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TECHNICAL NOTE

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AXIAL-LOAD FATIGUE TESTS ON 17-7 PH STAINLESS STEEL UNDER CONSTANT-AMPLITUDE LOADING

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AXIAL-LOAD FATIGUE TESTS ON 17-7 PH STAINLESS STEEL UNDER CONSTANT-AMPLITUDE LOADING

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SUMMARY

Axial-load fatigue tests were conducted at room temperature on notched and unnotched sheet specimens of 17-7 PH stainless steel in Condition TH 1050. The notched specimens had theoretical stress-concentration factors of 2.32, 4.00, and 5.00. All specimens were tested under completely reversed loading. S-N curves are presented for each specimen configuration and ratios of fatigue strengths of unnotched specimens to those of notched specimens are given. Predictions of the fatigue behavior of notched specimens near the fatigue limit were made.

INTRODUCTION

Stainless steels are commonly used in the construction of shells and fuel tanks for missiles and also for structural parts of other vehicles subjected to high temperatures. Since these structures are frequently subjected to repeated loads, additional information regarding the fatigue behavior and notch sensitivity of stainless steels would be of interest to the designer. Therefore, an investigation was conducted at room temperature to determine the fatigue properties and notch sensitivity of 17-7 PH stainless steel in Condition TH 1050. Notched and unnotched sheet specimens were tested under completely reversed axial loading (ratio of minimum stress to maximum stress equals minus one). The test results are presented in the form of S-N curves. A material constant was determined so that notch-size effect could be estimated by use of the Neuber technical stress-concentration factor. This constant was compared with the constant obtained from reference 1 for fatigue tests on a large variety of low-alloy steels.

SYMBOLS

K_F fatigue stress-concentration factor - ratio of maximum nominal stress in unnotched specimen at given lifetime to that in notched specimen of same lifetime

K_N — stress-concentration factor corrected for size effect (Neuber technical factor)

K_T — theoretical stress-concentration factor

R — ratio of minimum nominal stress to maximum nominal stress

S_{max} — maximum nominal stress, ksi

ρ — radius of curvature at base of notch, in.

ρ' — Neuber material constant, in.

ω — flank angle, radians

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SPECIMENS

Four specimen configurations were tested under cyclic loading. One had an hourglass shape (unnotched); one, a central hole; and two, edge notches. Details of these configurations are shown in figure 1. The notched specimens had theoretical stress-concentration factors K_T of 2.32, 4.00, and 5.00 (refs. 2 and 3). In addition, six standard tensile specimens were tested to determine the mechanical properties. All specimens were machined from 0.037-inch-thick sheets of 17-7 PH stainless steel after heat treating to condition TH 1050. All specimens, including tensile specimens, were machined so that the longitudinal axis of the specimen was parallel to the grain of the sheet. The specimen blanks were clamped in stacks, and all were initially machined along their longitudinal edges.

The notches in the specimens having edge notches were made by drilling a hole to the proper radius and then removing the material from the edge of the specimen to the center of the hole with a milling tool. The width of the milling tool was approximately equal to the diameter of the hole. The hole was made by first drilling a small hole and then enlarging it to the proper diameter by using progressively larger drills. This was done in order to minimize residual stresses due to machining. The last two drills removed approximately 0.0015 inch of material. The drilling speed used for both of the edge-notched configurations was 935 rpm. The two remaining specimen configurations were machined by mounting the specimen blanks on the headstock of a lathe and cutting with a stationary tool bit. The configuration with a central hole was made by boring a 3/4-inch-diameter hole at a speed of 40 rpm. The last two cuts removed 0.001 inch of material. The 12-inch radius of the unnotched specimen was machined at a speed of 9 rpm. The last two cuts were 0.001 inch deep. In all cases, the feed was approximately 0.005 inch per revolution. Careful machining produced clean edges on all notches and, consequently, no deburring was necessary.

