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TECHNICAL NOTE
D-111

FATIGUE STRENGTHS OF AIRCRAFT MATERIALS

AXIAL-LOAD FATIGUE TESTS ON EDGE-NOTCHED SHEET SPECIMENS OF 2024-T3 AND 7075-T6 ALUMINUM ALLOYS AND OF SAE 4130 STEEL WITH NOTCH RADII OF 0.004 AND 0.070 INCH

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SUMMARY

The present report gives results of axial-load fatigue tests on notched specimens of three sheet materials: 2024-T3 and 7075-T6 aluminum alloys and normalized SAE 4130 steel.

Two edge-notched specimens were designed and tested, each having a theoretical stress-concentration factor $K_t = 4.0$. The radii of the notches were 0.004 and 0.070 inch. Tests of these specimens were run at two levels of nominal mean stress: 0 and 20,000 psi.

Results of these studies extended information previously reported on tests of specimens with varying notch severity. They afford data on the variation of fatigue-strength reduction with notch radius and on the potential usefulness of Neuber's technical stress-concentration factor K_n.

INTRODUCTION

During the approximate period 1947 to 1952 a broad program was carried out at Battelle Memorial Institute under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics and at the Langley Aeronautical Laboratory of the NACA that involved a study of the fatigue strengths of metals commonly used in aircraft construction. A major objective of the investigation was to obtain basic data on the fatigue strengths of three sheet materials: 2024-T3 and 7075-T6 aluminum alloys, and normalized SAE 4130 steel.

From the Battelle studies five previous reports (refs. 1 to 5) present the following data:

(1) Results of fatigue tests on unnotched sheet specimens (ref. 1)

(2) Results of fatigue tests on sheet specimens notched with three different types of notches, including edge notches, having $K_t = 2.0$, and on sheet specimens notched with two different types of notches, including edge notches, having $K_t = 4.0$ (ref. 2)

(3) Results of fatigue tests on sheet specimens with severe edge notches having $K_t = 5.0$ (ref. 3)

(4) Results of fatigue tests on sheet specimens with mild edge notches having $K_t = 1.5$ (ref. 4)

(5) Results of fatigue tests on unnotched specimens of 2024-T3 and 7076-T6 aluminum alloys as determined in several laboratories (ref. 5)

During the last year of the program a study was made of the effect of notch root radius on the fatigue behavior of the three materials. The specimens contained edge notches with $K_t = 4.0$ (specimens with two edge notches having different root radii were tested). The data from this study have not been previously published; therefore, to provide complete documentation of the broad program, the present report has been prepared.

The authors wish to thank Mr. Paul Kuhn, then a member of the Structures Research Division of the NACA Langley Aeronautical Laboratory, for his help and guidance during this investigation.

SYMBOLS

A — Neuber parameter, dimension of "building blocks" of material, in.

K_f — fatigue notch factor, ratio of maximum stress for unnotched specimen to nominal maximum stress for notched specimen at same load ratio R and lifetime

K_n — Neuber technical stress-concentration factor

K_t — theoretical stress-concentration factor

R load ratio, ratio of minimum stress to maximum stress in cycle

r notch radius

EXPERIMENTAL PROCEDURE

The experimental procedure in the work described in this report was
W generally the same as that in the previous investigations of unnotched
1 and notched specimens (refs. 1 to 4). In this program fatigue tests on
2 the notched specimens were run at only two levels of mean stress: 0 and
5 20,000 psi. The materials used were supplied from selected stock retained
for this purpose at the Langley Aeronautical Laboratory of the NACA. Coupons were cut from 0.090-inch-thick commercial sheets of 2024-T3 and 7075-T6 aluminum alloys and from 0.075-inch-thick commercial sheets of normalized SAE 4130 steel. Static-strength properties of notched and unnotched sheet are given in table 1.

Figure 1 is a dimensional drawing of the notched specimens used in the fatigue tests. The dimensions of the notch were chosen, on the basis of available information, to give $K_t = 4.0$. Each notch was cut with tools especially designed to produce the contour desired. Machining cuts were successively lighter, so that the depth of the last two cuts was about 0.0005 inch. The notched specimens were electropolished after machining; 0.0008 inch of material was removed by this technique. All specimens were examined by a microscope comparator after electropolishing; the dimensions shown in figure 1 are representative of those measured during such examination. Figures 2 and 3 are photographs of typical fractures obtained with these specimens.

Fatigue tests were run on Krouse direct repeated-stress testing machines at speeds in the range 1,100 to 1,500 cycles per minute. A description of these machines is given in reference 1. The estimated precision of load measurement and maintenance was about ±3 percent in tension-tension tests. In tests involving reversal of load, sheet specimens were restrained from buckling by the use of guide plates. The estimation of precision of loading was indirect in these cases; it is believed that error in load value in reversed-load testing did not exceed ±5 percent.

RESULTS OF FATIGUE TESTS

Results of axial-load fatigue tests on edge-notched specimens with $K_t = 4.0$ and $r = 0.004$ and 0.070 inch are given in table 2. The results are plotted in the form of S-N curves in figure 4. All stress values reported are nominal net-area stresses.

DISCUSSION

The results of the study shown in figure 4 have been summarized in tabular form (see table 3). Data from reference 2 for specimens with an edge notch with $K_t = 4.0$ and $r = 0.057$ inch are included in the table. There is evidence from the tabulated data that for a particular lifetime at a specified mean stress the fatigue strength decreases as the notch radius increases. The magnitude of the decrease differs from material to material.

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The fatigue-strength reduction factors for various lifetimes and mean stresses have been calculated for the above data and are listed in table 4. In the calculations, the following definition for K_f has been used:

$$K_f = \frac{\text{Maximum stress for unnotched specimen}}{\text{Nominal maximum stress for notched specimens at same load ratio } R \text{ and lifetime}}$$

(This definition for K_f has been used in refs. 2, 3, and 4. Load ratio R is the ratio of the minimum stress to the maximum stress of the stress cycle.) Stress values for unnotched specimens of the two aluminum alloys tested at $R = -1.0$ were taken from table IV of reference 6. The remaining unnotched-specimen data came from references 1 and 5. The values in table 4 indicate the following trends:

(1) For a specified nominal mean stress, K_f is usually greatest at the longest lifetime and decreases with decreasing lifetime or increasing maximum stress.

(2) For a specified lifetime, K_f does not seem to vary in a consistent manner with mean stress.

(3) In comparing K_f values of notches with $r = 0.004$ inch with those of notches with either $r = 0.057$ or 0.070 inch it appears that, for a specified lifetime and nominal mean stress, K_f generally increases with increasing notch radius. This trend is somewhat less certain for the aluminum alloys when K_f values of notches having $r = 0.057$ and 0.070 inch are compared.

The trend noted in item (3) would be expected on the basis of the Neuber expression concerning the effect of notch radius on the ideal stress-concentration factor (ref. 7). Neuber ascribes this effect to the breakdown of the theory of elasticity as notch radius approaches elementary crystal dimensions. The large changes in stress over extremely short distances in this case make more noticeable the effects of anisotropy and inhomogeneity. Neuber's treatment presupposes that, in the limiting condition where notch radius is zero (such as a V-notch), a material is composed of "building blocks" of finite dimension A, which he considered a constant for each material. Using this concept, he developed the following expression for a technical or "practical" stress-concentration factor K_n for notches with zero flank angle in terms of the ideal factor K_t, notch radius r, and parameter A:

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$$K_n = 1 + \frac{K_t - 1}{1 + \sqrt{\frac{A}{r}}}$$

Examination of this function shows that for constant values of K_t, K_n will decrease as r decreases.

