TECHNICAL REPORT

AMRA TR 64-05

600 8976

18-p $0.50

THE INFLUENCE OF SECTION SIZE ON THE MECHANICAL PROPERTIES AND FRACTURE TOUGHNESS OF 7075-T6 ALUMINUM, 6Al-6V-2Sn TITANIUM, AND AISI 4340 STEEL

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FEBRUARY 1964

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The findings in this report are not to be construed as an official Department of the Army position.

Fracture toughness -
mechanical properties
Fracture

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AMCMS Code 5011.11.838
Basic Research in Physical Sciences
D/A Project 1A010501B010

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ABSTRACT

The influence of section size on mechanical properties, yield strength, tensile strength, elongation, reduction of area, notched tensile ratios, and fracture toughness was determined for 7075-T6 aluminum, 6Al-6V-2Sn titanium, and AISI 4340 steel. The tests were made on smooth tension specimens with diameters from 0.113 to 3.57 inches, and sharply notched specimens with diameters from 0.160 to 5.05 inches. The tensile fracture topography of the smooth and notched specimens is illustrated and discussed. The data show that yield and tensile strengths are not changed appreciably by increasing section size, but ductility and toughness properties are affected.

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INTRODUCTION

Numerous investigations have been conducted at room temperature on smooth and notched round tension specimens. These investigations have been primarily concerned with the effect of section size on tensile properties[1-3] and notch toughness.[4-6] The recent interest in the fracture of metals and fracture mechanics in general has focused attention on the effect of section size on crack toughness of notched cylindrical specimens.[7,8] This interest has also resulted in several recent publications of fracture surface analysis on both a microscopic scale[9] and a macroscopic scale.[10,11] While previous work[9,12] was primarily concerned with the fracture topography of 4340 steel, the purpose of the study covered by this report was to ascertain the fracture toughness of 7075-T6 aluminum, 6Al-6V-2Sn titanium, and 4340 steel over a broad range of sizes. Fracture topography measurements of 4340 steel as a function of section size augment prior investigations.[10,12]

MATERIALS AND PROCEDURES

Chemical Analysis and Heat Treatment

The materials used in this investigation together with their chemical analysis are shown in Table I. The 7075-T6 aluminum and the 6Al-4V-2Sn titanium were tested in the as-received condition while the 4340 steel was given the following heat treatment in the 5-1/4-inch section size.

Normalized at 1600 F for 4 hr followed by air cooling
Austenitized at 1550 F for 4 hr followed by an oil quench
Tempered at 1000 F for 4 hr followed by an oil quench
Tempered at 1000 F for 4 hr followed by an oil quench

TABLE I. Materials and Chemical Compositions

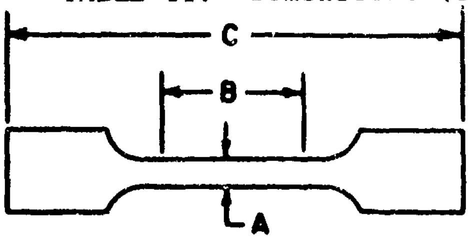
		CHEMICAL ANALYSIS (WEIGHT PERCENT)														
Material	Stock Diameter (inches)	Al	C	Cr	Cu	Fe	Mg	Mo	Mn	Ni	P	S	Si	Sn	V	Zn
7075-T6*	6-1/4	-	-	0.20	1.66	0.20	2.25	-	0.12	-	-	-	0.18	-	-	5.61
6Al-6V-2Sn**	4-1/2	5.64	0.021	-	0.56	0.45	-	-	-	-	-	-	-	2.26	5.32	-
4340	5-1/4	-	0.451	0.82	-	-	-	0.24	0.73	1.90	0.005	0.010	0.35	-	-	-

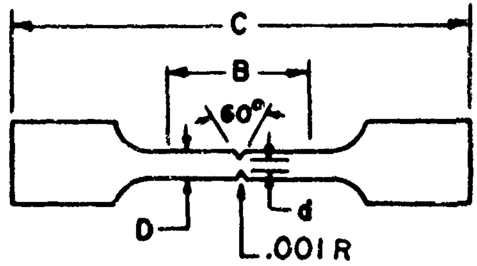
*Ti - 0.01
**O - 0.172, H - 0.0156, N - 0.007

Testing Procedures

Smooth and notched tension specimens of the sizes shown in Table II were tested. One specimen was tested for each size used. The smooth tension specimens were tested at 0.005 inch/inch/minute to 0.2

TABLE II. Dimensions (in inches) of Test Specimens Utilized





A	B	C
0.113	0.40	1-5/8
0.160	0.64	2-1/4
0.252	1.00	3
0.357	1.40	3-1/2
0.505	2.00	4-1/2
1.130	4.00	16-1/4
1.600	6.40	20
2.520	10.00	24
3.570	14.00	28

B	C	d	D
0.64	2-1/4	0.113	0.160
1.00	3	0.160	0.225
1.40	3-1/2	0.252	0.357
2.00	4-1/2	0.357	0.505
2.75	16-1/4	0.505	0.714
6.40	20	1.130	1.600
10.00	24	1.600	2.250
14.00	28	2.520	3.570
20.00	34	3.570	5.050

percent offset, thence at 0.02 inch/minute platen speed to fracture. The notched specimens were tested at a platen speed of 0.002 inch/minute. Specimens, 0.505 inch in diameter and smaller, were tested in a 120,000-pound hydraulic testing machine, while the larger specimens were tested in a 2,400,000-pound hydraulic testing machine. In lieu of an extensometer for direct measurement of specimen strain on the smooth specimens, 1.13-inch and larger, load platen displacement curves were obtained by use of a microformer deflectometer placed under the moving platen of the testing machine.

