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EFFECTS OF SURFACE AND THROUGH CRACKS ON FAILURE OF PRESSURIZED THIN-WALLED CYLINDERS OF 2014-T6 ALUMINUM

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16. Abstract

Cylinders with a 0.060-in. (0.152-cm) wall thickness and a mean diameter of 5.6 inches (14.3 cm) were tested at -320° F (77 K). Crack lengths were varied from 0.10 to 1.0 in. (0.25 to 2.5 cm). Surface-crack depths ranged from 36 to 98 percent of wall thickness. In only one test was the leak-before-break phenomenon observed. For all other tests, the failure stress for the surface crack was higher than for a through-the-thickness crack of equal length. The failure stresses for cylinders containing short cracks, were less affected by crack depth than for those with long cracks. The Irwin surface-crack analysis was used to determine an apparent fracture toughness, which was found to be essentially constant.

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EFFECTS OF SURFACE AND THROUGH CRACKS ON FAILURE OF PRESSURIZED THIN-WALLED CYLINDERS OF 2014-T6 ALUMINUM

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SUMMARY

Tests were conducted to determine the effects of surface cracks on the failure stresses of pressurized cylinders. The specimens were tested at -320° F (77 K). The cylinders were 0.060 inch (0.152 cm) thick with a mean diameter of 5.6 inches (14.3 cm). Crack lengths were varied from 0.10 to 1.0 inch (0.25 to 2.5 cm). Surface-crack depths ranged from 36 to 98 percent of the wall thickness.

For all tests but one, failure stresses for the surface cracks were higher than for a through-the-thickness crack of equal length. In only one test, was the leak-before-break phenomenon observed. In that case, the depth was 98 percent of the wall thickness.

Failure stresses for cylinders containing short cracks were much less affected by crack depth than for those with long cracks. For a crack approximately 0.12-inch (0.30-cm) long, the failure stress decreased linearly from 90.2 to 72.0 ksi (622 to 497 MN/m^2) as crack depth increased from 0 to 100 percent of the wall thickness. However, a 1.0-inch (2.5-cm) long crack had a linearly decreasing failure stress from 90.2 to 23.6 ksi (622 to 163 MN/m^2) for the same depth variation.

The Irwin surface-crack analysis was used to determine an apparent fracture toughness. This value was essentially constant, independent of crack length, depth, and failure- to yield-stress ratio.

INTRODUCTION

In this decade, with the advent of the space shuttle and the orbiting space observatory, the need for more information on the effects of flaws or cracks in pressurized structures has become more important. One design approach that tends to prevent catastrophic failure is that of leak-before-break. In this condition a crack grows through the wall thickness and allows leakage rather than burst. Such a leakage provides a warning of possible failure. Also, repairs of the structure or component might be possible.

In recent years many investigators have studied the effects of cracks on the failure stresses of pressurized structures. Such studies have been carried out by Peters and Kuhn (ref. 1), Getz, Pierce, and Calvert (ref. 2), Anderson and Sullivan (ref. 3), and others. However, all these have been studies of the effects of through-the-thickness cracks on failure stresses in relatively thin materials. Also, there have been several investigations of surface cracks in relatively thick materials. These include the results of Tiffany, Lorenz, and Hall (ref. 4), Masters, Haese, and Finger (ref. 5), and others. However, little data are presently available on surface cracks in thin-walled pressure vessels.

Therefore, this program was conducted to investigate the effects of surface flaws on the failure stresses of pressurized cylinders. The material selected was the aluminum alloy 2014-T6, which is currently being used in several vehicle systems. In such systems, the material may be subjected to cryogenic temperatures. Therefore, the tests were conducted at -320° F (77 K), where the material is more sensitive to the presence of flaws or cracks. The test specimen wall thickness was nominally 0.060 inch (0.152 cm). Flaw depths were varied from one quarter to full thickness. Crack lengths ranged from 0.10 to 1.0 inch (0.25 to 2.5 cm). Failure stresses and apparent fracture toughness values for the various cracks were obtained and discussed. Also, strain gages were used to determine when the plastic zone extended through the wall thickness.

SYMBOLS

a depth of surface crack (based on original fatigue shape)

c half-length of through crack or surface crack (based on original fatigue shape)

t wall thickness

K_c fracture toughness under plane-stress fracture conditions

K_{cn} nominal value of K_c, based on original crack length and final load

K_{Ic} opening-mode (plane strain) fracture toughness

K_Q apparent value of K_{Ic}

Φ complete elliptic integral of second kind for argument $k^2 = 1 - a^2/c^2$

σ uniaxial tensile fracture stress (based on gross area)

σ_H hoop fracture stress for pressurized cylinder

σ_{yb} biaxial yield strength in 2 to 1 stress field (0.2 percent offset)

σ_{ys} uniaxial yield strength (0.2 percent offset)

BASIS OF DATA ANALYSIS

Through-the-thickness cracks in thin materials usually exhibit failure characteristics associated with plane stress. In thick sections the mode of failure is that of plane strain. When testing specimens containing surface cracks, the relation between thick or thin sections and plane-strain or plane-stress conditions is not clearly defined. The constraint associated with surface cracks may result in the failure mode being that of mixed-mode fracture, that is, intermediate between plane stress and plane strain.

The Irwin equation (ref. 6) was used to calculate K_Q, an apparent value of K_{Ic}. Irwin's analysis assumes that surface crack fracture is governed by plane-strain conditions. The actual fracture conditions for the thin material used would probably be those of the mixed mode. Although Irwin suggested that it be restricted to cases of crack depths less than half the thickness, his analysis was applied to all tests, regardless of crack depth. The equation used is

$$K_Q = 1.1\,\sigma\left\{\frac{\pi a}{\left[\Phi^2 - 0.212\left(\frac{\sigma}{\sigma_{ys}}\right)^2\right]}\right\}^{1/2} \tag{1}$$

Because a biaxial stress state exists, σ and σ_{ys} were replaced by σ_H and σ_{yb}, respectively.