Landers and Hardrath have indicated in reference 6 that for hole-notched specimens of 2024-T3 and 7075-T6 aluminum alloys the parameter $A = 0.02$ inch provides good agreement between K_n and K_f, the fatigue notch factor. Experimental values of K_f at 10^7 cycles and zero mean stress for 2024-T3 and 7075-T6 aluminum alloys and SAE 4130 steel are plotted in figure 5. Curves of the above expression for K_n, with $K_t = 4.0$ and $A = 0.02$ inch, are also shown in the figure. The K_f values for the two aluminum alloys in figures 5(a) and 5(b) show good agreement with K_n obtained using $A = 0.02$ inch. However, K_f values for steel are quite different from the K_n curve when $A = 0.02$ inch is used. Adopting the approach for steel of Kuhn and Hardrath (ref. 8), a value of the Neuber parameter $A = 0.0027$ inch was selected. The broken curve in figure 5(c) computed with $A = 0.0027$ inch shows that there is a fit of the steel data with the Neuber concept comparable to that observed for the aluminum alloys.

To pursue this somewhat further, K_f values obtained during the broad program on edge-notched specimens for other values of K_t are plotted in figure 6 for the three materials along with the values obtained in the present investigation. The K_f values in the figures are not quite the same as those reported in references 1 to 4; instead, they have been recomputed in accordance with the revised unnotched-specimen data of reference 5. The solid lines in each figure represent K_n as a function of root radius r for the four notch severities studied. For the two aluminum alloys (figs. 6(a) and 6(b)), the Neuber parameter was $A = 0.02$ inch; whereas, for steel, $A = 0.0027$ inch.

From these figures it would appear that K_n can indicate the approximate trend of K_f for the range of notch severities and root radii investigated for the three materials. For each of the materials it appears that K_n is somewhat greater than K_f for small values of K_t. At high values of K_t, K_n is somewhat smaller than K_f. Thus, K_n would provide a conservative estimate of K_f for small values of K_t and an unconservative estimate for high values of K_t.

CONCLUSIONS

The following conclusions appear warranted from this study of axial-load fatigue tests on notched sheet specimens of 2024-T3 and 7075-T6 aluminum alloy and SAE 4130 steel:

1. For a constant value of theoretical stress-concentration factor K_t, namely, $K_t = 4.0$, the fatigue notch factor K_f generally increases as the root radius increases.

2. These fatigue notch factors for specimens with edge notches with $K_t = 4.0$ are in reasonable agreement with K_n values for notches with zero flank angle computed from

$$K_n = 1 + \frac{K_t - 1}{1 + \sqrt{\frac{A}{r}}}$$

where r is the notch radius and the parameter $A = 0.02$ inch for the two aluminum alloys and 0.0027 inch for normalized SAE 4130 steel.

3. In considering all data assembled during the broad program on specimens with edge-type notches with various values of K_t and root radius, the Neuber factor K_n was shown to be helpful in predicting the trend of the data using the above values of A. There was evidence,

however, that at high values of K_t the predictions would be unconservative, whereas, at low values of K_t, the predictions would be conservative.

Battelle Memorial Institute,
Columbus, Ohio, August 8, 1958.

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TABLE 1.- STATIC-STRENGTH PROPERTIES OF SHEET SPECIMENS

[Data for unnotched specimens taken from reference 1]

Specimen type	Average tensile properties			Comparative yield strength, psi
	Elongation in 2 in., percent	Yield strength for 0.2-percent offset, psi	Ultimate strength, psi	
2024-T3 aluminum alloy				
Unnotched	18.2	54,000	73,000	44,500
Notched (K_t = 4.0)				
r = 0.004 in.	----	------	61,500	------
r = 0.070 in.	----	------	69,500	------
7075-T6 aluminum alloy				
Unnotched	11.4	76,000	82,500	74,000
Notched (K_t = 4.0)				
r = 0.004 in.	----	------	76,200	------
r = 0.070 in.	----	------	80,000	------
Normalized SAE 4130 steel				
Unnotched	14.3	98,500	117,000	86,000
Notched (K_t = 4.0)				
r = 0.004 in.	----	------	117,000	------
r = 0.070 in.	----	------	126,800	------

TABLE 2.- AXIAL-LOAD FATIGUE TEST RESULTS FOR EDGE-NOTCHED SHEET SPECIMENS WITH $K_t = 4.0$

(a) 2024-T3 aluminum alloy

Specimen	Nominal maximum stress, psi	Lifetime, cycles	Remarks (a)
r = 0.004 in.			
	Nominal mean stress, 0 psi		
A24S1-5	32,500	8,000	
A21S1-5	26,000	30,000	
A19S1-6	21,000	104,000	
A19S1-5	16,000	379,000	
A20S1-5	14,000	760,000	
A18S1-6	12,500	1,096,000	
A24S1-4	11,250	1,287,000	
A25S1-5	11,250	11,390,000	
A25S1-4	10,700	11,226,000+	Did not fail
A25S1-3	10,000	11,281,000+	Do.
A20S1-6	10,000	13,420,000+	Do.
	Nominal mean stress, 20,000 psi		
A25S1-1	38,000	10,000	
A24S1-6	35,000	18,000	
A21S1-6	32,000	38,500	
A22S1-2	28,500	114,000	
A22S1-1	25,000	523,000	
A23S1-3	22,500	10,475,000+	Did not fail
r = 0.070 in.			
	Nominal mean stress, 0 psi		
A20S1-3	20,000	5,000	
A19S1-3	17,500	8,000	
A20S1-4	15,000	25,000	
A18S1-2	12,500	56,000	
A23S1-1	10,000	427,000	
A20S1-1	10,000	520,000	
A23S1-2	8,000	2,045,000	
A19S1-1	8,000	3,100,000	
A21S1-2	7,500	3,656,000	
A22S1-6	7,000	2,487,000	
A22S1-5	7,000	5,200,000	
A21S1-3	6,500	17,599,000+	Did not fail
	Nominal mean stress, 20,000 psi		
A20S1-2	35,000	8,000	
A21S1-4	31,250	16,800	
A18S1-1	27,500	66,000	
A19S1-2	25,000	201,000	
A22S1-4	24,000	10,183,000+	Did not fail
A22S1-3	23,750	13,223,000+	Do.
A19S1-4	22,500	11,570,000+	Do.

[a]Unless otherwise noted, specimen failed at notch root.

