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TECHNICAL NOTE

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EFFECTS OF CHANGING STRESS AMPLITUDE ON THE RATE OF FATIGUE-CRACK PROPAGATION IN TWO ALUMINUM ALLOYS

By C. Michael Hudson and Herbert F. Hardrath

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SUMMARY

A series of fatigue tests with specimens subjected to constant-amplitude and two-step axial loads were conducted on 12-inch-wide sheet specimens of 2024-T3 and 7075-T6 aluminum alloy to study the effects of a change in stress level on fatigue-crack propagation. Comparison of the results of the tests in which the specimens were tested at first a high and then a low stress level with those of the constant-stress-amplitude tests indicated that crack propagation was generally delayed after the transition to the lower stress level. In the tests in which the specimens were tested at first a low and then a high stress level, crack propagation continued at the expected rate after the change in stress levels.

INTRODUCTION

The evolution of the fail-safe design philosophy in aircraft construction has presented designers with a number of new design considerations. One of the most important of these considerations is the prediction of fatigue-crack propagation rates. A number of investigators have developed empirical expressions for predicting crack propagation rates by using the results of constant-stress-amplitude fatigue tests. This work has been extended to include tests in which fatigue cracks were propagated at first one stress level and then another, as a first step toward the study of effects of the variable-amplitude loading to which aircraft are subjected. In separate investigations, Jenney and Christensen (ref. 1) and Schijve (ref. 2) found that high load cycles succeeded by lower ones produced delays in fatigue-crack propagation. The present investigation was conducted to provide a more quantitative evaluation of the delay in fatigue-crack propagation in 2024-T3 and 7075-T6 aluminum-alloy specimens when these specimens are tested at two stress levels. These tests are referred to herein as two-step tests. The delay in crack propagation was measured by comparing the results of the two-step tests with the results of companion constant-amplitude tests.

SYMBOLS

N	number of cycles from crack initiation
N_c	number of cycles required to propagate crack to a given length at stress level in constant-amplitude tests
N_2	number of cycles required to propagate crack to a given length at second stress level in two-step tests
S_c	stress in constant-amplitude tests, ksi
S_1	initial stress in two-step tests, ksi
S_2	final stress in two-step tests, ksi

SPECIMEN PREPARATION

The materials for these tests were taken from the special stocks of 2024-T3 and 7075-T6 aluminum alloys described in reference 3 and retained at the Langley Research Center for fatigue testing. The tensile properties of the materials tested are given in table I. The specimen configuration used is shown in figure 1. Sheet specimens 12 inches wide, 35 inches long, and with a nominal thickness of 0.090 inch were used in this investigation. A 1/16-inch-diameter hole was drilled at the center of each specimen and a 1/32-inch-deep notch was cut into each side of the hole with a thread impregnated with fine valve-grinding compound. The thread was drawn across the edge to be cut with a reciprocating motion. A very gentle cutting process is involved in making notches in this manner; consequently the residual stresses resulting from cutting are believed to be small. The radii of the notches were within ±6 percent of 0.005 inch. The theoretical stress-concentration factor for this configuration was computed to be 7.9 by the method outlined in reference 4.

The surface area through which the crack was expected to propagate was polished with No. 600 alundum powder to facilitate observation of the crack. Fine lines were scribed on the specimen with a razor blade to define intervals along the crack path. No stress concentration was expected as a result of these scribe lines as they were parallel to the direction of loading.

TESTING MACHINES

Three types of axial-load testing machines were employed in this investigation. Fatigue machines operating on the subresonance principle (ref. 5) were employed for tests in which the applied load did not exceed 10 kips. The loading rate for these machines was 1,800 cpm. The cycles counter read in thousands of cycles. A 100,000-pound-capacity hydraulic fatigue machine (ref. 4) was employed for tests in which the applied load did not exceed 20 kips. This machine applied loads at the rate of 1,200 cpm, and its counter read in hundreds of cycles. A 120,000-pound-capacity hydraulic jack (ref. 6) was employed when the load was to exceed 20 kips. The jack applied load at the rate of 20 to 50 cpm depending upon the magnitude of the load. The cycles counter read in cycles.

TEST PROCEDURE

Both constant-amplitude and two-step axial-load fatigue tests were conducted. In the two-step tests the cracks were initiated and propagated to a desired length at one stress level and then propagated to failure at another. Tests in which the high stress cycles were applied initially will be referred to hereinafter as high-low two-step tests, and tests in which the low stress was applied initially will be referred to as low-high two-step tests. In the constant-amplitude tests, the fatigue cracks were initiated and propagated to failure at one stress level.

All the specimens were clamped between lubricated guides similar to those described in reference 7 in order to prevent buckling should the specimen be accidentally loaded in compression and to prevent out-of-plane vibrations during testing. A minimum tensile stress of 1 ksi was maintained in all tests.

Loads were monitored continuously by measuring the output of a strain-gage bridge attached to a weigh bar through which the load was transmitted to the specimen. The maximum error in loading was ±1 percent of the applied load.

In all tests crack growth was observed through 30-power microscopes. In the two faster testing machines a stroboscopic light was employed so that crack growth could be followed without interrupting the tests. All crack lengths were measured from the center of the specimens. The number of cycles required to propagate the crack to each scribed line was recorded so that the rate of crack propagation could be determined.

In a number of the low-high two-step tests it was desirable to use an initial stress level of 6 ksi. Since this stress was so close to the fatigue limit for the specimen configuration, it was decided to initiate the cracks at 10 ksi. The cracks were then propagated to the desired length at 6 ksi at which point the stress level was raised and the crack was propagated.

RESULTS AND DISCUSSION

Crack-propagation test results are summarized in tables II, III, and IV for low-high two-step tests, high-low two-step tests, and constant-amplitude tests, respectively. The quantity "number of cycles" given in these tables and in the figures is the mean of the numbers of cycles required to produce cracks of equal length on both sides of the specimens.

The results of tests conducted at constant-amplitude stress S_c were used as a reference, and all the two-step test data were compared with these results to determine the effects of the initial loading S_1 on subsequent propagation at a second stress level S_2. This comparison was made by plotting on the same figure the variation of crack length with number of cycles for both the constant-amplitude tests and the second portion of the two-step tests. The starting point for both curves was the crack length at the time of the change in stress levels in the two-step tests. The difference between the two curves is a measure of the effect of previous loading history.

Figure 2 shows the plots of the variation of crack length with number of cycles under load for the low-high test series. Inspection of the figure indicates that crack propagation at the second stress level was not generally affected by previous loading history in either material.

Figure 3 shows the same type of plots for the low stress portion of the high-low test series. Comparison of the curves for the constant and two-step tests indicates that crack propagation at the second stress level was significantly delayed in both materials as a result of previous loading history. Similar results were obtained by Jenney and Christensen (ref. 1) and Schijve (ref. 2) in their multistep tests. The delay in crack propagation which resulted from previous loading in the high-low tests is plotted against the second stress in figure 4. Examination of this figure reveals that for a given second stress the higher the initial stress the greater the delay in crack propagation. The probable cause of this delay in crack growth is the existence of residual compressive stresses at the tip of the crack at the time of the change in stress level. It is believed that these stresses were present as a result of the large amount of plastic deformation which occurred at the tip of the crack during propagation at the high stress level.

