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PLANE STRAIN FRACTURE TOUGHNESS OF 2219-T87 ALUMINUM ALLOY AT ROOM AND CRYOGENIC TEMPERATURES

by

CARL M. CARMAN
JOHN W. FORNEY
JESSE M. KATLIN

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Cleveland, Ohio
Richard N. Johnson and Gordon T. Smith

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FRANKFORD ARSENAL
Philadelphia, Pa. 19137

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ABSTRACT

The tensile properties and plane strain fracture toughness of 1/2 and 1 inch thick 2219-T87 aluminum alloy have been determined as a function of testing at temperatures from room to -423° F. The tensile and yield strengths of this material show a gradual increase as the testing temperature is decreased to -423° F while the elongation and reduction of area remain essentially unchanged.

The plane strain fracture toughness of this material is relatively insensitive to testing temperature and shows only a slight increase with decreasing testing temperature. Specimens machined so that the crack propagation is perpendicular to the rolling plane show somewhat higher values of plane strain fracture toughness than when crack propagation is parallel to the rolling plane. The plane strain fracture toughness of the 1 inch thick 2219-T87 aluminum alloy was somewhat lower than that of the 1/2 inch thick plate.

Illustrative examples are presented using these parameters in design.

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GLOSSARY

a	- Notch depth or 1/2 crack length
A	- Area
B	- Specimen thickness
d	- Beam depth
E	- Young's modulus
$\mathcal{G}$	- Strain energy release rate
$\mathcal{G}_{Ic}$	- Strain energy release rate for onset of fast fracture in oepning mode type of fracture
K	- Parameter describing the local elevation of the elastic stress field ahead of a crack
K_{Ic}	- Critical value of above parameter for onset of fast fracture in opening mode type of fracture
M	- Bending moment of beam
Q	- Form factor
r_{ys}	- Radius of plastic strain zone
T	- Surface tension
γ	- Poisson's ratio
ϵ	- Strain energy
σ	- Gross section stress
σ_{ys}	- 0.2% offset yield stress
ω	- Work function composed of surface tension and plastic deformation

Subscripts

c	- Critical value of a parameter
I	- First, or opening, mode of fracture

PLANE STRAIN FRACTURE TOUGHNESS OF 2219-T87 ALUMINUM ALLOY AT ROOM AND CRYOGENIC TEMPERATURES

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SUMMARY

Inasmuch as future upper stage rockets will use liquid hydrogen as a fuel, the propellant tanks will be required to operate at -423° F. It is therefore desirable to employ materials for these structures which will possess very high strength-to-density ratios and material properties which will be satisfactory at the minimum operating temperatures.

It appears that three types of alloys offer the promise of achieving the required strength in combination with adequate fracture toughness at -423° F. This report presents engineering design data for one such material - 2219-T87 aluminum alloy.

The suitability of 2219-T87 aluminum alloy for cryogenic tankage applications has been studied by determining the mechanical and fracture properties of the material at testing temperatures ranging from room to -423° F. Small round tensile specimens were developed to measure the tensile properties over the range of testing temperatures. Plane strain fracture toughness measurements were also made at these temperatures using the "pop-in" technique with a small notched bend specimen.

Special techniques utilizing the specific heat of vaporization of liquid helium were developed to test the specimens at -423° F. The tensile and yield strengths of the 2219-T87 aluminum alloy show a gradual increase as the testing temperature is decreased. The elongation and reduction of area remain essentially unchanged.

The plane strain fracture toughness of this material is relatively insensitive to testing temperature, showing only a slight increase with decreasing testing temperature. Tests performed on specimens with crack propagation perpendicular to the rolling plane show somewhat higher values of plane strain fracture toughness than tests performed on specimens with crack propagation parallel to the rolling plane. The plane strain fracture toughness of the one inch thick plate was somewhat lower than that of the 1/2 inch plate.

The data are summarized in terms of a part-through defect which will be stable at various operating temperatures and stress levels.

INTRODUCTION

The majority of liquid-fueled rocket booster tanks used in the past have been constructed of materials which have room temperature yield strength-to-density ratios generally not exceeding 650,000 inches. These rocket boosters use liquid oxygen as the fuel oxidizer and the operating temperature of the liquid oxygen tanks is -297° F. At this temperature, the maximum yield strength-to-density ratio of these materials is approximately 850,000 in. It is planned to fuel future rocket boosters with liquid hydrogen and the tanks would therefore have to function at -423° F. Before liquid hydrogen can be used, however, the engineering, mechanical, and fracture properties must be determined at -423° F for candidate materials.

It would be desirable to employ materials with the highest strength-to-density ratios to reduce launching weight, provided the material properties at the operating temperature were satisfactory. Data presented at the 1960 ASTM Symposium on Low Temperature Properties of High Strength Aircraft and Missile Alloys[1*] showed that the strength-to-density ratio of 850,000 inches could be exceeded substantially by several materials at cryogenic temperatures, namely, cold worked stable austenitic and metastable stainless steels, annealed alpha titanium alloys, and certain aluminum alloys of the copper-bearing series.

The presentation of these data was concerned mostly with the engineering mechanical properties at -423° F, and only a limited amount of the work covered fracture toughness investigations. Based on these papers, the Lewis Research Center of the National Aeronautical and Space Administration, Cleveland, Ohio, sponsored investigations concerning the fracture toughness characteristics at testing temperatures as low as -423° F to provide basic design data for the titanium and aluminum alloys.

A report[2] has been published recently by Frankford Arsenal which describes the plane strain fracture toughness characteristics of 5Al-2.5Sn ELI titanium alloy at room and cryogenic temperatures. The present report covers a similar type investigation using 2219-T87 aluminum alloy.

PROGRAM OBJECTIVES

The object of this program is to determine the basic engineering design parameters of 2219-T87 aluminum alloy at 70°, -110°, -320°, and -423° F.

*See REFERENCES.

MATERIAL

Nominal composition of the 2219-T87 aluminum alloy is given in Table I. The material was supplied as 1/2 inch and 1 inch thick rolled plate.

TABLE I.
Chemical Composition of
2219-T87 Aluminum Alloy

Component	Percent
Si	0.20 max
Fe	0.30 max
Cu	6.3
Mn	0.30
Mg	0.02 max
Zn	0.10 max
Ti	0.06
V	0.10
Zr	0.18

PROGRAM APPROACH

The objective of this program may be met by determing the engineering tensile properties and the fracture toughness characteristics of the material over the series of testing temperatures. The strength limitations due to brittle fracture may best be investigated by the application of the Griffith-Irwin fracture mechanics approach. Griffith[3] stated that for an ideally brittle material such as glass, the strain energy released per unit crack extension, at instability, was equal to twice the surface tension per unit crack extension:

$$\frac{d\ \epsilon_c}{B(da)} \geq \frac{2T}{B(da)} \tag{1}$$

For more ductile materials, however, the effect of the work absorbed by plastic deformation at the crack tip had to be accounted for. Irwin[4] proposed a work function be substituted for the surface tension term and, at instability, Equation 1 becomes

$$\frac{d\ \epsilon_c}{B(da)} \geq \frac{d\omega}{B(da)} \tag{2}$$

where ω = work function composed of two terms: (1) surface free energy, and (2) plastic deformation.

In the special case of a through-the-thickness crack in an infinitely large plate, Inglis[5] has solved the stress analysis for $\frac{d\omega}{dA}$, giving rise to Equation 3:

$$\frac{d\omega}{dA} = \frac{\pi \sigma^2 a}{E} = \mathcal{G} \tag{3}$$

Irwin[6] proposed that the events at the leading edge of a crack may be described in terms of a parameter, K, which is a function of the local elevation of the elastic stress field ahead of the crack. Crack propagation will take place when the stress intensity, K, reaches a critical value, K_c or K_{Ic} (fracture toughness), depending on the state of stress. Therefore, it may be shown that

$$K_c{}^2 = E\,\mathcal{G}_c \qquad \text{(plane stress)} \tag{4}$$

$$K_{Ic}{}^2 = \frac{E\,\mathcal{G}_{Ic}}{(1 - \nu^2)} \qquad \text{(plane strain)} \tag{5}$$

Since this program is primarily concerned with the plane strain fracture toughness, Equation 5 is applicable.

Measurement of Plane Strain Fracture Toughness

The measurement of the plane strain fracture toughness is complicated by the requirement that the plastic zone size at the crack tip be quite small relative to the specimen cross section. In the past this necessitated the use of relatively large specimens.

Historically, the circumferentially notched round specimen has been the most popular specimen. However, for the lower strength-high toughness materials, the major diameter necessary to prevent yielding of the net section is quite large. The requirements for the surface-flawed specimen also make the use of large specimens mandatory.

The slow notched bend test has been used extensively to measure the plane strain fracture toughness of materials. It has the advantage that, when relatively large specimens are required, the loads needed to break the specimens may be kept low by increasing the span of the specimens. Early work was primarily confined to quite large specimens with only the maximum load or a simple load deflection curve being recorded. Modern instrumentation has resulted in the use of smaller size notched bend specimens to obtain reliable plane strain fracture toughness data.

Recently, Boyle, Sullivan, and Krafft[7] developed a technique for measuring the plane strain fracture toughness using sharply notched sheet specimens. They observed that the initial burst of crack growth from the notch or fatigue crack occurred under plane strain conditions. This technique consists of determining the load-deflection curve of the specimen. The initial burst of crack extension, or "pop-in," may be detected as an inflection in the load-deflection curve.

Size is an important factor in selecting specimens for cryogenic testing. Large specimens require excessive amounts of costly cryogenic liquids to cool them. Consequently, it is desirable to use as small a specimen as possible and still be consistent with the experimental condition for obtaining valid fracture toughness measurements. Therefore, the small notched bend specimen was selected for this study. This specimen offers the advantage of small size and minimum breaking load. By using the "pop-in" technique, it may be possible to further reduce the specimen size.

In attempting to measure the plane strain fracture toughness of low strength-high toughness materials, it is necessary to determine the minimum size specimen which will give valid plane strain fracture toughness values. A preliminary survey of the effects of beam depth and notch depth was made using 1/4 inch thick 2014-T6 aluminum alloy, a different material. This material was used in a previous program,[9] and a plane strain fracture toughness value (K_{Ic}) of 32,000 psi $\sqrt{in.}$ at room temperature had been established. The validity of this K_{Ic} value was established by performing tests using circumferentially notched-fatigue cracked round specimens and pop-in tests of center cracked sheets and single edge notched specimens.

The general configuration of the notched bend specimen is shown in Figure 1. Three beam depths (1/2, 3/4, and 1 inch) and two crack depths (10 and 20 percent) were used for these tests. The specimens were machined with a notch root radius of 0.001 inch, maximum. Previous work[9] has shown that even for softer aluminum alloys, notch sharpness may affect the measured value of plane strain fracture toughness. Consequently, all of the notched bend bars were precracked in fatigue prior to testing. A small, high, elongation strain gage was cemented at the tip of the crack to detect the pop-in. The specimens were tested in three-point loading using an Instron testing machine. A schematic of the loading arrangement is shown in Figure 2. The output of the strain gage was fed into a strain gage preamplifier and a plot of load vs specimen deflection was obtained on the x-y recorder. The pop-in was detected as an inflection in the load-deflection curve.