TABLE 2.- AXIAL-LOAD FATIGUE TEST RESULTS FOR EDGE-NOTCHED

SHEET SPECIMENS WITH $K_t = 4.0$ - Continued

(b) 7075-T6 aluminum alloy

Specimen	Nominal maximum stress, psi	Lifetime, cycles	Remarks (a)
r = 0.004 in.			
	Nominal mean stress, 0 psi		
B28S1-2	35,000	11,000	
B24S1-5	26,000	31,500	
B22S1-6	22,000	93,000	
B23S1-6	17,000	217,000	
B22S1-5	14,000	353,000	
B21S1-6	13,000	482,000	
B23S1-5	10,000	3,375,000	
B24S1-6	9,000	5,045,000	
B28S1-4	8,700	11,299,000+	Did not fail
B27S1-2	8,000	14,874,000+	Do.
	Nominal mean stress, 20,000 psi		
B28S1-3	40,000	6,300	
B27S1-3	36,000	16,000	
B25S1-5	32,000	26,000	
B26S1-4	28,500	39,500	
B26S1-5	26,750	149,000	
B25S1-6	25,000	2,441,000	
B26S1-6	23,000	14,390,000+	Did not fail
r = 0.070 in.			
	Nominal mean stress, 0 psi		
B24S1-4	20,000	6,000	
B22S1-4	15,000	26,000	
B23S1-2	12,500	75,500	
B26S1-2	10,000	257,000	
B22S1-2	10,000	307,000	
B23S1-1	8,500	275,000	
B26S1-1	8,000	1,920,000	
B25S1-3	8,000	2,690,000	
B21S1-1	7,000	5,290,000	
B25S1-4	7,000	15,715,000+	Did not fail
B25S1-1	6,500	11,878,000+	Do.
B21S1-2	6,000	16,758,000+	Do.
	Nominal mean stress, 20,000 psi		
B24S1-1	35,000	5,000	
B24S1-3	31,250	9,700	
B22S1-1	27,500	23,000	
B23S1-4	26,000	35,000	
B21S1-4	23,750	438,000	
B23S1-3	23,125	1,540,000	
B24S1-2	23,000	10,506,000+	Did not fail
B21S1-3	22,500	16,490,000+	Do.

[a]Unless otherwise noted, specimen failed at notch root.

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TABLE 2.- AXIAL-LOAD FATIGUE TEST RESULTS FOR EDGE-NOTCHED SHEET SPECIMENS WITH K_t = 4.0 - Concluded

(c) Normalized SAE 4130 steel

Specimen	Nominal maximum stress, psi	Lifetime, cycles	Remarks (a)
r = 0.004 in.			
	Nominal mean stress, 0 psi		
C22N1-6	43,750	124,000	
C21M-6	40,000	215,000	
C23N1-5	35,000	379,000	
C25N1-6	30,000	919,000	
C26N1-4	25,000	1,546,000	
C27N1-1	22,500	3,193,000	
C26N1-5	20,000	14,394,000+	Did not fail
	Nominal mean stress, 20,000 psi		
C24N1-6	65,000	46,000	
C21M1-5	60,000	71,000	
C24N1-5	50,000	182,000	
C22N1-5	45,000	347,000	
C23N1-6	42,500	195,000	
C22N1-2	42,500	874,000	
C25N1-5	40,000	389,000	
C27N1-4	40,000	12,508,000+	Did not fail
C26N1-3	37,500	10,950,000+	Do.
r = 0.70 in.			
	Nominal mean stress, 0 psi		
C22N1-3	42,500	5,600	
C23N1-4	38,750	11,000	
C23N1-1	35,000	37,000	
C24N1-1	32,000	29,000	
C26N1-2	26,000	104,000	
C24N1-3	22,500	150,000	
C22N1-4	20,000	185,000	
C25N1-2	17,500	587,000	
C22N1-2	15,000	800,000	
C25N1-3	15,000	1,989,000	
C26N1-1	14,000	7,240,000	
C25N1-1	13,750	10,910,000+	Did not fail
C22N1-1	12,500	10,505,000+	Do.
	Nominal mean stress, 20,000 psi		
C24N1-4	57,500	9,800	
C24N1-2	50,000	24,000	
C21M1-4	39,000	74,000	
C21M1-1	33,000	297,000	
C25N1-4	32,000	1,064,000	
C21N1-3	32,000	11,368,000+	Did not fail

[a]Unless otherwise noted, specimen failed at notch root.

TABLE 3.- SUMMARY OF RESULTS OF AXIAL-LOAD FATIGUE TESTS

ON EDGE-NOTCHED SHEET SPECIMENS WITH $K_t = 4.0$

Nominal mean stress, psi	Notch radius, r, in.	Nominal maximum stress, psi, at lifetime, cycles, of -					
		10^4	5×10^4	10^5	5×10^5	10^6	10^7
2024-T3 aluminum alloy							
0	0.004	31.5×10^3	24.0×10^3	21.0×10^3	14.5×10^3	12.5×10^3	10.5×10^3
	[a].057	18.0	13.0	11.5	8.5	8.0	7.0
	.070	17.5	13.0	11.5	9.0	8.5	7.0
20×10^3	.004	37.5	31.0	28.5	25.5	24.5	23.0
	[a].057	32.0	27.0	25.0	25.0	24.0	24.0
	.070	33.5	27.5	26.5	24.5	24.0	23.5
7075-T6 aluminum alloy							
0	0.004	34.0×10^3	24.5×10^3	21.0×10^3	15.0×10^3	11.0×10^3	9.0×10^3
	[a].057	17.0	13.0	11.0	8.5	8.0	7.5
	.070	18.0	14.5	11.5	9.0	8.5	7.0
20×10^3	.004	38.5	29.0	27.5	26.0	25.5	24.0
	.057	31.0	25.0	24.0	23.0	23.0	23.0
	.070	31.5	26.0	25.0	24.0	23.5	23.0
Normalized SAE 4130 steel							
0	0.004	----------	----------	45.5×10^3	33.5×10^3	28.5×10^3	20.5×10^3
	[a].057	45.0×10^3	32.0×10^3	27.0	19.0	16.0	14.0
	.070	39.5	29.5	25.0	17.0	15.5	13.5
20×10^3	.004	----------	63.5	56.5	42.0	39.5	37.5
	[a].057	58.0	45.0	41.0	34.0	34.0	33.0
	.070	57.5	42.5	37.5	32.5	32.0	31.5

[a]Data for 0.057-in. notch radius taken from ref. 2.

