WADC TECHNICAL REPORT 55-18
SUPPLEMENT 1

DESIGN PROPERTIES OF HIGH-STRENGTH STEELS IN THE PRESENCE OF STRESS CONCENTRATIONS AND HYDROGEN EMBRITTLEMENT

Sup. 1. Effects of Hydrogen Embrittlement on High-Strength Steels (Fatigue Properties)

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FOREWORD

This report was prepared by Syracuse University under USAF Contract No. AF 33(616)-2362. The contract was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No.73605 "Design and Evaluation Data for Structural Metals" formerly RDO No. 614-13 "Design and Evaluation Data for Structural Metals", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. A. W. Brisbane as project engineer. This work was performed in the period between November 1954 and February 1955.

ABSTRACT

In Part II of this report data on the low-cycle rotating beam fatigue tests performed on hydrogen embrittled specimens of one heat of 4340 steel are presented and evaluated. The specimens were cathodically embrittled in a 10 percent sodium hydroxide solution, and tested on an R. R. Moore fatigue machine operated at approximately 250 rpm. All tests were limited to cycles ranging between 10 and 10,000.

The present report comprises a continuation of the work presented in Part I and as such it concerns itself with the same general purposes, namely, 1) the evaluation of hydrogen embrittlement of a steel heat treated to high strength levels and 2) the determination of suitable and sensitive means of evaluating such brittleness. While the low-cycle fatigue test reported here yielded valuable information, it is in no way as economical and sensitive as the static bend test reported in Part I.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. Whitmore
Technical Director
Materials Laboratory
Directorate of Research

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LIST OF ILLUSTRATIONS

SYMBOLS USED

K: Theoretical Stress Concentration Factor as derived by Neuber's theory.

E: Embrittled Specimens, i.e., specimens subjected to the hydrogen embrittling treatment described in the text.

U: Unembrittled Specimens, i.e., specimens not subjected to any embrittling treatment.

INTRODUCTION

The occurrence of premature service failures in high-strength steels is frequently a phenomenon caused by hydrogen absorbed by the steel during electroplating. (1)*

Most failures of this nature are sustained-load failures observed after a part was under an applied load for a certain length of time. It was shown in Part 1 of this report (2) that such failures also occur in a variety of laboratory tests and that the susceptibility of the steel condition as well as effects of various amounts of hydrogen are indicated by low strength and ductility in these tests. One of the important features of hydrogen embrittlenent is that it becomes more dangerous as the time of loading, to a constant stress in the laboratory tests, increases. These tests also confirmed that the dependance of hydrogen embrittlement upon the duration of loading can also be evaluated from tests performed with different rates of loading or straining. (1,3)

The present report relates to the occurrence of failures during repeated loading. No appraisal of the action of hydrogen under such loading conditions has been previously undertaken. In general, aircraft parts such as landing gears are subjected only to a rather limited number of repeated load cycles. Consequently, the tests reported on were limited to a low number of cycles, ranging between about 10 and 10,000. These tests are only of an exploratory nature. While a rather low-frequency, 250 rpm, was used for the rotating-beam fatigue test, this still comprises a high rate of loading, namely less than about 0.06 seconds from zero to maximum tension in each cycle. This renders the loading rate for these tests intermediate between impact and the fastest rate used in the study of the static properties. This also explains the quite small effects disclosed here.

*Bracketed numbers refer to Bibliography.

EXPERIMENTAL PROCEDURE

Material:

The material studied was 4340 steel received as 9/16 in. dia. bar stock having the following chemical composition:

C	Mn	P	S	Si	Ni	Cr	Mo
0.38	0.71	0.017	0.02	0.30	1.90	0.96	0.24

Test Specimen:

The fatigue specimen used is shown in Figure 1. All specimens were rough machined to approximately 0.015 in. oversize. Following heat treatment, the specimen was mechanically polished in a direction parallel to its axis by turning the specimen against a fine polishing belt moving parallel to the specimen and tightly pressed along its contour. This resulted in a smooth mirror-like surface on all specimens. In the case of notched specimens, the milder notch used (K = 2.5) was ground to proper dimensions, while the sharp notch (K = 8) was machined by means of a high-speed steel tool. Table I shows the radius of the notch contour corresponding to each of the stress-concentration factors as calculated by Neuber's theory.

An optical comparator with 62.5 diameter magnification was used to measure the notch diameters and the notch radii to the nearest 0.001 inch. In the case of specimens with a stress-concentration factor of 8, where the notch radius was less than 0.001 inch, see Table I, the measurements were only approximate. However, maximum care was taken to insure that the radius was slightly less than, if not equal to, 0.001 inch.

Heat Treatment:

Specimens were austenitized at 1600°F in graphite blocks and in a controlled atmosphere to reduce decarburization, oil quenched and tempered at temperatures ranging between 400°F and 800°F for one hour, to obtain the desired strength levels of between 290,000 psi to 210,000 psi. Tempering was followed by air cooling. Figure 2 shows the hardness of this heat of 4340 steel as a function of tempering temperature.

Hydrogen Impregnation and Content:

Hydrogen was cathodically introduced into the specimen in an electrolyte of 10 percent sodium hydroxide. A current density of approximately 1/2 ampere per square inch for 1/2 hour was used. This corresponds to the "medium hydrogen content" referred to in Part 1 of this report. The analysis for hydrogen content showed that the smooth specimen had 0.5 PPM for the 210,000 psi strength level, 0.4 PPM for the 270,000 psi strength level and 0.6 PPM for the 290,000 psi strength level. The notched specimen (K = 8) had 0.8 PPM for the 270,000 psi strength level. Hydrogen analysis of other strength level notched specimens was not made.

The specimens were embrittled in groups of five. Following embrittlement, the specimens were placed in a solution of dry ice and acetone (-80°C) to minimize diffusion of hydrogen. The time interval between the charging and the beginning of testing of any specimen of a set of five varied between 15 minutes and one hour.

Fatigue and Notch-Fatigue Tests:

All fatigue tests were of the rotating beam type performed at room temperature on an R. R. Moore fatigue machine operated by means of a geared-down motor at approximately 250 rpm. All tests were limited to cycles ranging between approximately 10 and 10,000 cycles.

Each series of tests on either smooth (K = 1) or notched (K = 2.5 and 8) hydrogen-embrittled specimens (Symbol E) consisted of 5 specimens. In addition, a number of specimens (3 to 5 each) were used to establish some basic curves for unembrittled (Symbol U) material. Because of the low scattering the various fatigue tests appear well established in spite of the small number of specimens tested.

EXPERIMENTAL RESULTS

The S-N curves for hydrogen-embrittled material have the general appearance expected for low-cycle fatigue curves of steels heat treated to high strength levels, Figures 3 to 7.

For the higher strength levels the curves for smooth specimens are located entirely above those for notched specimens, while for the 210,000 psi strength level the notch-fatigue curve intersects the smooth-fatigue curve at approximately 200 cycles. Between 1,000 and 10,000 cycles the notch-fatigue strength was found to be roughly one half the smooth-fatigue strength, which is in agreement with the results of unembrittled specimens, see Figures 3 to 7.