The plane strain fracture toughness was calculated from the load at pop-in and initial crack length, using a stress analysis developed by Bueckner.[10] His expression is

$$K_I = \frac{6M}{(d - a)^{3/2}} f(a/d) \tag{6}$$

The value of f(a/d) is given in Table II.

SPECIMEN DESIGNATION	d	a	B
1/2	.500 ± .002	.100 ± .001	2014-T6 0.250
3/4	.750 ± .003	.150 ± .001	2219-T87 0.500
1	1.000 ± .004	.200 ± .001	

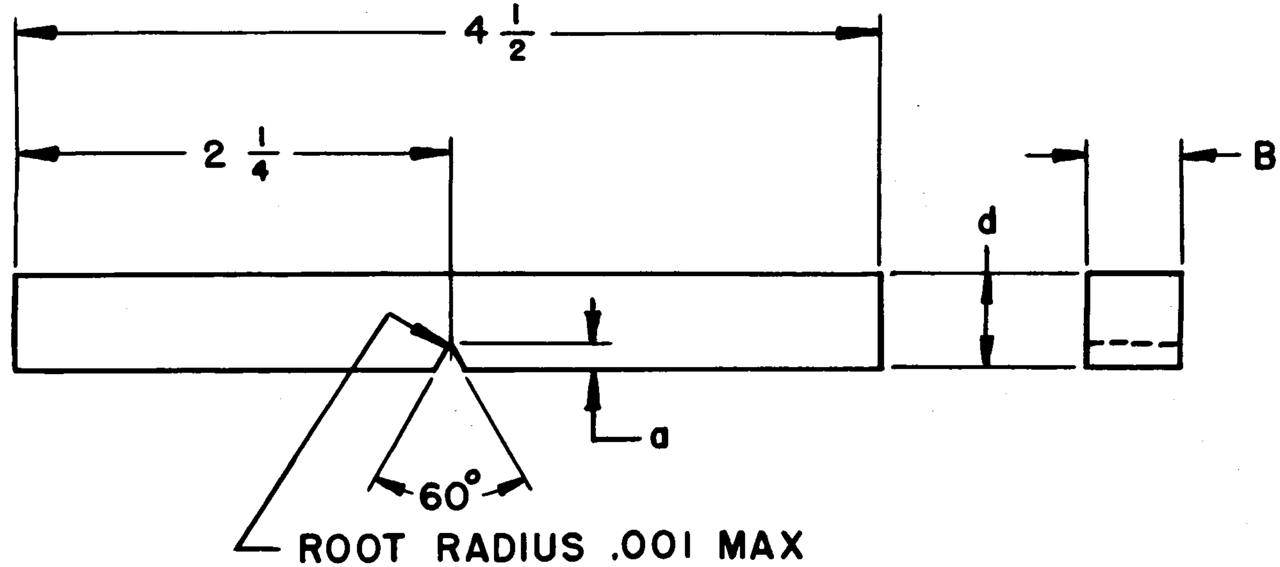

Figure 1. Notched Bend Specimen

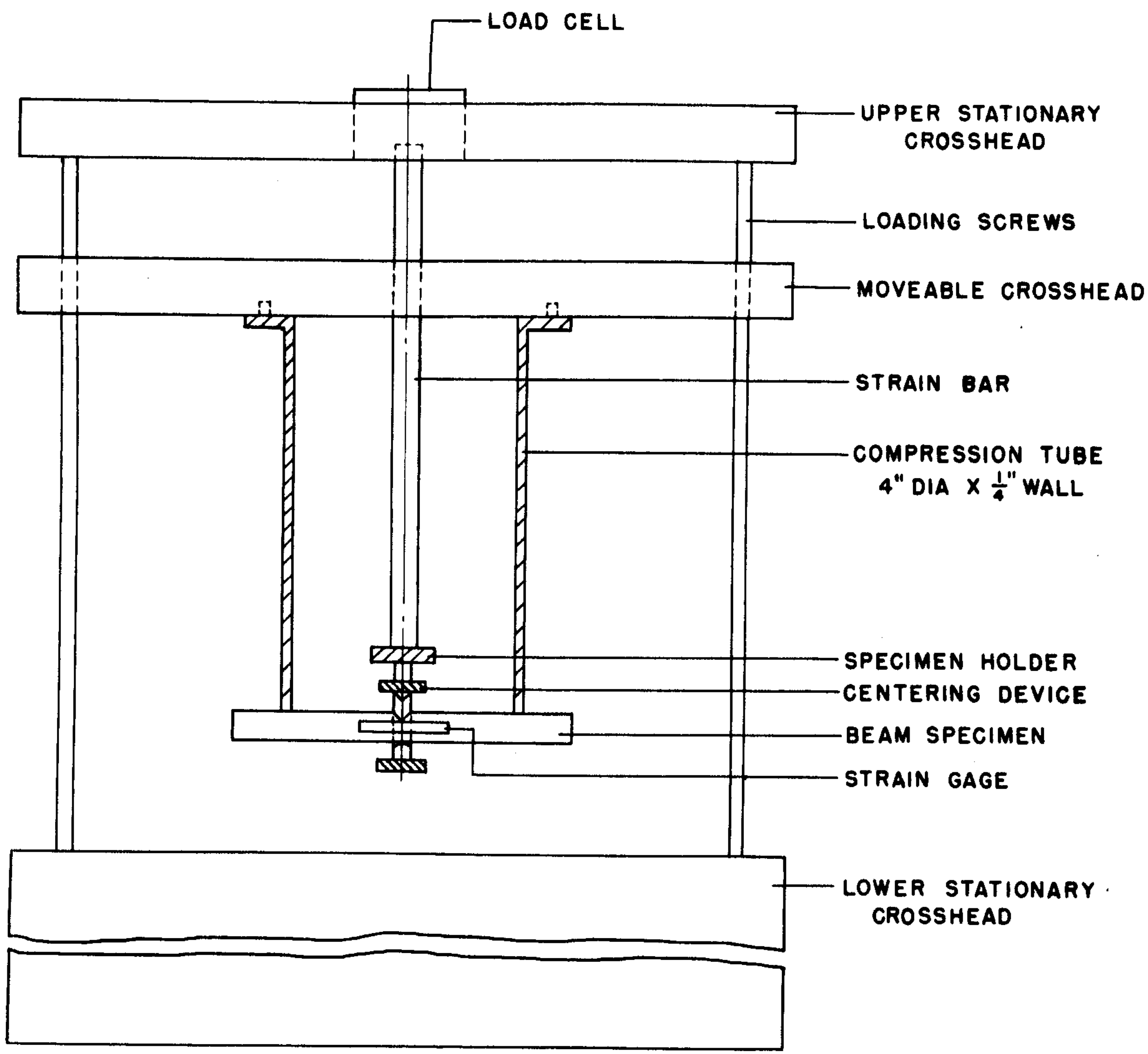

Figure 2. Method of Loading Notched Bend Specimens in Instron Testing Machine

TABLE II
Value of f(a/d) as a Function of a/d

a/d	0.05	0.10	0.20	0.30	0.40	0.50	0.60
f(a/d)	0.36	0.49	0.60	0.66	0.69	0.72	0.73

The room temperature plane strain fracture toughness data for 2014-T6 aluminum alloys are plotted as a function of the beam depth in Figure 3. It will be observed that the maximum value of K_{Ic} is less than the value of 32,000 psi $\sqrt{in.}$ Under these conditions, a plastic zone correction may be required. The radius of the plastic zone may be calculated[6] from

$$r_{ys} = \frac{{K_{Ic}}^2}{2\pi \, {\sigma_{ys}}^2} \tag{7}$$

The value of r_{ys} is added to the measured value of a. The new value of a is substituted in Equation 6 and K_{Ic} is calculated again. This process is repeated until the change in K_{Ic} is very small. The series rapidly converges so that only three or four calculations are needed to produce a negligible change in K_{Ic}. These values are plotted in Figure 3. In studies of the effect of specimen size on the measured values of plane strain fracture toughness of 7075-T6 aluminum alloys, Boyle, Sullivan, and Krafft[7] have shown that a minimum specimen size exists for valid measurements of the plane strain fracture toughness. Tests of larger specimen sizes do not appreciably alter the K_{Ic} values. These data for 2014-T6 aluminum alloy show the same trend as that reported for the 7075-T6 aluminum alloy. By analogy, then, the 3/4 inch beam depth should be the minimum specimen size.

Having established valid plane strain fracture toughness values for the 2014-T6 aluminum, it is possible to describe the necessary experimental conditions for accurate plane strain fracture toughness measurements. It was shown[7] that, for satisfactory pop-in measurement, the specimen thickness should be equal to at least four times the radius of the plastic zone size. Calculation of the radius of the plastic zone size gave a value of 0.0387 inch. The 0.25 inch thick specimen, therefore, was more than adequate to meet this requirement.

From the preceeding discussion it was decided that a specimen depth of 0.750 inch was necessary for accurate plane strain fracture toughness measurements. Krafft,[7] in his work on sheet specimens, has recommended that the specimen width be at least 20 times the radius of the plastic zone size. By analogy, the beam depth of the specimen should conform to this requirement. Therefore, a minimum beam depth of 0.774 inch was needed.