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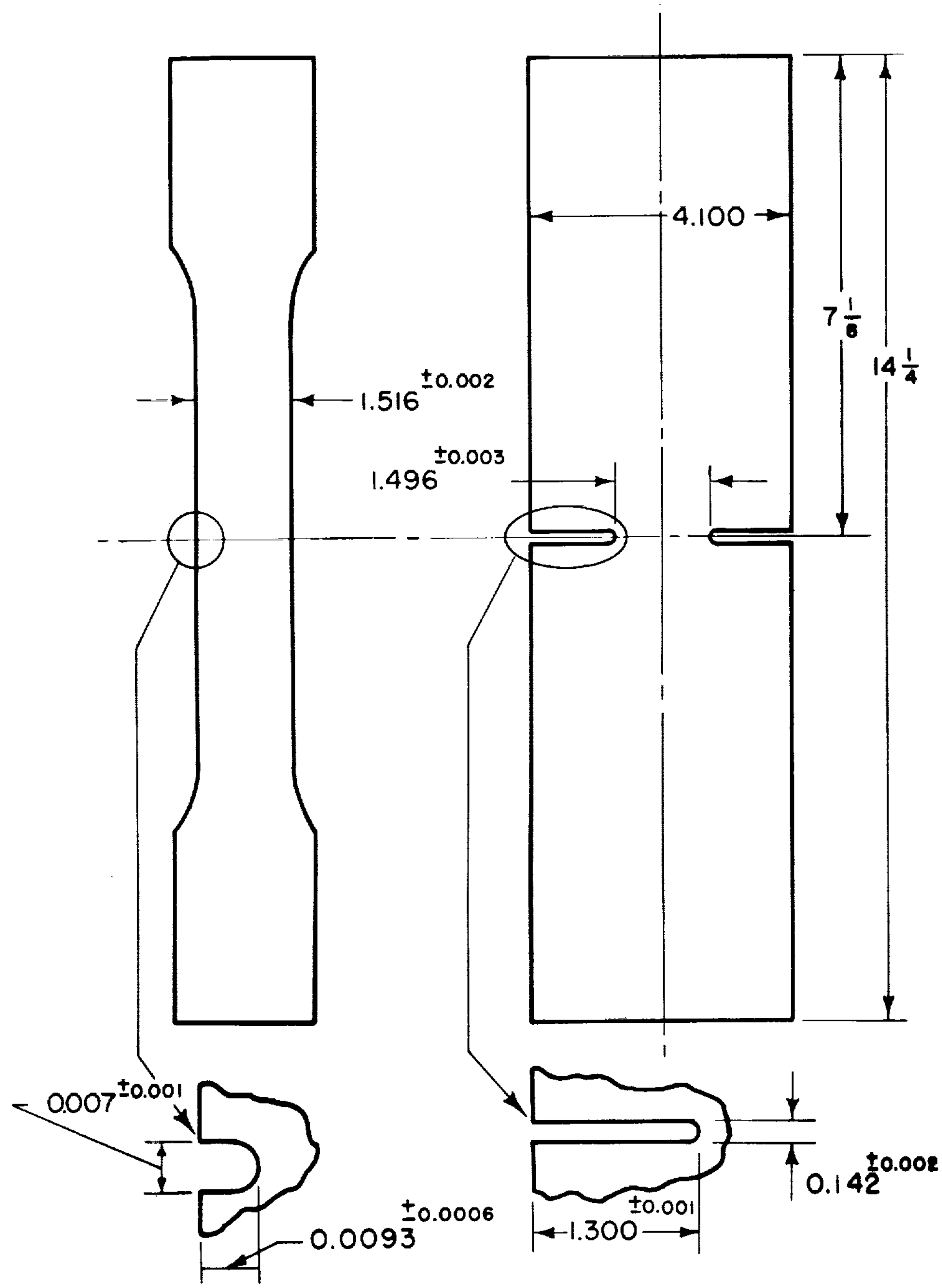
TABLE 4.- FATIGUE-STRENGTH REDUCTION FACTORS FOR EDGE-NOTCHED SHEET SPECIMENS WITH $K_t = 4.0$

Nominal mean stress, psi	Notch radius, r, in.	K_f at lifetime, cycles, of -			
		10^4	10^5	10^6	10^7
2024-T3 aluminum alloy					
0	0.004	1.70	1.70	2.00	2.00
	.057	3.00	3.15	3.15	3.00
	.070	3.10	3.15	2.95	3.00
20×10^3	.004	----	2.20	2.65	2.90
	.057	----	2.70	2.75	2.75
	.070	----	2.45	2.75	2.80
7075-T6 aluminum alloy					
0	0.004	1.60	1.70	2.25	2.35
	.057	3.15	3.25	3.10	2.80
	.070	3.00	3.15	2.95	3.00
20×10^3	.004	----	2.20	2.60	2.75
	.057	----	2.90	3.10	3.05
	.070	----	2.70	2.95	3.05
Normalized SAE 4130 steel					
0	0.004	----	1.45	1.80	2.35
	.057	1.30	2.40	3.25	3.40
	.070	1.30	2.60	3.35	3.55
20×10^3	.004	----	1.60	2.20	2.35
	.057	----	2.65	2.85	2.90
	.070	----	2.90	3.10	3.20



(a) Edge-notched specimen. (b) Notched specimen.

Figure 1.- Notch details of notched and edge-notched fatigue test specimens. $K_t = 4.0$.

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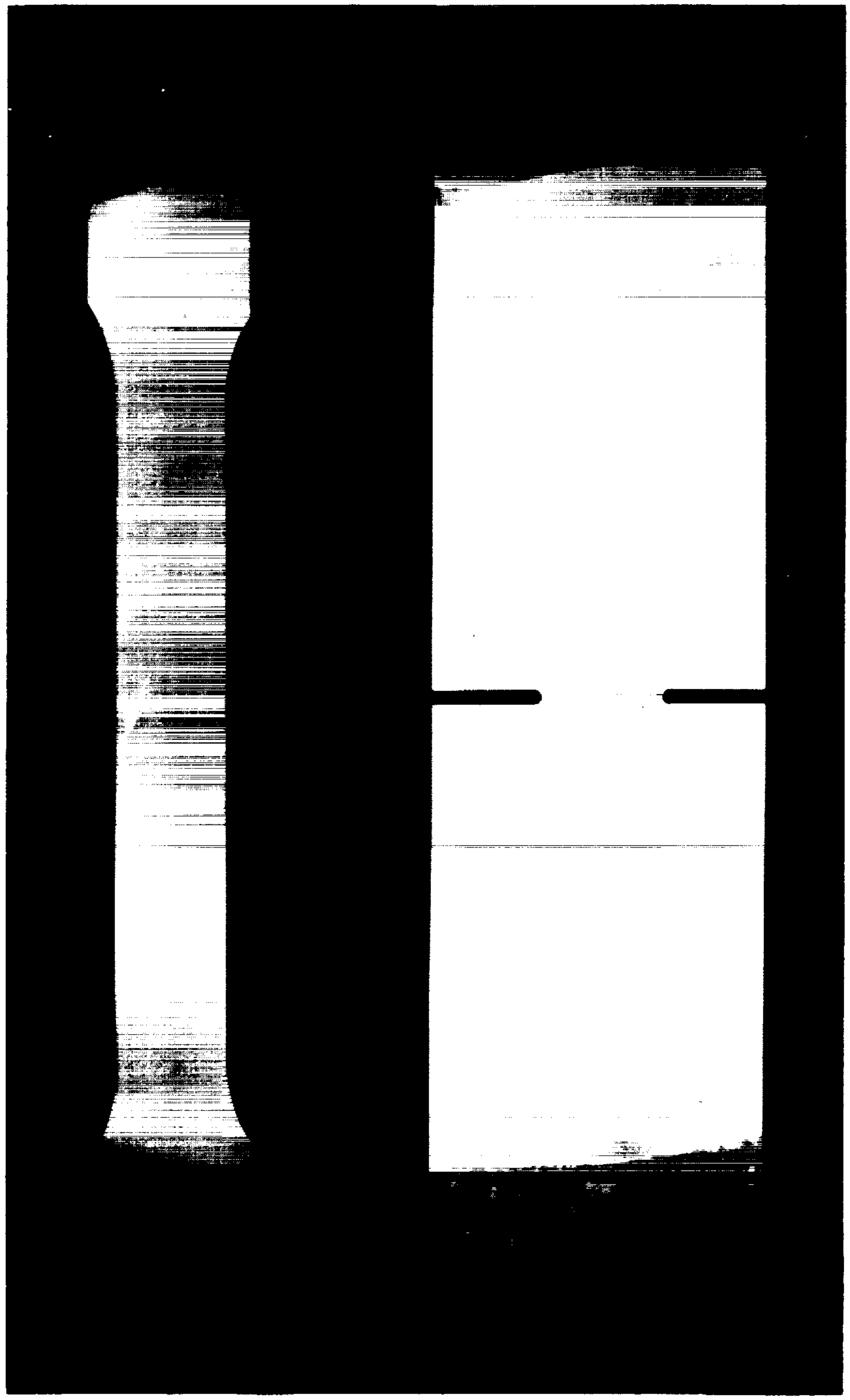
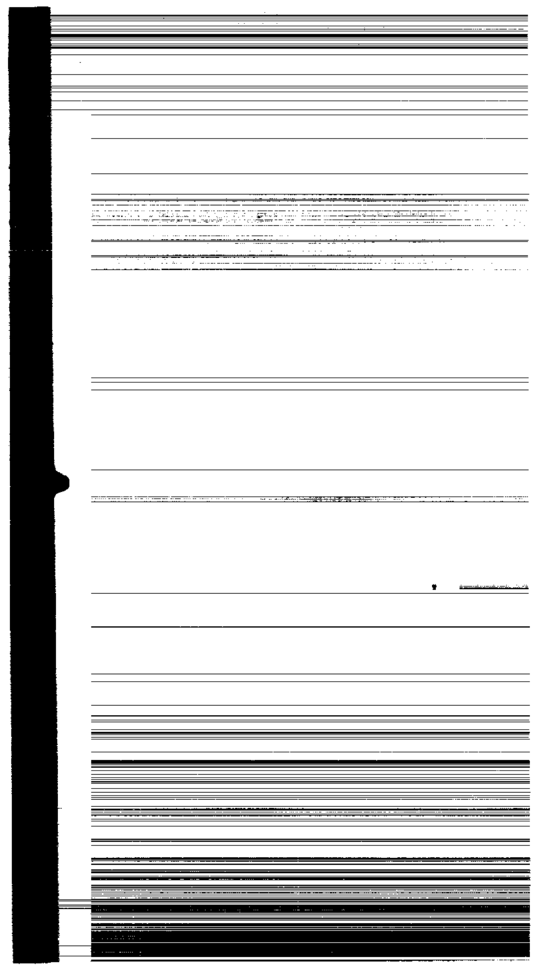