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It was also of interest to determine whether previous loading history affected the rate of crack propagation once crack growth had again started at the second stress level. This determination was made by a comparison of the number of cycles required to propagate the cracks equal increments in the high-low two-step tests and in the constant-amplitude tests with $S_c = S_2$. The interval over which this comparison was made began when the crack had propagated 0.1 inch past the crack length at which the stress levels were changed, and the interval extended to the point at which the specimens failed. This comparison is shown in figure 5. The reference line shown on the figure is the locus of points along which the test points would lie if the rates of propagation in the constant-amplitude and the high-low two-step tests were the same. The generally close proximity of the test results to the reference line indicates that there is little difference between the rates of propagation in the constant-amplitude and two-step tests.

In the high-low test series, the lowest stress at which fatigue cracks would propagate in 10^7 cycles was 16 ksi. This stress was considerably higher than the 10-ksi stress at which fatigue cracks were initiated and propagated to failure in constant-amplitude tests. Thus, it appears that the fatigue limit has increased. This result indicates that specimens subjected to variable-amplitude loadings may not be damaged by some stress cycles with magnitudes above the normal fatigue limit of the specimens.

These results help to explain why the linear cumulative-damage rule frequently produces erroneous estimations of the fatigue life of test specimens. This rule assumes that damage accumulates at a rate equal to the percentage of life used at a given stress level. Thus, this rule cannot predict the observed delay in crack propagation and the resultant increase in fatigue life.

In several instances a great deal of bifurcation was observed at the tip of the cracks following the transition to the second stress level. In the 2024-T3 specimen tested first at 30 ksi and then 16 ksi, for example, the crack which finally propagated to failure at 16 ksi started behind the tip of the crack produced by the 30-ksi loading (fig. 6). Figure 7 shows the crack tip after the change in stress levels for the 7075-T6 aluminum-alloy specimen tested first at 40 ksi and then 16 ksi. It appears that residual stresses produced by high stresses at the crack tip were sufficient to render other portions of the specimen more vulnerable to fatigue-crack growth at subsequent lower stresses.

CONCLUSIONS

Comparisons of the rates of crack propagation in constant- and variable-amplitude fatigue tests support the following general conclusions:

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1. When the initial stress level was higher than the second, crack propagation at the second stress level was delayed. It was also observed that for a given second stress level the higher the initial stress the greater the delay in propagation. The probable cause of this delay was the presence of residual compressive stresses at the tip of the crack which result from plastic deformation near the tip of the crack during propagation at the initial stress level.

2. Once crack propagation had commenced in the second step of the high-low tests, the propagation rate quickly approached that of constant-amplitude specimens tested at the same stress level and containing cracks of equal length.

3. Cracks propagated at the normal rate during the second stress level in the specimens tested first at a low and then a high stress level.

4. The fatigue limit of specimens tested at first a high and then a low stress level was increased following the application of the initial loading.

5. The results of these tests help explain why the linear cumulative-damage rule is often in error. This rule assumes that damage accumulates at a rate equal to the percentage of life used at a given stress level, and thus cannot predict the observed delay in propagation and the resultant increase in fatigue life.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., July 11, 1961.

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TABLE I

AVERAGE TENSILE PROPERTIES OF MATERIAL TESTED

	2024-T3	7075-T6
Yield stress (0.2-percent offset), ksi	52.05	75.50
Ultimate strength, ksi	72.14	82.94
Total elongation (based on 2-inch gage length), percent	21	12
Young's modulus, ksi	10,470	10,220
Number of specimens tested	147	152

TABLE II

AVERAGE NUMBER OF CYCLES REQUIRED TO PROPAGATE FATIGUE CRACKS FOLLOWING

THE CHANGE IN STRESS LEVELS IN THE LOW-HIGH TEST SERIES

Material	Initial stress, ksi	Number of cycles at initial stress	Second step stress, ksi	Crack length at change in stress levels, in.	Number of cycles required to propagate crack from length at change in stress levels to a length of -							Number of cycles from stress change to failure
					0.20 in.	0.30 in.	0.50 in.	0.70 in.	1.00 in.	1.40 in.	1.80 in.	
7075-T6	30	1,676	50	0.080	532	609	658					670
	[a]6	984,000	50	.087	423	488						501
	10	112,000	40	.095	655	910	1,116	1,155				1,157
	[a]6	494,000	30	.100	2,870	3,490	4,080	4,280	4,388			4,419
	[a]6	1,282,000	10	.200		31,000	61,700	78,100	92,000	102,400	108,000	110,000
2024-T3	30		50	0.140	77	145	183					187
	[a]6	2,522,000	50	.100	123	149						153
	10	671,000	40	.100	896	1,126	1,266	1,314	1,336			1,343
	[a]6	2,404,000	30	.100	2,640	3,642	4,135	4,640				4,798
	[a]6	5,251,000	10	.200		34,000	76,000	105,000	131,000	151,000	164,000	170,000

[a]Crack initiated at 10 ksi

TABLE III

AVERAGE NUMBER OF CYCLES REQUIRED TO PROPAGATE FATIGUE CRACKS FOLLOWING THE CHANGE IN STRESS LEVELS IN THE HIGH-LOW TEST SERIES

Material	Initial stress, ksi	Number of cycles at initial stress	Second step stress, ksi	Crack length at change in stress levels, in.	Number of cycles required to propagate crack from length at change in stress levels to a length of -										Number of cycles from stress change to failure
					0.20 in.	0.30 in.	0.40 in.	0.50 in.	0.60 in.	0.80 in.	1.00 in.	1.20 in.	1.60 in.	2.20 in.	
7075-T6	50	436	40	0.120	922	1,150	1,277	1,351	1,388	1,400					1,404
	50	949	30	.295			6,294	6,705	6,904	7,104	7,207	7,249	7,256		7,266
	50	693	20	.150	352,400	353,900	354,280	354,700	354,800	355,000	355,100	355,200	355,300		355,300
	50	858	14	.320	Did not propagate in 10^7 cycles										
	40	525	30	.200		1,565	1,974	2,233	2,408	2,600	2,698	2,738	2,745		2,746
	40	879	20	.265		82,000	88,600	89,700	90,400	91,000					91,300
	40	2,129	16	.395				1,266,000	1,270,000	1,274,700	1,277,900	1,279,600	1,282,700	1,285,300	1,286,200
	30	4,223	25	.220		2,360	3,310	3,900	4,280	4,830	5,000	5,300			5,500
	30	4,000	20	.160	8,000	11,000	12,700	14,000	14,900	16,200	16,900	17,400	17,900		17,900
	30	4,960	16	.395				84,000	87,000	90,000	93,000				96,000
2024-T3	50	440	40	0.160	407	707	786	832	861	885	897	905			907
	50	530	30	.340			6,300	11,150	12,406	13,176	13,393	13,550	13,570		13,577
	50	473	20	.200		1,000,000	1,047,000	1,052,700	1,056,400	1,061,000	1,062,000	1,062,500	1,062,600	1,062,700	1,062,700
	50	506	16	.249	Did not propagate in 10^7 cycles										
	40	1,860	30	.200		4,100	4,770	5,010	5,190	5,390	5,500	5,570	5,630	5,670	5,672
	40	1,212	20	.200		875,000	877,000	880,000	881,000	883,000	884,000	884,800	884,900		884,900
	40	1,456	16	.465				3,525,100	3,532,400	3,537,900	3,540,600	3,542,000	3,543,600		3,543,800
	30	3,860	25	.170	4,000	6,700	8,100	8,740	9,200	9,750	10,100	10,300	10,500		10,500
	30	5,549	20	.150	47,500	57,000	59,800	61,700	63,200	65,000	66,100	66,700	67,400	67,900	68,000
	30	7,266	16	.800							3,312,400	3,316,000	3,318,000	3,319,000	3,320,800