EXPERIMENTAL PROCEDURE

Material

The cylinders were fabricated from a single heat of unclad 2014-T6 extruded aluminum alloy tubing. The chemical analysis of this heat is given in table I. This same heat of material was used to obtain the data reported in reference 7.

The tensile properties of this material were obtained from reference 7 and are shown in table II. A complete description of the specimens and procedures is outlined in

TABLE I. - CHEMICAL COMPOSITION OF 2014-T6 ALUMINUM TEST MATERIAL

Specimen	Composition, wt. %										
	Cu	Fe	Si	Mn	Mg	Zn	Ni	Cr	Ti	Sn	Al
Cylinders	4.32	0.35	0.80	0.73	0.40	0.06	0.005	0.01	0.025	0.001	Bal.
Tensile[a]	4.45	0.60	0.92	0.69	0.57	0.05	-----	0.04	0.020	-----	Bal.

[a]From ref. 8.

TABLE II. - AVERAGE TENSILE PROPERTIES OF 2014-T6 ALUMINUM TEST MATERIAL

Specimen	Test temperature		0.2-Percent yield strength		Ultimate tensile strength	
	^{o}F	K	ksi	MN/m^2	ksi	MN/m^2
Cylinder (transverse)	70	293	63.3	440	71.5	490
	-320	77	75.0[a]	520	85.5	590
	-423	20	81.6	560	99.7	690
Tensile[b] (longitudinal)	70	293	65.0	450	72.3	500
	-320	77	75.2	520	86.7	600
	-423	20	80.3	550	99.7	690

[a]Biaxial yield strength experimentally determined to be equal to 85.8 ksi (592 MN/m^2).

[b]From ref. 8.

this reference. Also included in tables I and II are the chemical analysis and tensile properties from reference 8.

Fracture Specimens

The cylindrical specimens were machined from 6-inch (15.2-cm) outside diameter by 0.25-inch (0.63-cm) wall extruded tubing. The finished wall thickness was 0.060 inch (0.152 cm) with a mean diameter of 5.63 inches (14.3 cm). Longitudinal crack starters were made by electrical-discharge machining (EDM). The cracks were fatigue sharpened by pressure cycling using hydraulic oil. A complete description of this procedure is given in reference 9. For all specimens, the cyclic hoop stress was less than one-third the material yield strength. Figure 1 shows the specimen with cross-sectional views of the through-the-thickness crack and the surface crack. A photograph of a typical surface crack is shown in figure 2.

In some instances no fatigue crack growth was obtained in the length dimension. For these cases tangent lines were drawn at the ends of the fatigue region and extended to the specimen surface. The crack length was recorded to be the distance between these tangent and surface-line intersections as shown in figure 1.