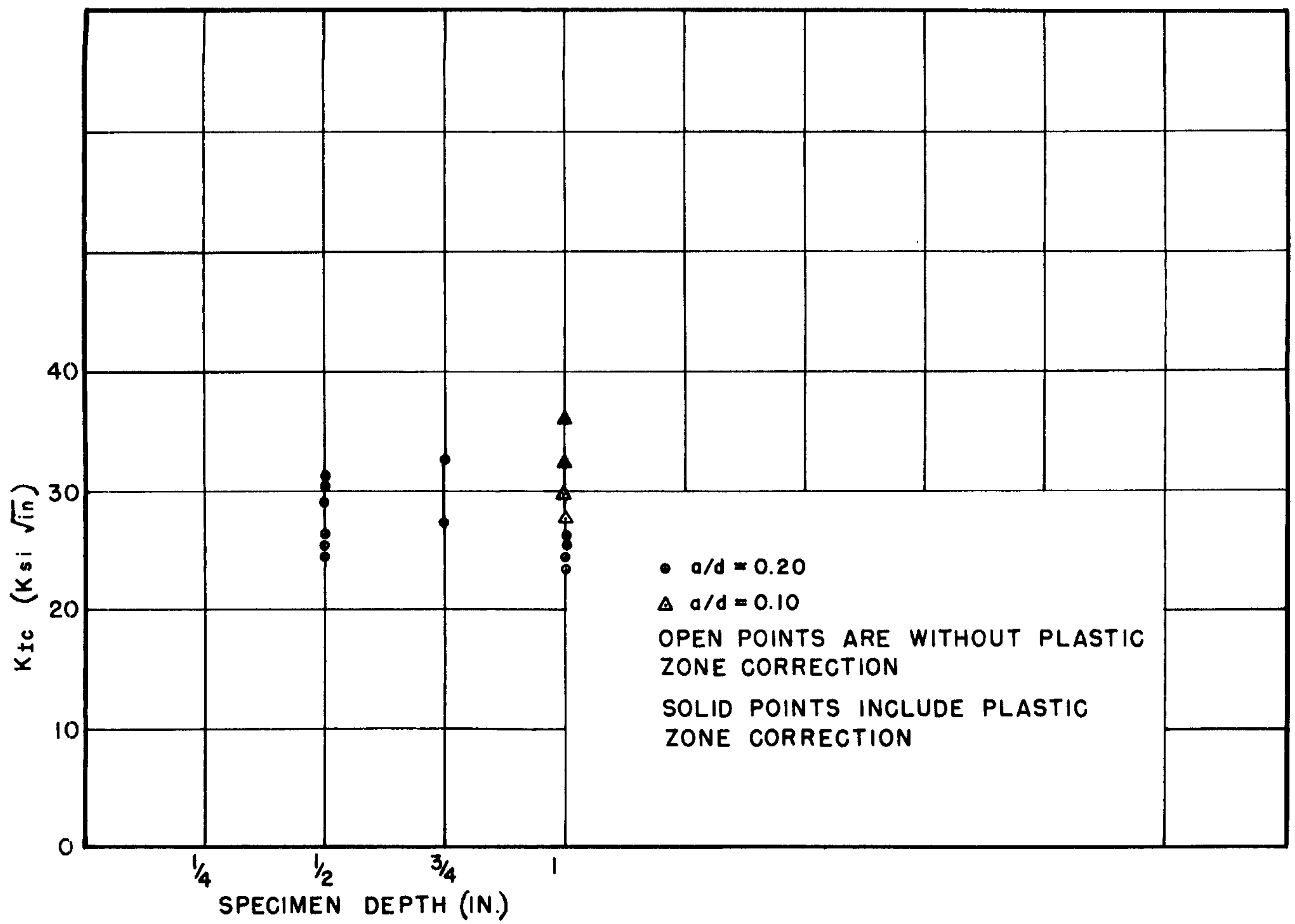

Figure 3. Plane Strain Fracture Toughness of 2014-T6 Aluminum Alloy as a Function of Beam Depth at Room Temperature

Gross[11] has stated that the limit of applicability of the specimen will be reached if the nominal stress at the crack tip reaches the yield stress of the material, as stated in

$$\frac{6M}{B\ (d-a)^2} = \sigma_{ys} \tag{8}$$

Solution of Equation 8 for d-a gave a value of 0.481 inch. With a 20 percent notch depth, this would give a beam depth of 0.601 inch. This criterion is somewhat less conservative than 20 times the plastic zone size.

Tensile Testing

As mentioned previously, larger consumptions of cryogenic coolants and the mechanical limitations of the cryostat necessitated the use of small specimens, consistent with obtaining valid data, for K_{Ic} measurements. This also holds true for the determination of the engineering tensile properties. Therefore, a small round tensile specimen, 0.160 inch in diameter (Figure 4) was used for these studies. Small strain gages were used to determine the strain of the specimen.

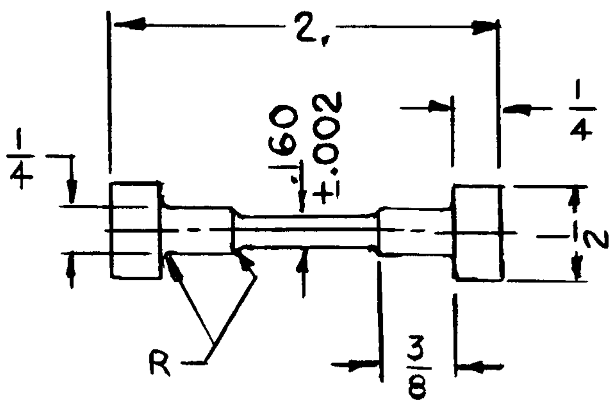

Figure 4. Small Round Tensile Specimen

EXPERIMENTAL TECHNIQUE

The experimental arrangement used for loading the notched bend specimens has been described previously. Specimens tested at ambient temperature were broken in air at approximately 70° F. Tests at -110°

and -320° F were conducted by immersing the compression column specimen and associated apparatus in a mixture of dry ice and acetone and in liquid nitrogen, respectively.

Since it was not practical, from a safety standpoint, to use liquid hydrogen in the laboratory, a system had to be developed whereby testing could be accomplished at -423° F. The method devised utilized the evaporating gas of liquid helium (-452° F) as the coolant. The cold gas passed over an electrical resistance heater controlled so that the emerging stream of heated gas maintained the test specimen at liquid hydrogen temperature. A schematic of the cryostat and associated apparatus used is shown in Figure 5.

A brief description of the operation of the cryostat follows. After placing the specimen in position in the holder, making all electrical connections, and sealing the cryostat to the testing machine, liquid nitrogen is introduced into the outer dewar until the proper level is obtained. This serves as a shield for the liquid helium system. Liquid nitrogen is then slowly introduced through inlet 18* into the inner dewar and allowed to boil. The boil-off gas fills the area 16 and then drops down into cup 11 as shown by 10. The gas then travels up through the opening at the bottom of the cold finger 9, over the heater and thermistor, over the specimen, and out the exhaust 3. Excess pressure is bled off by exhaust valve 4. Cooling with liquid nitrogen is continued until the specimen temperature is approximately -250° F. The system is now purged with helium gas, and liquid helium is then transferred into the inner (area 16) dewar. The path of the cold helium gas is the same as that of the nitrogen gas. However, when the temperature of the cold helium gas stream is below -423° F, the heater coil is energized to condition the gas stream to liquid hydrogen temperature. The temperature of the specimen is confirmed by means of a differential thermocouple. The specimen is maintained at temperature for 10 minutes prior to testing.

EXPERIMENTAL RESULTS AND DISCUSSION

One-half Inch Thick 2219-T87 Aluminum Alloy Plate

Engineering Tensile Properties

The engineering tensile properties of this material, as determined using the 0.160 inch diameter tensile specimens, are plotted in Figure 6 as a function of testing temperature, and the values are tabulated in Table III.

*Circled numbers refer to Figure 5.

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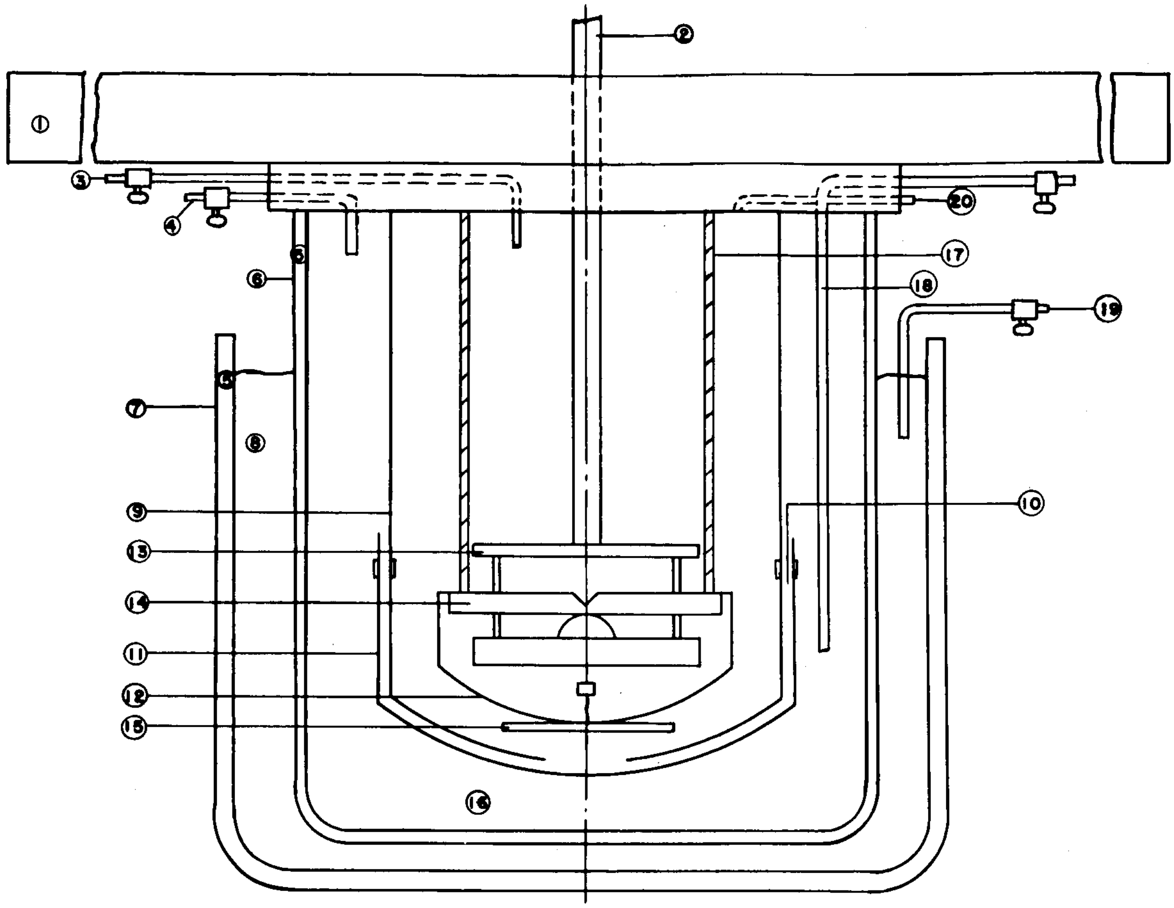

1. Moveable Crosshead
2. Strain Bar
3. Exhaust - Helium
4. Exhaust - Nitrogen & Helium
5. Vacuum
6. Inner Glass Dewar Flask
7. Outer Glass Dewar Flask
8. Liquid Nitrogen
9. Glass Cold Finger
10. Helium Gas Downflow Area
11. Outer Cup - Cold Finger
12. Wire Mesh Cage for Heater & Thermistor
13. Specimen Holder
14. Beam Specimen
15. Heater, Thermistor & Specimen Thermocouple
16. Liquid and/or Gaseous Helium
17. Steel Compression Tube
18. Liquid Helium Inlet
19. Liquid Nitrogen Inlet
20. Amphenole Plug for Instrumentation Lead Wires

Figure 5. Schematic of Cryostat and Associated Apparatus used for Tests Conducted at -423° F