Preliminary tests on all specimen configurations indicated a large amount of scatter in results. In order to reduce this scatter, the surface area at the midsection of each specimen (both sides) was hand polished in the longitudinal direction with a flat wooden block and emery paper. The paper and specimen were dry during the entire polishing process. Several operations were performed to obtain the polished surface. The first operation removed the scale left from heat treating and any deep pits that may have been on the surface. In order to do this quickly no. 280 emery paper was used. Three more operations were performed with nos. 320, 400, and 500 emery paper, respectively, to obtain the final polished surface. A total of approximately 0.002 to 0.003 inch of material was removed during polishing.

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EQUIPMENT AND TEST PROCEDURE

Axial-load fatigue-testing machines used for this investigation were equipped with a subresonant loading system and a hydraulic loading system. (See ref. 4.) Specimens which were expected to have a life greater than 10,000 cycles were tested with the subresonant system (1,800 cpm). All other specimens were tested with the hydraulic system (20 cpm).

The load on the specimen was measured by strain gages cemented to a weigh bar in series with the specimen. Electronic load monitoring equipment was used for visual observation of subresonant loads. Loads applied hydraulically were recorded continuously. All tests were conducted under completely reversed loading ($R = -1$). The maximum error in loading (subresonant and hydraulic) was ±2.5 percent of the applied load.

Guide plates similar to those described in reference 5 were used to prevent buckling of the specimens. Tissue-paper shims were placed between the guides and the specimens at the polished area to compensate for the material removed from the specimen by polishing. The light oil used to lubricate the surfaces of the specimen and guides was enough to hold the tissue paper in place. A low-voltage current was passed through the specimen to operate a relay which stopped the machine when the specimen failed.

RESULTS AND DISCUSSION

The tensile properties as found from the tests of standard tensile specimens are given in table 1. After heat treating, the specimens had a nominal hardness of Rockwell C43.

The results of the fatigue tests are presented in table 2 and are plotted as S-N curves in figure 2. The S-N curves for all the specimen configurations appear to be approximately parallel within the range tested. The scatter in results, based on a limited number of tests at a given stress level, was greatest for tests conducted on unnotched specimens and decreased for tests conducted on specimens with increasing values of K_T. Speed of testing (hydraulic versus subresonant) had a small effect on the results of tests conducted on unnotched specimens $(K_T = 1)$ and on specimens containing a central hole $(K_T = 2.32)$ but had no apparent effect on the results of tests conducted on specimens containing edge notches $(K_T = 4.00 \text{ and } 5.00)$.

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A plot of the fatigue stress-concentration factor K_F versus the maximum nominal stress S_{max} for notched specimens is presented in figure 3. In general, K_F had a maximum value somewhat less than K_T for low nominal stresses (stress at fatigue limit) and became progressively smaller at higher nominal stresses. An exception was the curve for specimens having a K_T of 2.32, where the slope was positive at low nominal stresses. The progressive reduction of K_F was probably the result of the maximum local stress entering the plastic region. The difference between K_T and K_F may be attributed to size effect, which is discussed next.

In reference 1 a method is proposed for estimating notch-size effects on fatigue tests of low-alloy steel specimens. The method was based on the computation of a stress-concentration factor K_N with the use of a mathematical formula developed by Neuber (ref. 3). This formula corrects the theoretical stress-concentration factor K_T for size effect and reads as follows:

$$K_N = 1 + \frac{K_T - 1}{1 + \frac{\pi}{\pi - \omega}\sqrt{\frac{\rho'}{\rho}}} \tag{1}$$