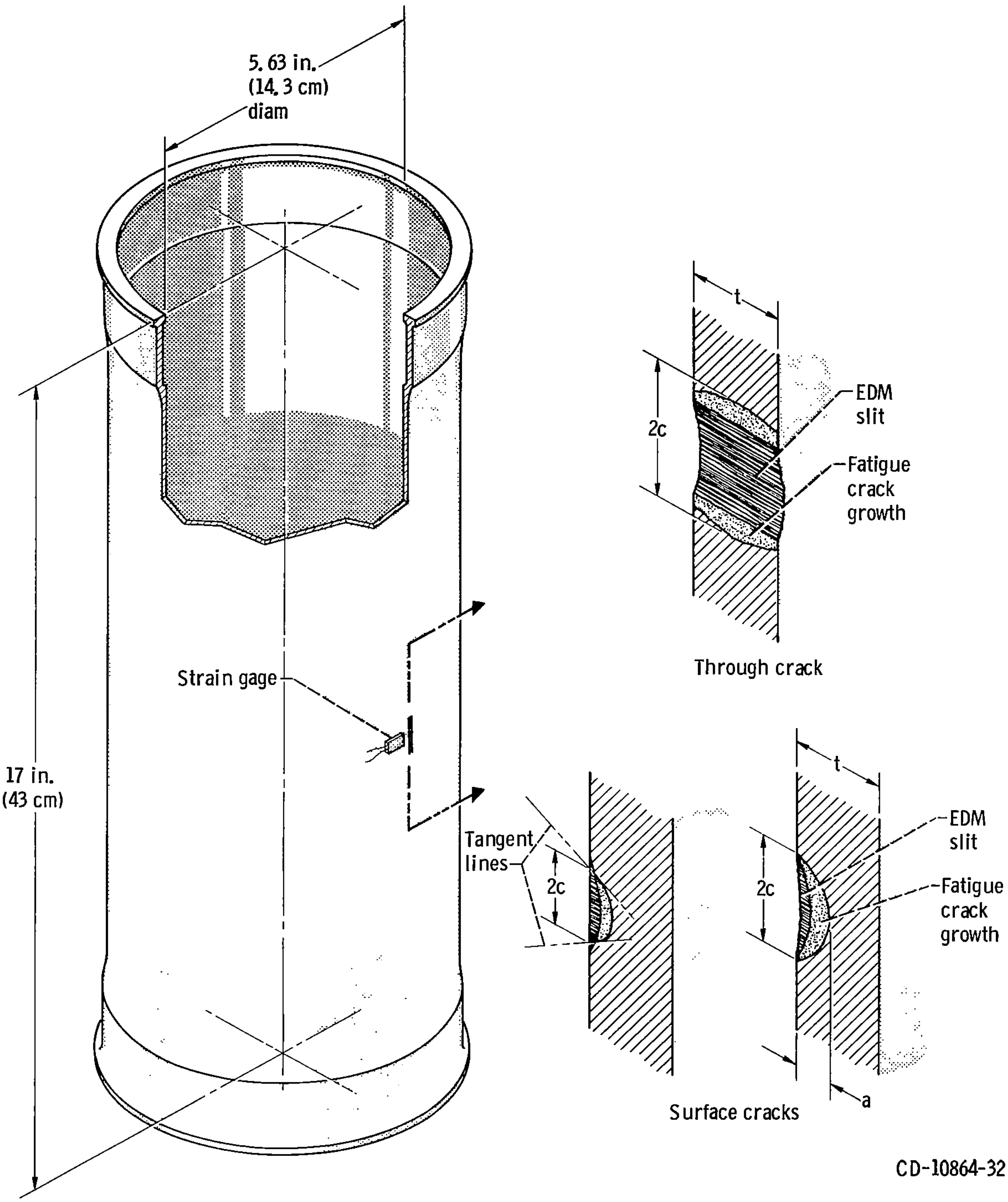


Figure 1. - Typical cylindrical test specimen showing crack shape and location. Width of slit, 0.005 inch (0.013 cm). Note: 2c = 0.10 to 1.0 inch (0.25 to 2.5 cm); a = 0.024 to 0.060 inch (0.061 to 0.152 cm).

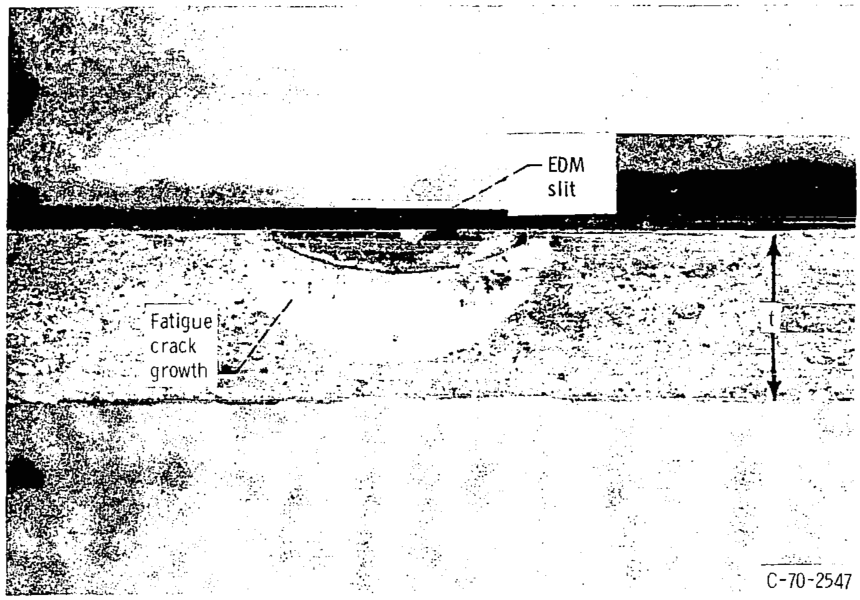


Figure 2. - Typical surface crack shape.

Apparatus and Procedure

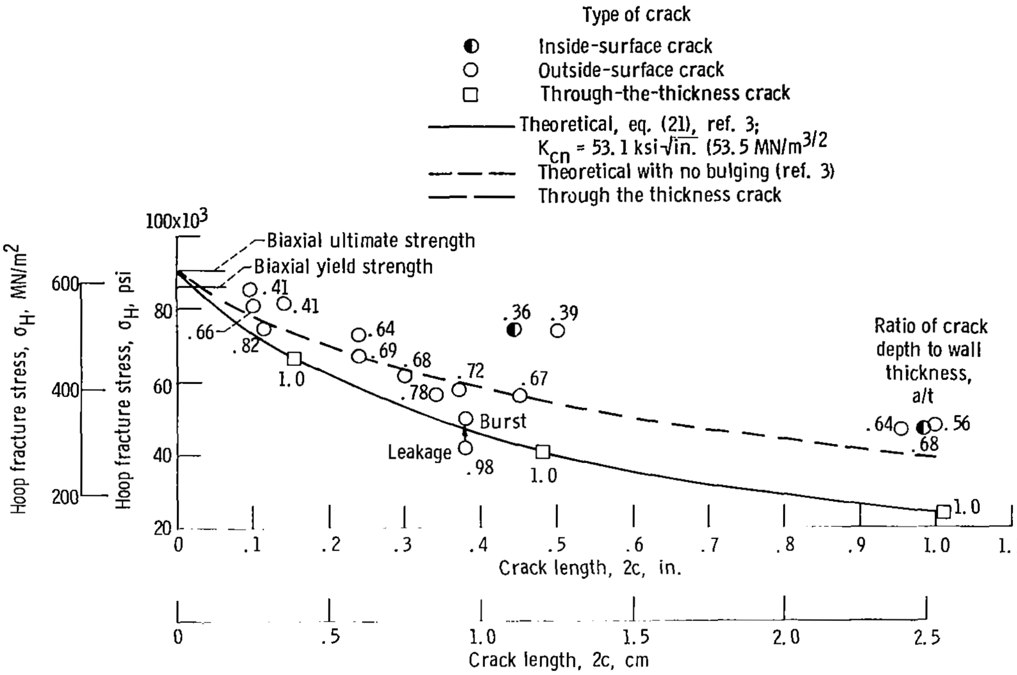
The open ends of the cylindrical specimens were sealed with special removable end closures. These closures were held in place by a low-melting-point alloy. The complete assembly was placed inside a cryostat and immersed in and filled with liquid nitrogen. Helium gas was used to pressurize the assembly to failure. Cryogenic liquid level was maintained several inches above the specimen using carbon resistors as level sensors. A complete description of the test procedure is given in reference 10. The method of sealing the through-the-thickness cracked specimens using Mylar tape is described in reference 2.