TABLE IV

AVERAGE NUMBER OF CYCLES REQUIRED TO INITIATE AND PROPAGATE FATIGUE CRACKS IN THE CONSTANT-AMPLITUDE TESTS

Material	Stress, ksi	Number of cycles required to initiate and propagate a crack to a length of -										Number of cycles to failure
		0.10 in.	0.20 in.	0.30 in.	0.40 in.	0.50 in.	0.60 in.	0.80 in.	1.00 in.	1.20 in.	1.60 in.	
7075-T6	50	575	840	910	954	963	964					964
	40	1,000	1,675	1,886	2,013	2,070	2,098	2,110				2,111
	30	2,250	4,000	4,780	5,150	5,350	5,500	5,660	5,720	5,750	5,770	5,780
	25	4,750	8,300	10,250	11,160	11,600	11,880	12,360	12,700			12,800
	20	10,000	16,560	19,750	21,940	23,340	24,250	25,380	26,080	26,580	27,190	27,500
	16	10,700	17,700	21,700	24,700	27,100	28,900	31,200	32,600	33,500		34,100
	14	11,000	27,000	34,000	39,100	43,100	46,200	50,200	53,000	54,700	56,800	58,000
	10		51,000	78,000	92,500	102,500	110,000	121,500	130,000	136,500	146,000	146,000
2024-T3	50	158	253	273	278							279
	40	800	1,380	1,540	1,610	1,660	1,680	1,700	1,718	1,720		1,722
	30	2,900	5,350	6,325	6,970	7,280	7,500	7,760	7,860	7,930	8,020	8,048
	25	5,750	11,100	14,540	15,850	16,680	17,210	17,750	18,040	18,250	18,270	18,500
	20	13,000	22,700	28,800	32,800	35,700	37,700	39,900	41,100	41,600	42,200	42,800
	16	34,500	56,800	67,900	76,700	84,100	89,300	94,900	97,600	99,000	100,600	102,200
	10	1,100,000	1,440,000	1,478,000	1,497,000	1,512,000	1,523,000	1,542,000	1,555,000	1,564,000	1,576,000	1,591,300

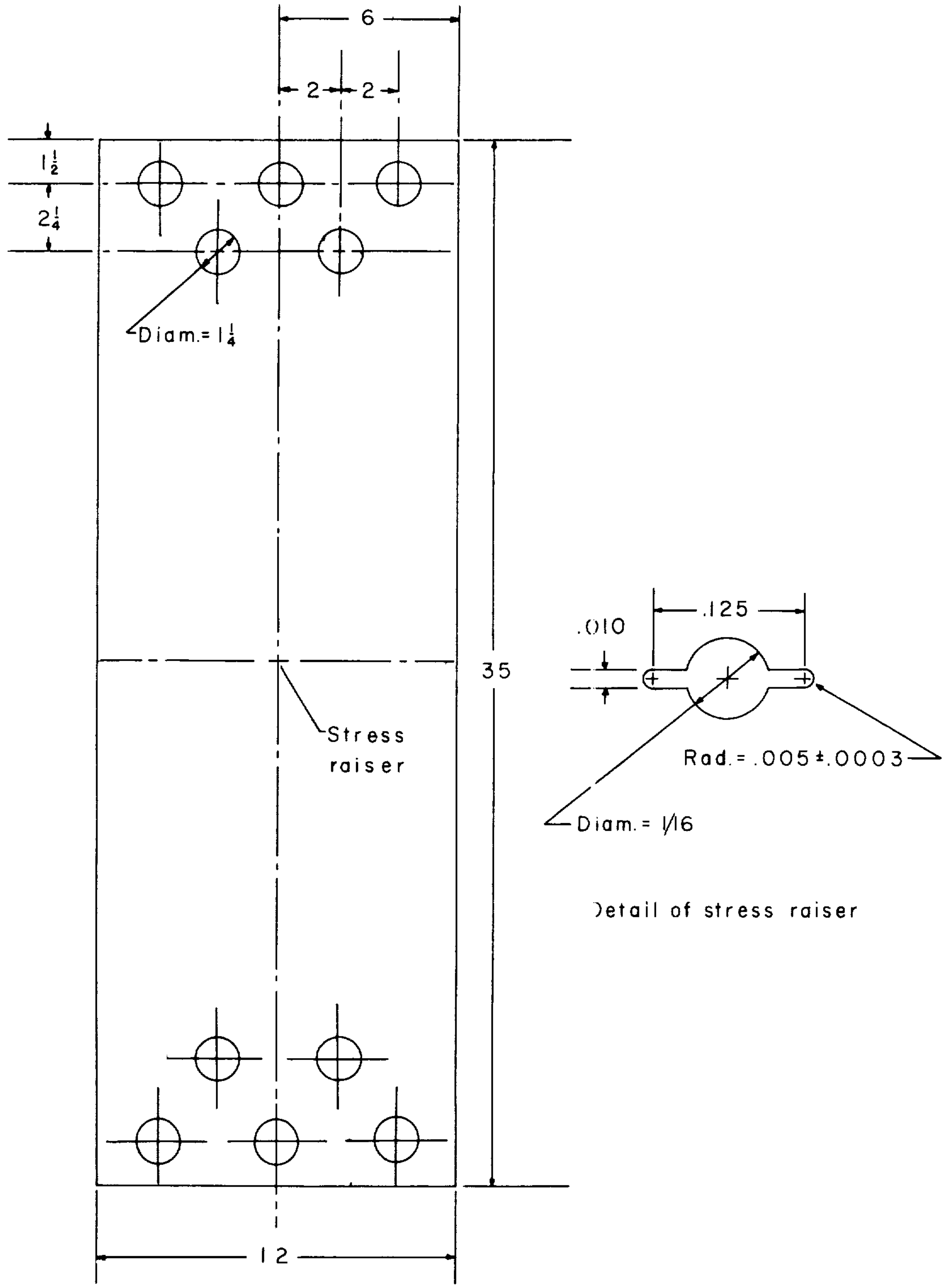

Figure 1.- Specimen configuration. All dimensions are in inches.