Compared to the results for unembrittled specimens, an adverse effect of hydrogen was usually observed in the range of lowest cycles. An exception is the smooth-fatigue strength of the 210,000 psi strength level, Figure 8 which was found to be identical for both embrittled and unembrittled specimens. In all other instances, Figures 8 and 9, the effect of hydrogen appears to vanish at between 1,000 to 10,000 cycles, for both smooth and notched specimens.

Figure 10 shows the smooth-fatigue strength at various number of cycles plotted against tempering temperature. Data from a different heat of 4340 steel for numbers of 10^5 cycles and higher (4) are included for comparison purposes. Figure 11 shows the same type of a plot for notched ($K = 8$) specimens. It is seen from Figures 10 and 11 that the effect of hydrogen on the smooth-fatigue and notch-fatigue strength is of concern only at tempering temperatures below 700°F (230,000 psi) and a life of 1,000 cycles or less. Further, it is seen that the effect of hydrogen on the notch-fatigue strength is not definitely more pronounced than it is on the smooth-fatigue strength. These statements, apply only to the loading rate used in these tests. From the test data discussed in Part I of this report considerably increased effects may occur at greatly reduced strain rates.

DISCUSSION AND CONCLUSIONS

It is seen from Figure 11, that for the notched-fatigue specimens the worst condition of embrittlement occurs for a tempering temperature of 500°F. This is in agreement with the results of the notch-tension test reported in Part 1 of this report, where the maximum reduction of strength occurred at tempering temperatures of 500 and 600°F.

The few fatigue tests performed for the same steel conditions but different stress concentrations cannot be evaluated because of the lack of corresponding unembrittled-fatigue curves. Their results, however, are in general agreement with those of unembrittled specimens tested in either tension or fatigue at high-cycle numbers (4). The static notch strength was found to be higher the lower the stress concentration is, while the fatigue strength and endurance limit varied only slightly within the range of stress concentration investigated ($K = 3$ to 8).

Furthermore, as already mentioned before, an extrapolation of the above discussed fatigue-test data to performance at lower strain rates appears improper. A considerably more extensive investigation covering the strain-rate variable would be necessary to obtain larger effects which would permit a more accurate evaluation of the role of hydrogen embrittlement during repeated loading. Even then, there is no evidence available to date which would enable a correlation of test data and service performance. Undoubtedly, such factors, as e.g. section size and type of loading (bending vs. tension) will play a different role in the presence than in the absence of hydrogen.

As a tool for the evaluation of hydrogen embrittlement, the normal, high-speed fatigue test is of little value. Also, the high cost involved in the preparation of specimens makes the test uneconomical. Among all the tests examined the static bend test appears to be the most practical as was pointed out in Part I of this report.

BIBLIOGRAPHY

(1) 1953 Sachs, G. and Beck, W., Survey of Low-Alloy Aircraft Steels Heat Treated to High-Strength Levels, Part 1 - Hydrogen Embrittlement, WADC Technical Report 53-254.

(2) 1954 Klier, E. P., Muvdi, B. B. and Sachs, G., Design Properties of High-Strength Steels in the Presence of Stress Concentration and Hydrogen Embrittlement, Part 1 - Effects of Hydrogen Embrittlement on High-Strength Steels (Static Properties), WADC Technical Report 55-18.

(3) 1954 Carls, M., Beck, W., Klier, E. P. and Sachs, G., An Investigation of the Effects of Strain Rate on Hydrogen Embrittlement, WAL Technical Report 53-893/154-14, Part 4.

(4) 1955 Sachs, G., Muvdi, B. B. and Klier, E. P., Design Properties of High-Strength Steels in the Presence of Stress Concentrations, WADC Technical Report 55-103 (incomplete).

APPENDIX

The numerical data obtained in this investigation are presented as follows:

Table I	- Stress-Concentration Factors and Corresponding Notch Radii for Notch Fatigue Rotating Beam Specimens.
Tables II and III	- Results of Tests on Embrittled Specimens.
Table IV	- Results of Tests on Unembrittled Specimens.

TABLE I

STRESS-CONCENTRATION FACTORS AND CORRESPONDING NOTCH RADII FOR NOTCH FATIGUE ROTATING BEAM SPECIMENS

D - IN.	d - IN.	STRESS-CONCENTRATION FACTOR, K	NOTCH RADIUS, r IN.
0.265	0.188	2.5	0.010
		8	0.0007

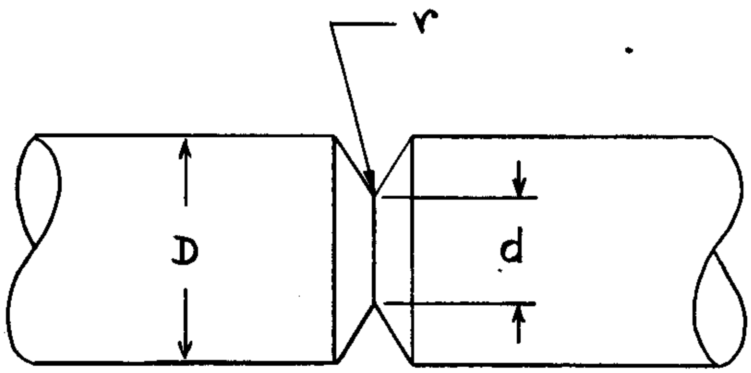


TABLE II

ROTATING BEAM LOW CYCLE FATIGUE DATA FOR HYDROGEN EMBRITTLED SMOOTH AND NOTCHED SPECIMENS FROM 9/16 IN. DIA. 4340 (1600°F/OIL)

10% NaOH SOLUTION: 447 MA. PER SQ. IN. FOR 1/2 HR.

TEMPERING TEMP. AND STRENGTH LEVEL	STRESS - 1000 PSI		LIFE - CYCLES	
	K = 1	K = 8	K = 1	K = 8
400°F (290,000 PSI)	342.0	280.0	30	5
	279.0	216.0	200	86
	244.0	230.0	325	142
	211.0	189 0	2,790	255
	153.0	126.0	(10,040)	1,969
600°F (250,000 PSI)	307.0	297.0	48	20
	268.0	214.0	94	274
	199.0	198.0	970	345
	157.0	163.0	8,128	1,040
	151.0	125.0	14,520	2,357
800°F (210,000 PSI)	306.0	325.0	28	20
	270.0	283.0	61	50
	246.0	213.0	104	312
	180.0	157.0	3,394	1,142
	155.0	128.0	6,259	2,488

( ) Did Not Fracture

TABLE III

ROTATING BEAM LOW CYCLE FATIGUE DATA FOR HYDROGEN EMBRITTLED SMOOTH AND NOTCHED SPECIMENS FROM 9/16 IN. DIA. 4340 (1600°F/OIL)

10% NaOH SOLUTION: 447 MA. PER SQ. IN. FOR 1/2 HR.