A metal foil strain gage (0.18 in. (0.46 cm) square) was placed adjacent to the crack as shown in figure 1. The gage was oriented in the hoop direction on the uncracked surface (opposite the surface crack). Thus, for an outside-surface crack, the strain gage was placed on the inside surface. For an inside-surface crack, the gage was located on the outside surface.

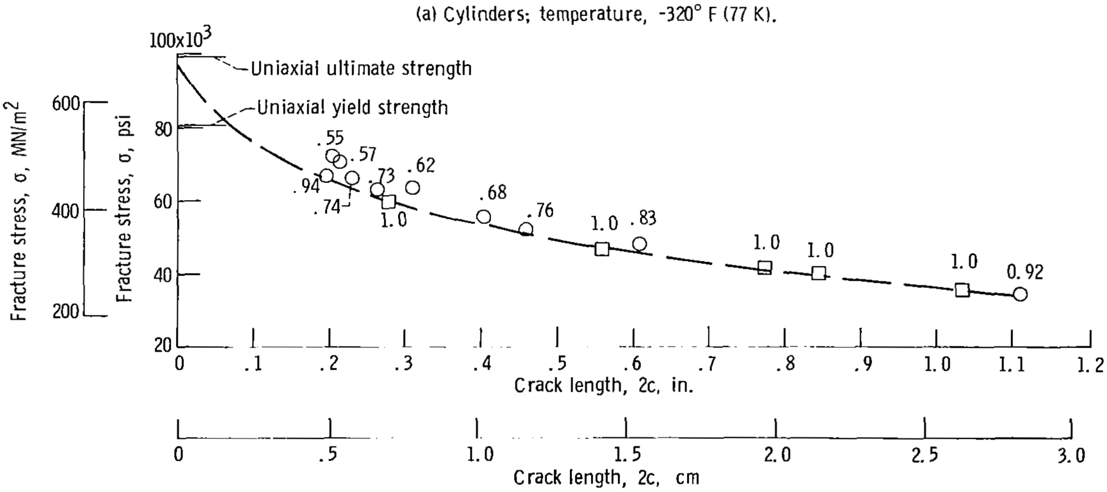
RESULTS AND DISCUSSION

Through-The-Thickness Versus Surface Crack

In figure 3(a) are plotted the hoop fracture stress for pressurized cylinders con-

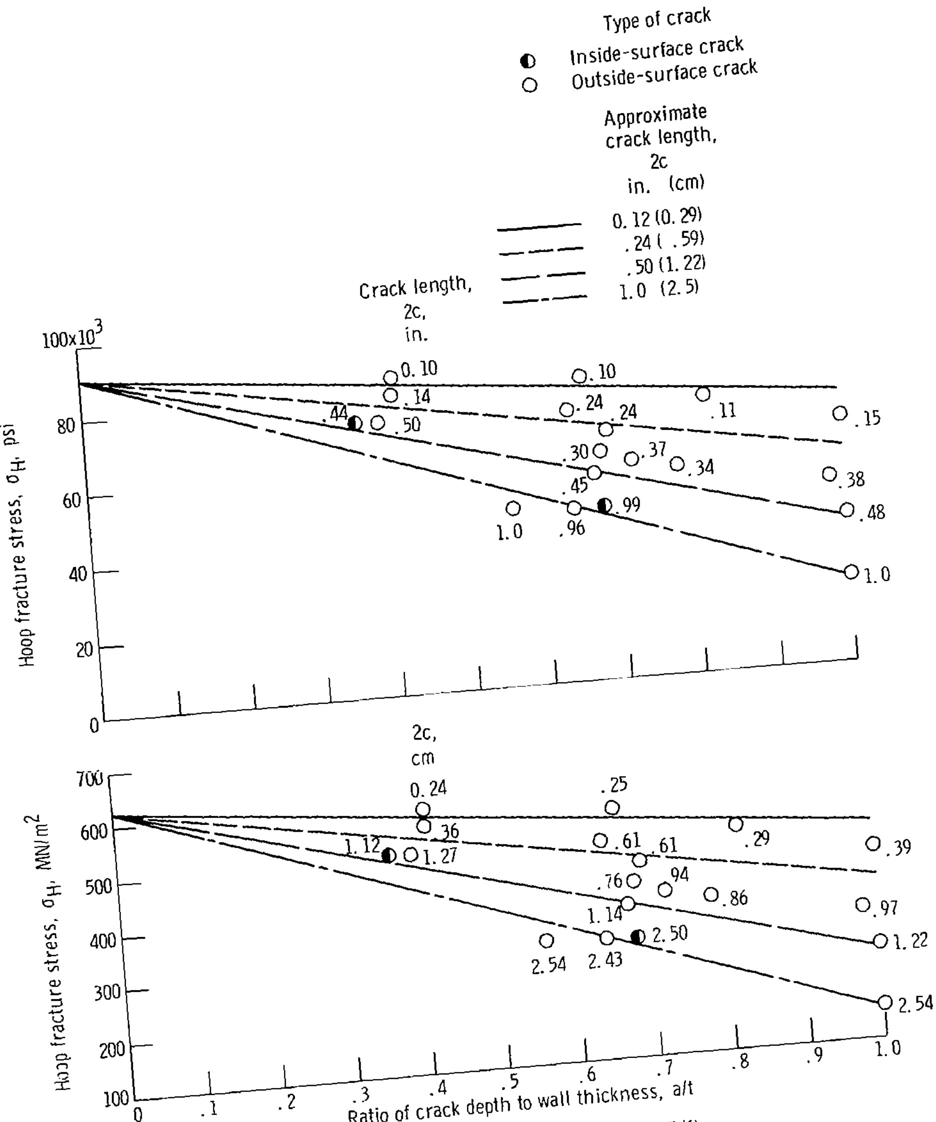


(a) Cylinders; temperature, -320° F (77 K).



