MECHANICAL PROPERTIES OF TITANIUM AND ALUMINUM ALLOYS AT CRYOGENIC TEMPERATURES

TECHNICAL REPORT WAL TR 340.2/1

BY

CHARLES F. HICKEY, Jr.

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WATERTOWN ARSENAL
WATERTOWN 72, MASS.
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ABSTRACT

Low temperature mechanical properties of titanium and aluminum alloys in both bar and sheet form were obtained as a function of testing temperature. For bar material tensile and Charpy impact data were obtained at temperatures ranging from room temperature to -452 °F for the tensile and from room temperature to -441 °F for the Charpy tests. For the material in the sheet form, notched tension sheet and unnotched tension sheet data were obtained at temperatures between room temperature and -320 °F. A unique aspect of this work is the fact that materials which were investigated in both the bar and sheet form were from the same heat.

The results of this investigation indicate that a majority of the titanium and nearly all the aluminum alloys are acceptable for applications in a cryogenic environment.

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REPORT APPROVAL:
Date: 25 May 1962
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CONTENTS

ABSTRACT

INTRODUCTION ................................................. 3

MATERIALS .................................................. 3

PROCEDURE .................................................. 4

RESULTS AND DISCUSSION

Titanium Alloys ............................................. 4
  Ti-7Al-4Mo ............................................. 4
  Ti-7Al-3Mo ............................................. 6
  Ti-6Al-4V ............................................... 6
  Ti-4Al-3Mo-1V .......................................... 6
  Ti-16V-2.5Al ............................................ 7
  Ti-13V-11Cr-3Al ......................................... 7
  Ti-7Al-4V, 6.5Al-3Mo-1V, and 155A ......................... 7
  Notched Tensile Ratio .................................... 7

Aluminum Alloys ............................................. 7
  6061-T6 .................................................. 8
  7075-T6 .................................................. 8
  2024-T3 and 2017-T4 ..................................... 8
  2024-T3 and Alclad 2024-T3 ................................ 8
  2014-T6 and 5086-H34 .................................... 8
  Notched Tensile Ratio .................................... 8

SUMMARY

  Titanium ................................................ 9
  Aluminum ............................................... 13
  Bar Versus Sheet Data .................................... 13

TABLES ..................................................... 16

APPENDIX A - MECHANICAL PROPERTY CURVES FOR TITANIUM ALLOYS . 23

APPENDIX B - MECHANICAL PROPERTY CURVES FOR ALUMINUM ALLOYS . 31

REFERENCES ............................................... 37
INTRODUCTION

With the current and ever-increasing interest in high strength and thin gage materials for missiles, rockets, aircraft, and component applications in a low-temperature environment, the mechanical properties of such materials have become of tremendous importance. Since a prime criterion used for selecting materials for such applications is the strength/weight ratio, titanium and aluminum alloys have been greatly emphasized. For any given strength level, their respective strength/weight ratios are approximately 1.7 and 2.8 times greater than that of steel. In recent years, there have been numerous publications on low-temperature mechanical properties of these materials at temperatures down to -320 F and in many cases as low as -423 F. Currently liquid hydrogen, -423 F, is the lowest temperature propellant being utilized, and data at lower temperatures have not been of great necessity. Therefore, little work has been done at temperatures below -423 F. However, in the future, data obtained at liquid helium temperature, -452 F, will be necessary in order to design systems which can withstand the lower temperature environment.

This report is a presentation of low-temperature mechanical property data which have been obtained from numerous titanium and aluminum alloys in both bar stock and sheet form. The investigation is unique because materials investigated in both the bar and sheet form are from the same heat.

Tensile and impact properties were obtained at temperatures ranging from room to liquid helium temperatures on the bar materials and tension sheet data from room temperature to -320 F for the sheet materials. The notch tensile ratios were determined on sheet specimens as a function of testing temperature, thus providing a criterion for resistance to brittle fracture.