Fracture Topography Measurements

The fractured surfaces of the 4340 steel specimens were examined at 10X and 20X, and the various zones of fracture configurations were measured with a stereoscopic microscope and a precision measuring engine which served as a stage. The measurement of each zone[10] (fibrous, radial and shear lip) was determined in terms of the radius or the lineal length along the radius of the tensile fracture. Fracture zone measurements were made on diameters at 90-degree intervals on all specimens.

TEST RESULTS

Mechanical Properties

The smooth and notched tensile properties of 7075-T6 aluminum 6Al-6V-2Sn titanium and 4340 steel are listed in Tables III and IV and plotted in Figures 1 through 7. The yield and tensile strengths of the material tested did not show any significant changes with bar diameter.

TABLE III. Smooth Tensile Properties

Material	Diameter (inches)	Area (inches)	Yield Strength at 0.2% (ksi)	Tensile Strength (ksi)	Elongation (%)	R.A. (%)
7075-T6 Aluminum	0.113	0.01	64.2	76.8	13.7	15.8
	0.160	0.02	61.5	74.75	12.5	15.1
	0.252	0.05	56.2	69.0	12.0	19.8
	0.357	0.10	61.5	75.2	16.4	21.6
	0.505	0.20	63.4	75.7	12.0	20.5
	1.130	1.00	60.0	72.5	-	17.7
	-	-	-	-	-	-
	2.520	5.00	59.2	72.4	10.0	14.7
	3.570	10.00	61.0	74.2	10.7	12.4
6Al-6V-2Sn Titanium	0.113	0.01	142.1	157.4	20.0	40.0
	0.160	0.02	130.0	146.5	19.1	44.4
	0.252	0.05	135.2	145.6	20.0	44.0
	0.357	0.10	140.2	148.5	18.6	43.2
	0.505	0.20	142.0	147.0	17.0	42.7
	1.130	1.00	126.0	138.5	14.4	33.5
	1.600	2.00	135.0	149.0	16.4	25.2
	2.520	5.00	-	142.6	10.0	31.4
4340 Steel	0.113	0.01	128.6	154.2	18.8	55.2
	0.160	0.02	128.4	155.3	15.0	48.4
	0.252	0.05	132.9	156.9	16.0	52.0
	0.357	0.10	128.0	152.8	17.9	52.1
	0.505	0.20	129.8	151.0	16.0	52.8
	1.600	1.00	130.0	147.0	8.1	47.2
	2.520	5.00	124.0	153.5	12.5	47.0

TABLE IV. Notched Tensile Properties

Material	Gross Diameter (inches)	NTS (ksi)	NTS/UTS	NTS/0.2% YS	K_{Ic}	K_t (Neuber)
7075-T6 Aluminum	0.160	92.0	1.25	1.51	15.2	10.7
	0.225	101.25	1.37	1.66	19.6	12.4
	0.357	89.5	1.21	1.47	22.2	15.5
	0.505	89.8	1.21	1.47	26.4	18.3
	0.714	88.0	1.19	1.44	30.8	21.5
	1.600	70.0	0.95	1.15	36.8	31.6
	2.250	55.0	0.745	0.90	34.2	37.0
	3.570	42.5	0.57	0.69	33.3	48.8
	5.050	58.3	0.79	0.96	54.2	55.4
6Al-6V-2SN Titanium	0.160	225.8	1.53	1.64	37.4	10.7
	0.225	220.0	1.50	1.60	42.5	12.4
	0.357	210.0	1.43	1.53	52.0	15.5
	0.505	190.0	1.29	1.38	55.8	18.3
	0.714	179.0	1.22	1.30	62.6	21.5
	1.600	150.0	1.02	1.09	79.0	31.6
	2.250	123.5	0.84	0.90	77.0	37.0
	3.570	101.7	0.69	0.74	79.6	48.8
4340 Steel	0.160	229.5	1.50	1.78	38.0	10.7
	0.225	242.5	1.58	1.88	46.7	12.4
	0.357	227.0	1.48	1.76	56.3	15.5
	0.505	209.8	1.37	1.63	61.6	18.3
	0.714	218.0	1.42	1.69	76.3	21.5
	1.600	198.5	1.30	1.54	104.5	31.6
	2.250	206.0	1.35	1.60	128.0	37.0
	3.570	179.5	1.17	1.39	141.0	48.8
	5.050	176.0	1.15	1.37	163.5	55.4

The ductility, however, as plotted in Figure 1, generally decreased with increasing bar diameter, and the reduction of area values for specimens larger than 0.505 inch decreased more abruptly than the elongation values.