(b) Tensile coupons; temperature, -423° F (20 K): data from reference 8.

Figure 3. - Strength of cracked 2014-T6 aluminum for various crack lengths and depths. Nominal thickness, 0.060 inch (0.152 cm).



(c) Cylinders; temperature, -320° F (77 K).

Figure 3. - Concluded.

taining either a surface or through-the-thickness crack with various crack lengths. For all tests but one, the failure stresses for the surface cracks, regardless of depth, were higher than those for corresponding through-the-thickness cracks of equal length. Also, there appears to be a definite layering of the surface-crack data. This layering appears to follow lines of constant a/t (ratio of crack depth to wall thickness) or constant a since t was essentially constant. Figure 3(b) shows the results obtained by Orange, Sullivan, and Calfo (ref. 8) with 2014-T6 uniaxial tensile specimens of the same thickness at -423° F (20 K). These data also tend to exhibit the layering effect but to a lesser degree. However, for a given crack length, the effect of changes in a/t is small for their tensile tests. This difference between uniaxial-tensile data and pressurized cylinders may be due to the pressure bulging phenomenon in the cylinders. In figure 3(a) the dashed curve represents the theoretical failure for through-the-thickness cracked cylinders if no bulging occurred. Thus, it represents the results for the 2 to 1 biaxial tensile specimen. If one assumes that all data points below this dashed curve would fall on or above it if no bulging were present, then the results for the tensile and cylinder data compare very well. However, different temperatures and heats of material may also have affected the results.

As previously mentioned, one surface-cracked specimen did fail at a stress level below the through-the-thickness crack curve. The failure was typical of what is called leak-before-break. Shown in figure 3(a) are the points at which leakage and burst occurred. It appears, for the material and test conditions of this report, that the a/t value must be extremely high before a leak-before-break condition is possible. In this case, the depth was 98 percent of the wall thickness.

Effects of Crack Length and Depth

Figure 3(c) is a cross-plot of figure 3(a). This was done to show more clearly the interaction between crack length and depth. The failure stress was found to vary linearly with crack depth along lines of constant crack length. Therefore, lines of constant crack length were drawn from the uncracked cylinder failure stress (biaxial ultimate strength) to the through-the-thickness crack failure stress. From the data it is apparent that the failure stress for cylinders containing short cracks was only moderately affected by changes in crack depth. For example, a 0.12-inch (0.30-cm) long crack had a linearly decreasing failure stress from 90.2 to 72.0 ksi (622 to 497 MN/m^2) as crack depth increased from 0 to 100 percent of the wall thickness. However, a 1.0-inch (2.5-cm) long crack had a linearly decreasing failure stress from 90.2 to 23.6 ksi (622 to 163 MN/m^2) for the same depth variation. Thus, it is apparent that the failure stresses for cylinders containing long cracks were more affected by changes in crack depth than were those for short cracks.

Apparent Fracture Toughness

The value of apparent fracture toughness K_Q for each surface-cracked specimen was calculated from equation (1) and reported in table III. These values are plotted in figure 4 against crack length, ratio of crack depth to wall thickness, and ratio of hoop fracture stress to biaxial yield stress. Also shown are the results obtained by Orange, Sullivan, and Calfo (ref. 8) using tensile specimens for a different heat tested at -423° F (20 K). Both the cylindrical pressure vessels and the tensile specimens gave a K_Q of approximately 24.0 ksi $\sqrt{in.}$ (26.4 $MN/m^{3/2}$). The K_Q values are independent of the previously mentioned parameters. The only trends that appeared (and these were very slight) were a decrease in K_Q with increase in crack length and an increase in

TABLE III. - FRACTURE TEST DATA FOR 2014-T6 ALUMINUM CYLINDERS AT -320° F (77 K)

Specimen	Specimen thickness, t		Crack depth, a		Crack length, 2c		Fracture stress, σ_H		Apparent fracture toughness, K_Q	
	in.	cm	in.	cm	in.	cm	ksi	MN/m^2	ksi $\sqrt{in.}$	$MN/m^{3/2}$
Outside-surface crack	0.061	0.155	0.025	0.064	0.096	0.244	85.3	589	23.5	25.9
			.040	.102	.100	.254	80.7	557	23.1	25.4
			.050	.127	.114	.290	74.1	511	22.8	25.1
			.025	.064	.140	.356	80.7	557	24.0	26.4
			.039	.099	.240	.610	72.9	503	27.3	30.0
			.042	.107	.240	.610	66.9	462	25.0	27.5
			.041	.104	.300	.762	61.3	423	23.6	26.0
			.047	.119	.340	.864	56.0	386	22.8	25.1
			.044	.112	.370	.940	58.4	403	23.1	25.4
			.060	.152	.380	.965	49.9[a]	344[a]	18.0[b]	19.8[b]
			.041	.104	.450	1.143	55.5	383	22.0	24.2
			.024	.061	.500	1.270	73.7	509	23.5	25.9
			.039	.099	.955	2.426	46.9	324	18.4	20.3
			.034	.086	1.000	2.540	47.9	331	17.4	19.1
Inside-surface crack	0.061	0.155	0.022	0.056	0.442	1.123	73.9	510	22.8	25.1
	.061	.155	.042	.107	.985	2.502	46.8	323	17.3	19.0
No crack	0.060	0.152	0	0	0	0	90.2	622	-----	-----
Through-the-thickness crack	0.062	0.157	0.062	0.157	0.154	0.391	66.0	455	-----	-----
	.062	.157	.062	.157	.481	1.222	40.2	277	-----	-----
	.061	.155	.061	.155	1.012	2.570	23.6	163	-----	-----

[a]Leakage occurred at 41.0 ksi (283 MN/m^2).
[b]Computed using stress at leakage.