MATERIALS

The materials selected for this investigation included 7Al-4Mo, 7Al-3Mo, 6AI-4V, 4AI-3Mo-1V, 16V-2.5AI, 13V-12Cr-3Al, 7AI-4V, 6.5AI-3Mo-1V, and 155A for the titanium alloys and 6061-T6, 7075-T6, 2017-T4, 2024-T4, 2014-T6, Al clad 2024-T3, and 5086-H34 for the aluminum alloys. Table I is a tabulation of the chemical composition of the titanium alloys. The bar was 5/8 inch in diameter and the sheet 0.060 inch in thickness. The nominal chemical composition of the aluminum alloys is presented in Table II. The aluminum bar was 5/8 inch in diameter and the sheet 0.050 inch in thickness.
PROCEDURE

Standard V-notch Charpy impact and 0.252 inch tension specimens were obtained from the bar materials of both the titanium and aluminum alloys. The specimens obtained from the sheet materials of both metals were of a special design and included both unnotched and notched type specimens. Figures 1a and 1b contain sketches of the unnotched and notched tension sheet specimens selected for this program. All notched specimens had a 30 percent notch and a stress concentration factor ($K_t$) of 11.2 except for the titanium materials tested at -320 F. For testing at this temperature, the specimens were further modified by decreasing the width between the notches in an effort to assure fracture in the notched area. The $K_t$ for this design was 10.0. The notch radius in all cases was 0.002 inch.

The stress concentration factors were calculated by means of the following equation:

$$K_t = \sqrt{\frac{1/2 \text{ width between notches}}{\text{radius of notch}}}$$

Titanium and aluminum 0.252-inch tension specimens were tested on a 60,000-pound capacity Universal hydraulic machine. A strain rate of 0.005 inch per minute up to 0.2 percent offset followed by a platen displacement of 0.02 inch per minute to fracture was used for titanium bar materials tested between room temperature and -320 F. For aluminum bars and also for titanium bars tested at -452 F a constant platen displacement of 0.01 inch per minute was used. All tensile testing below -320 F was conducted in a tensile cryostat.

Sheet specimen testing for both alloy materials was performed on a 30,000-pound capacity Tinius Olsen hydraulic machine, using the same testing procedure as for bar form.

V-notch Charpy impact specimens were tested on a 240 ft-lb Sonntag machine for temperatures down to -320 F. An impact cryostat was used for obtaining Charpy values at -441 F.

All titanium alloys were tested in the mill-annealed condition.

RESULTS AND DISCUSSION

Titanium Alloys

A tabulation of the titanium test data is presented in Tables III and IV, and curves representing the mechanical properties of each alloy are shown in Appendix A.

Ti-7Al-4Mo

Strength values for this titanium alloy, as shown in Figure A-1, increase over the decreasing temperature span except for the notch strength.
NOTCHED AND UNNOTCHED TENSION SHEET SPECIMEN DESIGN
indicating that the material is notch sensitive, especially at the lower temperatures. (A plot of notch tensile ratio as a function of testing temperatures for all titanium materials is shown in Figure A-8). Bar and sheet (unnotched specimen) strength data are similar; however, bar elongation values are consistently higher than sheet. V-notch Charpy impact values decreased from 16 ft-lb at +212 F to 10.8 ft-lb at -441 F.

**Ti-7Al-3Mo**

Figure A-2 is a plot of the mechanical properties of Ti-7Al-3Mo. Tensile strength values increased at approximately the same rate as yield values as testing temperature decreased. Notched values decreased as a function of testing temperature, thus indicating notch sensitivity. For the most part, ductility is only slightly sensitive to a low-temperature environment, even at -452 F. Impact values decreased from 11.8 to 6.4 ft-lb over the temperature range investigated.

**Ti-6Al-4V**

Tensile and yield strength data for both bar and sheet of this titanium alloy are shown in Figure A-3. Bar and sheet data show approximately the same increase in strength as testing temperature is decreased and except for the data at -240 F, where the bar values are higher, there is little difference between bar and sheet data. Results from notched specimens show that the material is not notch sensitive down to -240 F. The respective notch tensile ratio values at -240 and -320 F are 0.92 and 0.78. It is noteworthy to mention that reduction of area values ranged from 52 percent at room temperature to 32 percent at -452 F. Elongation values of the material in bar form are somewhat higher than those of the material in sheet form and this property is temperature sensitive below -320 F. Impact properties are temperature sensitive; however, this alloy still exhibits a value of 13.8 ft-lb at -441 F.