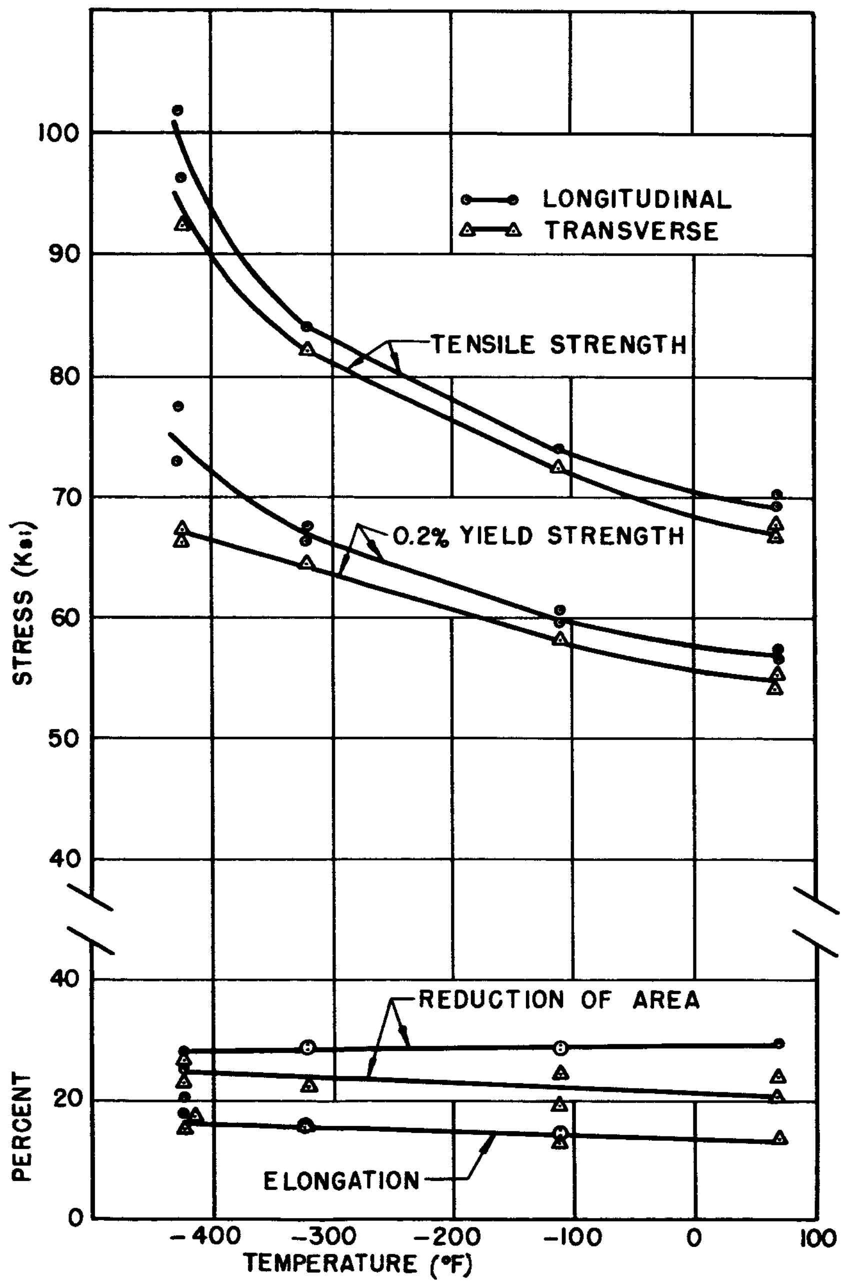

Figure 6. Tensile Properties of 1/2 inch thick Plate of 2219-T87 Aluminum Alloy as a Function of Testing Temperature

TABLE III.
Tensile Properties of 1/2 inch thick 2219-T87 Aluminum Alloy Plate

Test Temp (°F)	Direction	Strength (psi) Yield at 0.20% Offset	Tensile	Elongation (%)	Reduction of Area (%)
Ambient	Longitudinal	57,300	70,000	16.4	29.9
Ambient	Longitudinal	56,500	69,000	15.1	29.9
Ambient	Transverse	55,100	66,700	12.9	23.5
Ambient	Transverse	54,400	67,400	13.9	20.1
-110	Longitudinal	60,400	73,500	15.6	27.9
-110	Longitudinal	59,500	73,800	14.7	28.9
-110	Transverse	58,000	72,300	12.9	24.5
-110	Transverse	58,500	72,100	13.8	19.1
-320	Longitudinal	67,500	83,800	15.6	28.9
-320	Longitudinal	66,300	83,800	16.4	28.9
-320	Transverse	64,500	81,900	14.7	22.5
-423	Longitudinal	77,500	102,000	20.4	25.5
-423	Longitudinal	72,800	96,100	17.3	27.9
-423	Transverse	67,000	96,100	17.3	23.5
-423	Transverse	66,500	92,500	15.6	26.5

The strength properties of this material are not greatly sensitive to the testing temperature. However, a gradual increase in yield and tensile strengths did occur upon decreasing the testing temperature to -423° F. The elongation and reduction of area were not affected by reducing the testing temperature. These values are in close agreement with those reported by Tiffany.[12]

Plane Strain Fracture Toughness

In accordance with the concepts advanced earlier, it is necessary to determine the minimum specimen size to obtain valid plane strain fracture toughness values. A series of notched bend bars, having a 20 percent notch with depths varying from 1/2 to 1-1/2 inches, was machined from the 1/2 inch thick 2219-T87 aluminum alloy plate. The experimentally determined plane strain fracture toughness values are plotted as a function of specimen depth in Figures 7, 8, 9, and 10, and the values are tabulated in Table IV.

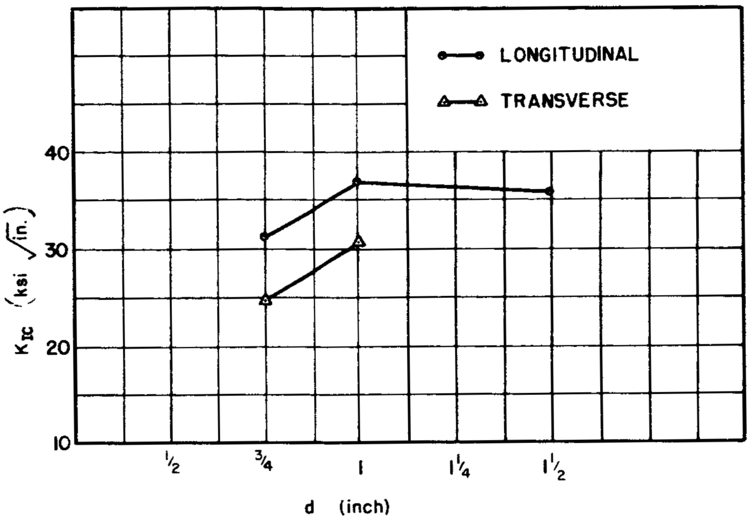

Figure 7. Plane Strain Fracture Toughness of 2219-T87 Aluminum Alloy as a Function of Beam Depth, for Room Temperature Tests

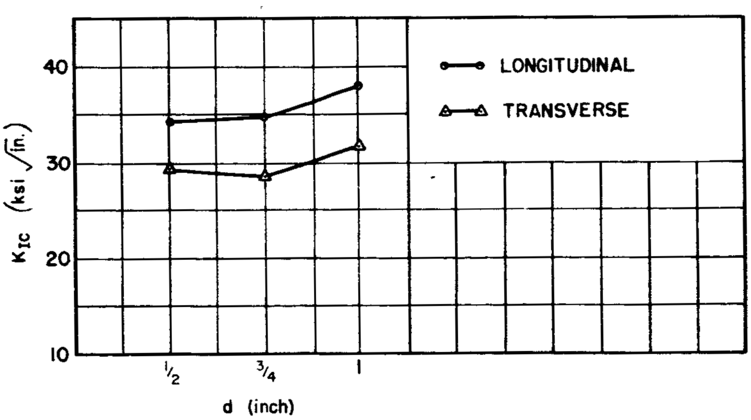

Figure 8. Plane Strain Fracture Toughness of 2219-T87 Aluminum Alloy as a Function of Beam Depth, for -110° F Tests

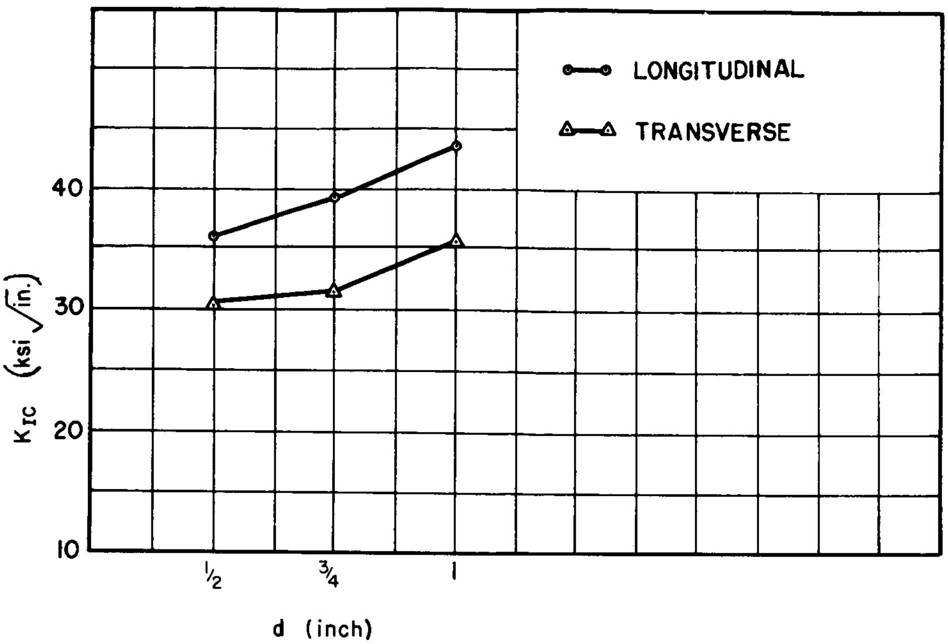

Figure 9. Plane Strain Fracture Toughness of 2219-T87 Aluminum Alloy as a Function of Beam Depth, for -320° F Tests

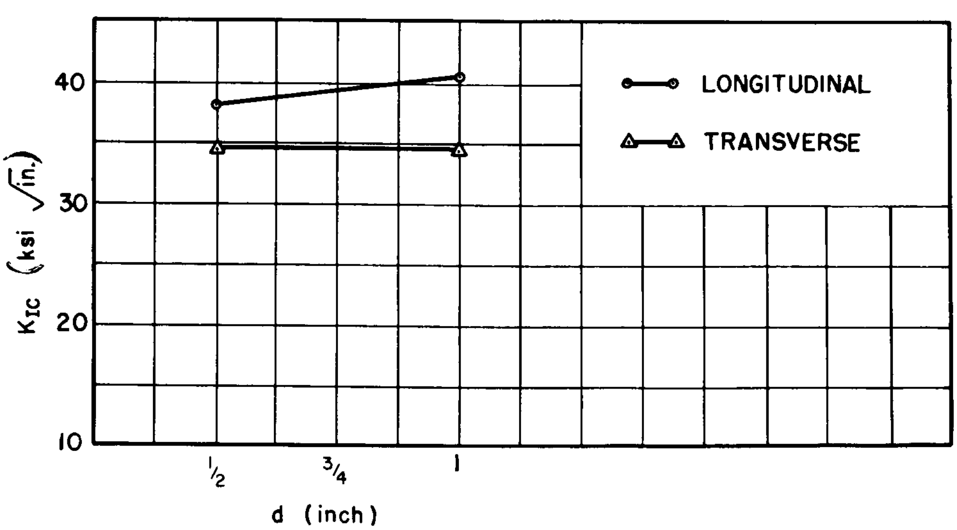

Figure 10. Plane Strain Fracture Toughness of 2219-T87 Aluminum Alloy as a Function of Beam Depth, for -423° F Tests