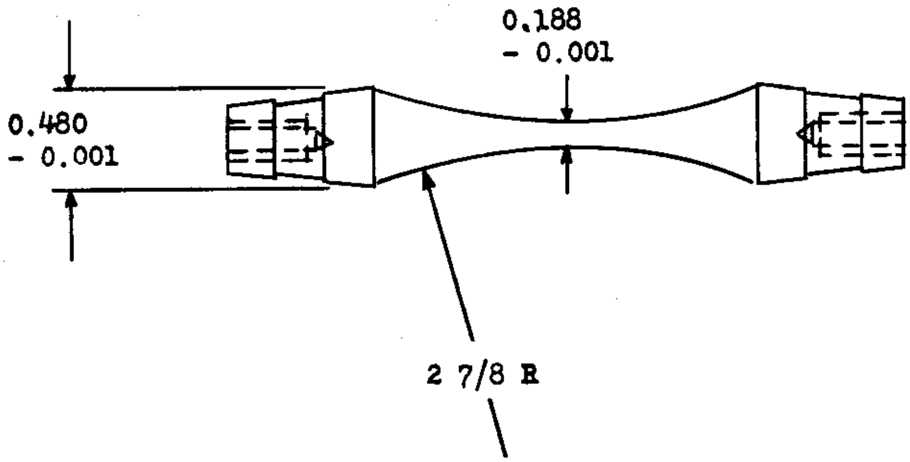
TEMPERING TEMP. AND STRENGTH LEVEL	STRESS - 1000 PSI			LIFE - CYCLES		
	K = 1	K = 2.5	K = 8	K = 1	K = 2.5	K = 8
500°F (270,000 PSI)	305.0	306.0	295.0	34	11	0
	335.0	276.0	254.0	60	19	6
	270.0	214.0	215.0	320	177	78
	233.0	153.0	156.0	990	937	722
	157.0	123.0	127.0	8,724	2,092	1,297
700°F (230,000 PSI)	328.0	293.0	307.0	26	15	10
	277.0	243.0	222.0	105	96	226
	243.0	213.0	161.0	319	246	837
	188.0	183.0	177.0	2,620	439	923
	122.0	124.0	96.0	(10,000)	1,862	5,795

( ) Did Not Fracture

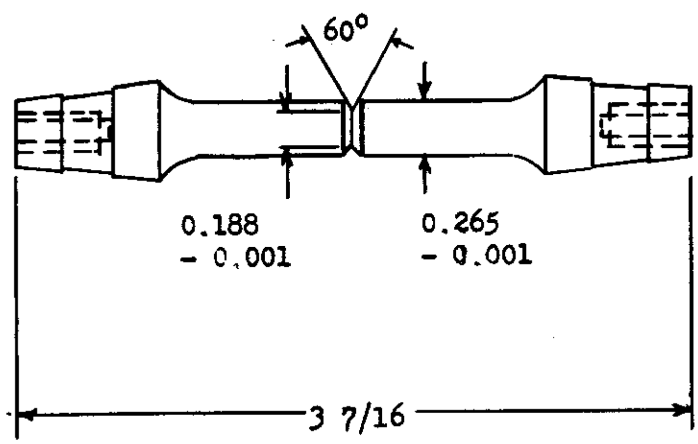
TABLE IV

ROTATING BEAM LOW CYCLE FATIGUE DATA FOR UNEMBRITTLED SMOOTH AND NOTCHED SPECIMENS FROM 9/16 IN. DIA. 4340 (1600°F/OIL)

TEMPERING TEMP. AND STRENGTH LEVEL	STRESS - 1000 PSI		LIFE - CYCLES	
	K = 1	K = 8	K = 1	K = 8
400°F (290,000 PSI)	338.0	307.0	252	10
	276.0	222.0	703	95
	246.0	131.0	1,666	1,090
		111.0		1,840
		98.0		2,800
600°F (250,000 PSI)		360.0		30
		308.0		80
		217.0		515
		193.0		556
		134.0		1,674
800°F (210,000 PSI)	276.0	325.0	50	61
	246.0	280 0	225	80
	185.0	215.0	2,625	423
		158.0		1,551
		122.0		2,914



SMOOTH FATIGUE SPECIMENS



NOTCHED FATIGUE SPECIMENS

FIG. 1 ROTATING BEAM FATIGUE SPECIMENS USED IN THIS INVESTIGATION.

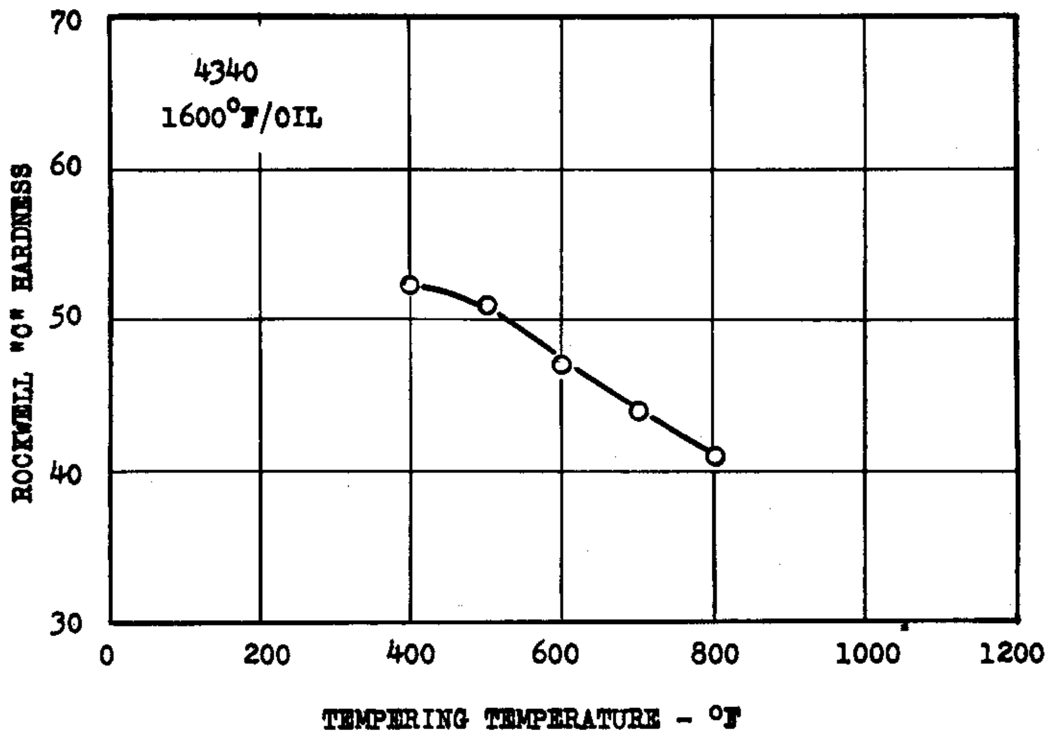


FIG. 2 HARDNESS AS A FUNCTION OF TEMPERING TEMPERATURE FOR THE 4340 STEEL STUDIED.