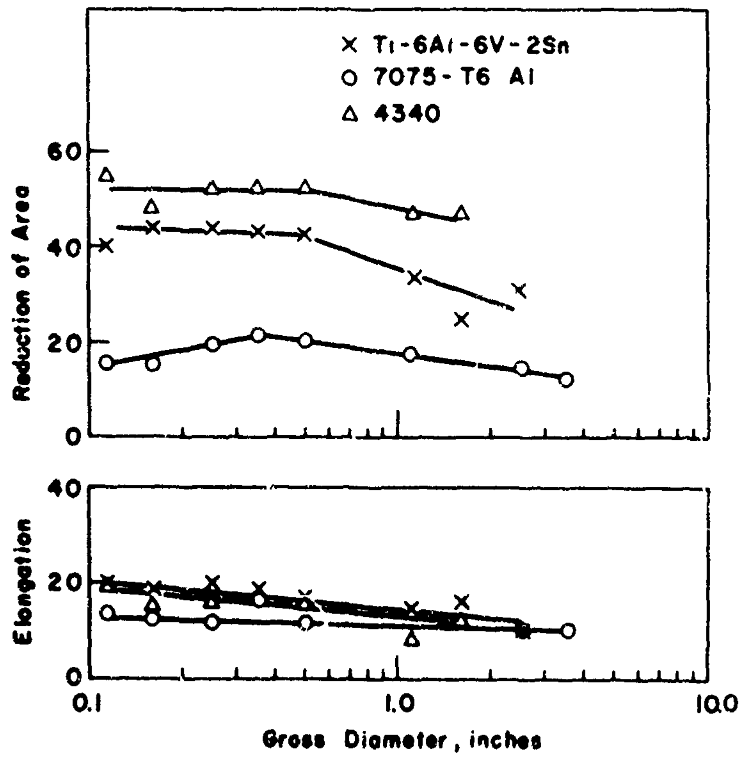


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Figure 1. REDUCTION OF AREA AND ELONGATION VERSUS SECTION SIZE

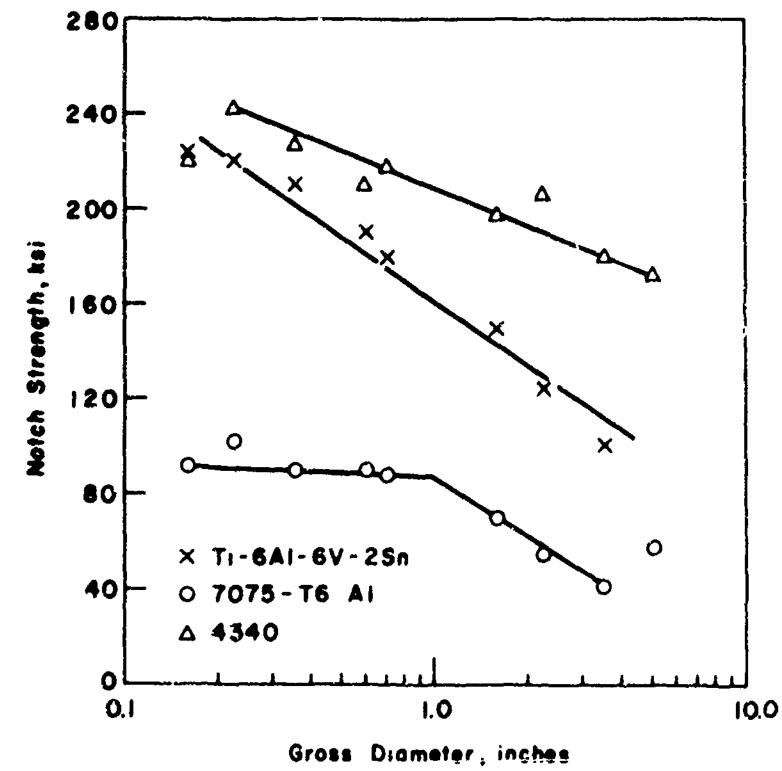

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Figure 2. NOTCH STRENGTH VERSUS SECTION SIZE

The notch strength of the 4340 steel plotted in Figure 2 decreases with increased bar diameter, reflecting size effects and increasing stress concentration, together with decreasing stress gradient. The decrease in notch strength of the 4340 steel tempered at 1000 F does not agree with recently published data by Klier et al[11] which showed no change in notch strength with increasing section size from 0.3 to 1.5 inches. The probable cause of this difference is the test section length of the Klier specimens, which were not changed proportionately with increased section size (1.00 inch for the 0.3-inch-diameter specimens and 1.5 inches for the 1.5-inch-diameter specimens). The notch strength of the 7075-T6 aluminum generally remained constant with increased bar diameter up to 0.505 inch. Beyond this size, the notch strength decreased markedly to a low value of 42 ksi at the 3.57-inch size. The notch strength of the 5.05-inch specimen, however, was approximately 16 ksi higher than the 3.57-inch specimen. This increase in notch strength could not be resolved by a hardness survey. The notch strength of the 6Al-6V-2Sn titanium alloy decreased from 226 ksi for the 0.160-inch specimen to 102 ksi for the 3.57-inch specimen. The notch/yield strength ratios plotted in Figure 3 generally follow the same trend as the notch strength plotted in Figure 2. Notch/yield strength ratios below 1.0 were obtained with 7075-T6 aluminum and 6Al-6V-2Sn titanium specimens larger than 1.60-inch diameter.