TABLE IV.
Plane Strain Fracture Toughness as a Function of Specimen Size and Temperature for One-half Inch Thick 2219-T87 Aluminum Alloy

Test Temp (°F)	Specimen Depth (in.)	Direction	Load (lb)	Initial Crack Length (in.)	K_{Ic} (psi $\sqrt{in.}$)	K_{Ic} Average (psi $\sqrt{in.}$)
70	3/4	Longitudinal	1835	0.1696	31,200	
	3/4	Transverse	1420	0.1716	24,600	
	1	Longitudinal	3450	0.2119	37,000	
	1	Transverse	2865	0.2156	30,900	
	1-1/2	Longitudinal	5300	0.3754	34,800	
	1-1/2	Longitudinal	5690	0.3756	37,200	
	1-1/2	Longitudinal	5740	0.3626	36,400	36,100
-110	1/2	Longitudinal	1120	0.1025	33,800	
	1/2	Longitudinal	1090	0.1132	34,500	34,200
	1/2	Transverse	910	0.1180	29,300	
	1/2	Transverse	960	0.1097	29,500	29,400
	3/4	Longitudinal	2050	0.1672	34,900	
	3/4	Transverse	1715	0.1607	28,400	
	1	Longitudinal	3460	0.2104	37,600	
	1	Longitudinal	3640	0.2103	38,300	37,900
	1	Transverse	2890	0.2157	30,900	
	1	Transverse	3080	0.2106	32,800	31,800
-320	1/2	Longitudinal	1090	0.1178	35,800	
	1/2	Longitudinal	1100	0.1175	36,200	36,000
	1/2	Transverse	900	0.1236	30,100	
	1/2	Transverse	956	0.1176	30,700	30,400
	3/4	Longitudinal	2290	0.1705	39,300	
	3/4	Longitudinal	2350	0.1634	39,400	39,400
	3/4	Transverse	1880	0.1662	31,800	
	3/4	Transverse	1730	0.1642	30,800	31,300
	1	Longitudinal	4125	0.2140	44,900	
	1	Longitudinal	4080	0.2166	43,700	44,300
	1	Transverse	3370	0.2100	35,600	
	1	Transverse	2590	0.2722	32,800	34,200
-423	1/2	Longitudinal	1118	0.1148	35,800	
	1/2	Longitudinal	1240	0.1187	40,600	38,200
	1/2	Transverse	1050	0.1205	34,400	
	1/2	Transverse	1090	0.1122	34,100	34,300
	1	Longitudinal	2800	0.3178	40,500	
	1	Longitudinal	3200	0.2759	41,200	
	1	Longitudinal	2930	0.2904	39,300	40,300
	1	Transverse	2850	0.3026	39,600	
	1	Transverse	3175	0.2167	34,300	
	1	Transverse	2750	0.2750	35,200	36,300

Following the discussion of the data for the 2014-T6 aluminum alloy, it may be concluded that the one inch deep beam is sufficiently large for this material. It was felt that room temperature data for longitudinal specimens would provide adequate information since the toughness in the other directions is usually less and the yield strength increases with decreasing test temperature. These conditions would require a smaller minimum size specimen for the cryogenic temperatures. Data obtained at -320° F show that a one inch beam depth was needed even at this temperature; therefore, a one inch beam depth was selected for all test temperatures.

Possible variation of the plane strain fracture toughness with respect to crack orientation is of practical importance to the designer. In thick plates it is possible to study the plane strain fracture toughness of the material with respect to anisotropy. The orientation of the various specimens is shown in Figure 11. In this figure, the "L" and "T" designations give the orientation of the specimens relative to the rolling direction of the plate; in the "S" series, the direction of crack propagation is parallel to the rolling plane, while specimens in the "D" series are so oriented that the path of crack propagation is perpendicular to the rolling plane.

In Figure 12, the plane strain fracture toughnesses for one inch beam depth LS and TS specimens are plotted as a function of testing temperature, and the data are given in Table V. The plane strain fracture toughness of this material is relatively insensitive to testing temperature. These data show a trend similar to that reported by Tiffany[11] (solid points).

In order to compare the effects of crack orientation on the plane strain fracture toughness of the 1/2 inch thick plate of 2219-T87 aluminum alloy, only beam depths of 1/2 inch could be used. Lower bound plane strain fracture toughness values* obtained for the LS and TS series using 1/2 inch beam depth specimens are plotted in Figure 13 as a function of testing temperature. These data show a general depression of the measured plane strain fracture toughness at testing temperatures above -423° F. The data points for -423° F are in agreement with those obtained using large specimens.

Similar data for the LD and TD series are shown in Figure 14. Comparison of Figures 13 and 14 shows that the lower bound plane strain fracture toughness for cracks propagating perpendicular to the rolling plane of the plate is greater than for cracks propagating parallel to the rolling plane. Similar behavior has been observed by Tiffany[13] using surface-flawed specimens.

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*Plane strain fracture toughness values calculated using data obtained from specimens which are too small have been arbitrarily defined as lower bound values. These values are always less than the true plane strain fracture toughness.

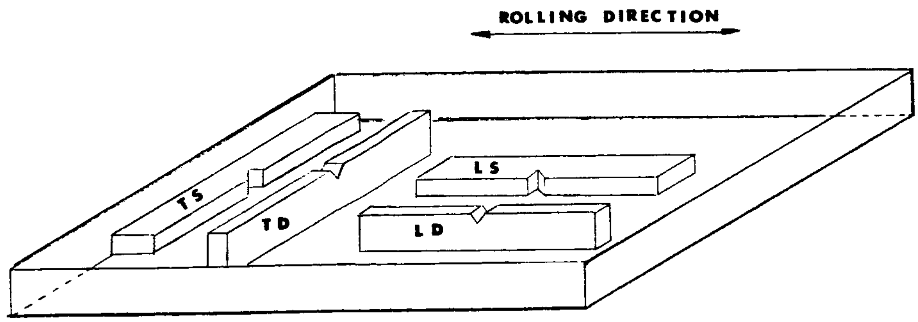

Figure 11. Orientation of Test Specimens with Respect to Plate

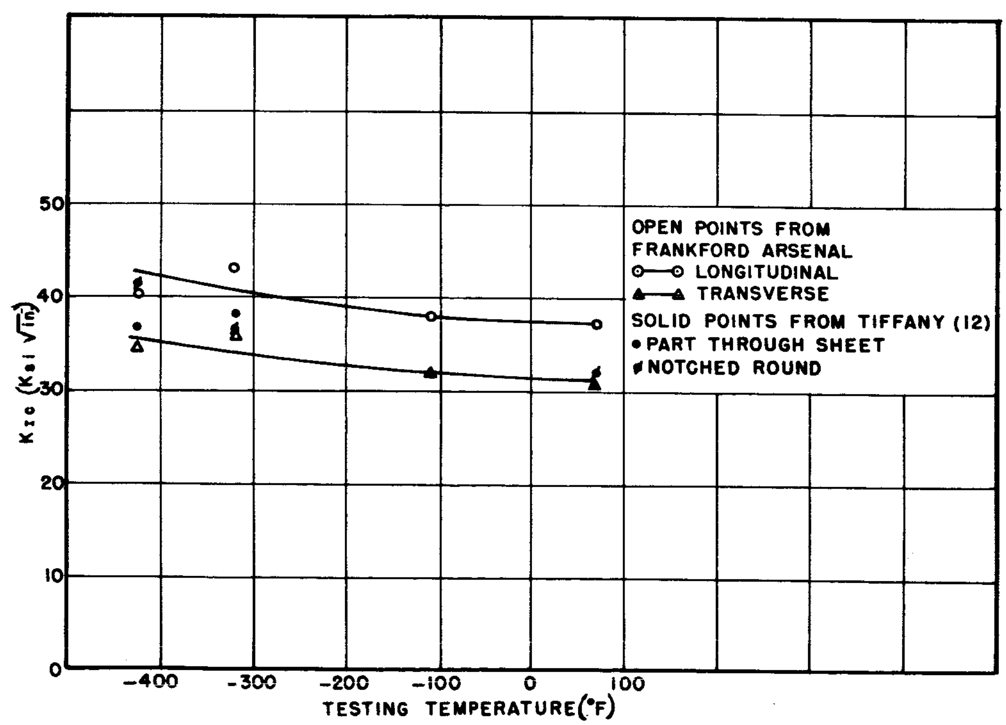

Figure 12. Plane Strain Fracture Toughness of 1/2 Inch Thick 2219-T87 Aluminum Alloy Plate as a Function of Testing Temperature (Crack growth parallel to rolling plane)

It is believed that the higher energy absorption for cracks propagating perpendicular to the rolling plane was due to delamination of the plate. These delaminations are quite apparent upon examination of the fracture surface (Figure 15).