This formula corrects for size in that it incorporates the absolute size of the notch. It should be noted that all notch configurations tested in the present investigation had a flank angle ω equal to zero and therefore the above formula reduces to:

$$K_N = 1 + \frac{K_T - 1}{1 + \sqrt{\frac{\rho'}{\rho}}} \qquad (2)$$

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In reference 1 the authors found that the material constant ρ' was a function of the ultimate tensile strength of the material and plotted a curve over a large range of tensile strengths for several low-alloy steels. This curve yields a material constant ρ' of 0.000225 inch for the ultimate tensile strength of the material used in the present investigation. This value of ρ' was used in equation (2) to compute K_N for each notch configuration in order to predict the S-N curves for notched specimens. The predictions were made by dividing the appropriate value of K_N into values obtained from the S-N curve for unnotched specimens near the fatigue limit. It was assumed that the predictions could be made without serious error since the maximum local stresses are usually elastic in the vicinity of the fatigue limit for unnotched specimens where notch-size effects were computed. The predicted curves (fig. 4) are seen to fall below the experimentally determined S-N curves. Thus, the stainless steel used in this investigation is somewhat less notch sensitive than the average of results obtained in tests of lower alloy steels. In order to obtain a better prediction of the S-N curves for notched specimens near the fatigue limit, progressively larger values of ρ' were used to compute K_N. Reasonably good agreement was obtained between predicted and experimental S-N curves for notched specimens when a value of $\rho' = 0.00232$ inch was used to compute K_N. Predictions based on $\rho' = 0.00232$ inch are also plotted in figure 4.

Static tensile tests were conducted on each specimen configuration. Load was applied at a uniform rate to produce failure in a period of about 1 minute. The results of these tests, which are presented in table 3 and also appear in table 2, indicate that the tensile strengths of notched specimens are 7 to 9.1 percent higher than those of the unnotched specimens. Similar results have been reported (ref. 6) for steel specimens. Tests conducted with the load applied at a uniform rate to produce failure in about 10 minutes gave results only 3 percent lower than the results given in table 3. Thus, there was little effect due to loading rate in a range commonly used for static tests.

CONCLUDING REMARKS

The results of axial-load fatigue tests on notched and unnotched sheet specimens of 17-7 PH stainless steel in Condition TH 1050 are presented in the form of S-N curves. Specimens had theoretical stress-concentration factors K_T of 1.00, 2.32, 4.00, and 5.00 and were tested under completely reversed loading. A material constant ρ' of 0.00232 inch was found to give reasonably good agreement between Neuber technical factors K_N and fatigue stress-concentration factors K_F in the vicinity of the fatigue limit. In general, K_F decreased with increasing nominal stress. Speed of testing (hydraulic versus subresonant) had a small effect on the results of tests conducted on unnotched specimens $\left(K_T = 1\right)$ and on specimens containing a central hole $\left(K_T = 2.32\right)$ but had no apparent effect on the results of tests conducted on specimens containing edge notches $\left(K_T = 4.00 \text{ and } 5.00\right)$. The static tensile strengths of notched specimens are approximately 8 percent higher than those of the unnotched specimens.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., July 28, 1960.

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TABLE 1

TENSILE PROPERTIES OF 17-7 PH STAINLESS STEEL

IN CONDITION TH 1050

	Yield stress (0.2 percent offset), ksi	Ultimate tensile strength, ksi	Total elongation in 2-inch gage length, percent	Young's modulus, ksi
	194.3	204.4	4.5	29,100
	190.9	202.0	6.5	28,430
	198.1	209.1	5.0	28,960
	194.1	203.6	5.0	28,530
	193.8	203.1	4.5	28,500
	198.2	208.1	5.0	29,050
Average	194.9	205.0	5.1	28,760

TABLE 2

RESULTS OF AXIAL-LOAD FATIGUE TESTS ON SHEET SPECIMENS OF 17-7 PH STAINLESS STEEL IN CONDITION TH 1050

(a) Unnotched; R = -1

Maximum nominal stress, ksi	Cycles to failure	Loading system
199.1	Static test	Hydraulic
190	617	
190	711	
180	779	
180	973	
180	1,503	
160	1,782	
160	2,769	
160	3,004	
160	4,025	
140	19,000	Subresonant
140	22,000	
120	42,000	
120	65,000	
120	71,000	
110	151,000	
100	122,000	
100	218,000	
100	272,000	
100	382,000	
90	1,176,000	
90	1,181,000	
85	2,213,000	
82.5	10,840,000	
80	1,749,000	
80	37,074,000	
77.2	910,000	
77	5,941,000	
76	19,129,000	
74	[a]100,173,000	

[a]Did not fail.