**Ti-4Al-3Mo-1V**

Figure A-4 is a plot of the mechanical properties of Ti-4Al-3Mo-1V. It is apparent that the tensile and yield strength data show a large increase as testing temperature is decreased with the data from the bar material being higher than the data from the unnotched sheet specimens. Notched strength values are higher than unnotched results at all temperatures, thus indicating that this material is not notch sensitive. Reduction of area values range from 62 percent at room temperature to 35 percent at -452 F. Elongation is rather insensitive to a decreasing temperature environment, dropping gradually from 20 percent at room temperature to 15 percent at -320 F and then sharply to 9 percent at -452 F. In general, elongation values of sheet material are slightly higher than those of bar material. Impact values for this material are very high, but they decrease rapidly as temperature decreases to -320 F. The value of 17.1 ft-lb at -320 F does not change appreciably at -441 F, thus this material exhibits good impact properties at ultra low temperatures.
Ti-16V-2.5Al

Mechanical properties versus testing temperature for Ti-16V-2.5Al are shown in Figure A-5. With the exception of room temperature properties, the strength of the bar material was consistently higher than the strength of the sheet material down to -240 F. Bar material data below -240 F could not be obtained since specimens tested at -320 F broke before the desired offset was reached. The notch tensile ratio for this material is extremely sensitive to a temperature environment below -105 F. The ratio at -105 F is 0.96 and it drops to 0.58 at -320 F. Ductility values indicated that bar material is sensitive to the temperature environment below -105 F. The impact properties of this material are low at all temperatures.

Ti-13V-11Cr-3Al

Data on Ti-13V-11Cr-3Al are presented in Figure A-6. Mechanical properties of this alloy are extremely sensitive to a decrease in testing temperature. Strength values are similar for the material in both bar and sheet forms except for the notch tensile properties which are somewhat higher down to -105 F and thereafter decrease drastically at the lower temperatures. The notch tensile ratio ranges from a maximum of 1.12 at room temperature to a low of 0.33 at -320 F.

Ti-7Al-4V, 6.5Al-3Mo-1V, and 155A

Figure A-7 contains data obtained from Ti-7Al-4V, Ti-6.5Al-3Mo-1V, and Ti-155A alloys in bar form. The tensile strength for the materials increased uniformly over the temperature range investigated. Ductility and impact values for Ti-7Al-4V and Ti-6.5Al-3Mo-1V were superior to those of Ti-155A at -240 F and below.

Notched Tensile Ratio

Figure A-8 is a plot of the notch tensile ratio as a function of testing temperature (room temperature to -320 F) for the titanium sheet materials described in Figures A-1 to A-7. The Ti-7Al-3Mo-1V is both notch and temperature insensitive. All notch tensile ratios for this material lie between 1.09 and 1.18. Notch tensile properties for the remainder of the alloys are temperature sensitive. The Ti-13V-11Cr-3Al material showed the greatest notch tensile ratio decrease, being 1.12 at room temperature and dropping to 0.33 at -320 F. Room temperature values were 1.0 or greater for all alloys except for Ti-7Al-3Mo and Ti-7Al-4Mo. These two materials each had a value of 0.91.

Aluminum Alloys

A tabulation of the aluminum test data is presented in Tables V and VI and curves representing the mechanical properties of each alloy are shown in Appendix B.
6061-T6

Figure B-1 is a plot of the mechanical properties for aluminum alloy 6061-T6 in both the bar and sheet form. Data on the material in bar form showed a marked increase in tensile strength at -452 F without a loss in ductility. Impact values were insensitive to the low temperature environment. Notch tensile ratio values ranged from 1.06 at room temperature to 0.93 at -320 F. A plot of notch tensile ratio as a function of testing temperature for the aluminum alloys is shown in Figure B-6.

7075-T6

Figure B-2 shows results from 7075-T6 in both bar and sheet form. Tensile strength values of the bar material increased from 82,000 psi at room temperature to 116,000 psi at -452 F. Ductility and impact decrease slightly over the low temperature range. Data on the sheet material point out that this material is notch sensitive. It has a room temperature value of 0.89 which decreases to 0.67 at -320 F.

2024-T4 and 2017-T4

The effect of cryogenic testing temperatures on the mechanical properties of 2024-T4 and 2017-T4 in bar form are shown in Figure B-3.

Tensile and yield strengths increased approximately 40,000 psi over the temperature range investigated, with the major environmental effect occurring between -320 and -452 F. Ductility and impact showed no appreciable decrease as the temperature decreased.

