi | 50  | 70  | 66  | U |
PH 13-8 No Stainless Steel Data (continued)

<table>
<thead>
<tr>
<th>Properties</th>
<th>25</th>
<th>400</th>
<th>500</th>
<th>700</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross (transverse)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2% plastic deformation, 100 hr, basl</td>
<td>MA</td>
<td>U</td>
<td>150</td>
<td>106</td>
<td>95</td>
</tr>
<tr>
<td>0.2% plastic deformation, 1000 hr, basl</td>
<td>MA</td>
<td>U</td>
<td>140</td>
<td>95</td>
<td>20</td>
</tr>
<tr>
<td>Stress Rupture (transverse)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rupture, 10 hr, basl</td>
<td>MA</td>
<td>U</td>
<td>161</td>
<td>130</td>
<td>75</td>
</tr>
<tr>
<td>Rupture, 1000 hr, basl</td>
<td>MA</td>
<td>U</td>
<td>160</td>
<td>125</td>
<td>90</td>
</tr>
<tr>
<td>Stress Corrosion (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUL TYS, 1000 hr maximum</td>
<td>no cracks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>6.6 x 10^-6 in./in./F (80 to 900 F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>0.279 lb./in.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Values are average of triplets 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 3 specimens.

(c) U, unavailable; MA, no applicable.

(d) Average of 6 tests.

(e) Six longitudinal slow bend specimens were tested. Specimen size was 0.750-inch thick by 1.500 inches wide with a span of 6 inches. The average Fd, obtained was 121.0 ksi /in. Since the size ratio, 2.5 (Fd/FTYS)², was greater than 1 of the specimen thickness and crack length in all tests, this Fd value is not a valid FTYS value by existing ASTM criteria.

(f) "±" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, ± = ± FTYS. ±Fσ represents the Hooker-Douglas tensile-stress strain-stress strain equations.

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

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**FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF PH 13-8 No (K1000) FORGED BAR**

**FIGURE 2. EFFECT OF TEMPERATURE ON THE COMBUSTIVE PROPERTIES OF PH 13-8 No (K1000) FORGED BAR**
FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED FH 13-8 No (87100) FORGED BAR

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED ($K_I = 3.0$)
FH 13-8 No (87100) FORGED BAR

FIGURE 5. STRESS-REPTURE AND CREEP DEFORMATION CURVES FOR
FH 13-8 No (87100) FORGED BAR (LONGITUDINAL)
7049-T76 Aluminum Extrusions

Material Description

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

The material evaluated was a 4-inch x 4-inch extrusion supplied by Kaiser with the following composition:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>7.6</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.3</td>
</tr>
<tr>
<td>Copper</td>
<td>1.3</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.15</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.25 max</td>
</tr>
<tr>
<td>Iron</td>
<td>0.35 max</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.10 max</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.22 max</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Processing and Heat Treatment

Specimens were tested in the as-received -T76 temper.