L-59-3030

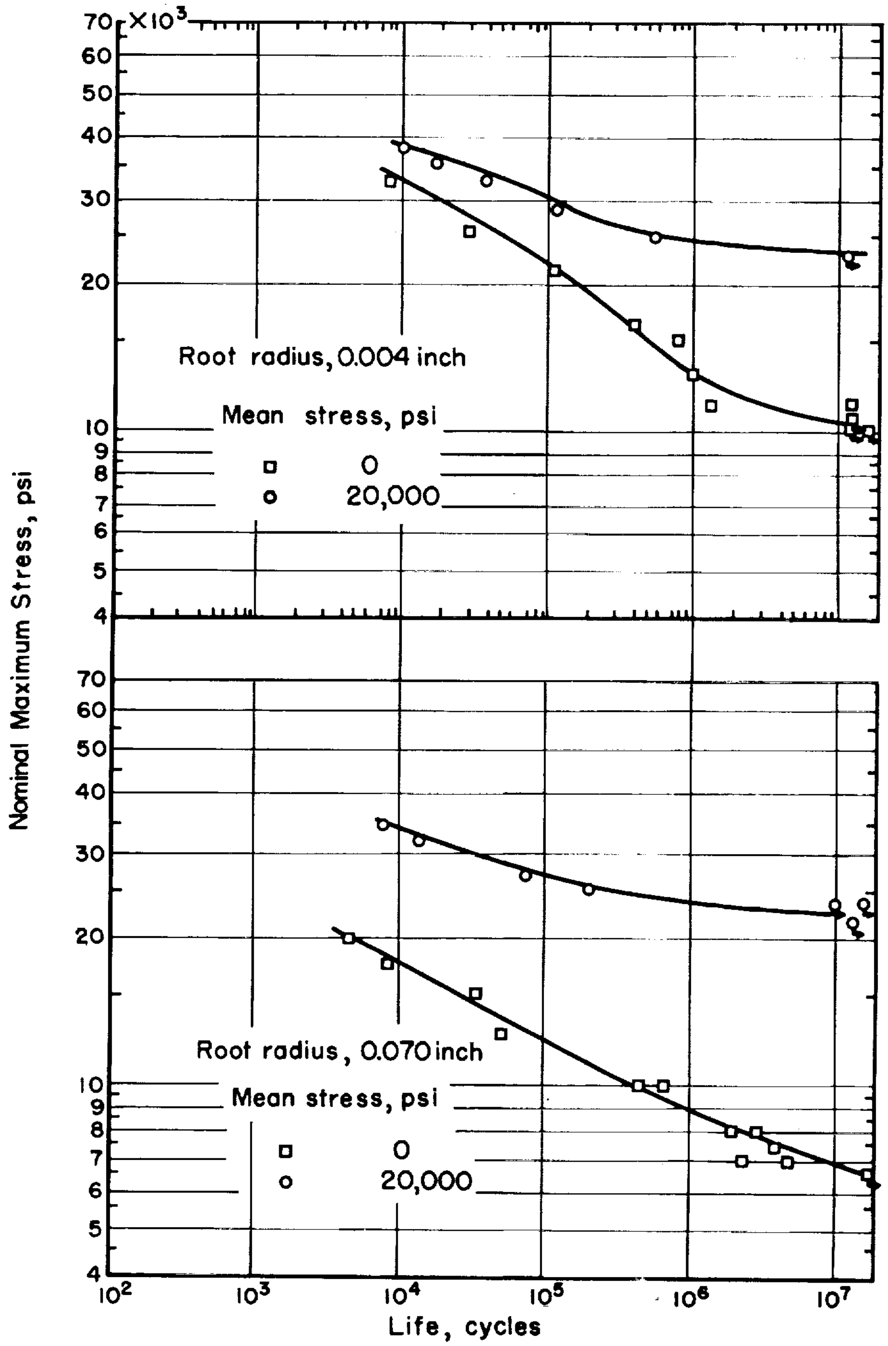
Figure 2.- Typical fatigue failures of notched specimens.