TABLE V.
Plane Strain Fracture Toughness of
One-half Inch Thick 2219-T87 Aluminum Alloy Plate
(Crack Propagation Parallel to Rolling Plane)

Test Temp (°F)	Direction	Load (lb)	Initial Crack Length (in.)	K_{Ic} (psi $\sqrt{in.}$)
70	Longitudinal	3450	0.2119	37,000
	Transverse	2865	0.2156	30,900
-110	Longitudinal	3460	0.2104	37,600
	Longitudinal	3640	0.2103	38,300
	Transverse	2890	0.2157	30,900
	Transverse	3080	0.2106	32,800
-320	Longitudinal	4125	0.2140	44,900
	Longitudinal	4105	0.2150	44,100
	Longitudinal	4080	0.2166	43,700
	Transverse	3320	0.2170	36,000
	Transverse	3370	0.2100	35,600
	Transverse	2590	0.2722	32,800
-423	Longitudinal	2800	0.3178	40,500
	Longitudinal	3200	0.2759	41,200
	Longitudinal	2930	0.2904	39,300
	Transverse	2850	0.3026	39,600
	Transverse	3175	0.2167	34,300
	Transverse	2750	0.2750	35,200

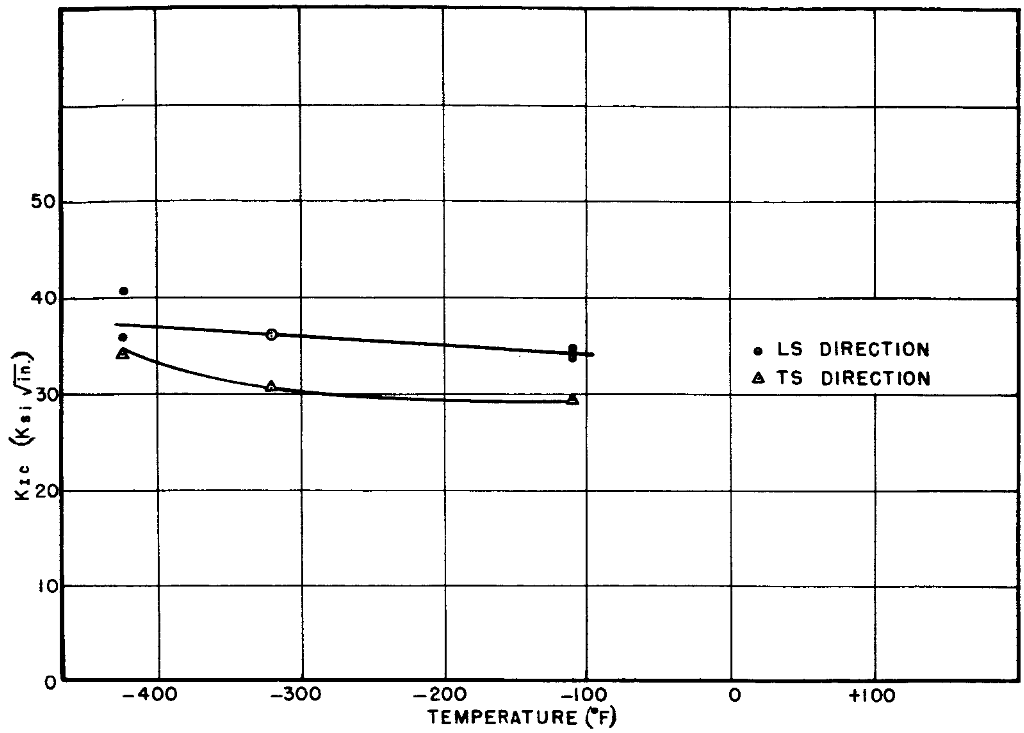

Figure 13. Lower Bound Plane Strain Fracture Toughness of 1/2 Inch Thick 2219-T87 Aluminum Alloy Plate as a Function of Testing Temperature (Crack growth parallel to rolling plane)

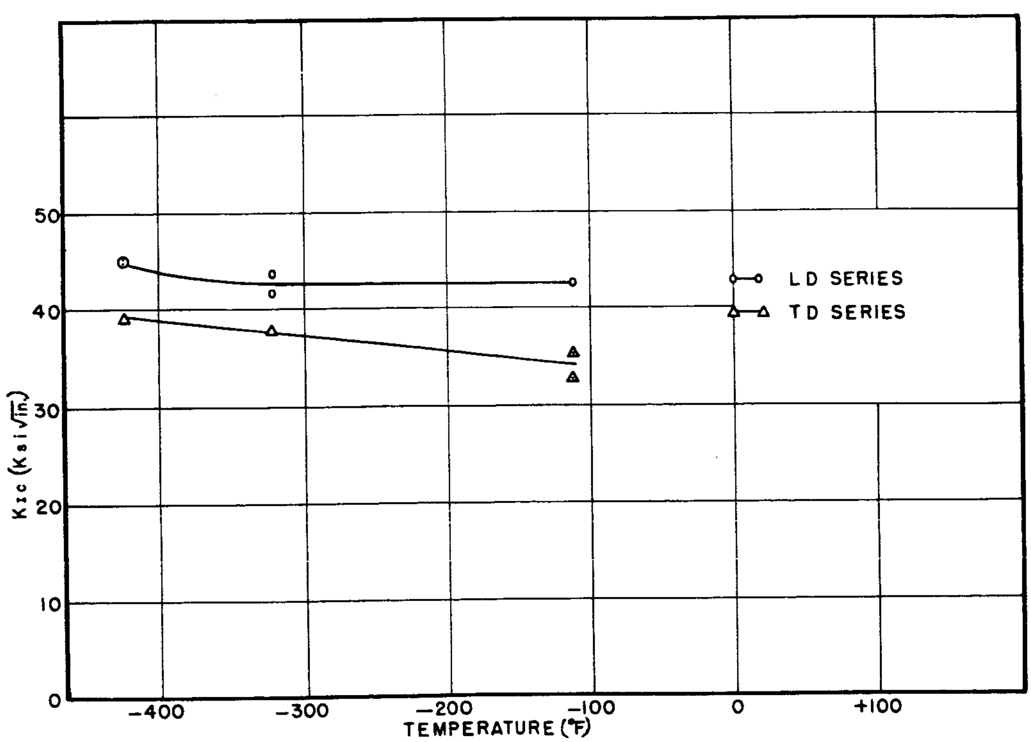

Figure 14. Lower Bound Plane Strain Fracture Toughness of 1/2 Inch Thick 2219-T87 Aluminum Alloy Plate as a Function of Testing Temperature (Crack growth perpendicular to rolling plane)

One Inch Thick 2219-T87 Aluminum Alloy Plate

Engineering Tensile Properties

The engineering tensile properties of this material are plotted in Figure 16 as a function of testing temperature, and the data are summarized in Table VI. Essentially the same comments are pertinent regarding these data as for the data from the one-half inch plate.

TABLE VI.
Tensile Properties of One Inch Thick 2219-T87 Aluminum Alloy Plate

Test Temp (°F)	Direction	Strength (psi) Yield at 0.20% Offset	Tensile	Elongation (%)	Reduction of Area (%)
Ambient	Longitudinal	54,200	66,200	14.7	28.9
Ambient	Longitudinal	54,500	67,200	17.3	30.9
Ambient	Transverse	55,000	66,700	12.9	21.1
Ambient	Transverse	53,800	67,500	12.7	
-110	Longitudinal	58,000	70,600	14.7	26.5
-110	Longitudinal	57,000	70,100	14.2	27.9
-110	Transverse	56,700	71,200	11.1	16.7
-110	Transverse	54,800	71,200	11.1	19.1
-320	Longitudinal	65,500	81,600	16.4	28.9
-320	Longitudinal	67,000	82,000	18.2	30.9
-320	Transverse	66,100	83,900	12.9	21.1
-320	Transverse	66,000	83,050	12.9	24.5
-423	Longitudinal	71,200	95,000	22.2	28.9
-423	Longitudinal	70,600	92,700		27.9
-423	Transverse	68,000	96,000	16.4	19.1
-423	Transverse	76,200	96,100	16.9	24.5

Plane Strain Fracture Toughness

The plane strain fracture toughness of this plate was determined using a small bend specimen which was one-half inch thick by one inch deep. The values of plane strain fracture toughness determined using specimens oriented in the LS and TS directions are shown as a function of testing temperature in Figure 17 and are tabulated in Table VII.

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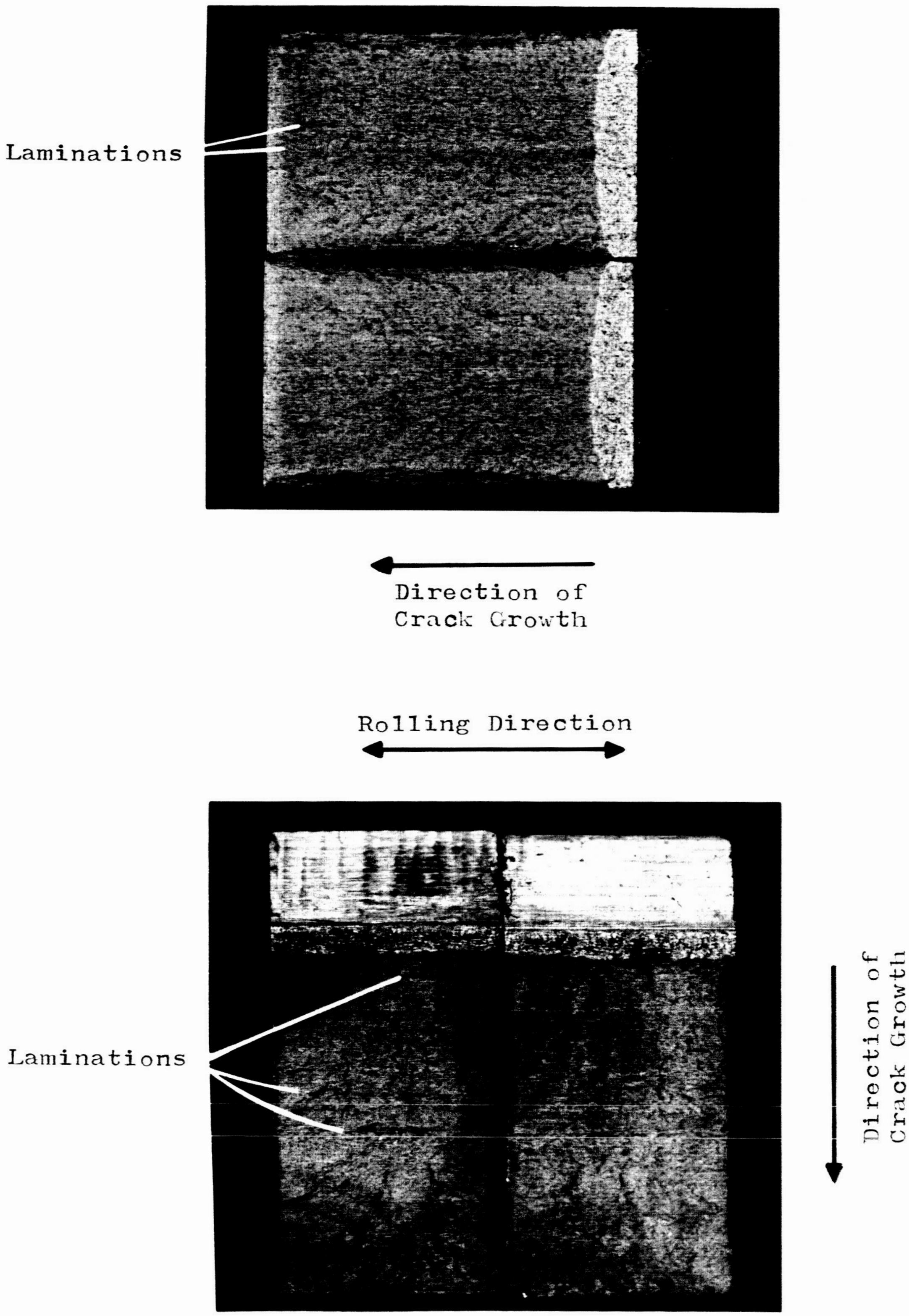


Figure 15. Fracture Surfaces of Bend Specimens showing Delaminations for Cracks Propagating Perpendicular to the Rolling Plane of the Plate