<table>
<thead>
<tr>
<th>7049-T76 Aluminum Alloy Data (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness: 4-inch x 4-inch extrusion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties</th>
<th>Temperature, °F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250</td>
</tr>
<tr>
<td>Tension</td>
<td></td>
</tr>
<tr>
<td>TYS (longitudinal), ksi</td>
<td>83.4</td>
</tr>
<tr>
<td>TYS (transverse), ksi</td>
<td>76.3</td>
</tr>
<tr>
<td>TYS (short transverse), ksi</td>
<td>75.9</td>
</tr>
<tr>
<td>TYS (transverse), ksi</td>
<td>67.9</td>
</tr>
<tr>
<td>TYS (short transverse), ksi</td>
<td>67.9</td>
</tr>
<tr>
<td>e (longitudinal), percent in 2 in.</td>
<td></td>
</tr>
<tr>
<td>e (transverse), percent in 2 in.</td>
<td>U</td>
</tr>
<tr>
<td>e (short transverse), percent in 2 in.</td>
<td>U</td>
</tr>
<tr>
<td>RA (longitudinal), percent</td>
<td>33.6</td>
</tr>
<tr>
<td>RA (transverse), percent</td>
<td>23.3</td>
</tr>
<tr>
<td>RA (short transverse), percent</td>
<td>21.6</td>
</tr>
<tr>
<td>E (longitudinal), 10^6 psi</td>
<td>10.7</td>
</tr>
<tr>
<td>E (transverse), 10^6 psi</td>
<td>9.9</td>
</tr>
<tr>
<td>E (short transverse), 10^6 psi</td>
<td>10.6</td>
</tr>
<tr>
<td>Compression</td>
<td></td>
</tr>
<tr>
<td>CTS (longitudinal), ksi</td>
<td>78.8</td>
</tr>
<tr>
<td>CTS (transverse), ksi</td>
<td>74.7</td>
</tr>
<tr>
<td>Kc (longitudinal), 10^6 psi</td>
<td>10.9</td>
</tr>
<tr>
<td>Kc (transverse), 10^6 psi</td>
<td>10.5</td>
</tr>
<tr>
<td>Shear (b)</td>
<td></td>
</tr>
<tr>
<td>SUS (longitudinal), ksi</td>
<td>45.4</td>
</tr>
<tr>
<td>SUS (transverse), ksi</td>
<td>42.8</td>
</tr>
<tr>
<td>Impact (c)</td>
<td></td>
</tr>
<tr>
<td>V-notch Charpy, ft. lb.</td>
<td></td>
</tr>
<tr>
<td>(longitudinal)</td>
<td>5.8</td>
</tr>
<tr>
<td>(transverse)</td>
<td>1.6</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td></td>
</tr>
<tr>
<td>Kic (longitudinal), ksi/ft.</td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td>U</td>
</tr>
<tr>
<td>Axial Fatigue (transverse)(e)</td>
<td></td>
</tr>
<tr>
<td>Unmatched, R = 0.1</td>
<td></td>
</tr>
<tr>
<td>10^6 cycles, ksi</td>
<td>70</td>
</tr>
<tr>
<td>10^6 cycles, ksi</td>
<td>53</td>
</tr>
<tr>
<td>10^6 cycles, ksi</td>
<td>39</td>
</tr>
</tbody>
</table>
7049-T76 Aluminum Alloy Data (continued)

<table>
<thead>
<tr>
<th>Properties</th>
<th>RT</th>
<th>250</th>
<th>350</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Fatigue (transverse) (continued)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Notched, $K_c = 3.0$, $R = 0.1$</td>
<td>48</td>
<td>65</td>
<td>65</td>
<td>N</td>
</tr>
<tr>
<td>$10^6$ cycles, ksi</td>
<td>19</td>
<td>17</td>
<td>17</td>
<td>U</td>
</tr>
<tr>
<td>$10^7$ cycles, ksi</td>
<td>11</td>
<td>7</td>
<td>7</td>
<td>U</td>
</tr>
<tr>
<td>Creep (transverse)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2% plastic deformation, 100 hr, ksi</td>
<td>NA</td>
<td>36</td>
<td>13</td>
<td>2.4</td>
</tr>
<tr>
<td>0.2% plastic deformation, 1000 hr, ksi</td>
<td>NA</td>
<td>23</td>
<td>7</td>
<td>1.1</td>
</tr>
<tr>
<td>Stress Rupture (transverse)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rupture, 100 hr, ksi</td>
<td>NA</td>
<td>44</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>Rupture, 1000 hr, ksi</td>
<td>NA</td>
<td>39</td>
<td>12</td>
<td>3.5</td>
</tr>
<tr>
<td>Stress Corrosion (g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80% TYS, 1000 hr maximum</td>
<td>no cracks</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Coefficient of Thermal Expansion
12.9 x 10^-6 in./in./°F (30 to 712°F)

Density
0.094 lb./in.³

(a) Values are average of triplicate tests conducted at Battelle under the subject nominal values otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 4 tests.

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

(d) Average of 6L and 6T tests.

(e) Six longitudinal slot bend specimens were tested. Specimen size was 0.750-ininch thick by 1.500 inches wide with a span of 6 inches. The average $K_c$ obtained was 50.1 ksi/√in. Since the size ratio, 2.3 ($L_s/TYS)^{1/2}$, was greater than both the specimen thickness and crack length in all tests, this $K_c$ value is not a valid $K_c$ value by existing AFFN criteria.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = \min/S_{max}$. $K_{IC}$ represents the Hower-Petersen theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3.15% NaCl.