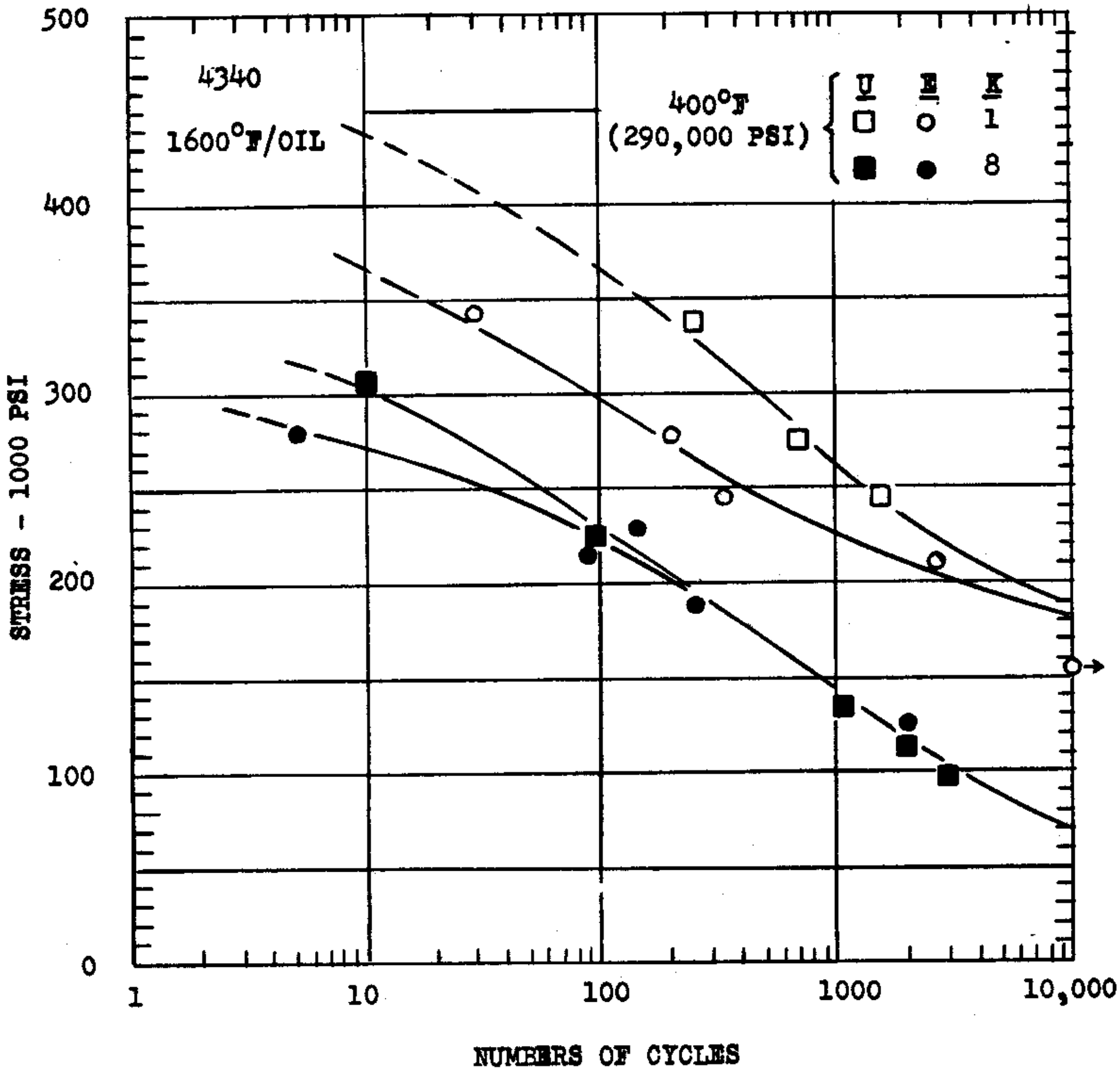


FIG. 3 S-N CURVES FOR UNEMBRITTLED AND EMBRITTLED, SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 9/16 INCH DIAMETER 4340 STEEL.

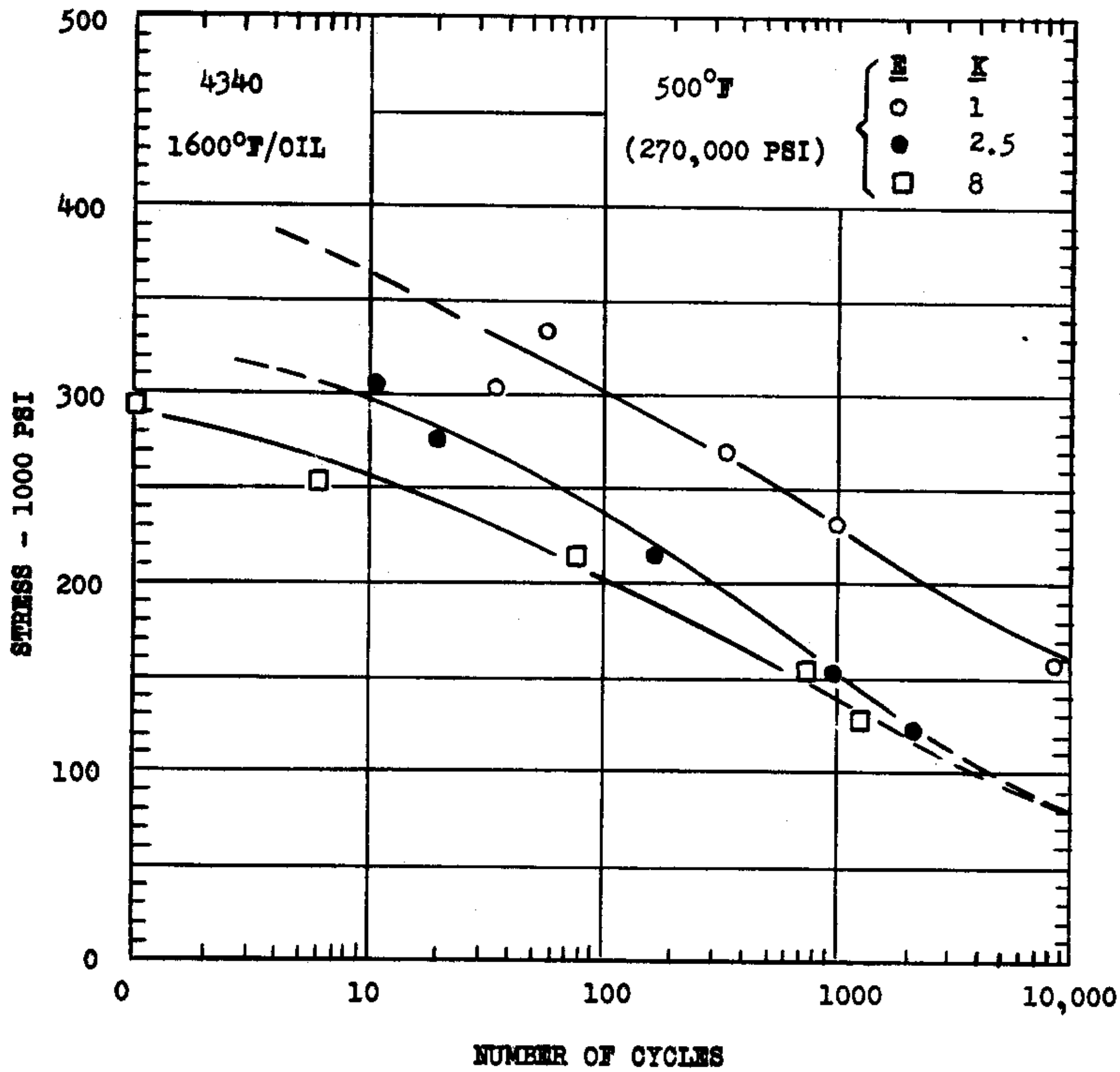


FIG. 4 S-N CURVES FOR EMBRITTLED, SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 9/16 INCH DIAMETER 4340 STEEL.