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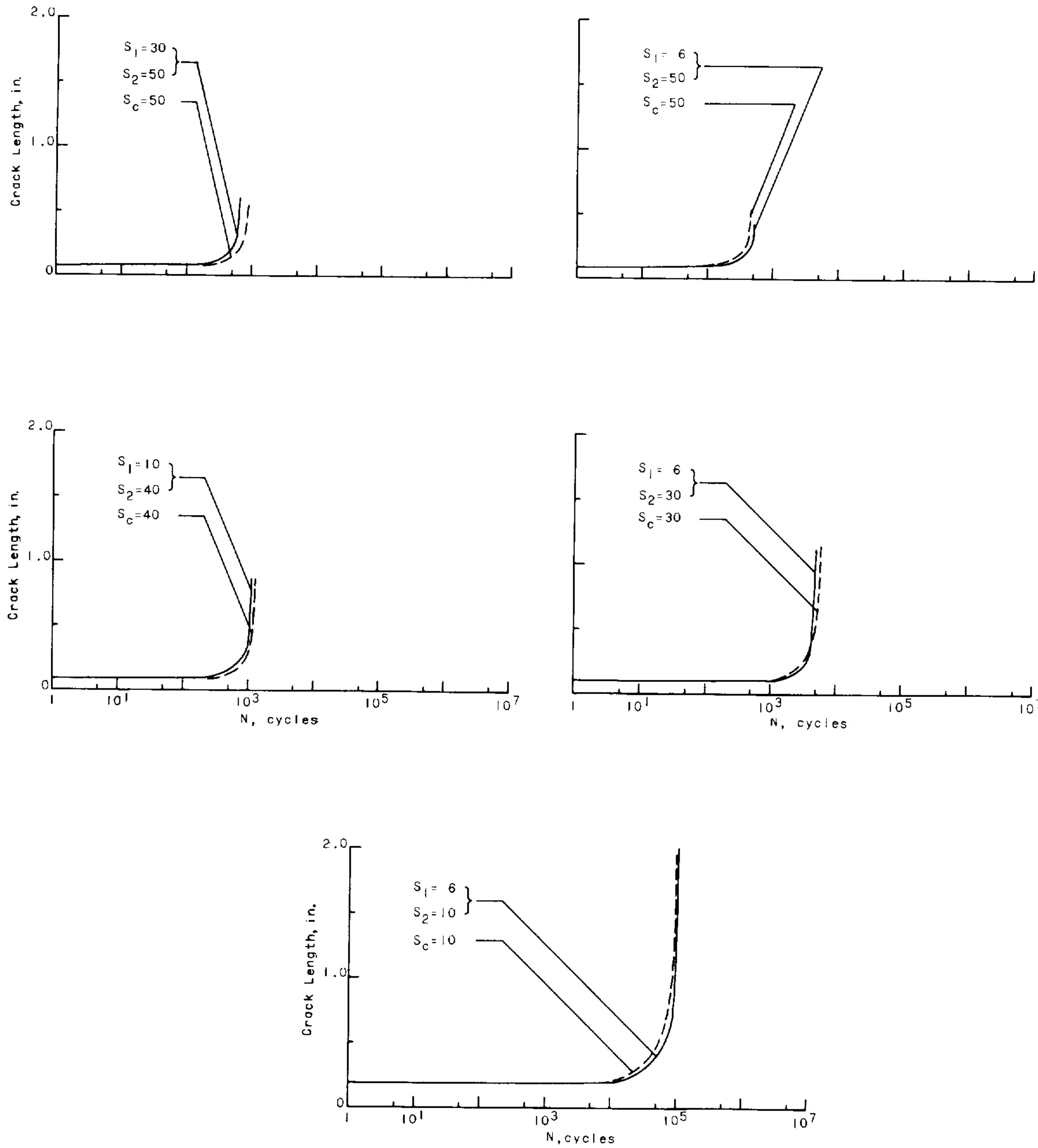
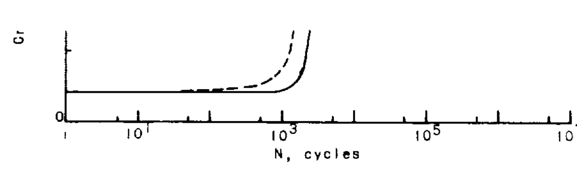


(a) Specimens of 7075-T6 aluminum alloy.

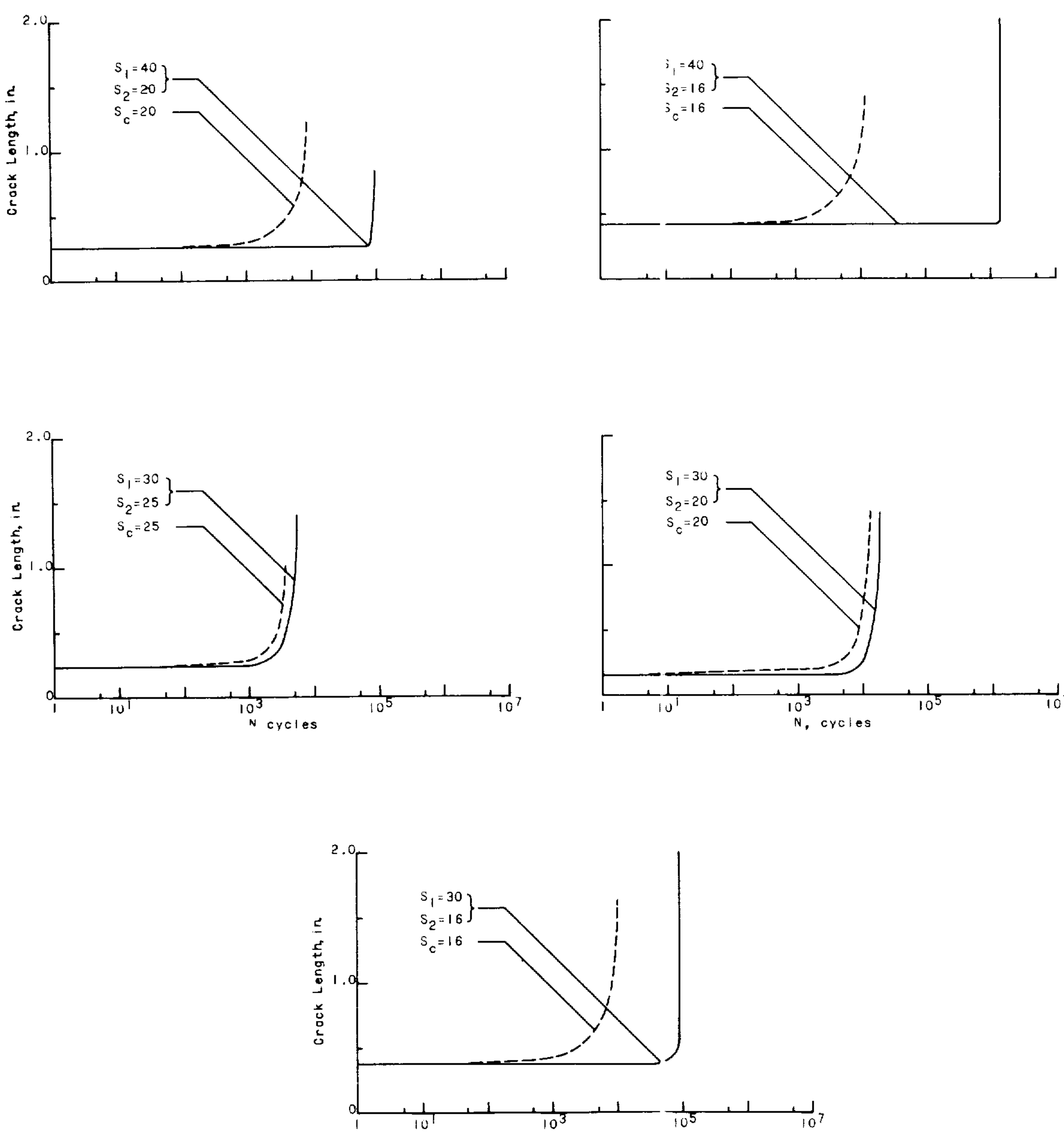
Figure 2.- Crack-propagation curves for the constant-amplitude tests and the high-stress portion of the low-high tests. All stresses are in ksi.