TABLE 2.- Continued

RESULTS OF AXIAL-LOAD FATIGUE TESTS ON SHEET SPECIMENS

OF 17-7 PH STAINLESS STEEL IN CONDITION TH 1050

(b) $K_T = 2.32$; $R = -1$

Maximum nominal stress, ksi	Cycles to failure	Loading system
217.2	Static test	Hydraulic
140	67	↓
140	91	
120	191	
120	206	
100	647	
100	692	
80	826	
80	1,209	
80	2,221	↓
80	10,000	Subresonant
70	3,664	Hydraulic
70	6,670	↓
60	21,084	
60	74,610	Subresonant
60	85,760	↓
50	369,600	
40	1,516,000	
40	1,664,000	
40	41,837,000	
38	54,199,000	
36	[a]140,815,000	↓

[a]Did not fail.

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TABLE 2.- Continued

RESULTS OF AXIAL-LOAD FATIGUE TESTS ON SHEET SPECIMENS

OF 17-7 PH STAINLESS STEEL IN CONDITION TH 1050

(c) $K_T = 4.0$; $R = -1$

Maxium nominal stress, ksi	Cycles to failure	Loading system
213.1	Static test	Hydraulic
140	26	↓
120	52	↓
100	70	↓
100	75	↓
80	249	↓
80	289	↓
70	645	↓
60	1,432	↓
60	1,972	↓
50	4,188	↓
50	7,000	Subresonant
40	28,000	↓
30	166,000	↓
30	213,000	↓
25	21,444,000	↓
23	10,181,000	↓
23	17,904,000	↓
21	[a]103,174,000	↓

[a]Did not fail.

TABLE 2.- Concluded

RESULTS OF AXIAL-LOAD FATIGUE TESTS ON SHEET SPECIMENS

OF 17-7 PH STAINLESS STEEL IN CONDITION TH 1050

(d) $K_T = 5.0$; $R = -1$

Maximum nominal stress, ksi	Cycles to failure	Loading system
213.1	Static test	Hydraulic
140	14	↓
120	26	
100	49	
80	179	
80	258	
60	608	
60	1,041	
50	2,279	
50	3,796	
40	7,392	
40	11,172	↓
30.7	67,000	Subresonant
30	97,000	↓
20	1,492,000	
20	1,750,000	
17	104,155,000	
15	[a]97,615,000	
10	[a]90,256,000	↓

[a]Did not fail.

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TABLE 3

STATIC TENSILE STRENGTHS OF NOTCHED AND UNNOTCHED SPECIMENS

Specimen configuration	K_T	Ultimate tensile strength, ksi	Percent increase over unnotched
Unnotched	1.00	199.1	
Central hole	2.32	217.2	9.1
Edge notch	4.00	213.1	7.0
Edge notch	5.00	213.1	7.0