2024-T3 and Alclad 2024-T3

Figure B-4 is a plot of data obtained from notched and unnotched sheet specimens of 2024-T3 and Alclad 2024-T3. Strength properties showed a gradual increase while elongation values decreased over the low temperature range down to -320 F. Room temperature notch tensile ratios are between 0.8 and 1.0 for both alloys and these values change little due to testing temperature.

2014-T6 and 5086-H34

Data from notched and unnotched sheet specimens of 2014-T6 and 5086-H34 are shown in Figure B-5. Strength properties of both materials plus elongation values for 5086-H34 tend to increase with a decrease in testing temperature. The room temperature notch tensile ratio for the materials is in the order of 0.9 and this value is altered very little at the lower temperatures.

Notched Tensile Ratio

Figure B-6 is a plot of the notch tensile ratio for the aluminum sheet materials as a function of testing temperature (room temperature to -320 F). The alloy 6061-T6 tends to exhibit the most favorable ratio,
having a room temperature value of 1.65 which decreases to only 0.93 at -320 F. The Ti-13V-11Cr-3Al material was found to be the most notch sensitive of the alloys investigated. Its room temperature value of 0.89 was slightly higher than two other alloys; however, this value decreased with temperature to a ratio of 0.0% at -320 F.

**Summary**

Titanium

A summary of yield strength and impact values versus testing temperature is shown in Figures 2 and 3 respectively. As indicated in Table III, tensile specimens for Ti-16V-2.5Al and Ti-13V-11Cr-3Al broke in a brittle manner prior to yielding at -320 F, therefore, these materials are not recommended for low temperature applications. The remainder of the titanium alloys were tested from room temperature to -452 F. In general, Ti-7Al-4Mo and Ti-7Al-3Mo had the highest strength properties at the respective testing temperatures, while Ti-4Al-3Mo-1V exhibited the lowest strength properties.

A summary plot is not shown for ductility. In general, however, these properties fared quite well at -452 F. Exceptions to this are elongation values for Ti-6Al-4V and Ti-4Al-3Mo-1V and reduction of area for Ti-155A. Reduction of area values also decreased for Ti-6Al-4V and Ti-4Al-3Mo-1V, however; they were still reasonably high.

Impact properties were very encouraging at -452 F. The Ti-155A and Ti-6.5Al-3Mo-1V alloys were the only materials to decrease appreciably between -320 and -452 F. The titanium alloys 4Al-3Mo-1V and 6Al-4V showed the highest properties over the testing range; 16V-2.5Al and 13V-11Cr-3Al were the lowest.

Based upon a tensile impact criterion, utilization of the following alloys is advocated for a liquid helium environment: Ti-7Al-4Mo, Ti-7Al-3Mo, Ti-6Al-4V, Ti-4Al-3Mo-1V, Ti-7Al-4V, and Ti-6.5Al-3Mo-1V.

Figure 4 is a plot of notch tensile ratio versus unnotched tensile strength as a function of testing temperature. Such a plot is most informative because the tensile strength per notch tensile ratio as a function of testing temperature can also be depicted. This is of major value for in many design applications the engineer must select an optimum notch tensile ratio and strength combination.

An examination of Figure 4 shows that Ti-4Al-3Mo-1V has a high notch tensile ratio even at -320 F; however, its strength range is limited. In general, the remaining alloys exhibit a fairly uniform decrease in notch tensile ratio and an increase in tensile strength as the testing temperature is decreased. An exception is Ti-13V-11Cr-3Al which decreases only slightly in notch tensile ratio between room temperature and -105 F, then
**Figure 2**

Effect of testing temperature on the yield strength of titanium alloys.

- Specimens broke in brittle manner prior to yielding at \(-520\) °F.
EFFECT OF TESTING TEMPERATURE ON THE IMPACT PROPERTIES OF TITANIUM ALLOYS

FIGURE 3
EFFECT OF TESTING TEMPERATURE ON THE NOTCH TENSILE CHARACTERISTICS OF TITANIUM ALLOYS

\[ K_f = 11.2 \]
\[ K_f = 10.0 (-320 F) \]
\[ R = 0.002 \text{ in.} \]
drastically at -210 F. This is characteristic of this alloy for it undergoes a ductile to brittle transition between -105 and -240 F.