L-59-3031

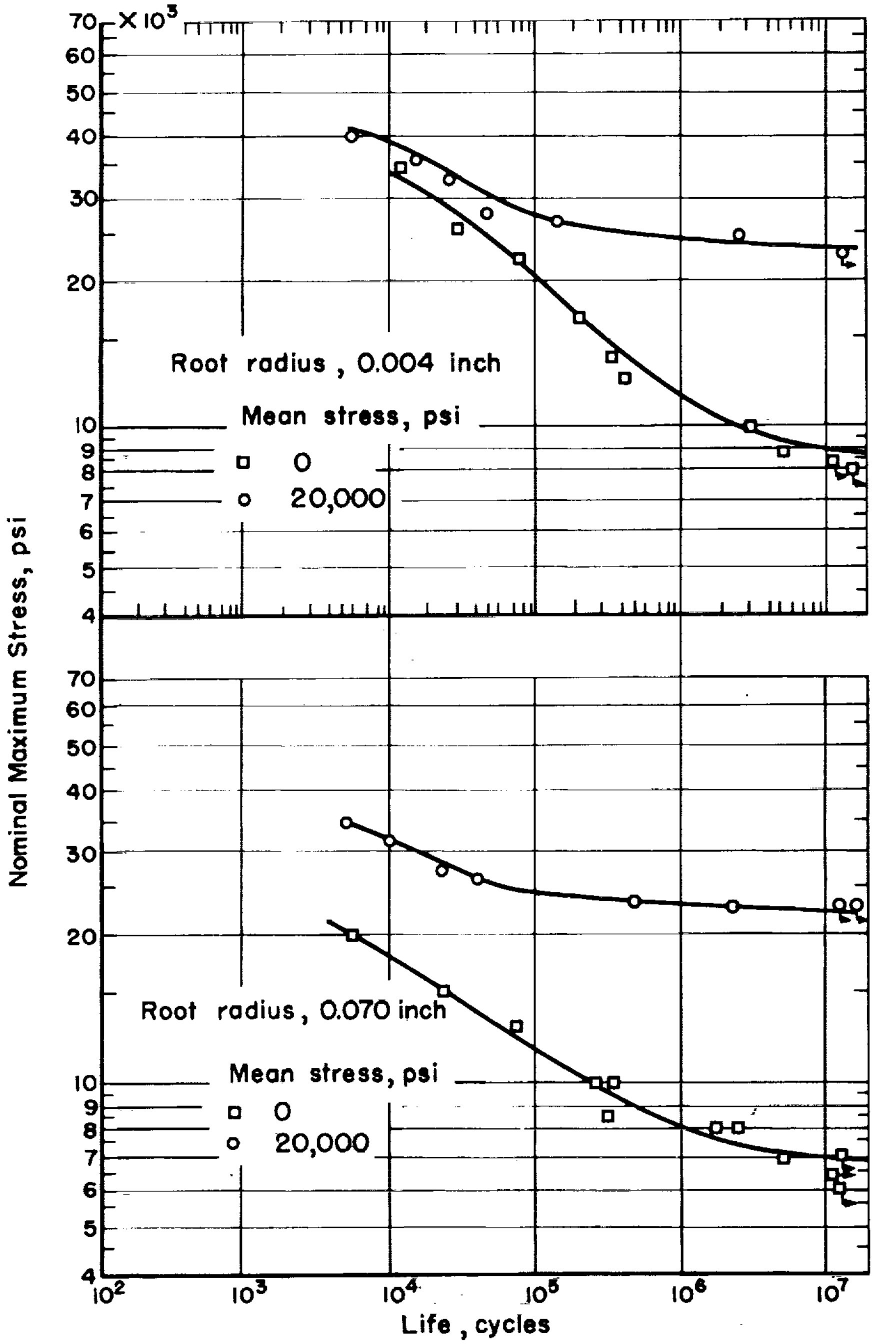
Figure 3.- Fatigue failure of edge-notched specimen. K_t = 4.0; root radius, 0.004 inch.

W-125



(a) 2024-T3 aluminum alloy.

Figure 4.- Results of axial-load fatigue tests on edge-notched sheet specimens. $K_t = 4.0$.

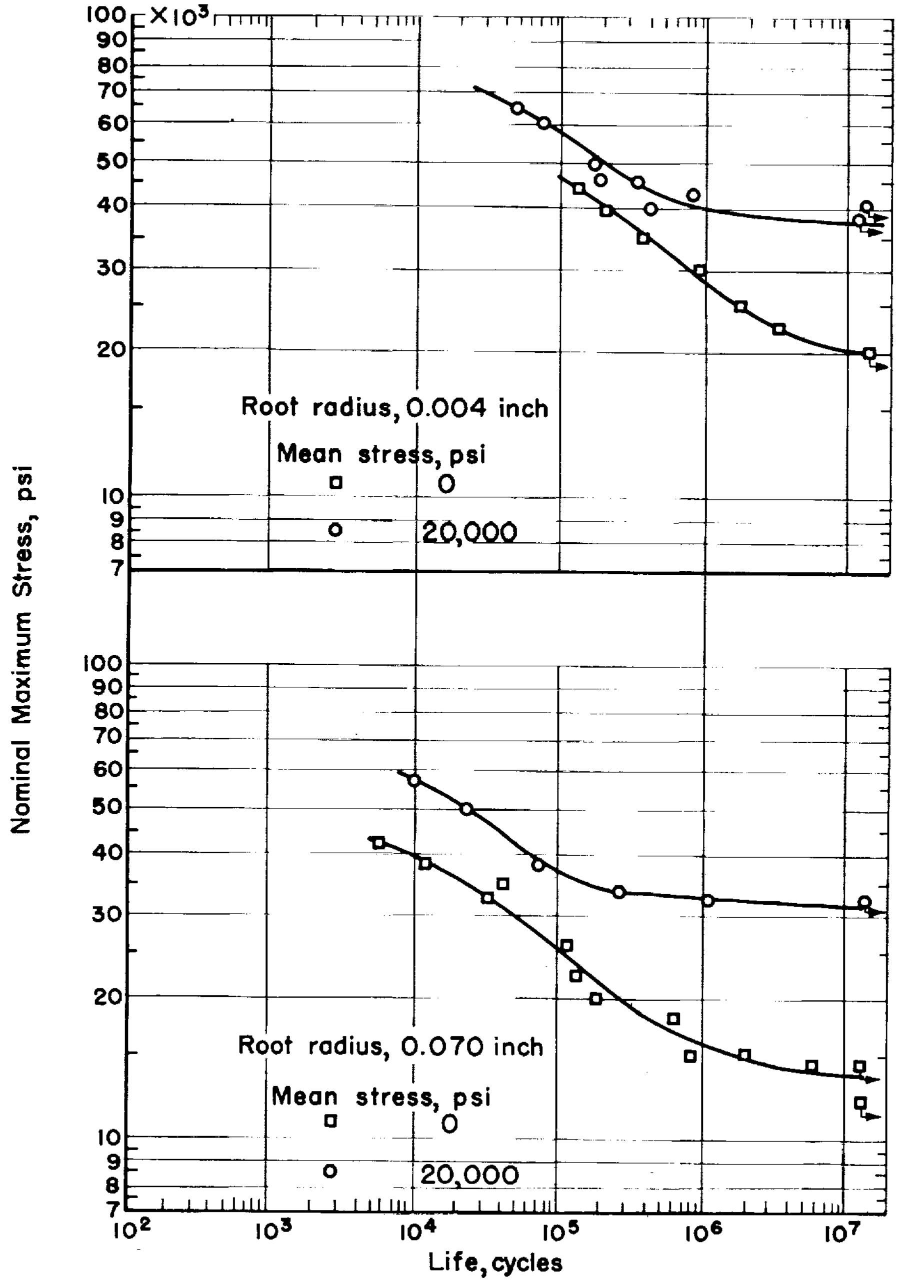


(b) 7075-T6 aluminum alloy.

Figure 4.- Continued.