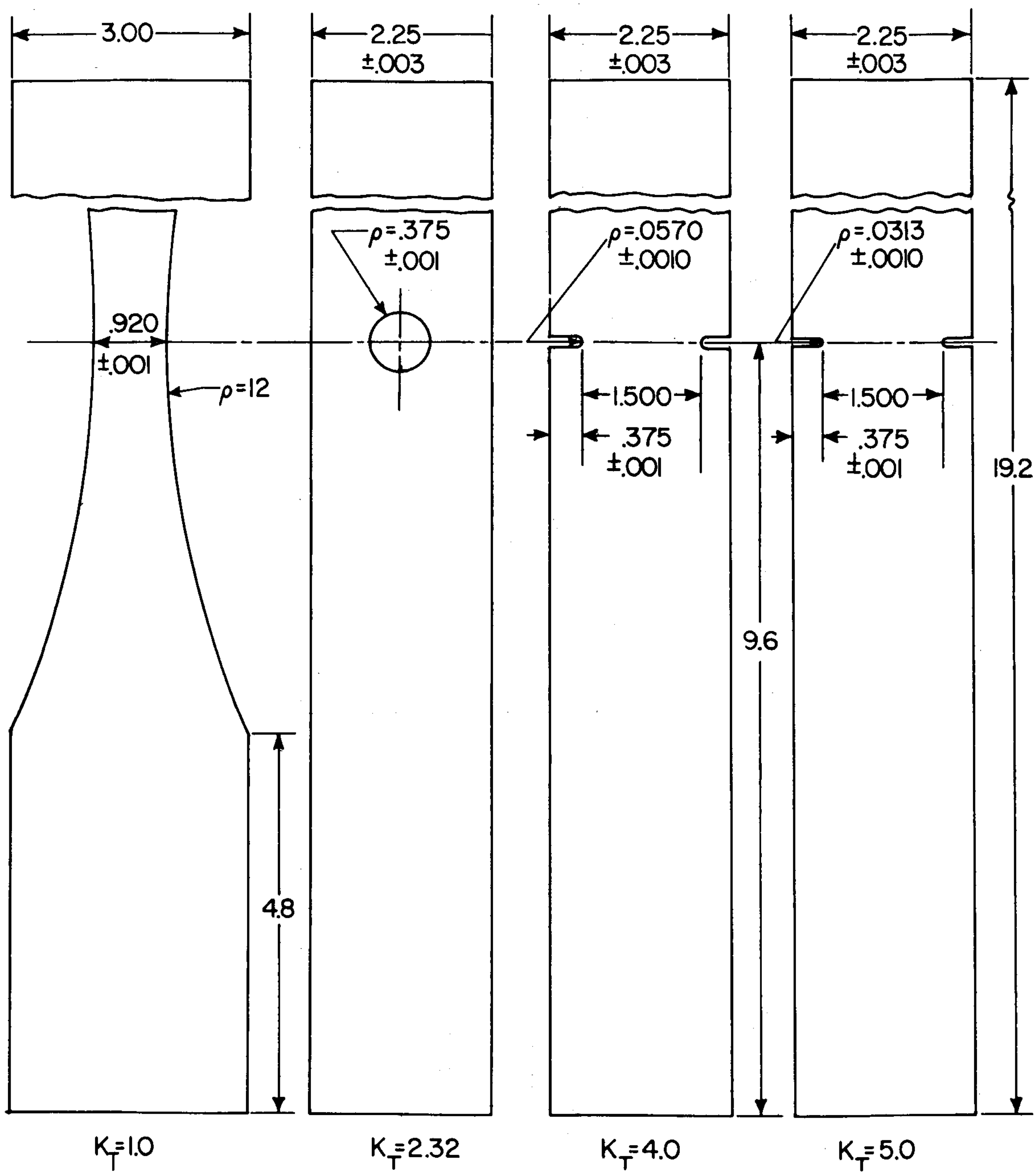

Figure 1.- Configurations of sheet specimens. All dimensions are in inches.