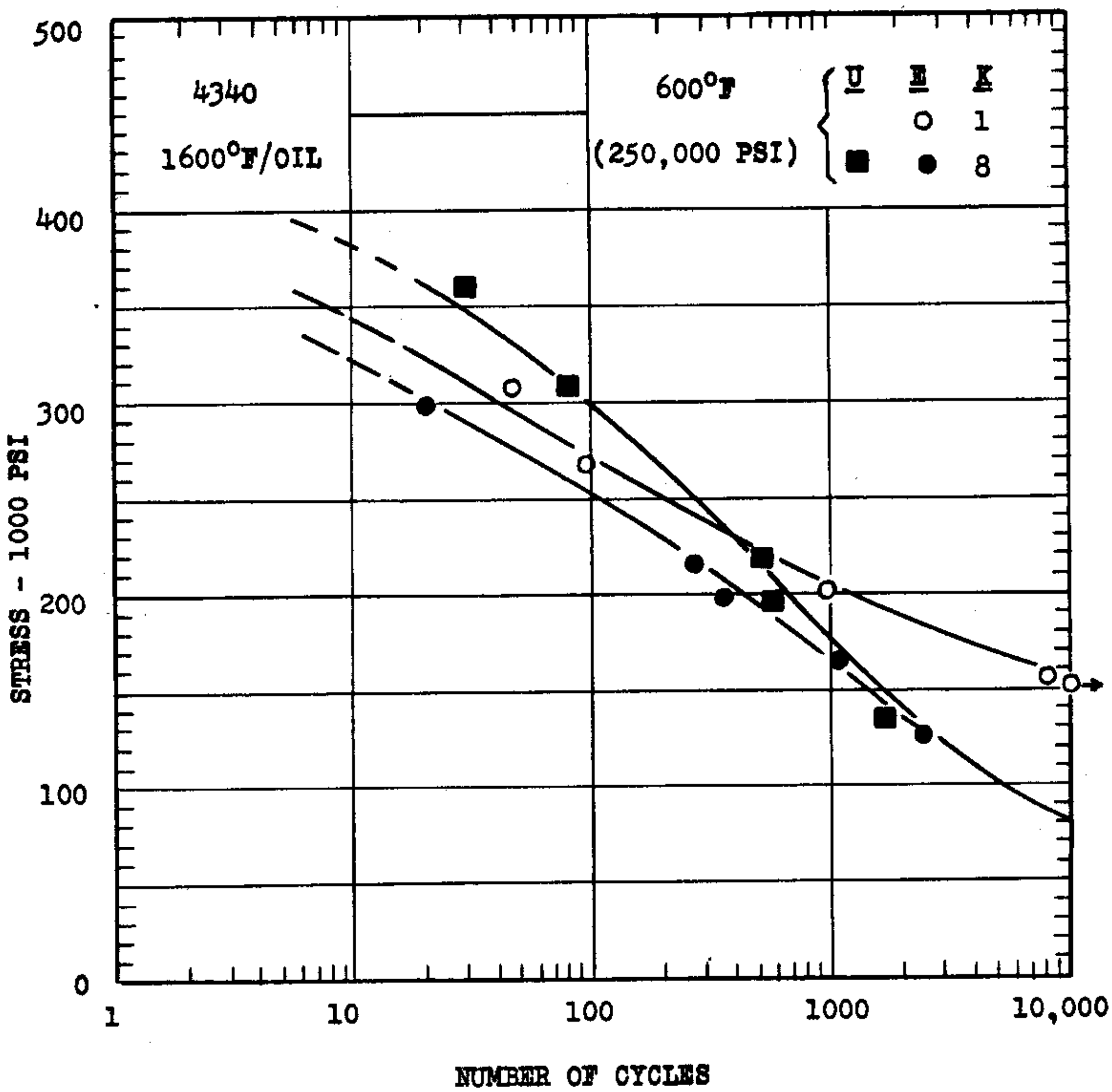


FIG. 5 S-N CURVES FOR UNEMBRITTLED AND EMBRITTLED SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 9/16 INCH DIAMETER 4340 STEEL.

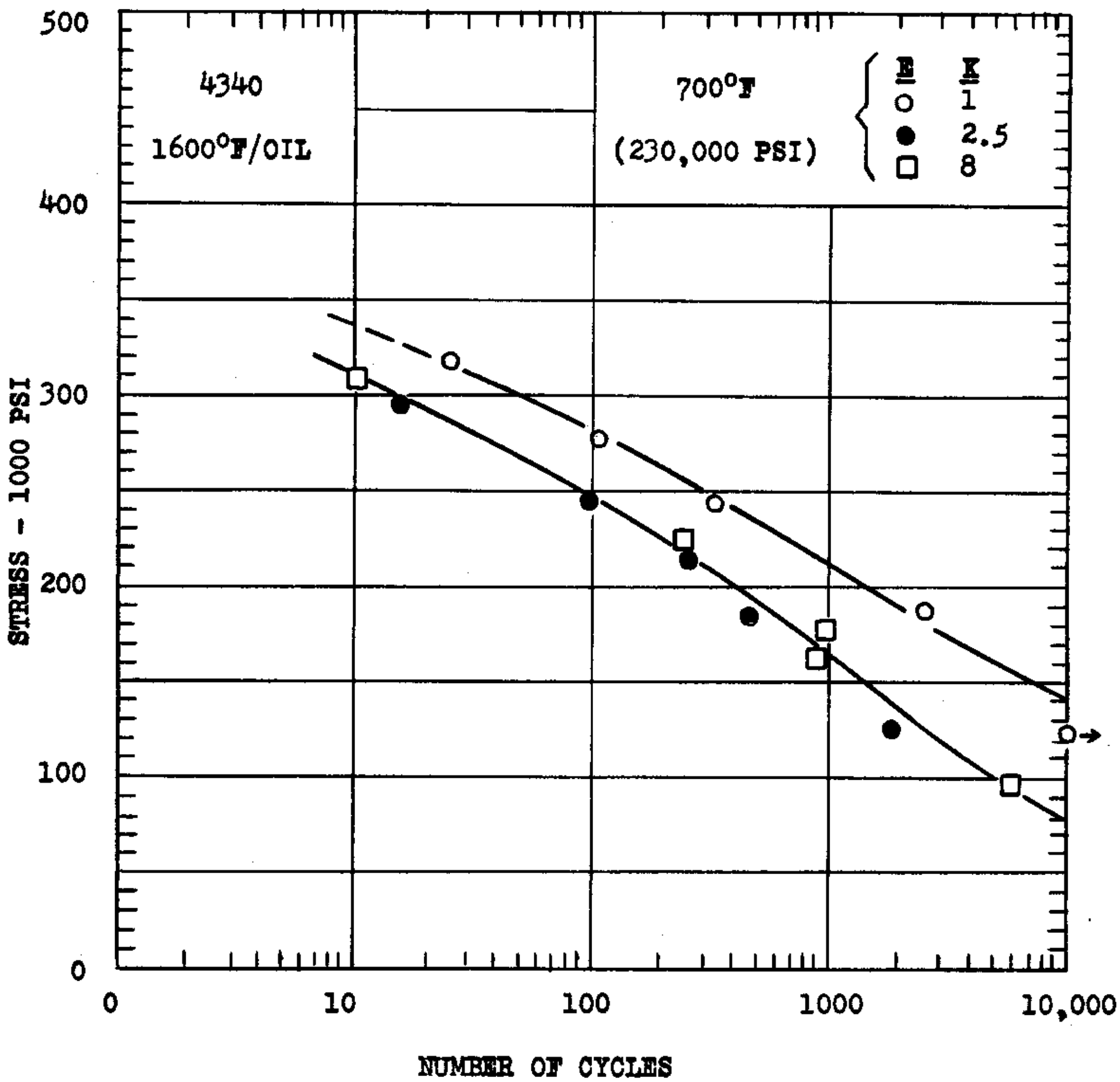


FIG. 6 S-N CURVES FOR EMBRITTLED, SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 9/16 INCH DIAMETER 4340 STEEL.