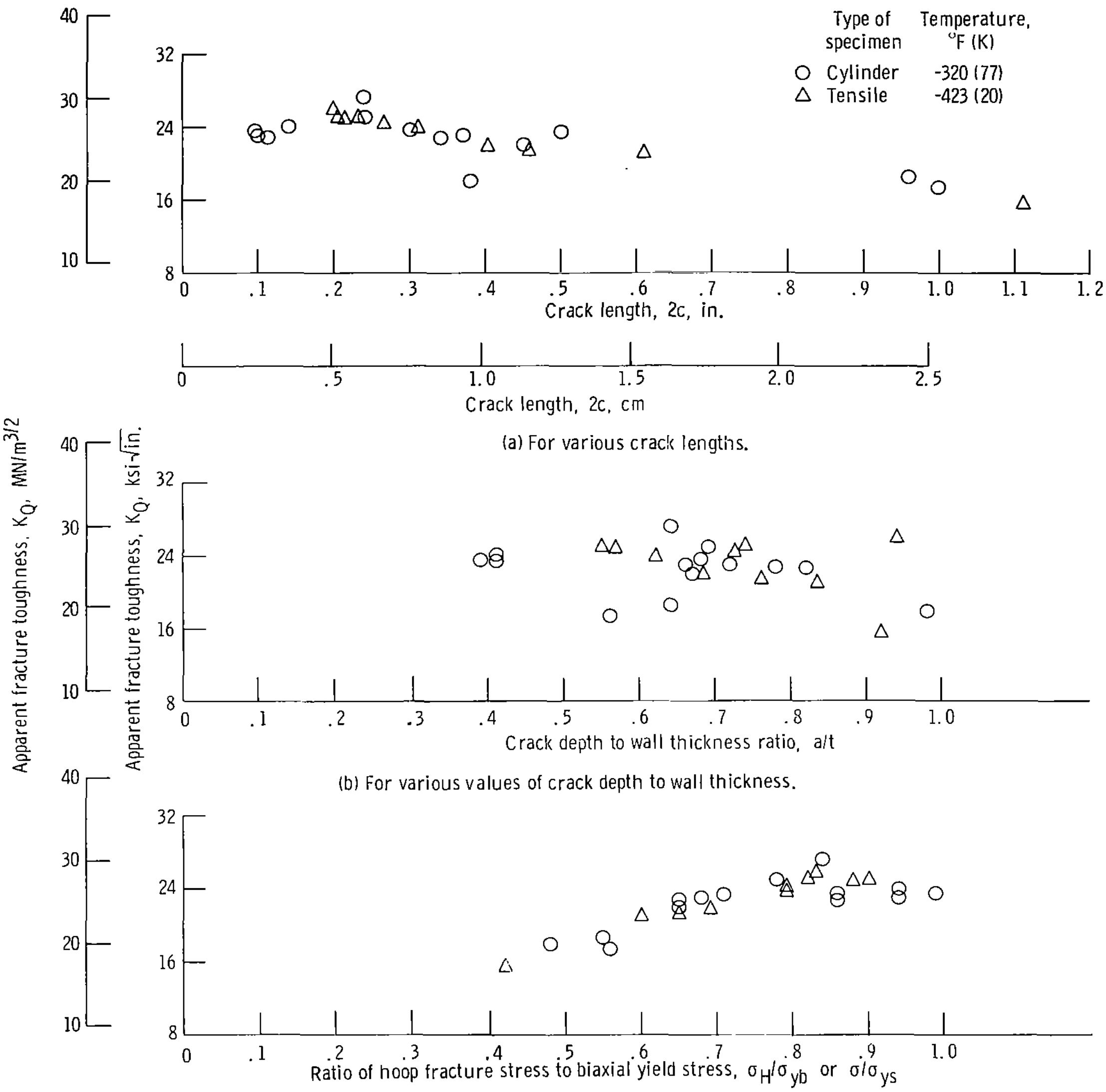


Figure 4. - Apparent fracture toughness of surface-cracked 2014-T6 aluminum. Nominal wall thickness, 0.060 inch (0.152 cm).

K_Q with an increase in hoop fracture to biaxial yield stress ratio. Thus, it might be possible to use K_Q as a parameter for correlating uniaxial tensile data with cylindrical pressure-vessel data. However, much more information is needed before this generalization can be made.

The values of K_Q obtained using equation (1) are probably not true values for K_{Ic}. The material thickness recommendations as set forth in reference 11 for "valid" K_{Ic} tests were not met. Recent data in reference 12 on much thicker sections of 2014-T62 aluminum show K_Q values of approximately 40 ksi $\sqrt{in.}$ (44.0 $MN/m^{3/2}$) for longitudinal tensile specimens.

Effects of Plastic Zone

Figure 5 shows the results obtained from a strain-gage mounted on the surface opposite the crack. The exact location is shown in the inset of figure 5(a). In each figure the dashed curve represents the hoop strain measured on an uncracked cylinder. Figures 5(a) and (b), for crack lengths of 0.50 and 0.25 inch (1.22 and 0.61 cm), respectively, show large deviations from the strain in an uncracked cylinder for high values of a/t. This deviation is the result of the plastic zone extending through the thickness of the material.