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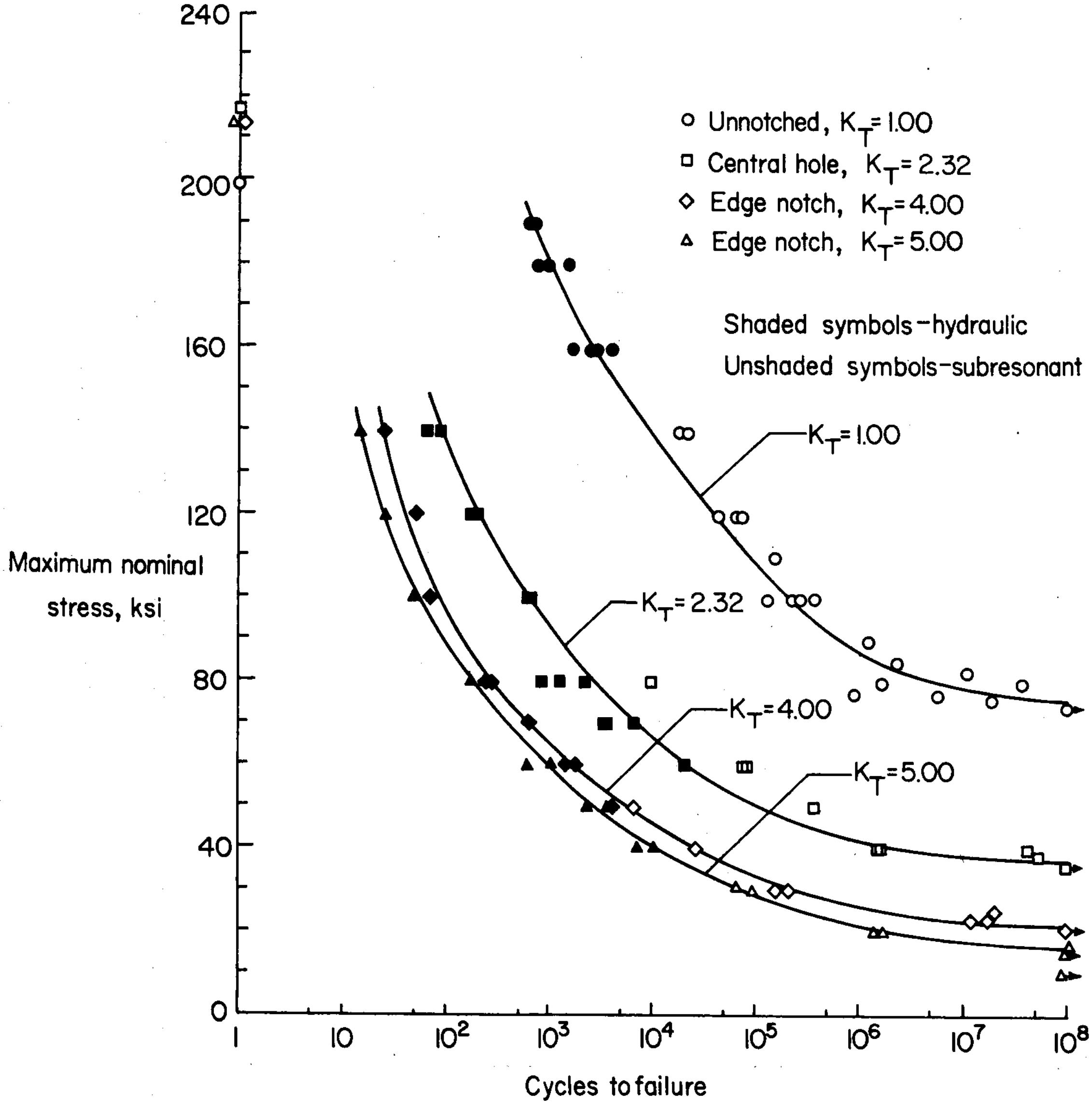

Figure 2.- Results of axial-load fatigue tests on notched and unnotched sheet specimens of 17-7 PH stainless steel in Condition TH 1050. R = -1.