It has been suggested[7] that cylindrical, sharply notched specimens can be used to determine plane section fracture toughness, K_{Ic}, properties of materials. This technique is suitable if the material being evaluated is brittle. In the case where materials

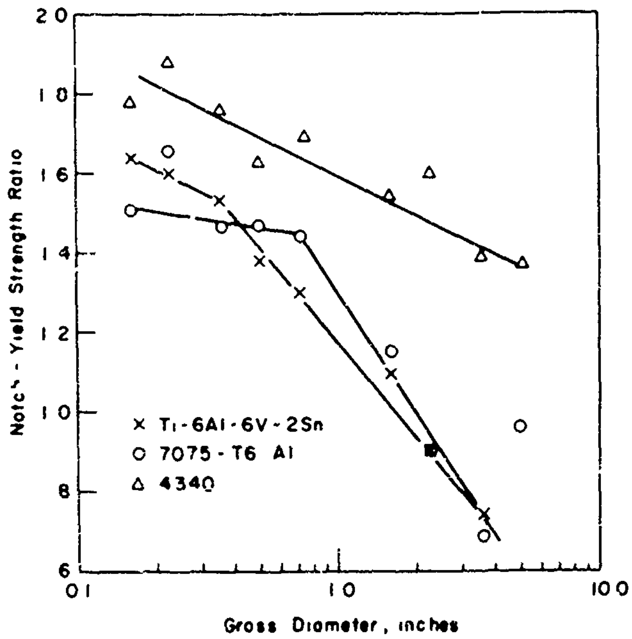

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Figure 3. NOTCH-YIELD STRENGTH RATIO VERSUS SECTION SIZE

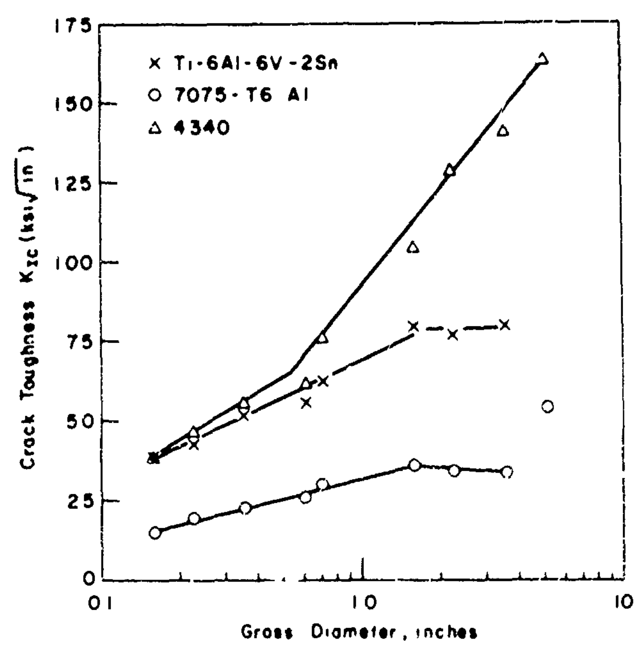

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Figure 4. CRACK TOUGHNESS (K_{Ic}) VERSUS SECTION SIZE

may be moderately tough, it is necessary to test fairly large specimens. This is illustrated for the crack toughness data of 4340 steel shown in Figure 4, where even at the 5.05-inch specimen diameter the notch yield strength ratio was 1.37, considerably higher than the 1.10 required for valid K_{Ic} determinations. On the other hand, the lower toughness 7075-T6 aluminum and 6Al-6V-2Sn titanium meet the requirements at the 1.60-inch section size and K_{Ic} values of 36.8 ksi $\sqrt{in.}$ and 79 ksi $\sqrt{in.}$ are obtained for the aluminum and titanium alloys. Reference to Figure 3 shows that notch yield strength ratios 1.09 and 1.15 were obtained for the aluminum and titanium at the 1.60-inch section size. Wundt-type summary plots of the notch strength of 7076-T6 aluminum, 6Al-6V-2Sn titanium, and 4340 steel as a function of section size are shown in Figures 5, 6, and 7 with K_{Ic} as the parameter. Yield and tensile data are also included in the plots.

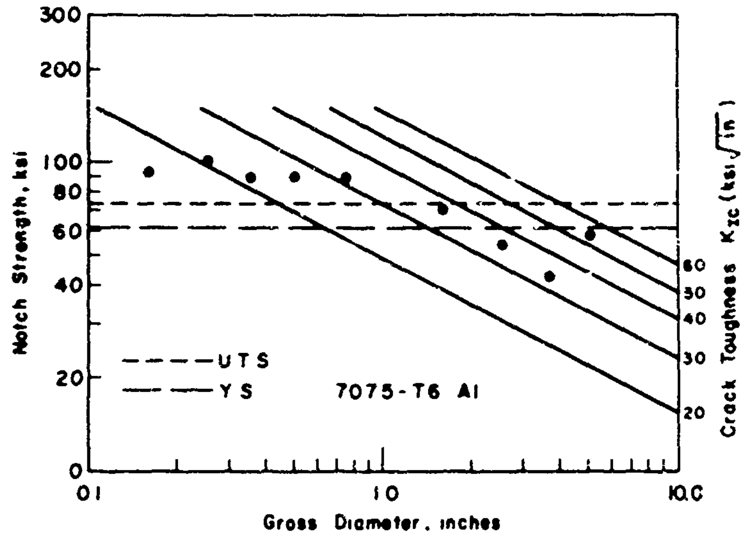

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Figure 5. NOTCH STRENGTH VERSUS SECTION SIZE OF 7075-T6 Al WITH K_{Ic} AS THE PARAMETER