The actual size of the plastic zone has been studied by many investigators. A summary of these studies along with some experimental results is given in reference 13. Based on the conclusions of this reference, the start of this deviation at about 40 ksi (276 MN/m^2) appears reasonable.

In figure 5(c), for a crack length of only 0.10 inch (0.25 cm), no appreciable deviation from the results for an uncracked cylinder was observed, regardless of the a/t value. This may be the result of the insensitivity of the relatively large strain gage (0.18 in. (0.46 cm) square) to a highly localized strain around a very short crack. Also, on this short crack, the location of the gage was quite critical and could have been misalined since the crack and gage were on opposite surfaces.

Figure 5(d) is a plot of the hoop strain for cracks having nearly equal a/t values in contrast to constant 2c of figures 5(a) to (c). From these data, it appears that the plastic-zone size is a function of crack length as well as crack depth.

Inside Versus Outside Surface Cracks

In order to determine possible differences between failure stresses associated with inside- and outside-surface cracks, two test specimens were tested which contained

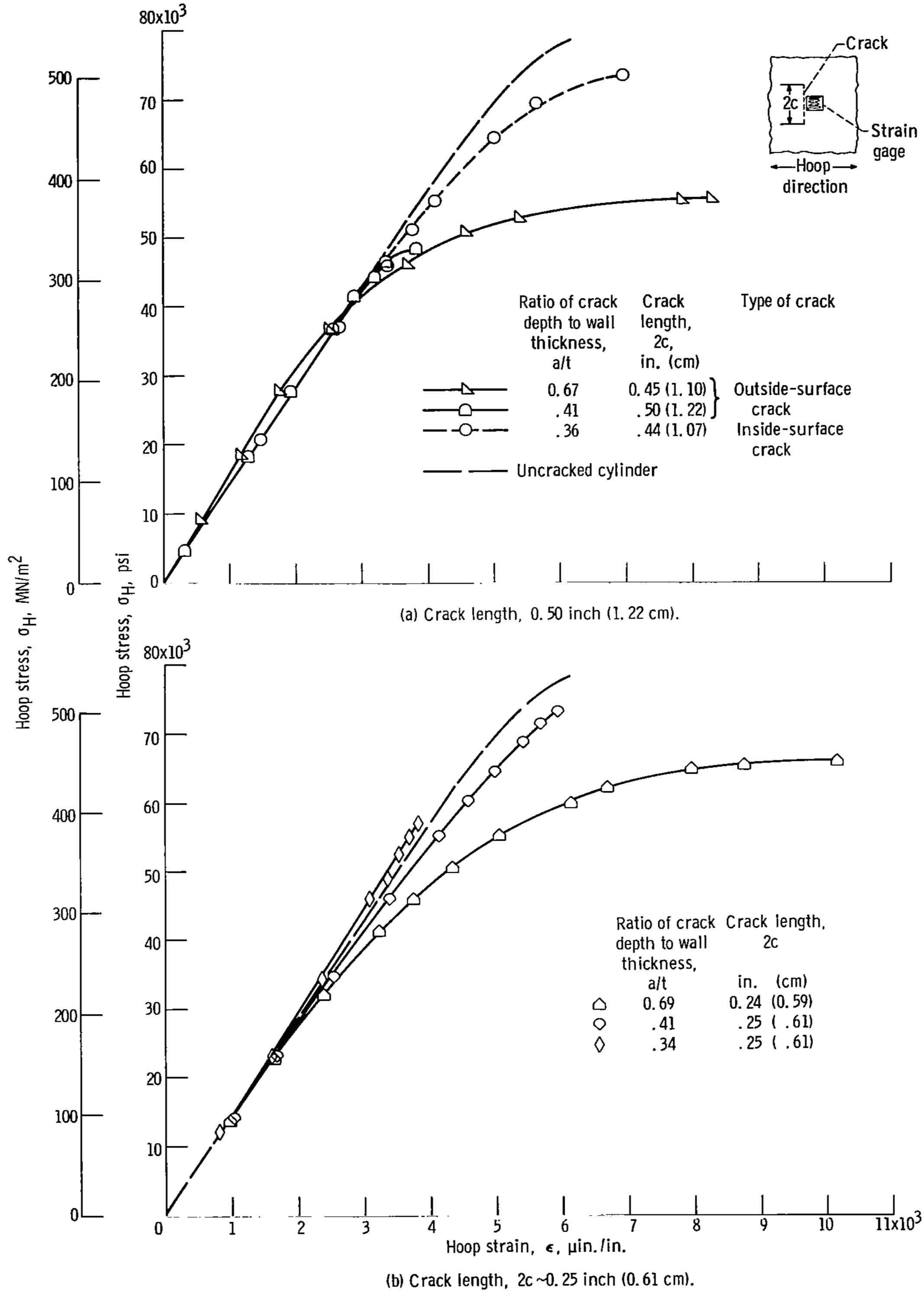
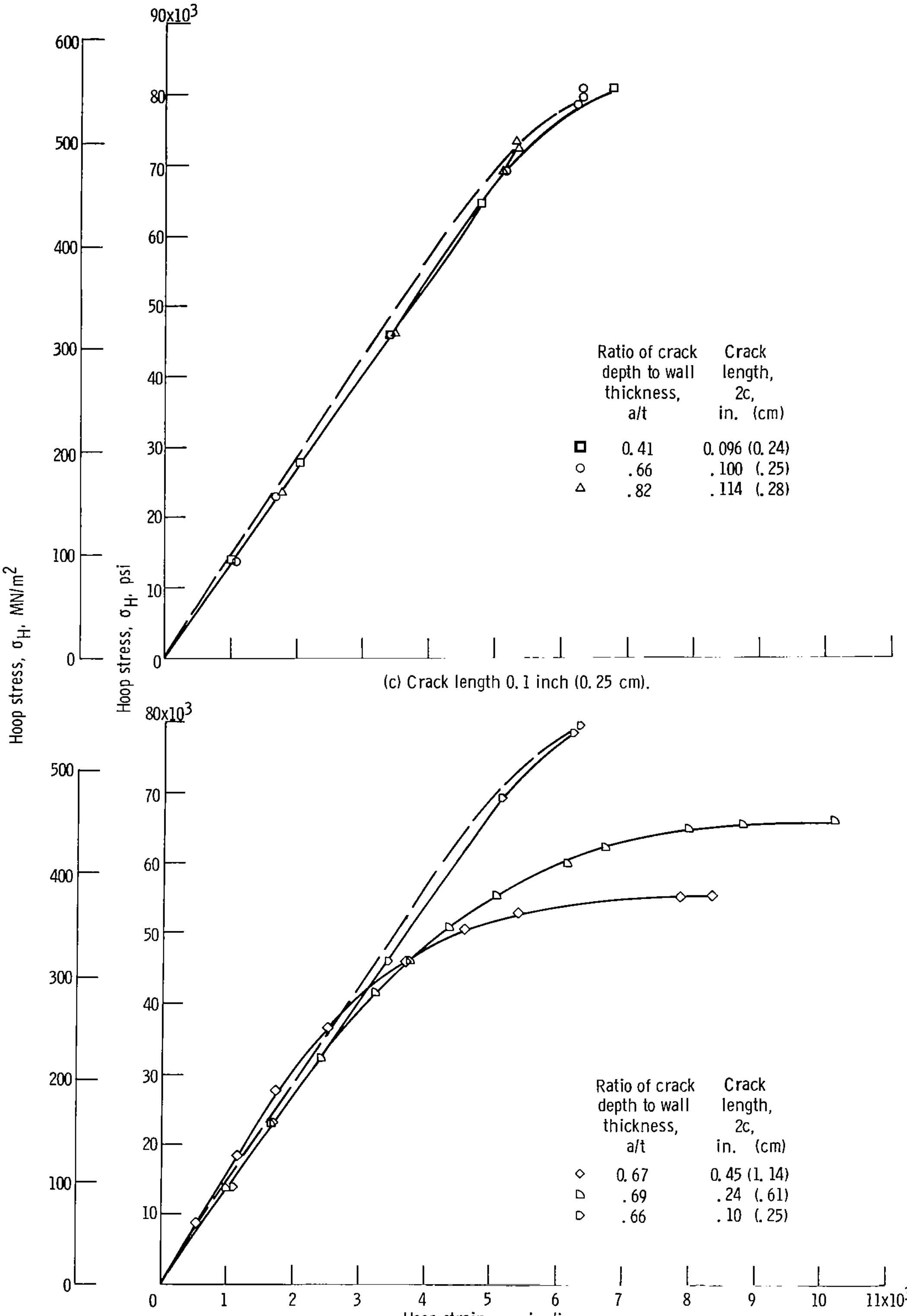