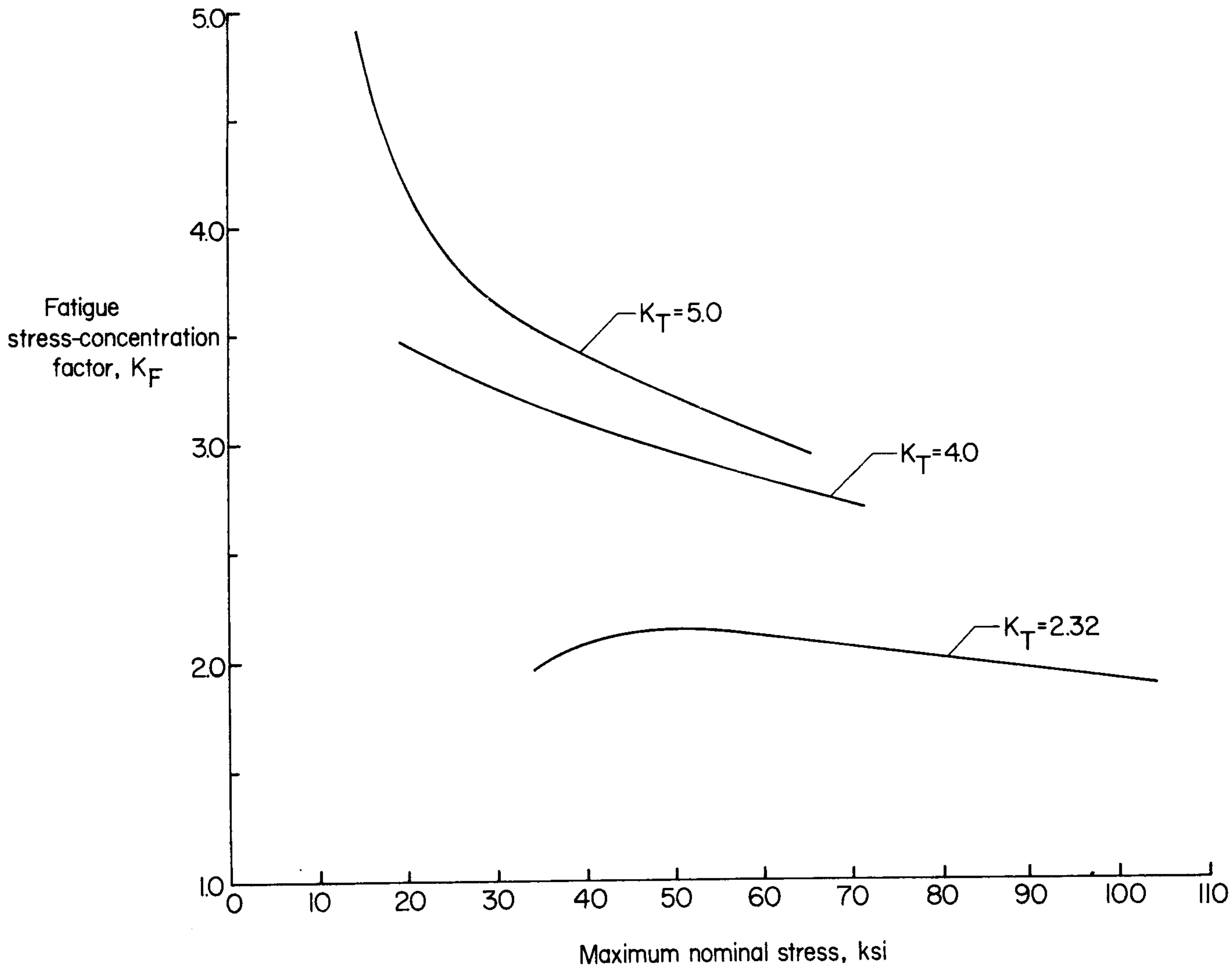

Figure 3.- Variation of fatigue stress-concentration factor with maximum nominal stress of notched specimens. R = -1.