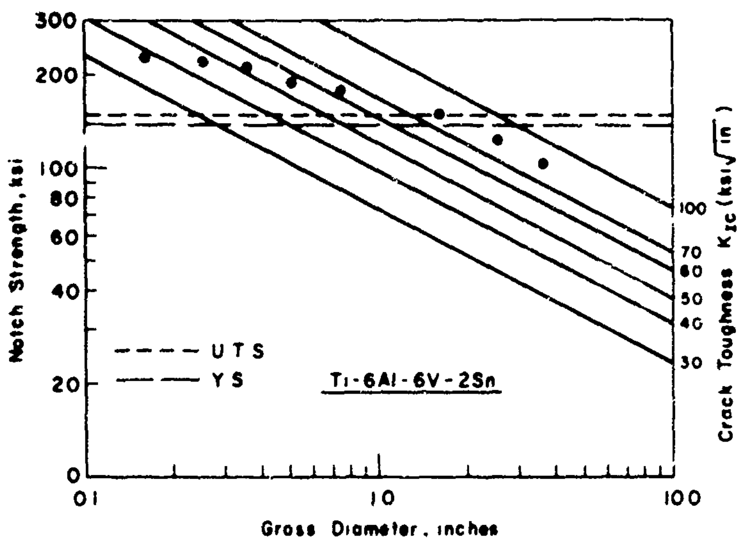

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Figure 6. NOTCH STRENGTH VERSUS SECTION SIZE OF Ti-6Al-6V-2Sn WITH K_{Ic} AS THE PARAMETER

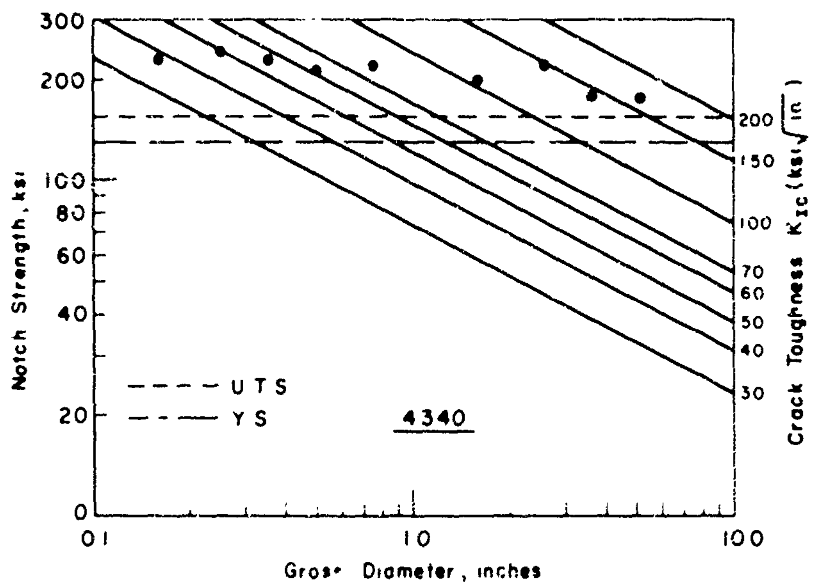

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Figure 7. NOTCH STRENGTH VERSUS SECTION SIZE OF AISI 4340 WITH K_{Ic} AS THE PARAMETER

Fracture Topography

Fracture of the smooth specimens of 4340 steel initiated at an inclusion or void and propagated toward the periphery. This process resulted in three zones of configurations which progressed from the origin in the following sequence:

1. Fibrous zone, composed of circumferential ridges indicative of slow crack growth;
2. Radial zone, comprised of radial markings which appear to be shear elements indicative of accelerated crack propagation; and
3. Shear lip zone, containing a smooth shear element near the termination of the fracture.

Measurements of these zones on the fractured specimens indicated that the size of each zone increased with increasing section size, but the rate of increase for each respective zone differed. The various zone sizes are tabulated in Table V and illustrated as a function of section size in Figure 8. It is noted that both the fibrous zone and the shear lip zone increased with increasing bar diameter. It is also noted that the fibrous zone is approximately one-half the shear lip width. It is worth while mentioning, however, that the increase in fibrous zone is actually a decrease in percent fibrous fracture of the fracture surface. The increase in shear lip size from 0.013 inch for the 0.113-inch specimen to 0.123 inch for the 2.52-inch specimen does not agree with recently published data[13] which showed no change in shear lip size of specimens of 4340 steel from 0.357-inch diameter to 3.57-inch diameter.

TABLE V. Lineal Zone Size (inches)

Material	Smooth				Notched		
	Specimen Diameter	Fibrous	Radial	Shear Lip	Shank Diameter	Fibrous	Radial
7075-T6 Aluminum	3.570	-	-	0.242			
	2.520	-	-	0.154			
	1.600	-	-	-			
	1.130	-	-	0.098			
	0.505	-	-	0.123			
	0.357	-	-	0.065			
	0.252	-	-	0.028			
	0.160	-	-	0.014			
	0.113	-	-	0.044			
6Al-6V-2Sn Titanium	2.520	-	-	0.177			
	1.600	-	-	0.136			
	1.130	-	-	0.099			
	0.505	-	-	0.045			
	0.357	-	-	0.032			
	0.252	-	-	0.024			
	0.160	-	-	0.016			
	0.113	-	-	0.018			
4340 Steel	3.570	-	-	-	5.050	0.023	1.761
	2.520	0.056	0.727	0.123	3.570	0.020	1.231
	1.600	0.059	0.445	0.081	2.250	0.040	0.756
	1.130	-	-	-	1.600	0.022	0.542
	0.505	0.015	0.131	0.031	0.714	0.029	0.221
	0.357	0.0'2	0.086	0.029	0.505	0.034	0.139
	0.252	0.015	0.050	0.023	0.357	0.022	0.101
	0.160	0.015	0.021	0.017	0.225	0.015	0.061
	0.113	0.005	0.019	0.013	0.160	0.022	0.032