14


2.0
Length, in
1.0
$S_1=30$
$S_2=50$
$S_c=50$
$S_1=6$
$S_2=50$
$S_c=50$

16


Crack Length, in
2.0
1.0
0
$S_1=40$
$S_2=20$
$S_c=20$
$S_1=40$
$S_2=16$
$S_c=16$
$S_1=30$
$S_2=25$
$S_c=25$
$S_1=30$
$S_2=20$
$S_c=20$
$S_1=30$
$S_2=16$
$S_c=16$
N cycles
N, cycles
1
10^1
10^3
10^5
10^7

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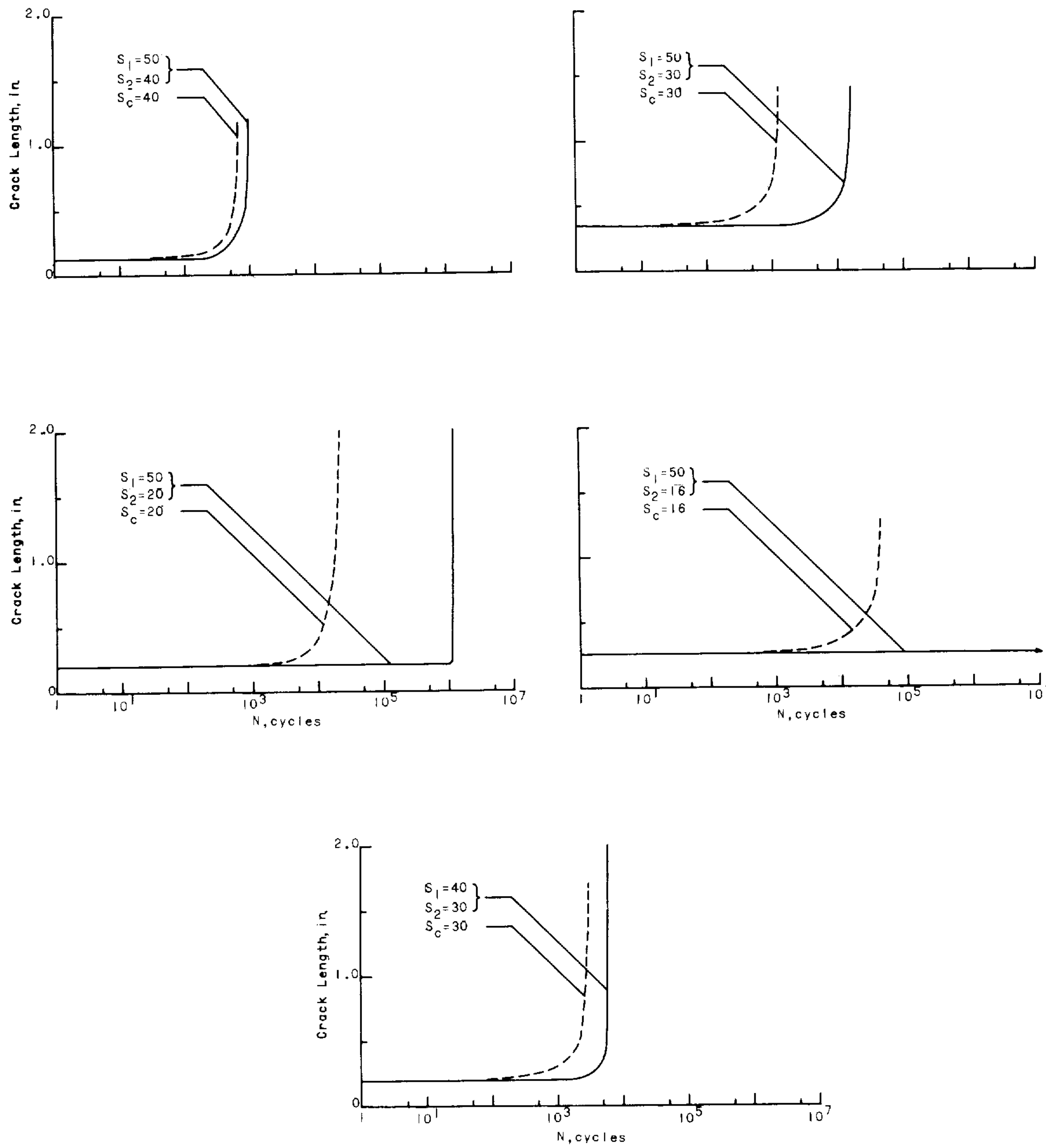
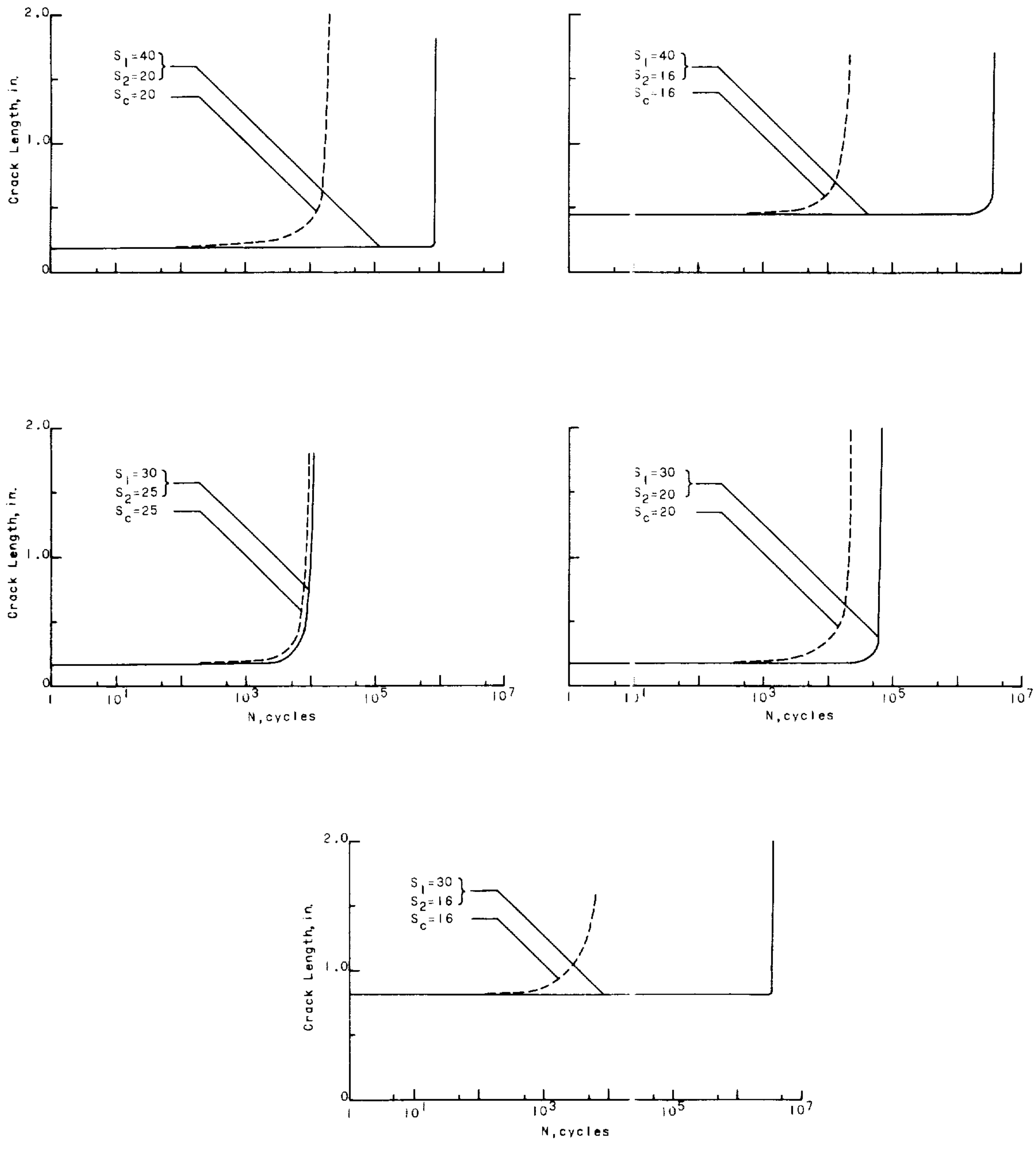