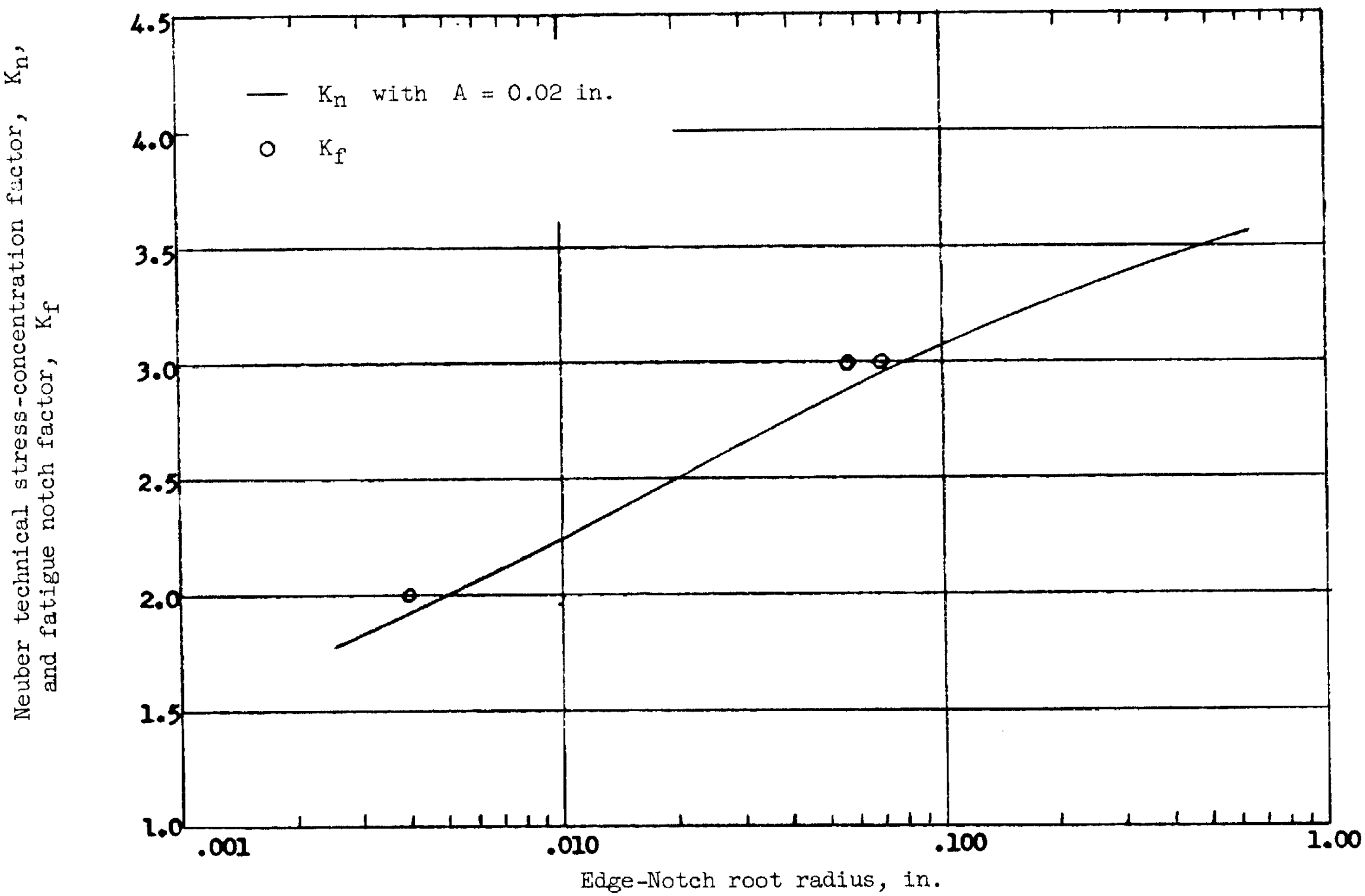
W-125

W-125



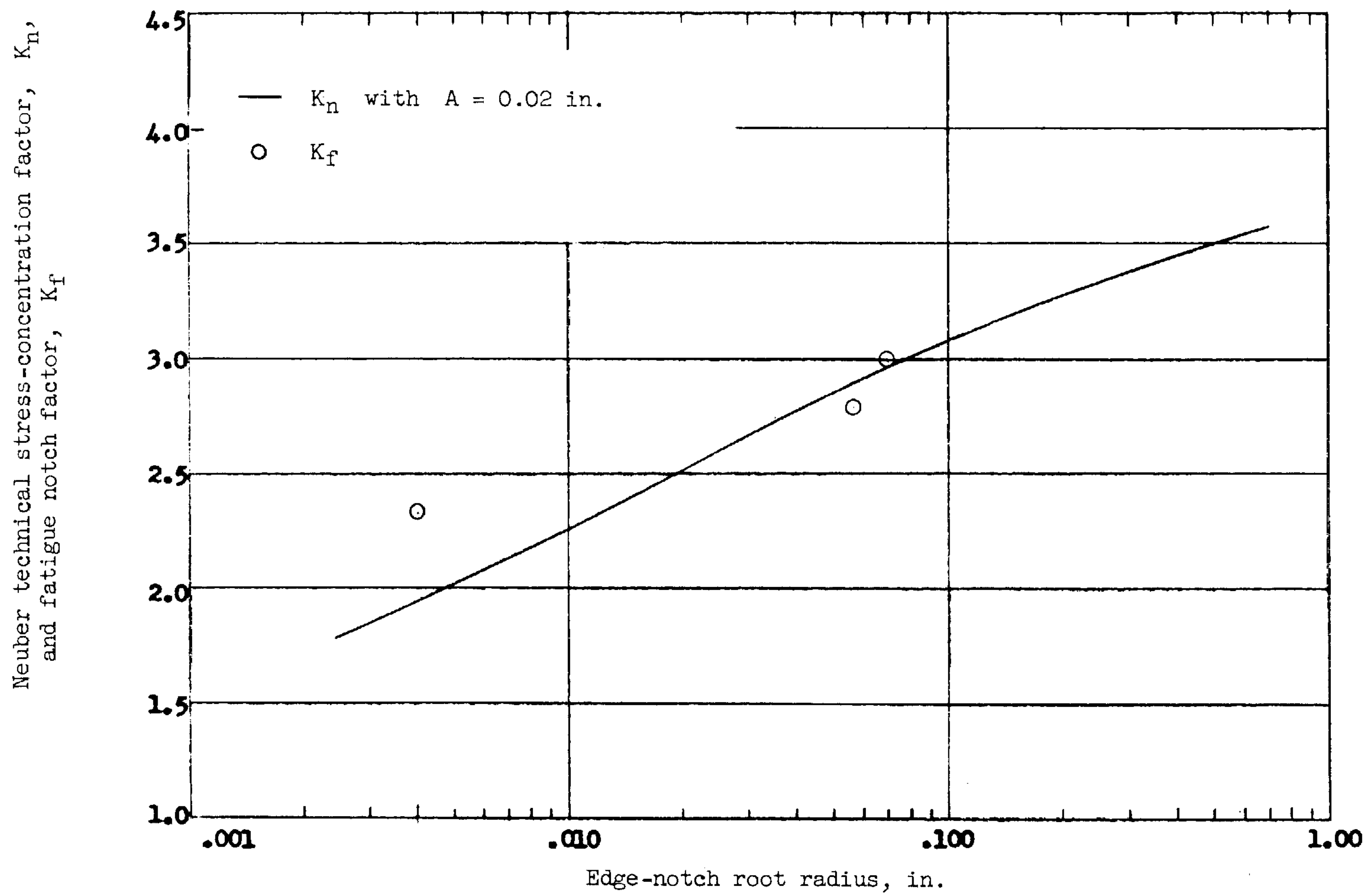
(c) Normalized SAE 4130 steel.

Figure 4.- Concluded.