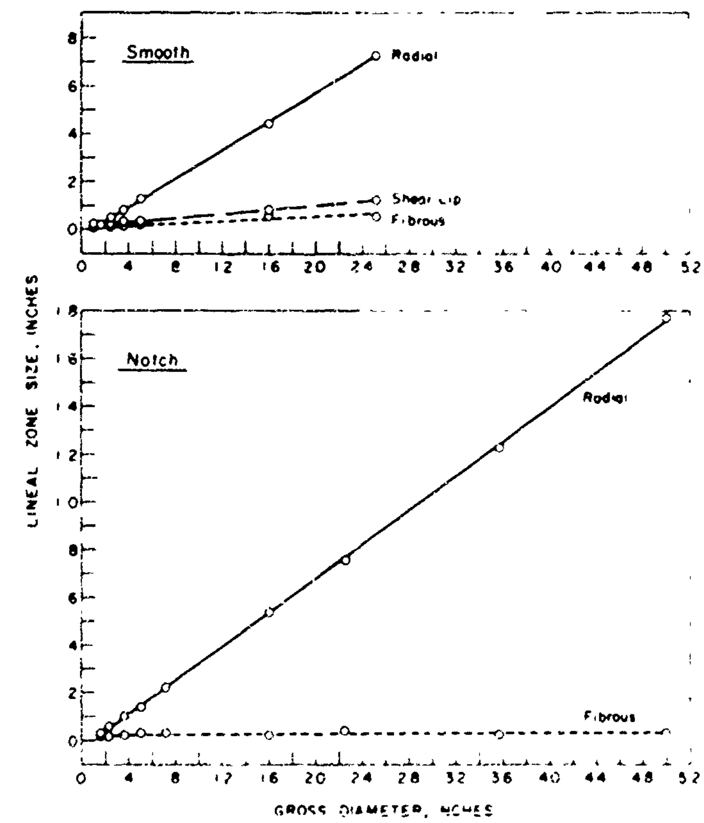

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Figure 8. LINEAL ZONE SIZE VERSUS SECTION SIZE OF AISI 4340

Crack initiation in the notched bar of 4340 steel occurred at the notch and progressed circumferentially toward the interior of the specimen. Although the fibrous and radial zones of the notch specimens are in opposite locations to those of the smooth specimens, the sequence in both cases is identical with respect to the direction of crack propagation. These characteristics are illustrated in Figure 9A. The fibrous zone of the notch specimen generally remained constant with increasing section size, increasing stress concentration factor, and decreasing stress gradient, which reflects the maximum slow crack growth possible for this material condition. The texture of the radial zone of the fracture surface of both notched and smooth specimens is rougher at the area of final separation reflecting an increased rate of crack propagation.[14] Evidence of this is shown in Figure 10, a composite photograph of the fractured surfaces of the largest smooth and notched specimens used in this investigation.

The internal final area of separation of the notched specimens as evidenced by this investigation does not agree with the description advanced by Klier and Weiss.[11] The assumption advanced by these authors suggested the area of rough texture to be a second nucleus and that propagation is in a direction opposite to that inferred by the interpretation of this study. Since any concept of crack propagation must at present be based on vestigial evidence, individual interpretations may be somewhat controversial.

Discrimination of the fibrous and radial zones, previously described for the steel specimens, was difficult for the fractured titanium specimens, therefore only the shear lip measurements are included in Table V. The shear lip increased in size with increasing specimen diameter. The fracture topography of the notched specimens of this alloy can be described as the three stages illustrated in Figure 9b. The initial stage extended completely around the circumference of the fractured surface on both the 0.160-inch and 0.357-inch diameter specimens. Thus for the smaller specimens the initial stage appeared as a ring, but on the larger specimen, this stage was crescent- or horseshoe-shaped. The second stage was more rapid in propagation and started as an arc at a location approximately 180 degrees from the origin and advanced through the specimen, converging toward the origin until the final area of separation was reached. This process resulted in the second stage having the general shape of a fan. The direction of propagation can be ascertained by following the increasing roughness of the markings in this second stage.

The fracture topography of the 7075-T6 aluminum alloy was similar to that described for the titanium alloy. Measurements determined that the shear lip also increased in size with increasing specimen diameter. The first stage of fracture of the notched specimens of this alloy also appeared as a ring and extended completely around the circumference of the fractured surface at specimen diameters less than 1.60 inch. For larger sizes this stage receded circumferentially and acquired the shape of a horseshoe, but never attained the crescent shape observed on the fractured specimens of 6Al-6V-2Sn titanium.