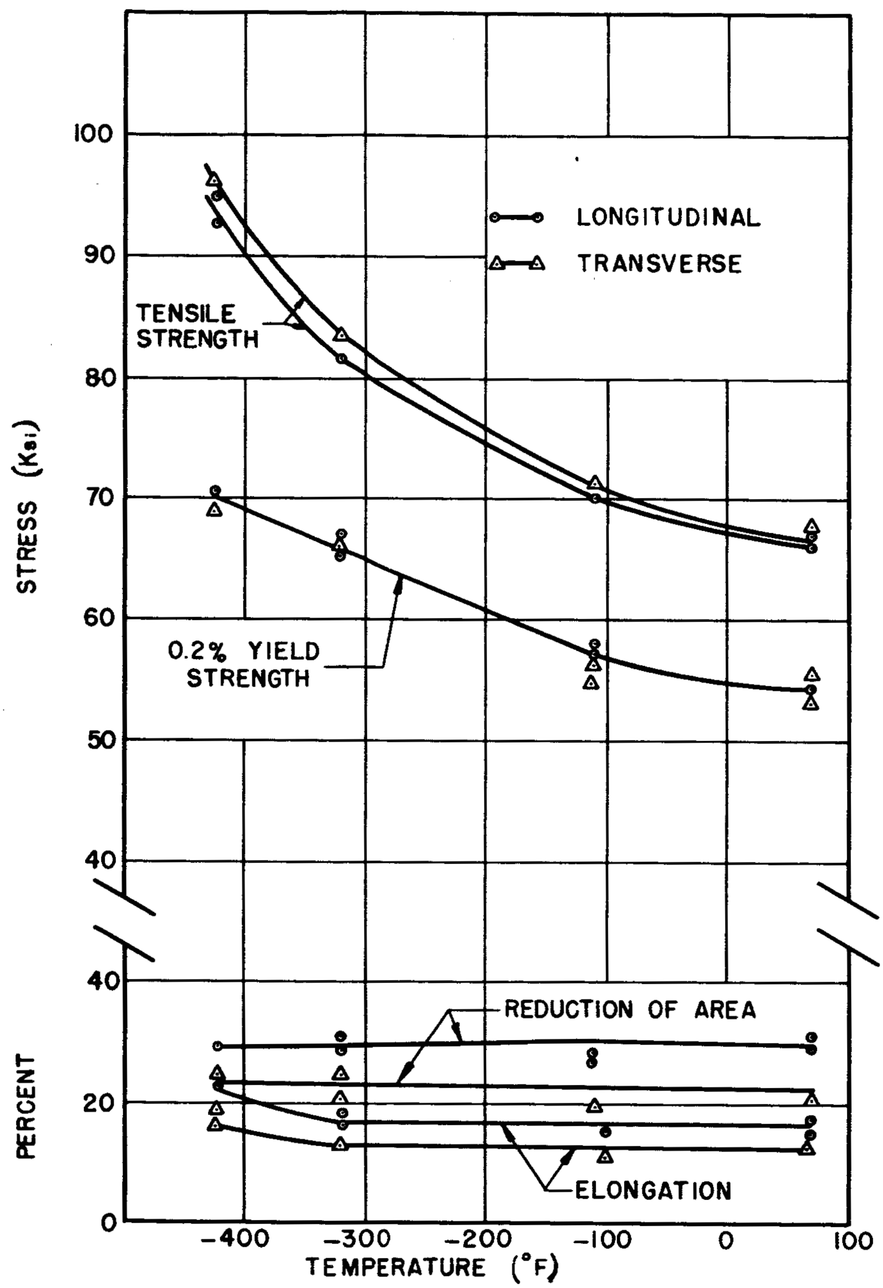
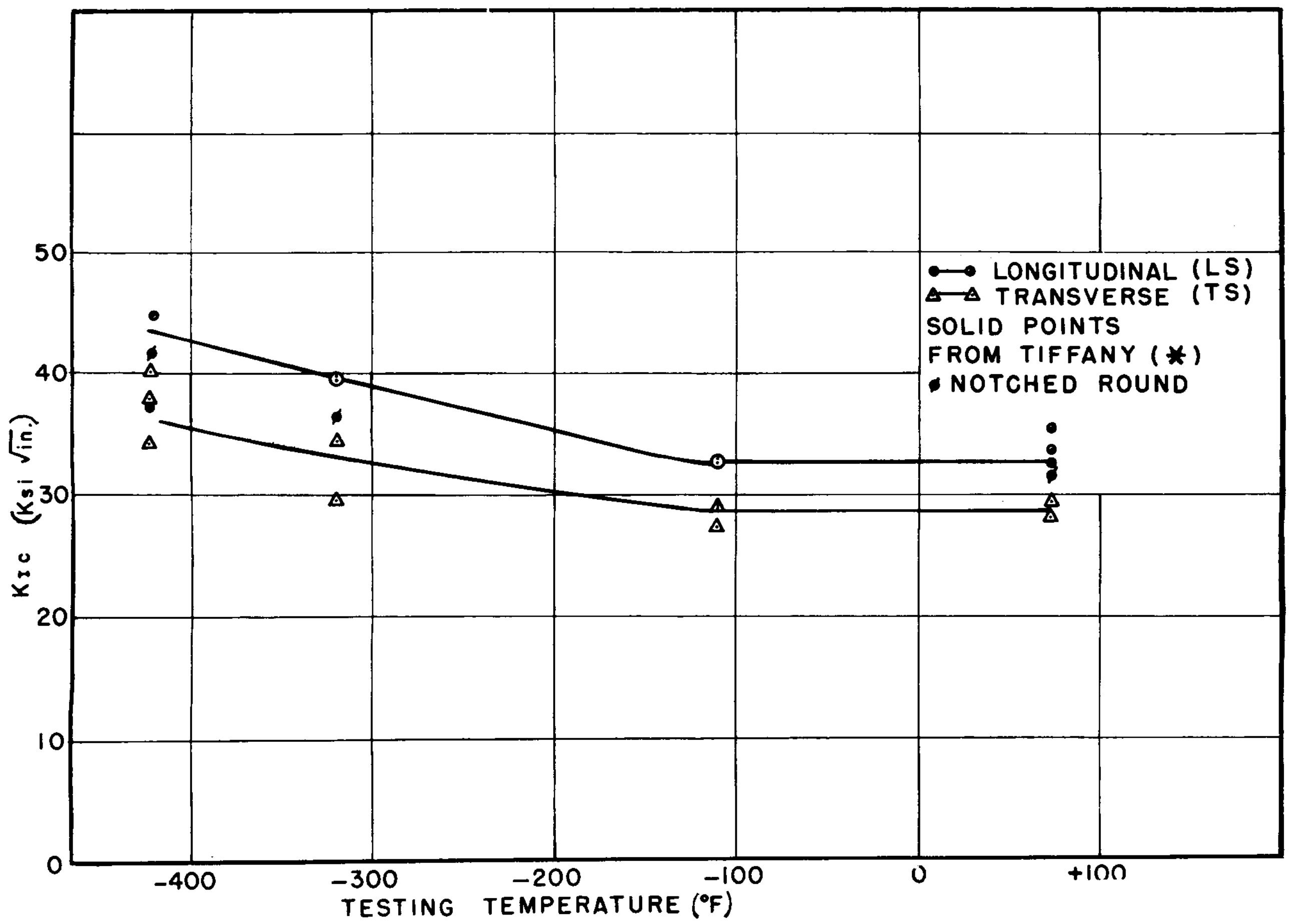


Figure 16. Tensile Properties of One Inch Thick Plate of 2219-T87 Aluminum Alloy as a Function of Testing Temperature



*Obtained through private communication with C. F. Tiffany.

Figure 17. Plane Strain Fracture Toughness of One Inch Thick 2219-T87 Aluminum Alloy Plate as a Function of Testing Temperature (Crack growth parallel to rolling plane)

TABLE VII.
Fracture Toughness of One Inch Thick 2219-T87 Aluminum Alloy Plate
(Crack Growth Parallel to Rolling Plane)

Test Temp (°F)	Direction	Load (lb)	Initial Crack Length (in.)	K_{Ic} (psi $\sqrt{in.}$)
70	Longitudinal	2875	0.2566	35,700
	Longitudinal	2640	0.2753	33,200
	Longitudinal	2610	0.2718	32,600
	Transverse	2485	0.2523	29,100
	Transverse	2365	0.2589	28,400
	Transverse	2340	0.2643	28,500
-110	Longitudinal	2730	0.2561	32,600
	Longitudinal	2550	0.2855	33,000
	Longitudinal	2650	0.2529	31,300
	Transverse	2300	0.2632	27,800
	Transverse	2470	0.2547	29,300
	Transverse	2420	0.2519	28,700
-320	Longitudinal	3175	0.2707	39,300
	Longitudinal	3150	0.2777	39,900
	Longitudinal	3400	0.2519	40,100
	Transverse	2840	0.2651	34,800
	Transverse	2820	0.2624	34,400
	Transverse	2720	0.2516	29,400
-423	Longitudinal	3700	0.2615	44,800
	Longitudinal	3590	0.2603	37,100
	Longitudinal	3875	0.2437	44,500
	Transverse	3410	0.2340	37,700
	Transverse	3300	0.2580	34,100
	Transverse	3225	0.2752	40,100

These data show a gradual trend of increasing plane strain fracture toughness with decreasing testing temperature below -110° F. The general level of plane strain fracture toughness reported here is somewhat lower than that of the 1/2 inch thick plate. These values of K_{Ic} are in closer agreement with those reported by Tiffany. However, this would be anticipated since Tiffany's specimens were taken from relatively heavy plate, i.e., up to 2-1/2 inches in thickness.