(b) Specimens of 2024-T3 aluminum alloy.

Figure 3.- Continued.



(b) Concluded.

Figure 3.- Concluded.

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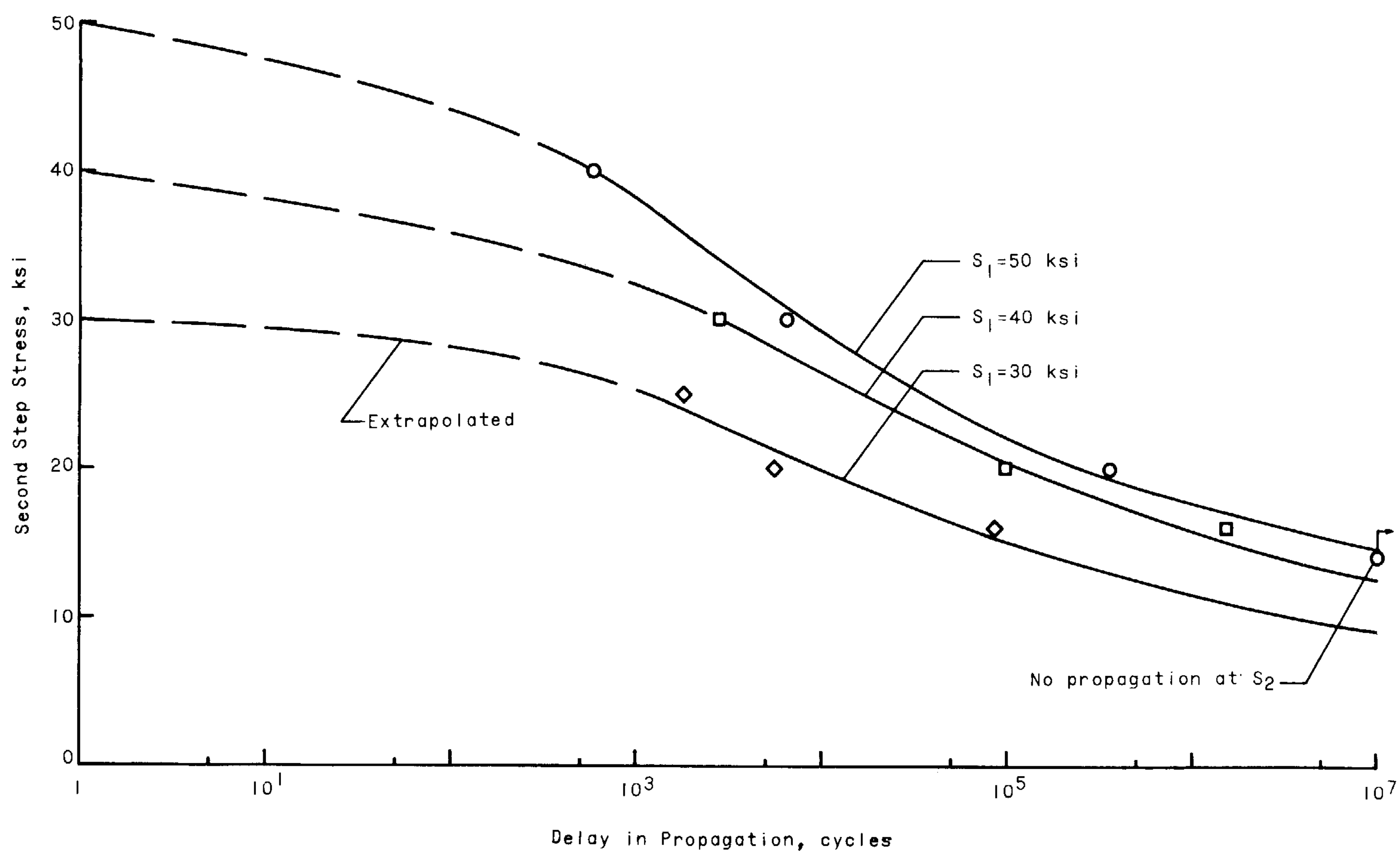
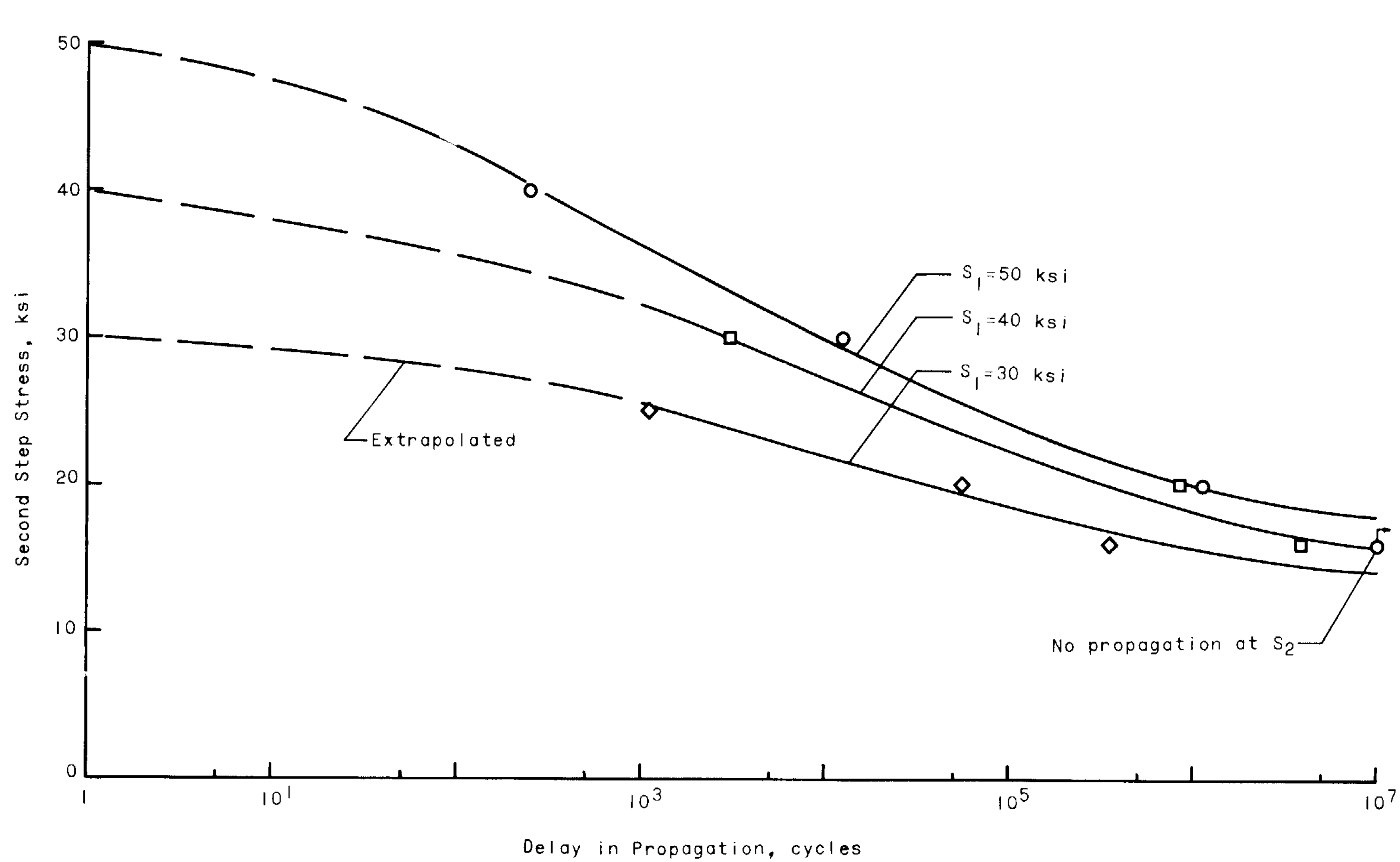