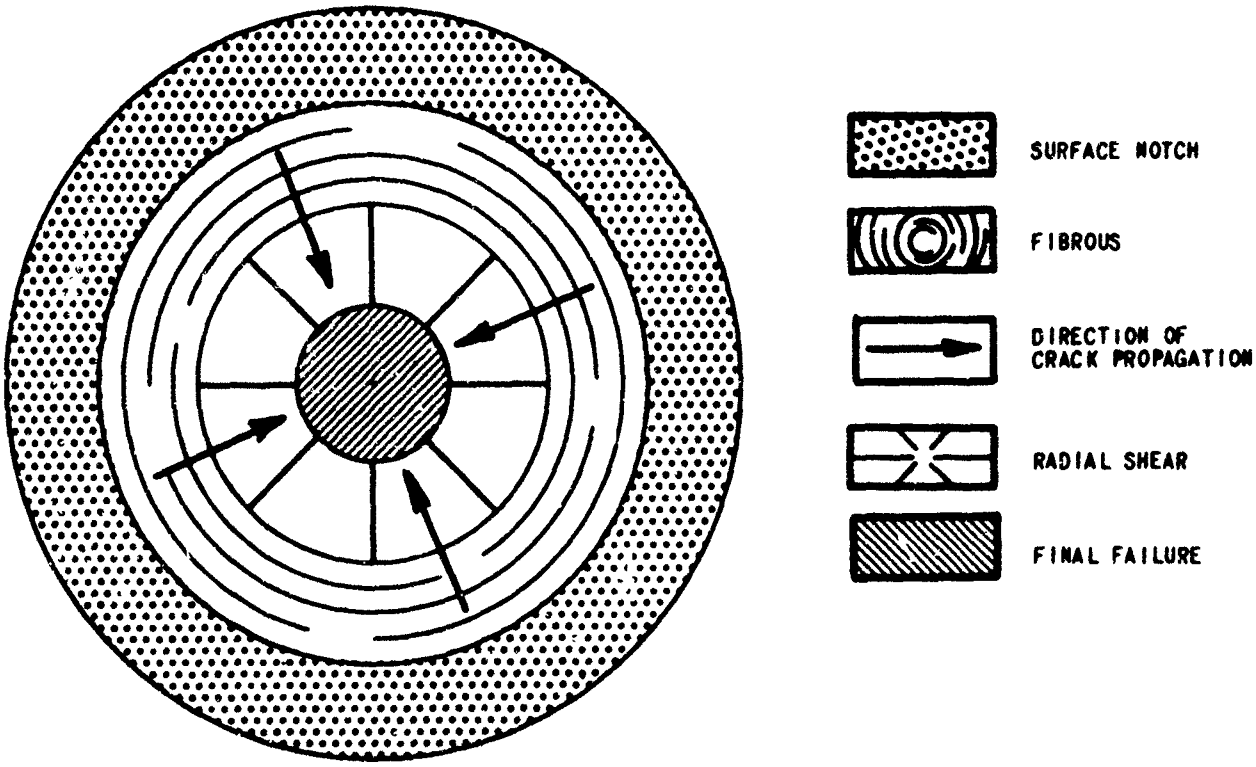

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Figure 9A. FRACTURE SURFACE MARKINGS IN NOTCH ROUND SPECIMENS OF AISI 4340 STEEL

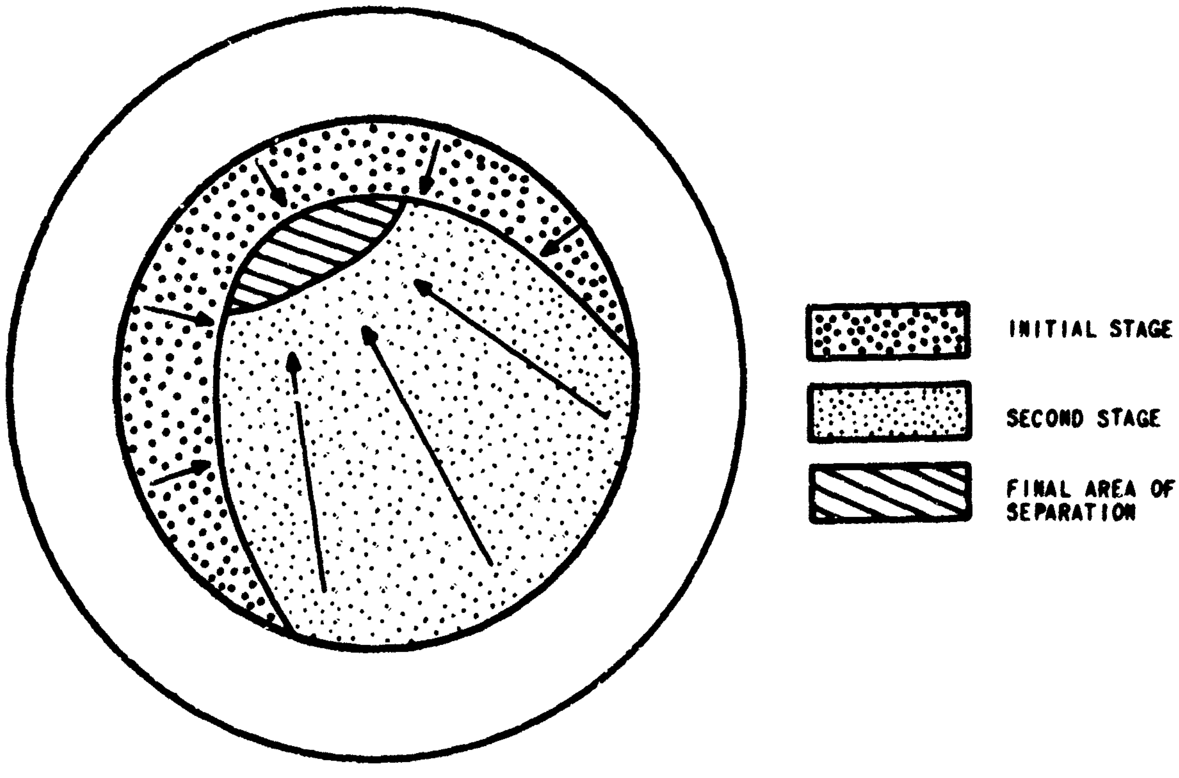

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Figure 9B. VARIOUS FRACTURE STAGES OF NOTCHED SPECIMENS OF 7075-T6 ALUMINUM AND 6Al-6V-2Sn TITANIUM