The data obtained for the LD and TD series of specimens are shown as a function of testing temperature in Figure 18 and are tabulated in Table VIII. The level of plane strain fracture toughness determined with these specimens was approximately 30 percent higher

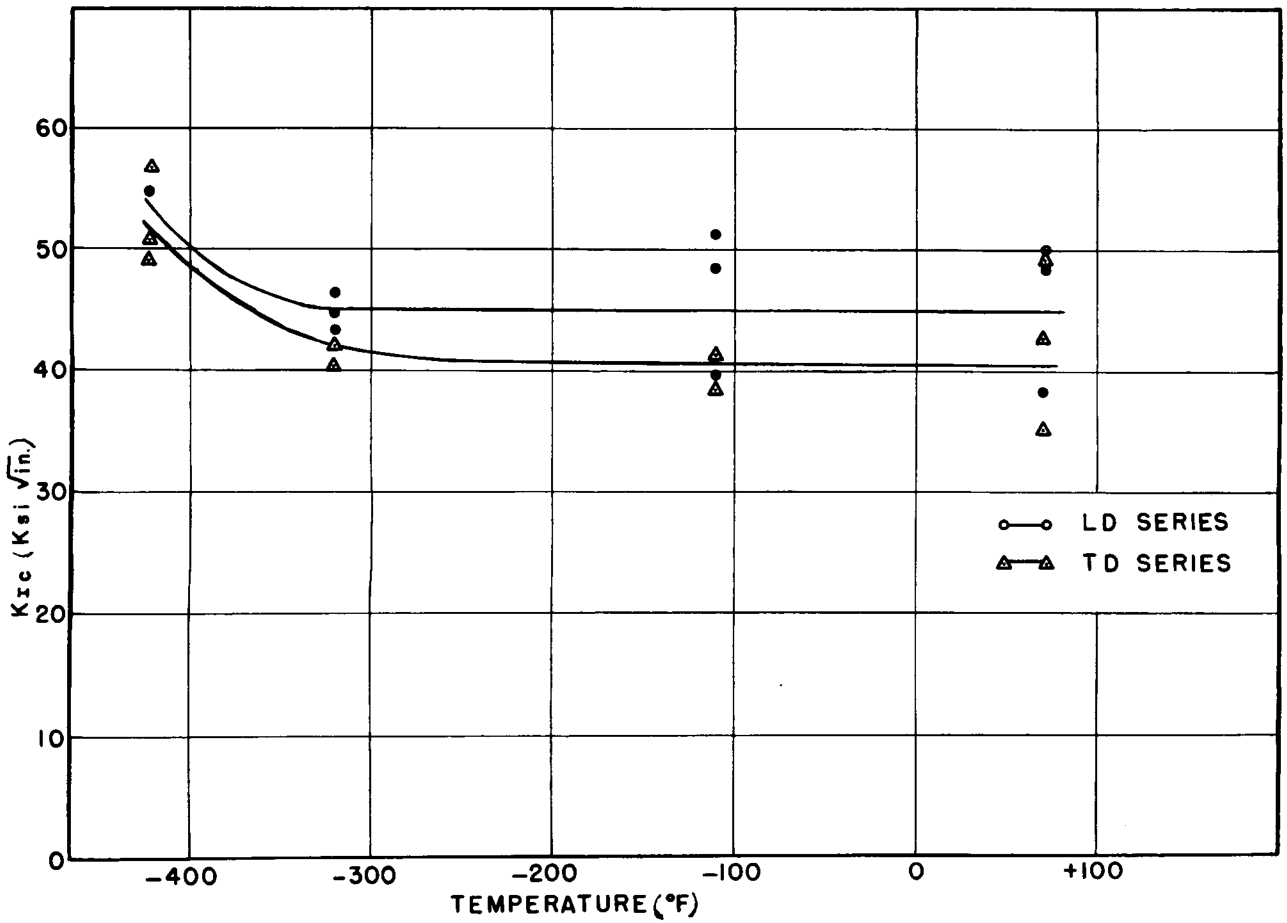


Figure 18. Plane Strain Fracture Toughness of One Inch Thick 2219-T87 Aluminum Alloy Plate as a Function of Testing Temperature (Crack growth perpendicular to rolling plane)

than for comparable specimens taken in the LS and TS orientation. This effect may be attributed to delaminations in the short transverse direction.

TABLE VIII.
Fracture Toughness of One Inch Thick 2219-T87 Aluminum Alloy Plate
(Crack Growth Perpendicular to Rolling Plane)

Test Temp (°F)	Direction	Load (lb)	Initial Crack Length (in.)	K_{Ic} (psi $\sqrt{in.}$)
70	Longitudinal	3930	0.2703	48,400
	Longitudinal	4075	0.2639	49,600
	Longitudinal	3550	0.2248	38,300
	Transverse	3410	0.2706	42,700
	Transverse	3975	0.2682	49,100
	Transverse	3050	0.2473	37,900
-110	Longitudinal	4110	0.2515	48,400
	Longitudinal	4800	0.2211	51,400
	Longitudinal	3760	0.2165	39,700
	Transverse	3570	0.2489	41,400
	Transverse	3240	0.2555	38,600
	Transverse	3500	0.2516	41,300
-320	Longitudinal	4190	0.2077	43,100
	Longitudinal	4010	0.2148	44,900
	Longitudinal	4370	0.2165	46,500
	Transverse	3600	0.2350	40,300
	Transverse	3690	0.2426	42,100
	Transverse	3680	0.2425	42,000
-423	Longitudinal	4700	0.2460	54,600
	Longitudinal	4500	0.2591	55,000
	Longitudinal	4700	0.2480	54,500
	Transverse	4175	0.2566	49,400
	Transverse	4740	0.2593	56,600
	Transverse	4310	0.2594	51,600

DESIGN CONSIDERATIONS

Of the many considerations to which the designer must devote attention, those discussed in this report are the yield stress and plane strain fracture toughness.

The data for the yield stress at the various test temperatures have been tabulated and are self-explanatory. In Figure 19, the crack depth for instability is plotted as a function of gross section stress for a panel containing a semielliptical crack. Examination of these curves shows that plane strain instability will be achieved before a crack could develop through the plate thickness. Consequently, design consideration must be directed toward the maximum size of defect which is stable at the operating stress. An example of the use of this figure as an aid to engineering design follows.

If a structure were to be fabricated of the one inch thick 2219-T87 aluminum alloy for service at -320° F, the K_{Ic} in the direction of interest would be determined from Table VIII (e.g., LD K_{Ic} = 45,000 psi $\sqrt{\text{in.}}$). If the design stress for this structure were approximately 80 percent of the yield strength (53,000 psi), then, as determined from Figure 19, the maximum allowable depth of defect would be 0.24 inch. If the structure were fabricated from this material for use at -423° F and the crack were propagating perpendicular to both the plane of the plate and rolling direction (TD), the K_{Ic} would be 52,500 psi $\sqrt{\text{in.}}$ If the minimum crack depth which would be detected by nondestructive means were 0.200 inch, the "a" in Figure 19 would be 0.200 inch and the maximum allowable stress at which this structure could be operated would be approximately 67,000 psi. These values, however, do not include any allowance for a safety factor.

CONCLUSIONS

It may be concluded that

1. The tensile properties of 2219-T87 aluminum alloy are relatively insensitive to testing temperature. The yield strength varies from approximately 57,300 psi at room temperature to 75,000 psi at -423° F.

2. The plane strain fracture toughness of 2219-T87 aluminum alloy is also relatively insensitive to testing temperature. The plane strain fracture toughness varies from 36,100 psi $\sqrt{\text{in.}}$ at room temperature to 40,300 psi $\sqrt{\text{in.}}$ at -423° F.

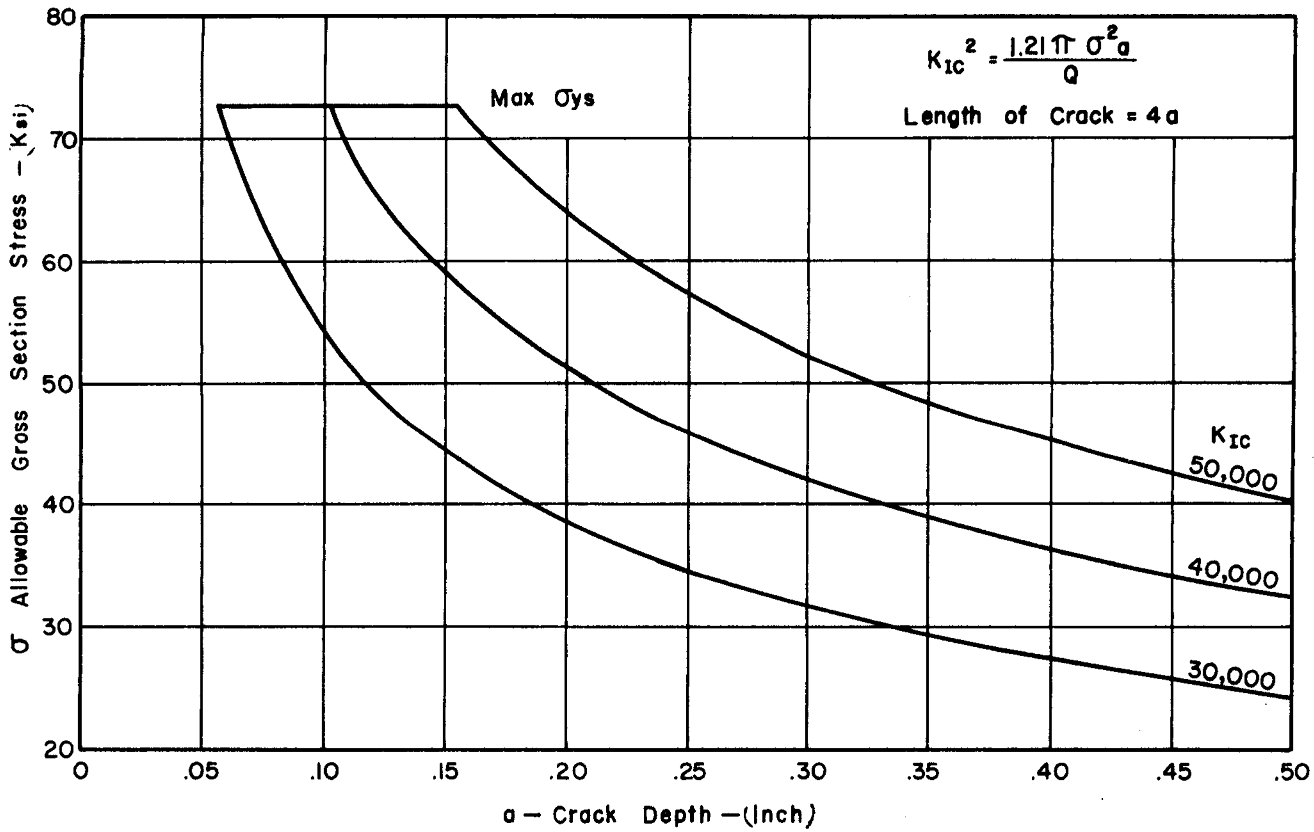


Figure 19. Variation of Critical Crack Depth for Instability as a Function of the Gross Section Stress for Several K_{Ic} Values

3. The plane strain fracture toughness of 2219-T87 aluminum alloy is sensitive to the orientation of the specimen in the plate. Those specimens oriented so that the crack propagation is perpendicular to the rolling plane show higher values of plane strain fracture toughness. This effect has been ascribed to delamination in the plate.

4. The plane strain fracture toughness of the one inch thick 2219-T87 aluminum alloy plate is somewhat lower than the value obtained for the one-half inch thick plate.

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The tensile properties and plane strain fracture toughness of 1/2 and 1 inch thick 2219-T87 aluminum alloy have been determined as a function of testing at temperatures from room to -423° F. The tensile and yield strengths of this material show a gradual increase as the testing temperature is decreased to -423° F while the elongation and reduction of area remain essentially unchanged.

The plane strain fracture toughness of this material is relatively insensitive to testing temperature and shows only a slight increase with decreasing testing temperature. Specimens machined so that the crack propagation is perpendicular to the rolling plane show somewhat higher values of plane strain fracture toughness than when crack propagation is parallel to the rolling plane. The plane strain fracture toughness of the 1 inch thick 2219-T87 aluminum alloy was somewhat lower than that of the 1/2 inch thick plate.

Illustrative examples are presented on using these parameters in design.

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