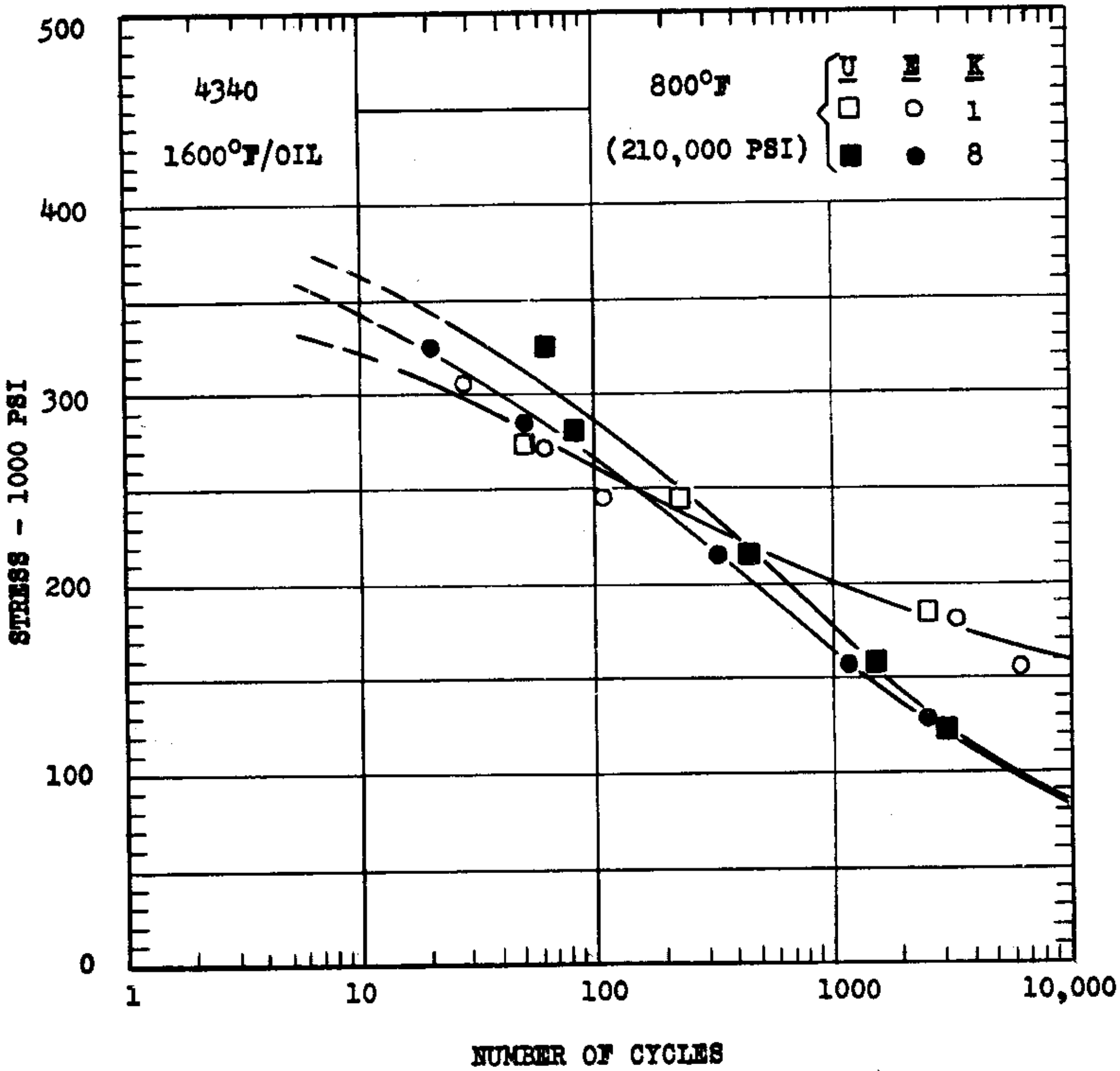


FIG. 7 S-N CURVES FOR UNEMBRITTLED AND EMBRITTLED, SMOOTH AND NOTCHED ROTATING BEAM FATIGUE SPECIMENS FROM 9/16 INCH DIAMETER 4340 STEEL.