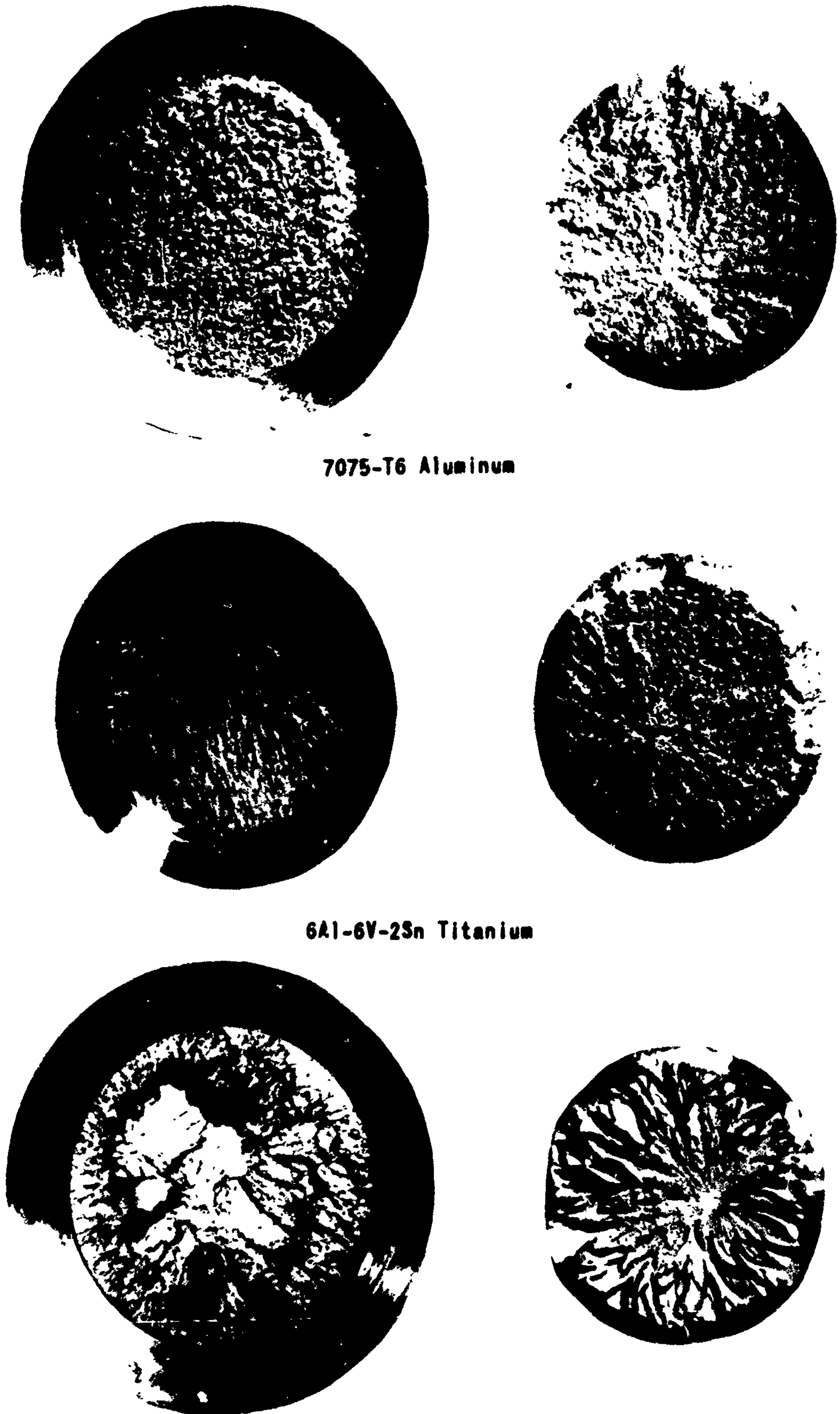

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Figure 10. TENSILE FRACTURE TOPOGRAPHY OF LARGEST SMOOTH AND NOTCHED SPECIMENS TESTED

SUMMARY

Mechanical properties of 7075-T6 aluminum, 6Al-6V-2Sn titanium and 4340 steel have been determined on smooth specimens from 0.113 inch to 3.57 inches in diameter and on notched specimens from 0.160 inch to 5.05 inches in diameter. Crack toughness values and some fracture topography measurements were also obtained.

The yield and tensile strengths of the materials tested did not show any significant changes with bar diameter. The notch strength and notch/yield strength ratios of all materials decreased with increasing bar diameter. Notch/yield strength ratios below 1.0 were obtained with specimens of 7075-T6 aluminum and 6Al-6V-2Sn titanium larger than 1.60 inch in diameter. The crack toughness K_{Ic} of 4340 steel could not be determined as there was considerable plastic yielding even at the 5.05-inch size. However, K_{Ic} values of 36.8 ksi $\sqrt{in.}$ and 79 ksi $\sqrt{in.}$ were obtained for the 7075-T6 aluminum and 6Al-6V-2Sn titanium alloys at the 1.60-inch specimen diameter.

Fracture of the smooth specimens initiated in the interior of the specimens and propagated toward the periphery, while fracture of the notched specimens initiated at the base of the notch and propagated toward the interior of the specimen.

Fracture zone measurements of the smooth specimens showed that the shear lip size increased with specimen diameter for all materials tested. The fibrous zone of the smooth 4340 steel specimens also increased with specimen diameter.

The fibrous zone of the notched 4340 steel specimen did not change appreciably with increasing specimen diameter, reflecting the maximum slow crack growth for this material condition.

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