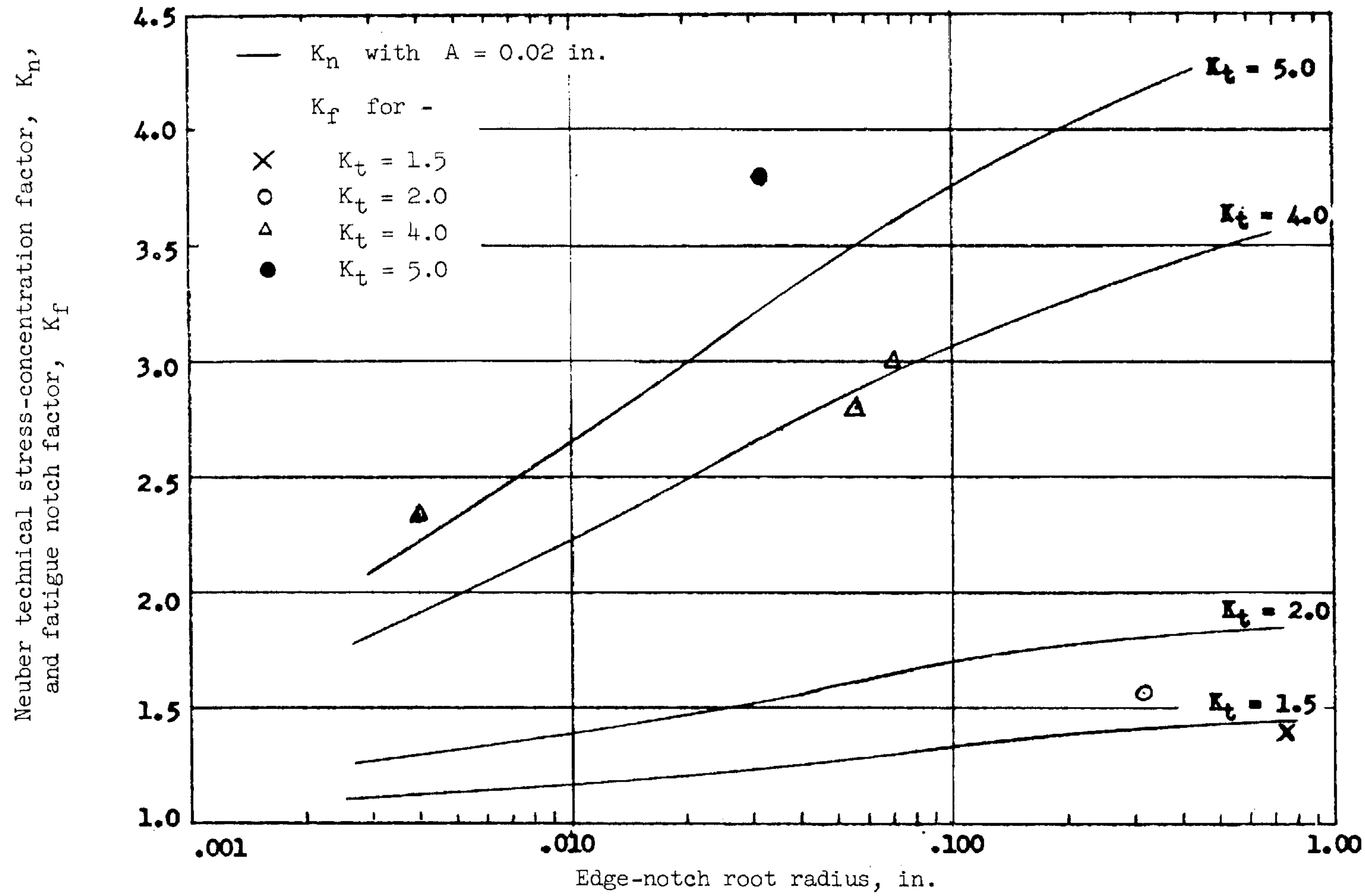
(a) 2024-T3 aluminum alloy.

Figure 5.- Comparison of K_f with K_n for specimens having edge notches of various root radii. $K_t = 4.0$; stress is reversed.



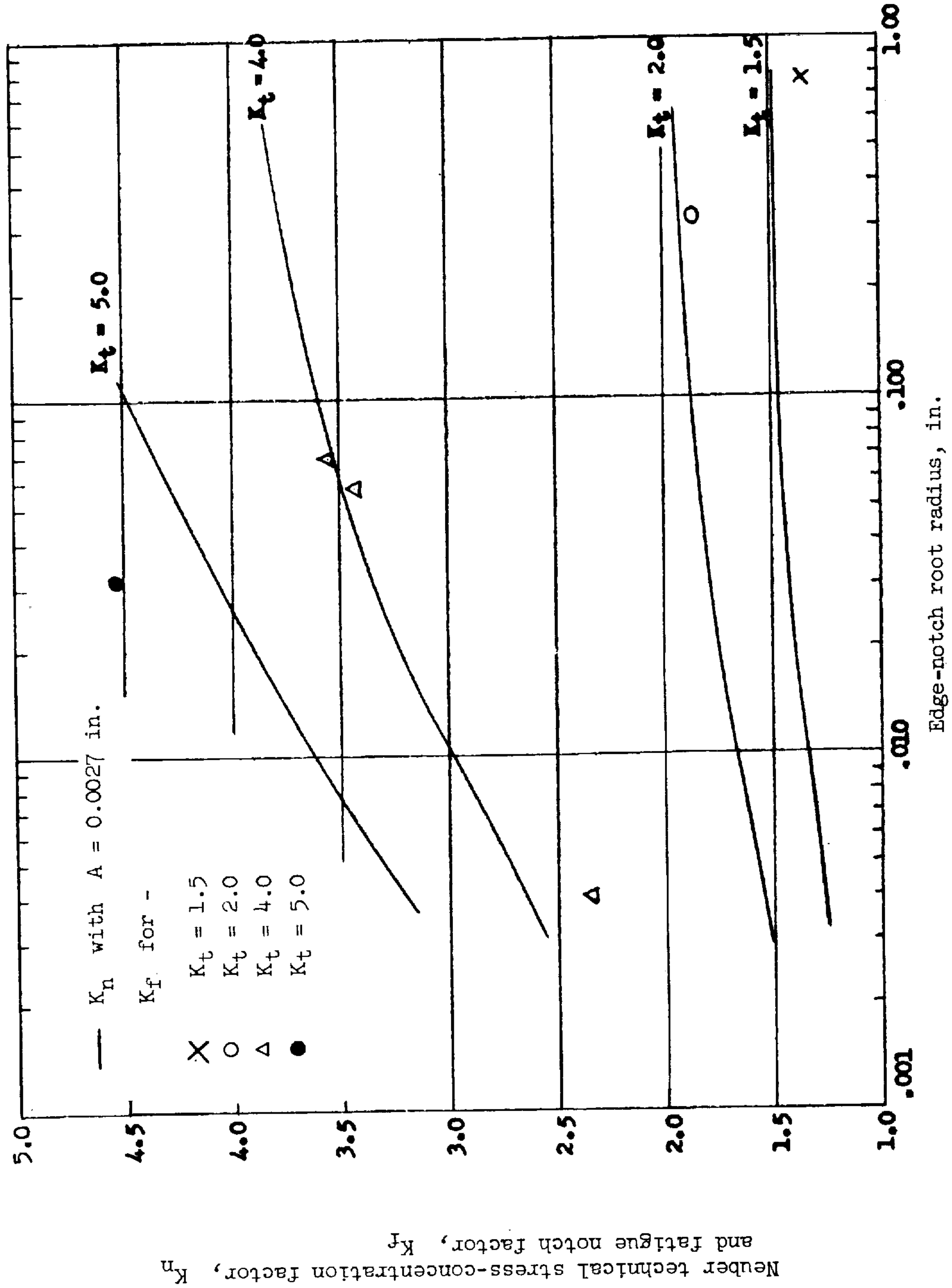
(b) 7075-T6 aluminum alloy.

Figure 5.- Continued.



(b) 7075-T6 aluminum alloy.

Figure 6.- Continued.



(c) Normalized SAE 4130 steel.

Figure 6.- Concluded.