Aluminum

Tensile data were obtained from room temperature to -452 F and impact data from room temperature to -144 F for 6061-T6, 7075-T6, 2024-T6, and 2017-T4 aluminum alloys in the bar form. A summary plot of these data is shown in Figures 5a and 5b. Yield strength values increase and impact values decrease only slightly with the decreased temperature environment. Ductility values are not summarized; however, the results indicated that there is no appreciable loss in ductility at the low temperatures. Thus, it can be stated that these alloys may be considered for usage in a liquid helium environment.

Figure 6 is a plot of notch tensile ratio versus unnotched tensile strength for the aluminum sheet alloys. It is noted that 6061-T6 has the highest notch tensile ratio; however, it is also lowest in tensile strength. In general, the data show an increase in tensile strength and decrease in notch tensile ratio with decreased testing temperature. Exceptions are 2024-T3 and Alclad 2024-T3, which show a slight increase in notch tensile ratio with decreased testing temperature.

The value of the notch tensile test as a criterion of toughness is evidenced for 7075-T6. As mentioned earlier, based upon a tensile impact criterion, this material appeared acceptable for low temperature applications in the bar form. However, in sheet form it can be seen that it is notch sensitive as the testing temperature is decreased. Thus, it appears that in the sheet form 7075-T6 would not be suitable for low temperature applications unless it would be desirable to sacrifice toughness for increased strength.

Bar Versus Sheet Data

In general, strength properties were higher for bar than for sheet material of the same heat. For titanium this difference ranged from a minimum of approximately 3,000 to 5,000 psi in the 6Al-4V and 13V-11Cr-3Al alloy to a maximum of 28,000 psi for Ti-16V-2.5Al. The two aluminum alloys of the same heat were approximately 3,000 psi higher in the bar form.

An exception to the general trend is Ti-7Al-3Mo. In this material the sheet values are higher at all temperatures by an average of 7,000 psi.

A possible explanation for the variance in bar and sheet data, especially in titanium, may lie in the fact that each form received a different type and amount of working, thus giving rise to a different structure and texture.

It should also be recognized that due to the difference in specimen geometry, one cannot justifiably compare bar and sheet values. However, trendwise, it can be stated that in general the bar values are slightly superior to those obtained from the sheet.
FIGURE 5a: EFFECT OF TESTING TEMPERATURE ON THE YIELD STRENGTH OF ALUMINUM ALLOYS

FIGURE 5b: EFFECT OF TESTING TEMPERATURE ON THE IMPACT PROPERTIES OF ALUMINUM ALLOYS

FIGURES 5a & 5b
Figure 6

Effect of testing temperature on the notch tensile characteristics of aluminum alloys.

- RT
- -105 F
- -240 F
- -320 F

Materials:
- 6061-T6
- ALCLAD 2024-T3
- 5086-H34
- 2024-T3
- 2014-T6
- 7075-T6

Symbols:
- ○ RT
- □ -105 F
- ● -240 F
- ■ -320 F

Parameters:
- $K_I = 11.2$
- $R = 0.002$ in.
<table>
<thead>
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<th>Ti Alloy</th>
<th>Heat</th>
<th>C</th>
<th>N</th>
<th>Al</th>
<th>V</th>
<th>Mo</th>
<th>Cr</th>
<th>O_p</th>
<th>H_d</th>
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<tbody>
<tr>
<td>7Al-4Mo</td>
<td>X 70004</td>
<td>0.065</td>
<td>0.007</td>
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<td>-</td>
<td>4.19</td>
<td>-</td>
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<td>0.0036</td>
</tr>
<tr>
<td>7Al-3Mo</td>
<td>1 129-S</td>
<td>0.036</td>
<td>0.014</td>
<td>7.03</td>
<td>-</td>
<td>2.70</td>
<td>-</td>
<td>0.094</td>
<td>0.0110</td>
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<td>6Al-4V</td>
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<td>0.025</td>
<td>0.008</td>
<td>5.84</td>
<td>4.23</td>
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<td>-</td>
<td>0.071</td>
<td>0.0050</td>
</tr>
<tr>
<td>4Al-3Mo-1V</td>
<td>X 70006</td>
<td>0.045</td>
<td>0.009</td>
<td>3.85</td>
<td>0.96</td>
<td>3.07</td>
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<td>0.025</td>
<td>0.025</td>
<td>2.79</td>
<td>15.80</td>
<td>-</td>
<td>-</td>
<td>0.080</td>
<td>0.0018</td>
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<tr>
<td>13V-11Cr-3Al</td>
<td>X 70003</td>
<td>0.028</td>
<td>0.013</td>
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<td>13.18</td>
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<td>10.96</td>
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</table>

NOTE: All alloys listed were received in bar and sheet form.