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7049-T76 EXTENSION

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7049-T76 EXTENSION
Ti-6Al-2Sn-4Zr-6Mo Alloy

Material Description

Initially, this alloy was developed by the Titanium Metals Corporation as an off-shoot of the Ti-6Al-4V-2Sn-4Zr-4Mo high temperature alloy. Studies had shown that increasing the molybdenum content beyond the 2 percent level resulted in an alloy having improved room and elevated temperature strength with good creep resistance. During early development, investigations were limited to the evaluation of the alloy as a heavy section forging alloy. Promising high temperature properties achieved in heat-treated sections up to 3 inches suggest the alloy might also be useful as a sheet alloy since it should be air hardenable at sheet gages.

The material used in this evaluation was 0.075 inch sheet obtained from TMCA. It had the following composition:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>5.98</td>
</tr>
<tr>
<td>Tite</td>
<td>1.99</td>
</tr>
<tr>
<td>Zirconium</td>
<td>3.64</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>5.86</td>
</tr>
<tr>
<td>Iron</td>
<td>0.057</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.10</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.004</td>
</tr>
<tr>
<td>Titanium</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Processing and Heat Treatment

Specimens were machined in the as-received condition and heat-treated as follows:

1. 1600°F, 15 minutes, air cooled.
2. 1325°F, 15 minutes, air cooled.
3. 1100°F, 2 hours, air cooled.

<table>
<thead>
<tr>
<th>Ti-6Al-2Sn-4Zr-6Mo Data (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition: Solution treated and aged</td>
</tr>
<tr>
<td>Thickness: 0.075-in. sheet</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties</th>
<th>Room</th>
<th>400°F</th>
<th>700°F</th>
<th>1000°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension (longitudinal), ksi</td>
<td>168.0</td>
<td>148.5</td>
<td>140.7</td>
<td>105.3</td>
</tr>
<tr>
<td>Tension (transverse), ksi</td>
<td>169.4</td>
<td>150.0</td>
<td>142.0</td>
<td>106.6</td>
</tr>
<tr>
<td>TYS (longitudinal), ksi</td>
<td>160.0</td>
<td>127.7</td>
<td>114.3</td>
<td>97.3</td>
</tr>
<tr>
<td>TYS (transverse), ksi</td>
<td>163.0</td>
<td>130.7</td>
<td>117.0</td>
<td>98.9</td>
</tr>
<tr>
<td>e (longitudinal), percent in 2 in.</td>
<td>12.3</td>
<td>16.0</td>
<td>14.3</td>
<td>36.3</td>
</tr>
<tr>
<td>e (transverse), percent in 2 in.</td>
<td>11.6</td>
<td>16.2</td>
<td>14.3</td>
<td>35.3</td>
</tr>
<tr>
<td>E (longitudinal), 10⁸ psi</td>
<td>17.5</td>
<td>16.3</td>
<td>15.1</td>
<td>12.8</td>
</tr>
<tr>
<td>E (transverse), 10⁸ psi</td>
<td>17.2</td>
<td>15.6</td>
<td>14.6</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Compression

<table>
<thead>
<tr>
<th>Properties</th>
<th>Room</th>
<th>400°F</th>
<th>700°F</th>
<th>1000°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTS (longitudinal), ksi</td>
<td>167.5</td>
<td>133.3</td>
<td>123.3</td>
<td>110.7</td>
</tr>
<tr>
<td>CTS (transverse), ksi</td>
<td>170.6</td>
<td>138.0</td>
<td>126.7</td>
<td>112.7</td>
</tr>
<tr>
<td>E_C (longitudinal), 10⁸ psi</td>
<td>19.4</td>
<td>17.9</td>
<td>16.3</td>
<td>13.9</td>
</tr>
<tr>
<td>E_C (transverse), 10⁸ psi</td>
<td>18.9</td>
<td>17.6</td>
<td>16.1</td>
<td>13.6</td>
</tr>
</tbody>
</table>