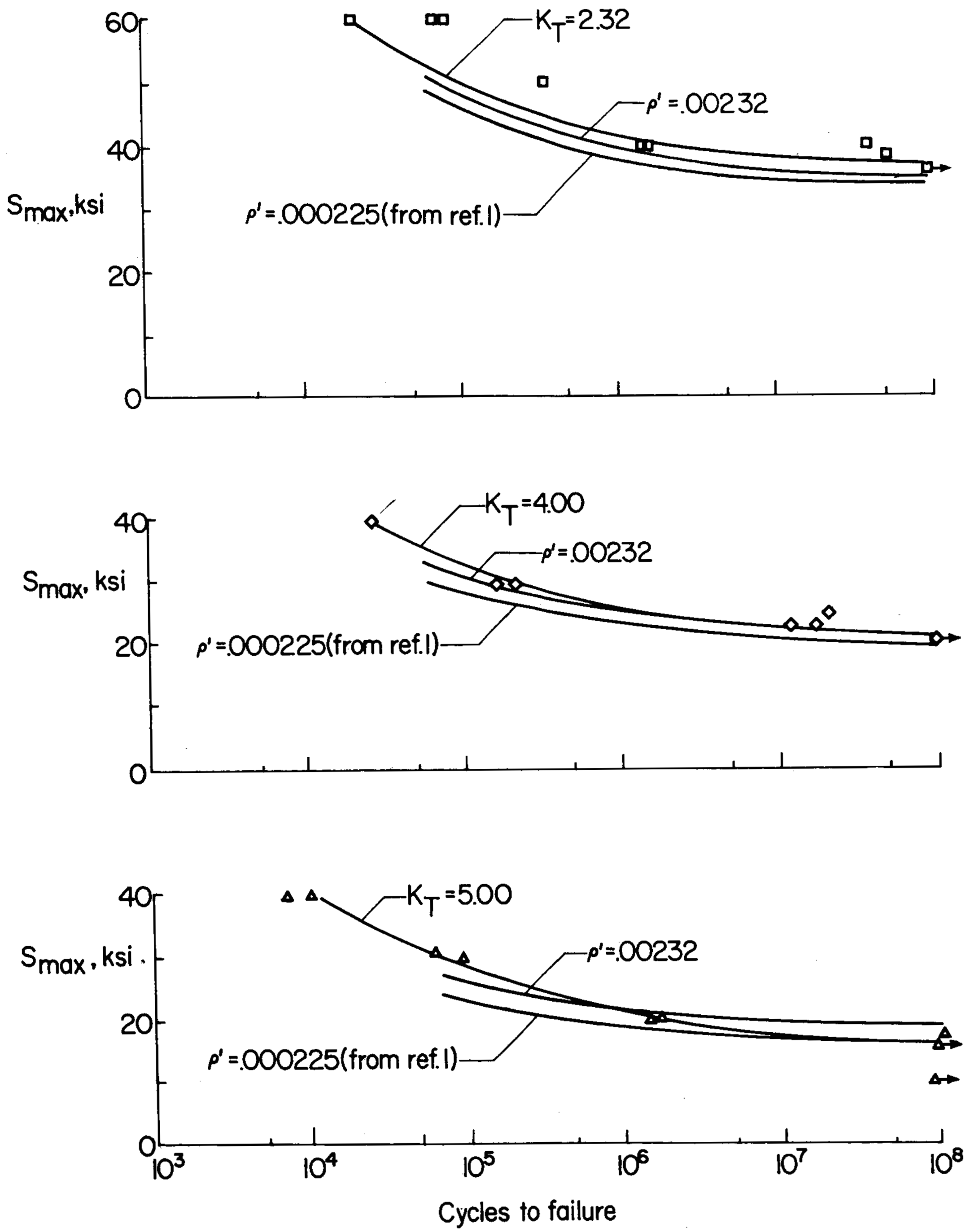

Figure 4.- Predictions of the fatigue behavior near the fatigue limit by use of the Neuber technical factor.