Alloys 7Al-4V, 6.5Al-3Mo-1V, and 155A were received in bar form only. Analyses for these alloys are not available.

Bar Diameter 5/8 inch

Sheet Thickness 0.060 inch

Condition - Mill annealed
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<tr>
<th>Al Alloys</th>
<th>Form</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
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<td>6061-T6</td>
<td>Bar and Sheet</td>
<td>0.40 to 0.80</td>
<td>0.70</td>
<td>0.15 to 0.40</td>
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<td>0.80 to 0.35</td>
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<tr>
<td>7075-T6</td>
<td>Bar and Sheet</td>
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<td>0.70</td>
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<td>Bar</td>
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<td>1.00</td>
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<td>0.25</td>
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<td>2024-T4</td>
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<td>2014-T6</td>
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<td>5086-H34</td>
<td>Sheet</td>
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Bar Diameter 5/8 inch

Sheet Thickness 0.050 inch
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<tr>
<th>Titanium Alloy</th>
<th>Temperature (deg F)</th>
<th>Yield Strength (0.1%) (ksi)</th>
<th>Tensile Strength (ksi)</th>
<th>Elongation (%)</th>
<th>Reduction of Area (%)</th>
<th>Impact (ft-lb)</th>
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<td>160</td>
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<sup>a</sup> Testing Temperature +212 F
<sup>b</sup> Testing Temperature -40 F
<sup>c</sup> Testing Temperature -441 F
<sup>d</sup> Specimen broke in brittle manner prior to yielding
### TABLE IV

LOW-TEMPERATURE MECHANICAL PROPERTIES OF TITANIUM SHEET MATERIALS IN SHEET THICKNESS OF 0.060 INCH

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<th>TS (ksi)</th>
<th>EL (%)</th>
<th>NTS (ksi)</th>
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APPENDIX A

MECHANICAL PROPERTY CURVES FOR TITANIUM ALLOYS

Fig. A-1: Low Temperature Mechanical Properties of Ti-7Al-4Mo Alloy

-23-  FIGURE A-1
TESTING TEMPERATURE, °F

LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-7Al-3Mo ALLOY

FIGURE A-2
Figure A-3 shows the low temperature mechanical properties of Ti-6Al-4V alloy. The graphs display the tensile strength, yield strength, elongation and reduction, and Charpy impact values as functions of testing temperature. The data is presented for both UNNOTCHED and NOTCHED samples.
Testing Temperature, °F

Low Temperature Mechanical Properties of Ti-4Al-3Mo-1V Alloy

Figure A-4
LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-16V-2.5Al ALLOY

NOTE: AT -320 F SPECIMEN BROKE BEFORE DESIRED OFFSET (0.1%) WAS REACHED.
FIGURE A-8

LOW TEMPERATURE MECHANICAL PROPERTIES OF Ti-13V-11Cr-3Al ALLOY
Low temperature mechanical properties of titanium alloys

Figure A-7
Effect of Testing Temperature on Notch Tensile Ratio of Titanium Alloys

- Ti-7Al-3Mo
- Ti-7Al-4Mo
- Ti-6Al-4V
- Ti-4Al-3Mo-1V
- Ti-6V-2.5Al
- Ti-13V-11Cr-3Al

$K_t = 11.2$

$K_t = 10.0$ (-320 F)

$R = 0.002$ inch
APPENDIX B
MECHANICAL PROPERTY CURVES FOR ALUMINUM ALLOYS

FIGURE B-1

LOW TEMPERATURE MECHANICAL PROPERTIES OF 6061-T6 ALLOY
FIGURE B-2
LOW TEMPERATURE MECHANICAL PROPERTIES OF 7075-T6 ALLOY
LOW TEMPERATURE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

FIGURE B-3
TESTING TEMPERATURE, °F

LOW TEMPERATURE MECHANICAL PROPERTIES ON ALUMINUM ALLOYS

FIGURE B-4
LOW TEMPERATURE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

FIGURE B-5
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