Shear (b)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Room</th>
<th>400°F</th>
<th>700°F</th>
<th>1000°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS (longitudinal), ksi</td>
<td>94.8</td>
<td>94.8</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>SUS (transverse), ksi</td>
<td>98.1</td>
<td>98.1</td>
<td>U</td>
<td>U</td>
</tr>
</tbody>
</table>

Fracture Toughness (d)

| K_c (crack direction LT), ksi/√m | 132 | U   | U   | U   |

Artificial Fatigue (transverse) (e)

<table>
<thead>
<tr>
<th>Denotation, R = 0.1</th>
<th>10⁶ cycles, ksi</th>
<th>10⁸ cycles, ksi</th>
<th>10⁹ cycles, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unnotched, R = 0.1</td>
<td>140</td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>Notched, R = 0.1</td>
<td>70</td>
<td>85</td>
<td>85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Denotation, R = 0.1</th>
<th>10⁸ cycles, ksi</th>
<th>10⁹ cycles, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unnotched, R = 0.1</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Notched, R = 0.1</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>
T1-6Al-2Sn-4Zr-6Mo Data (continued)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HT 800 900 1100</td>
</tr>
<tr>
<td>Creep (transverse)</td>
<td></td>
</tr>
<tr>
<td>0.2% plastic deformation, 100 hr, ksi</td>
<td>NA 112 29 1.9</td>
</tr>
<tr>
<td>0.2% plastic deformation, 1000 hr, ksi</td>
<td>NA 98 14 3.1</td>
</tr>
<tr>
<td>Stress Rupture (transverse)</td>
<td></td>
</tr>
<tr>
<td>Rupture, 100 hr, ksi</td>
<td>NA 142 101 19</td>
</tr>
<tr>
<td>Rupture, 1000 hr, ksi</td>
<td>NA 140 90 7.5</td>
</tr>
<tr>
<td>Stress Corrosion (f)</td>
<td></td>
</tr>
<tr>
<td>80% TYS, 1000 hr maximum</td>
<td>no cracks</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td></td>
</tr>
<tr>
<td>3.5 x 10⁻⁶ in./in./F (80 to 1000 F)</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
</tr>
<tr>
<td>0.165 lb./in.³</td>
<td></td>
</tr>
</tbody>
</table>

(a) Values given are average of triplicate tests conducted at Battelle unless otherwise indicated. Values for fatigue, creep, and stress-rupture are from curves generated using a greater number of tests.

(b) Single-shear sheet-type specimen; average of 3 tests.

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

(d) Specimens were full sheet thickness x 18 inches x 36 inches with EBM file in center.

(e) "X" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, X = Smin/Smax. "Kc" represents the Neuber-Peterson theoretical stress concentration factor.

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

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**FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF T1-6Al-2Sn-4Zr-6Mo SHEET**

**FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF T1-6Al-2Sn-4Zr-6Mo SHEET**
Figure 2. Axial Load Fatigue Results for Unnotched Ti-6Al-2Sn-4Zr-6Mo Sheet.

Figure 3. Stress-Rupture and Plastic Deformation Curves for Ti-6Al-2Sn-4Zr-6Mo Sheet (Transverse).

Figure 4. Axial Load Fatigue Results for Notched (K_t = 3.0) Ti-6Al-2Sn-4Zr-6Mo Sheet.
Inconel 702 Alloy Data