(a) Specimens of 7075-T6 aluminum alloy.

Figure 4.- Delay in propagation as a result of changing stress levels in the high-low test series.



(b) Specimens of 2024-T3 aluminum alloy.

Figure 4.- Concluded.

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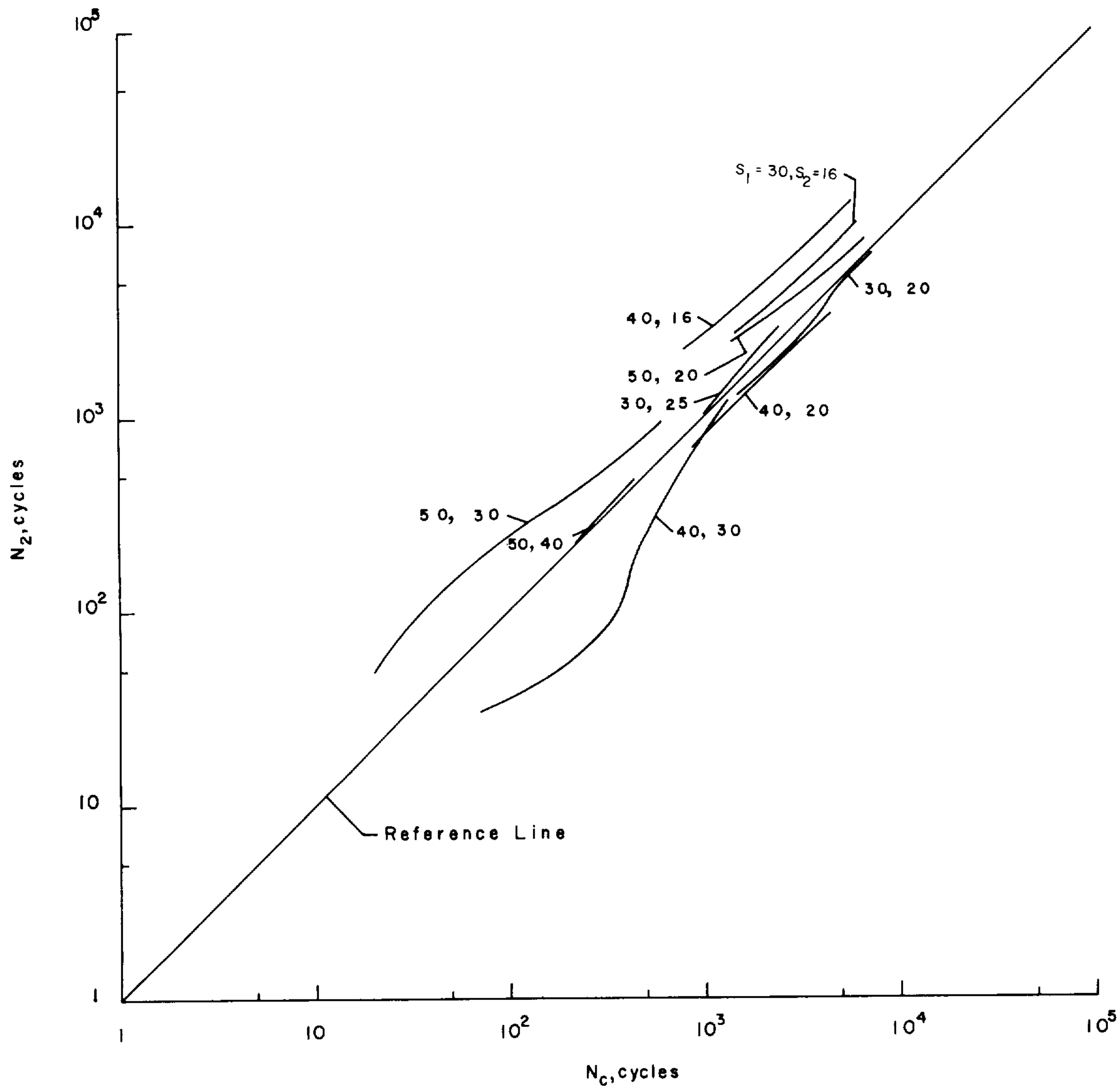
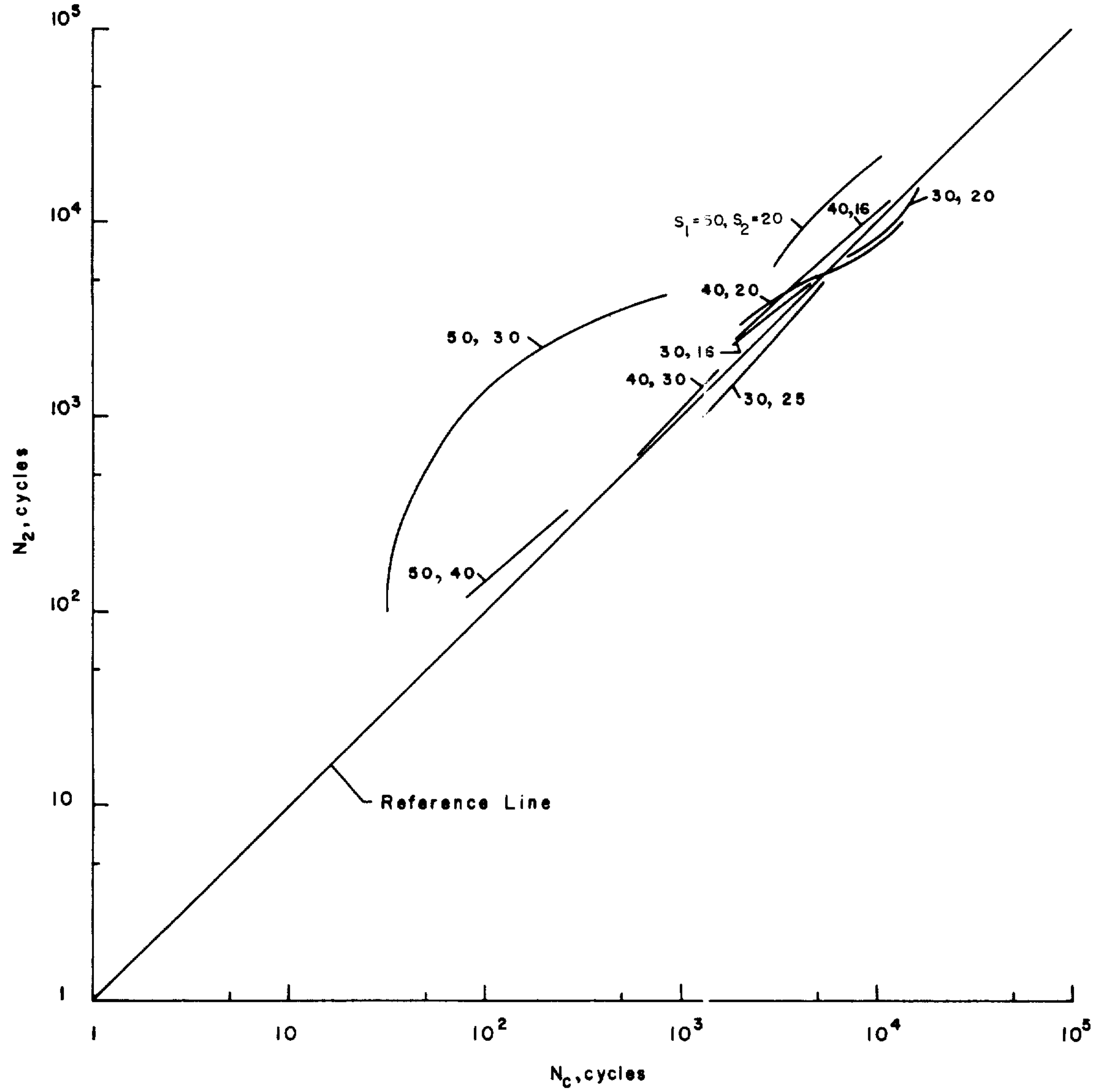


(a) Specimens of 7075-T6 aluminum alloy.

Figure 5.- Comparison of crack propagation in constant-amplitude and high-low two-step tests after 0.1-inch crack growth at S_2. Cycles are those required to produce equal increments of crack growth. All stresses are in ksi.