Figure 5. - Surface strain as function of hoop stress for various crack depths in 2014-T6 aluminum at -320° F (77 K). Nominal thickness, 0.060 inch (0.152 cm).



(c) Crack length 0.1 inch (0.25 cm).

(d) Crack depth to wall thickness ratio, 0.67.

Figure 5. - Concluded.

surface cracks on the inside of the cylinder. All other specimens tested had the crack on the outside surface. The crack dimensions were very similar to those of previously tested outside-surface cracks. In figures 3(a) and (b) are shown the results of these tests. There appears to be no difference in the failure stress for similar cracks whether on the inside or outside surface.

Strain gage data were not available for all test specimens. Therefore, a direct comparison of the hoop strain for inside- and outside-surface cracks could not be made. In figure 5(a) the hoop strain on the outside surface adjacent to an inside crack is plotted. This plot appears to agree reasonably well with the results shown for outside-surface cracks.

SUMMARY OF RESULTS

Tests were conducted to determine the effects of surface cracks on the failure stresses of pressurized cylinders. The test specimens were fabricated from 2014-T6 aluminum and were tested at -320° F (77 K). The cylinders were 0.060-inch (0.152-cm) thick with a mean diameter of 5.6 inches (14.3 cm). Various notch lengths and depths were studied. The following results were obtained:

1. For all tests but one, the failure stresses for the surface cracks (regardless of depth) were higher than those for a through-the-thickness crack of equal length. In only one test, of a very deep flaw, was the leak-before-break phenomenon observed. In that case, the depth was 98 percent of the wall thickness.

2. The failure stresses, for cylinders containing short cracks were much less affected by crack depth than for those with long cracks. For a crack length of approximately 0.12 inch (0.30 cm), the failure stress decreased linearly from 90.2 to 72.0 ksi (622 to 497 MN/m^2) as crack depth increased from 0 to 100 percent of the wall thickness. However, a 1.0-inch (2.5-cm) long crack had a linearly decreasing failure stress from 90.2 to 23.6 ksi (622 to 163 MN/m^2) for the same depth variation.

3. The Irwin surface crack analysis was used to determine an apparent fracture toughness. This value was found to be 24.0 ksi $\sqrt{\text{in.}}$ (26.4 $MN/m^{3/2}$), and it was essentially constant and independent of crack length, depth, and failure- to yield-stress ratio. However, the material wall thickness was too small to obtain "valid" fracture toughness results as recommended by standards published by the ASTM.

4. Two specimens were tested that contained inside-surface cracks. There appears to be no difference in the failure stresses for similar cracks whether on the inside or outside surface.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 6, 1970,
124-08.

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