**Condition:** Aged
**Thickness:** 0.010-inch sheet

<table>
<thead>
<tr>
<th>Property</th>
<th>225°F</th>
<th>650°F</th>
<th>1500°F</th>
<th>2500°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS (longitudinal), ksi</td>
<td>152.7</td>
<td>139.0</td>
<td>120.7</td>
<td>66.7</td>
</tr>
<tr>
<td>TS (transverse), ksi</td>
<td>151.0</td>
<td>127.7</td>
<td>123.3</td>
<td>67.3</td>
</tr>
<tr>
<td>TS (longitudinal), ksi</td>
<td>66.8</td>
<td>55.7</td>
<td>52.5</td>
<td>64.6</td>
</tr>
<tr>
<td>TS (transverse), ksi</td>
<td>98.4</td>
<td>86.3</td>
<td>85.3</td>
<td>63.1</td>
</tr>
<tr>
<td>e (longitudinal), percent in 2 in.</td>
<td>34.2</td>
<td>35.8</td>
<td>35.5</td>
<td>6.3</td>
</tr>
<tr>
<td>e (transverse), percent in 2 in.</td>
<td>34.2</td>
<td>35.8</td>
<td>35.5</td>
<td>6.3</td>
</tr>
<tr>
<td>S (longitudinal), 10^6 psi</td>
<td>35.5</td>
<td>29.6</td>
<td>29.2</td>
<td>29.2</td>
</tr>
<tr>
<td>S (transverse), 10^6 psi</td>
<td>33.2</td>
<td>23.9</td>
<td>27.7</td>
<td>7.6</td>
</tr>
<tr>
<td>Compression</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTS (longitudinal), ksi</td>
<td>99.4</td>
<td>91.0</td>
<td>90.2</td>
<td>62.0</td>
</tr>
<tr>
<td>CTS (transverse), ksi</td>
<td>101.0</td>
<td>92.6</td>
<td>91.0</td>
<td>65.5</td>
</tr>
<tr>
<td>E (longitudinal), 10^6 psi</td>
<td>34.4</td>
<td>35.0</td>
<td>37.4</td>
<td>37.6</td>
</tr>
<tr>
<td>E (transverse), 10^6 psi</td>
<td>34.7</td>
<td>33.9</td>
<td>36.6</td>
<td>37.7</td>
</tr>
<tr>
<td>Elastic Modulus (ksi)</td>
<td>(4)</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>Fracture Toughness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K_c, ksi /√ft</td>
<td>(4)</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>Axial Fatigue (transverse)</td>
<td>(4)</td>
<td>U</td>
<td>U</td>
<td>U</td>
</tr>
</tbody>
</table>

The wrought, extruded bar used was 0.005 inch sheet from Huntington Alloy Products Division, S.A., HUNTINGTON. The composition was as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.01</td>
</tr>
<tr>
<td>Nickel</td>
<td>62.35</td>
</tr>
<tr>
<td>Iron</td>
<td>34.90</td>
</tr>
<tr>
<td>Beryllium</td>
<td>0.007</td>
</tr>
<tr>
<td>Other</td>
<td>0.15</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.01</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.01</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.10</td>
</tr>
<tr>
<td>Nickel</td>
<td>79.50</td>
</tr>
</tbody>
</table>

The wrought extruded was in the re-cast and annealed condition and then aged at 1400°F for 1 hour.
Table 7.2: Alloy Data (continued)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>80°F</th>
<th>120°F</th>
<th>160°F</th>
<th>200°F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Group (Temperature)**

- 80°F: plastic deformation, 120°F: 0.61
- 120°F: plastic deformation, 160°F: 0.61

**Stress-Rupture (Temperature)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>600°F</th>
<th>800°F</th>
<th>1000°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>122</td>
<td>75</td>
<td>32</td>
</tr>
<tr>
<td>Sample B</td>
<td>120</td>
<td>55</td>
<td>11</td>
</tr>
</tbody>
</table>

**Chemical of Thermal Properties**

- C: 0.17 ± 0.01
- Mn: 0.30 ± 0.01
- Si: 0.03 ± 0.01
- P: 0.01 ± 0.005
- S: 0.005 ± 0.0005

**Figure 1. Effect of Temperature on the Tensile Properties of Inconel 701 Sheet (Aged)**

**Figure 2. Effect of Temperature on the Compressive Properties of Inconel 701 Sheet (Aged)**
Inconel 706 Alloy

Material Description

Inconel alloy 706 is a precipitation-hardenable, nickel-iron-chromium alloy with characteristics similar to those of Inconel 718, except that 706 has improved machinability. It has high strength at temperatures ranging from cryogenic to 1300°F. It also has good resistance to oxidation and corrosion over a broad range of temperatures and environments.

Fabrication of the alloy is enhanced by its good formability and weldability. Alloy 706 has excellent resistance to postweld strain-age cracking.