(b) Specimens of 2024-T3 aluminum alloy.

Figure 5.- Concluded.

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Direction of propagation

Crack tip at change in stress levels

Point where crack initiated at 16ksi

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Figure 6.- Surface of the 2024-T3 specimen tested first at 30 ksi and then 16 ksi. (x20)

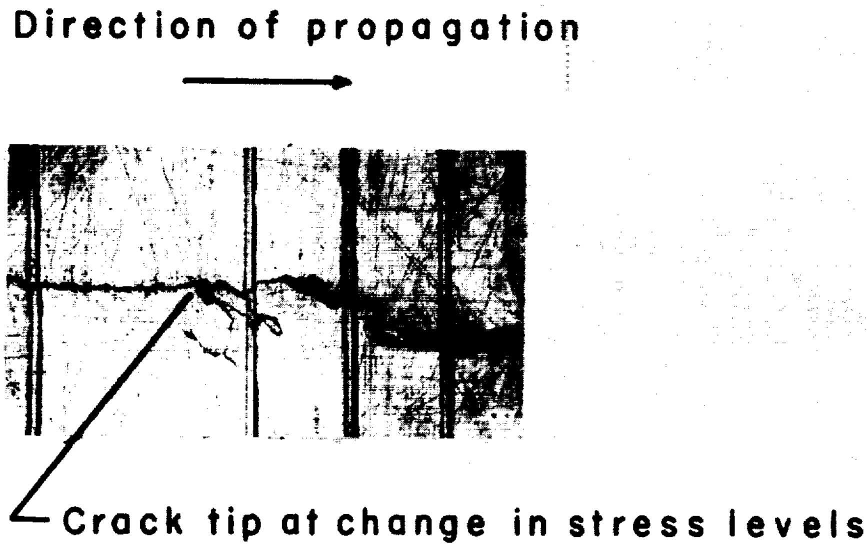

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Figure 7.- Surface of the 7075-T6 specimen tested first at 40 ksi and then 16 ksi. (×26)

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