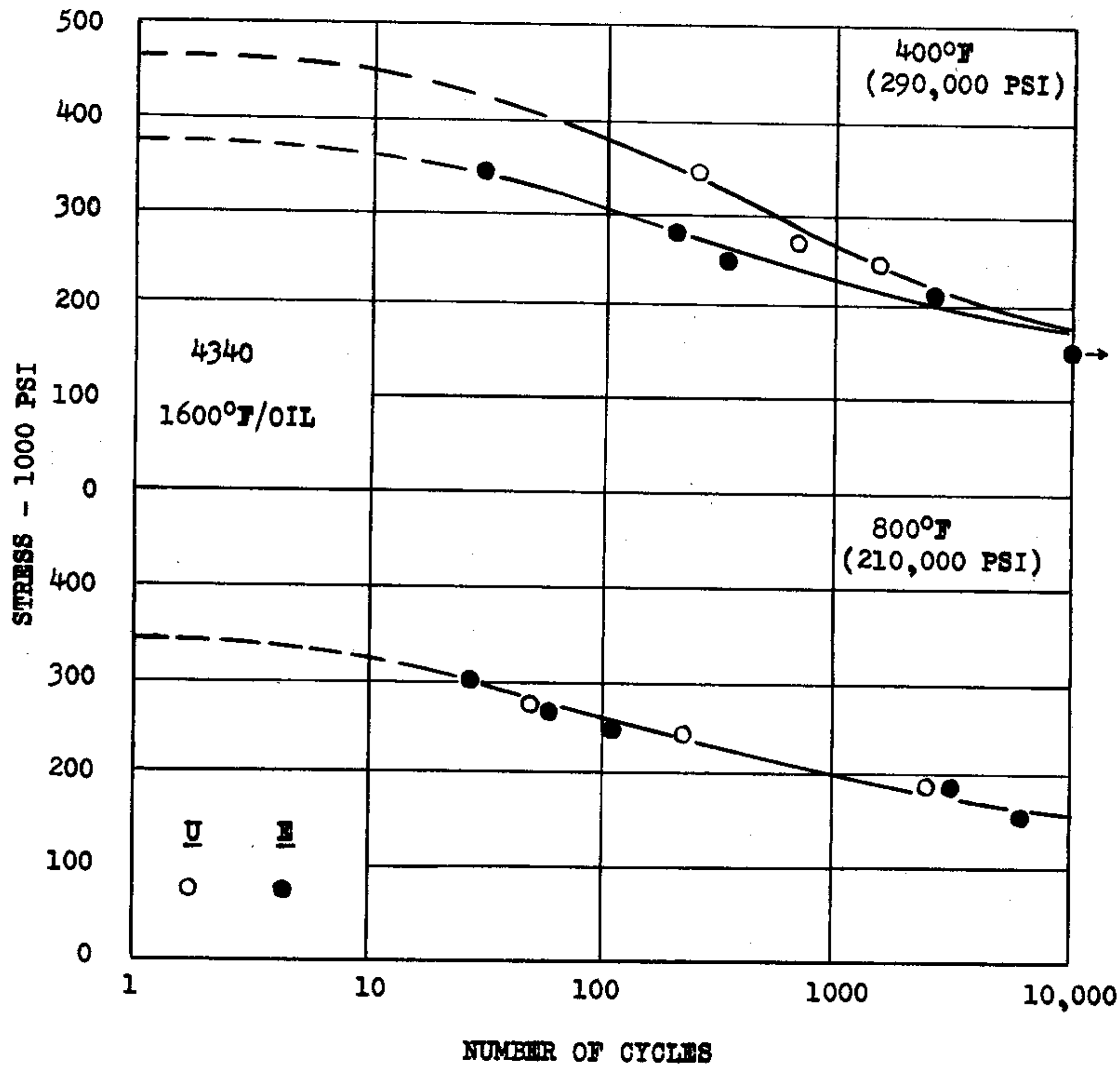


FIG. 8 S-N CURVES FOR UNEMBRITTLED AND EMBRITTLED, SMOOTH ROTATING BEAM FATIGUE SPECIMENS FROM 9/16 INCH DIAMETER 4340 STEEL.

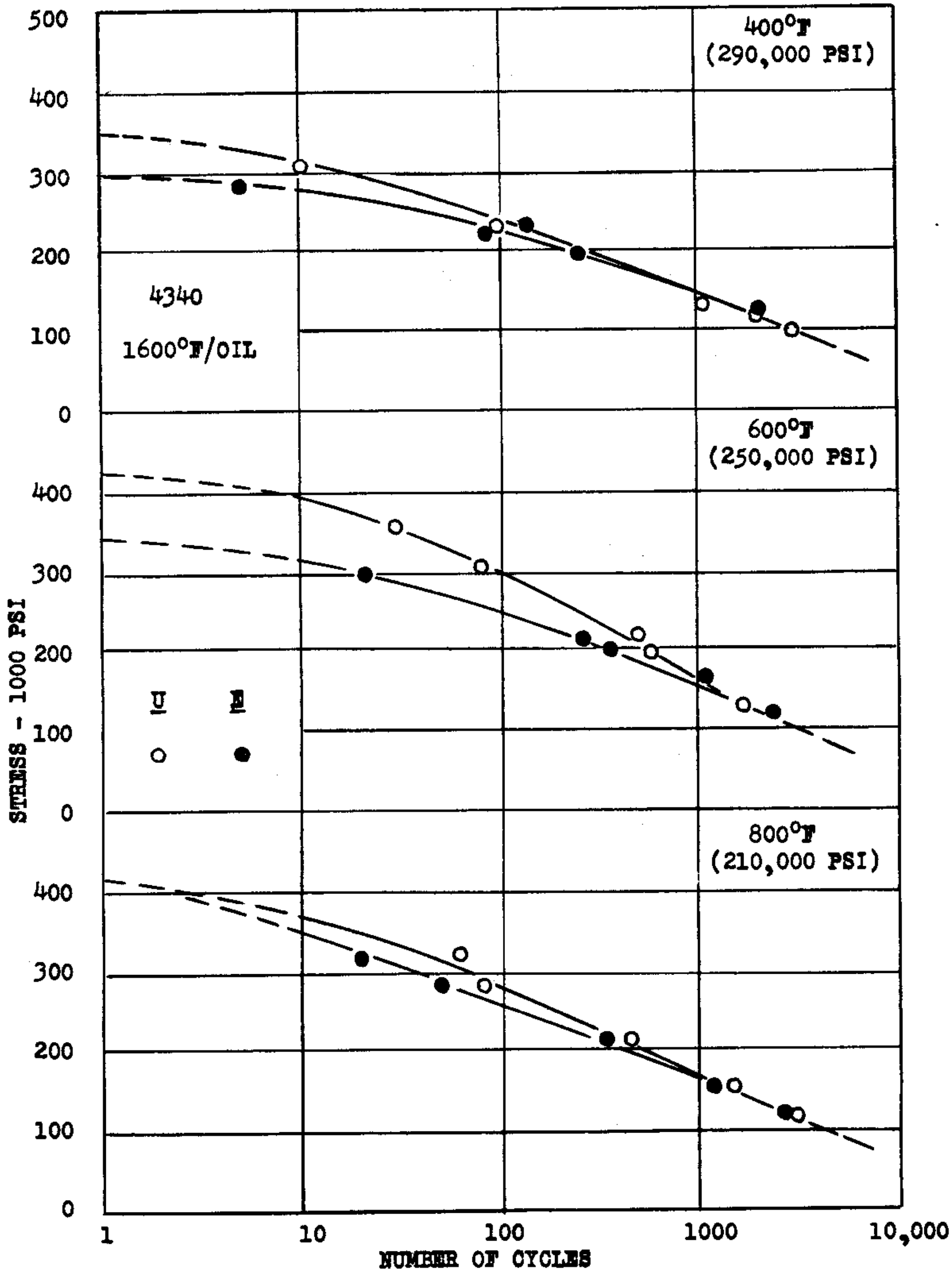


FIG. 9 S-N CURVES FOR UNEMBRITTLED AND EMBRITTLED, NOTCHED (K=8) ROTATING BEAM FATIGUE SPECIMENS FROM 9/16 INCH DIA. 4340 STEEL.