The material used in this evaluation was obtained as a 6-inch-square forging from Inco Ltd. West Rotherham, UK. The composition was as follows:

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.03</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.12</td>
</tr>
<tr>
<td>Iron</td>
<td>34.50</td>
</tr>
<tr>
<td>Boron</td>
<td>0.007</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.75</td>
</tr>
<tr>
<td>Copper</td>
<td>0.02</td>
</tr>
<tr>
<td>Chromium</td>
<td>16.22</td>
</tr>
<tr>
<td>Titanium</td>
<td>1.62</td>
</tr>
<tr>
<td>Columbium plus</td>
<td>2.96</td>
</tr>
<tr>
<td>Nickel</td>
<td>43.12</td>
</tr>
</tbody>
</table>

Processing and Heat Treatment

The 6-inch-square material was press forged to a 3 inch x 6 inch forging to make specimens blank easier to obtain. After machining, specimens were heat treated as follows:

1. 1800°F, 2 hours, air cool,
2. 1550°F, 3 hours, air cool,
3. 1325°F, 8 hours, furnace cool to 100°F, hold for 18 hours, air cool.

\[
\begin{array}{c|c|c}
\text{Properties} & \text{RT} & \text{600°F} \\
\hline
\text{Tension} & \text{ksi} & \text{ksi} \\
\hline
\text{(longitudinal)} & 177.7 & 156.3 \\
\text{(transverse)} & 176.0 & 157.7 \\
\hline
\text{Compresson} & \text{ksi} & \text{ksi} \\
\hline
\text{(longitudinal)} & 149.0 & 126.7 \\
\text{(transverse)} & 149.0 & 129.9 \\
\hline
\text{Shear} & \text{ksi} & \text{ksi} \\
\hline
\text{(longitudinal)} & 117.0 & 117.0 \\
\text{(transverse)} & 117.0 & 117.0 \\
\hline
\text{Fracture Toughness} & \text{ksi} & \text{ksi} \\
\hline
\text{Kc (longitudinal)} & \text{(a)} & \text{(a)} \\
\text{Kc (transverse)} & \text{(a)} & \text{(a)} \\
\hline
\text{Axial Fatigue (transverse)} & \text{ksi} & \text{ksi} \\
\hline
\text{Notched, } R = 0.1 & \text{ksi} & \text{ksi} \\
\text{10^7 cycles, 10^8 cycles} & \text{121} & \text{121} \\
\text{10^9 cycles, 10^10 cycles} & \text{60} & \text{60} \\
\text{Notched, } R = 0.2, R = 0.1 & \text{ksi} & \text{ksi} \\
\text{10^7 cycles, 10^8 cycles} & \text{121} & \text{121} \\
\text{10^9 cycles, 10^10 cycles} & \text{60} & \text{60} \\
\end{array}
\]
Inconel 706 Alloy Data (continued)

<table>
<thead>
<tr>
<th>Property</th>
<th>RT</th>
<th>500</th>
<th>900</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tests (transverse)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2% offset deformation, 100 hr. lbf</td>
<td>NA</td>
<td>155</td>
<td>153</td>
<td>85</td>
</tr>
<tr>
<td>0.2% offset deformation, 1000 hr. lbf</td>
<td>NA</td>
<td>191</td>
<td>111</td>
<td>75</td>
</tr>
<tr>
<td>Stress rupture (transv. &amp; lbf)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Room temp., 100 hr, lbf</td>
<td>NA</td>
<td>154</td>
<td>153</td>
<td>70</td>
</tr>
<tr>
<td>Room temp., 1000 hr, lbf</td>
<td>28</td>
<td>135</td>
<td>150</td>
<td>70</td>
</tr>
<tr>
<td>Stress corrosion (a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E82 TTS, 1000 hr, no cracks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>6.3 x 10^-6 in/in/F (70 to 1500 F)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>0.30 lb/ft^3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Figure 3:** Axial load fatigue results for notched and unnotched 7075-T6511 forged bars (stress-rupture heat treatment).

**Figure 4:** Axial load fatigue results for notched (R = 3.0) 7075-T6511 forged bars (stress-rupture heat treatment).

**Figure 5:** Stress-rupture and plastic deformation curves for notched 7075-T6511 forged bars (stress-rupture heat treatment) (transverse).