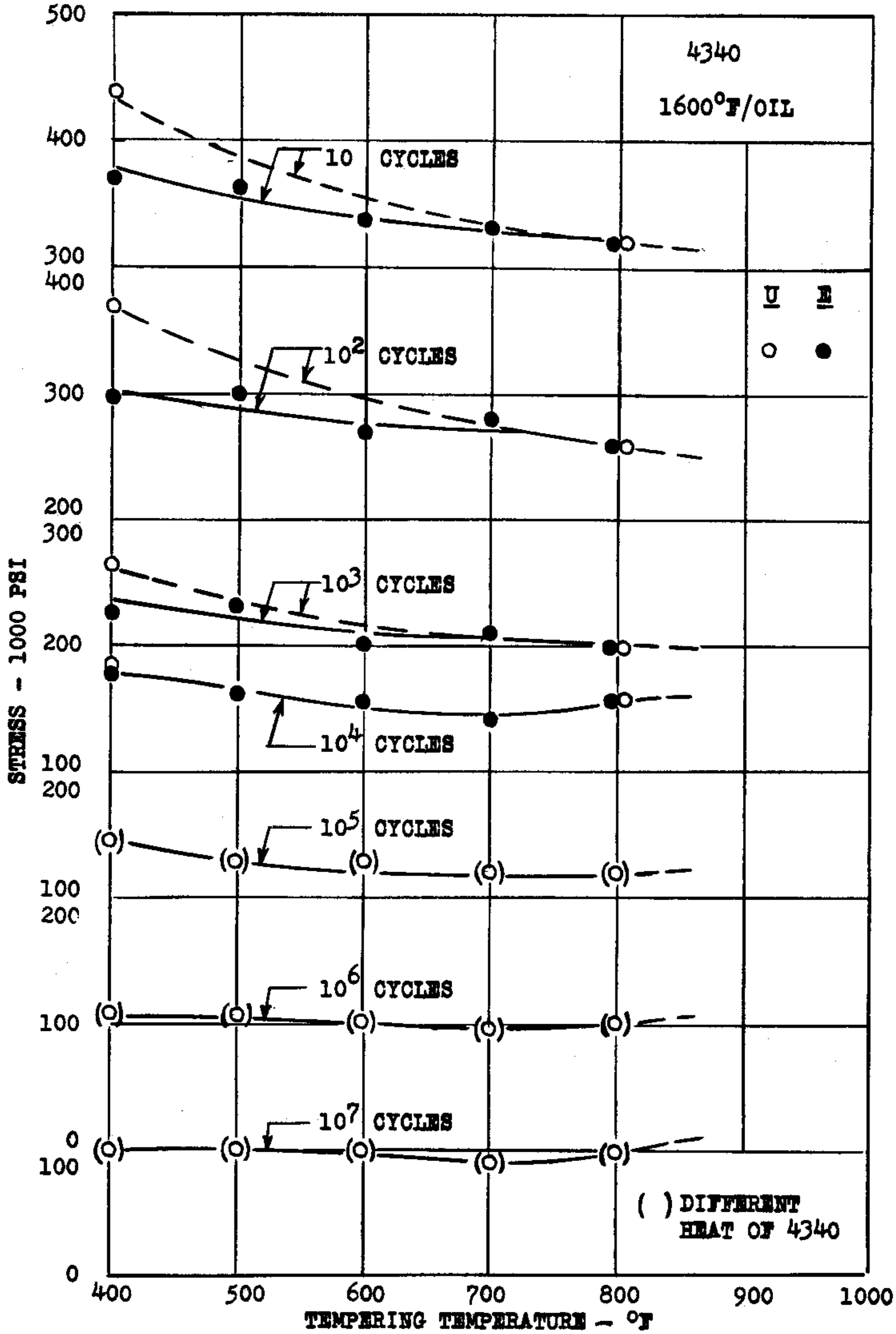


FIG. 10 ROTATING BEAM FATIGUE STRENGTH AS A FUNCTION OF TEMPERING TEMPERATURE FOR SMOOTH SPECIMENS FROM 9/16 INCH DIA. 4340 STEEL.

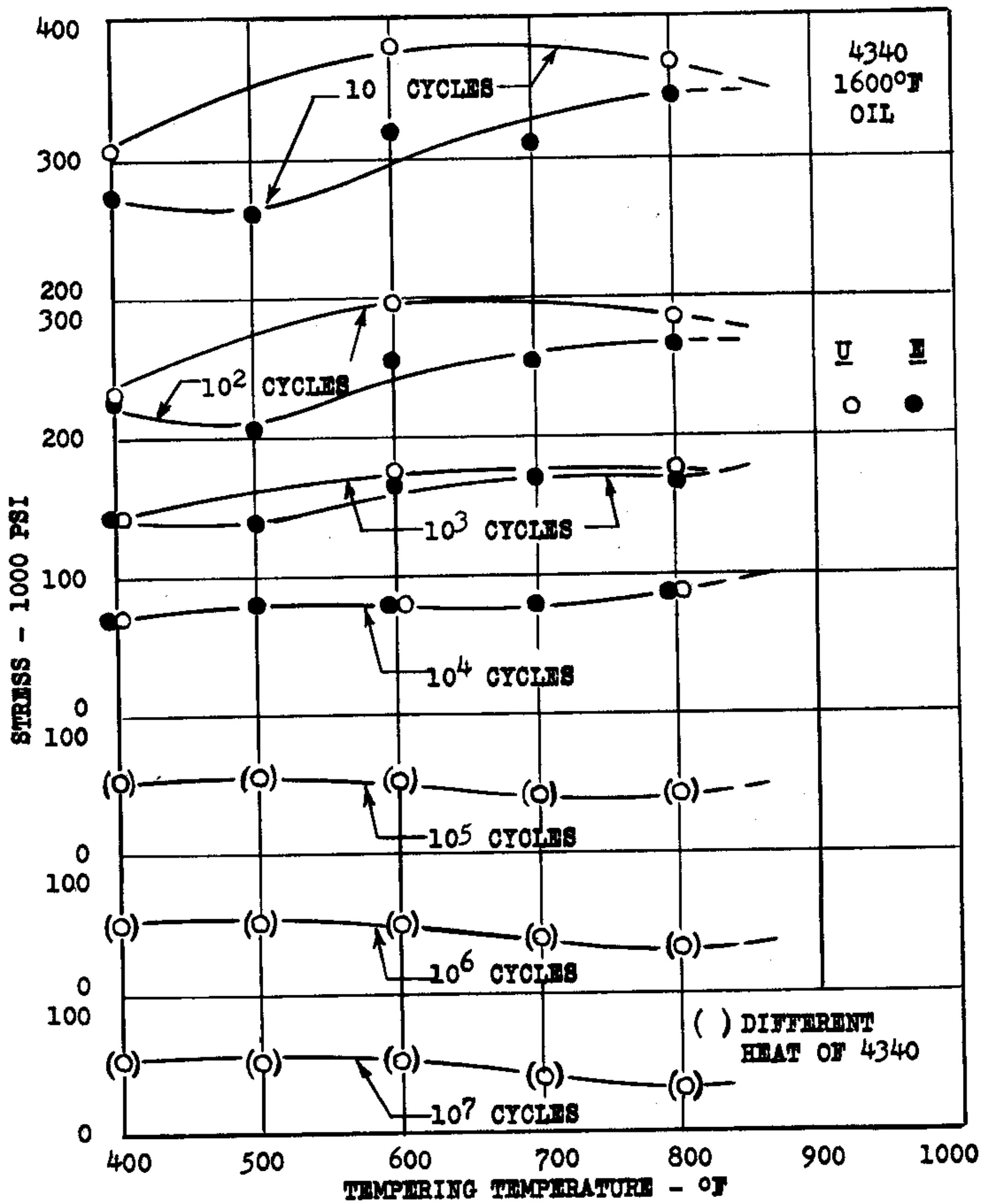


FIG. 11 ROTATING BEAM FATIGUE STRENGTH AS A FUNCTION OF TEMPERING TEMPERATURE FOR NOTCHED SPECIMENS (K=8) FROM 9/16 DIAMETER 4340 STEEL.