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WADC TECHNICAL REPORT 54-488
PART 1

STRESS-RUPTURE, FATIGUE AND NOTCH SENSITIVITY PROPERTIES OF HIGH TEMPERATURE ALLOYS

Part 1. S-816 Alloy

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FOREWORD

This report was prepared by the University of Minnesota under USAF Contract No. AF 33(038)-20840. The contract was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No. 73604, "Fatigue Studies", formerly RDO No. 614-16, "Fatigue Properties of Structural Materials", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Walter J. Trapp acting as project engineer.

In addition to the authors, the following personnel of the University of Minnesota contributed to this work. F. D. DeMoney served as project engineer during the first stages of this project and most of the test work was performed under the direct supervision of R. Erickson. H. F. Binder was responsible for the metallographic work and L. Huppert, C. Knudson, L. Lease, R. Lenhart served as technicians. Drafting work and manuscript preparation were by B. Gulbrandson, M. Chapin, D. Schultz, and H. Thomas.

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ABSTRACT

Fatigue and stress-rupture data obtained under various combinations of mean and alternating axial stress and static creep data are presented and discussed for S-816 alloy at 75°, 1350°, 1500° and 1650° F. Tests were performed under axial stress on unnotched specimens and specimens having theoretical notch sensitivity factors of 2.4 and 3.4. The data are presented as S-N curves and stress range diagrams to show the effect of specimen notch, temperature, alternating-to-mean stress ratio, and stress magnitude on the fatigue and stress-rupture properties.

The role of both creep and fatigue as factors in rupture is discussed with particular reference to temperature and alternating-to-mean stress ratio.

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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SECTION I. INTRODUCTION

The fatigue and creep properties of S-816 alloy reported in this paper were investigated as a part of a program on the notch sensitivity of heat resistant alloys at elevated temperatures. Besides S-816 alloy, this program involves 6% Molybdenum alloy, 16-25-6 Timken alloy, Stellite 31 (X-40), Waspalloy and M-252, for which data will be presented in later reports.

Creep and stress rupture tests under static conditions performed at the Wright Air Development Center are included in this report for completeness.

Although the creep of unnotched specimens during the fatigue tests at various stress ratios was recorded, these data are not included in this report. They will, however, be presented in WADC TR 54-488, Pt 2 to cover the results on all the materials listed above.

SECTION II. TEST PROGRAM

Fatigue tests were conducted at 75°, 1350°, 1500°, and 1650° F and stress magnitudes adjusted to cause failure in a range from 10^3 to 2.8×10^7 cycles (0.3 minutes to 130 hours). Static creep and stress-rupture tests were performed at 1350° and 1500° F only and stresses adjusted for failure up to 500 hours.

In order to cover the stress ratios ranging from static tension to reversed stress fatigue as uniformly as possible, selected steps of alternating-to-mean stress ratio are used rather than selected steps of mean stress. The ratio of alternating stress to mean stress (alternating-mean ratio "A") selected for this work are A = 0 (static tension), 0.25, 0.67, 2.0, and ∞ (reversed axial stress).

Three types of specimens were used with stress concentration factors of K_t = 1.0, 2.4, and 3.4.

SECTION III. TEST MATERIAL AND SPECIMENS

3.1 Test Material

The test material of S-816 alloy, type 1153 was furnished by the Allegheny Ludlum Steel Corporation in bars of 3/4 inch diameter, annealed and ground.

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The chemical composition as furnished by the manufacturer is shown in Table I.

The specimen blanks were heat treated by the University of Minnesota as follows: one hour at 2300° F and quench in water, age at 1400° F for 16 hours and furnace cool.

The micrographs of the solution treated material, presented in Figure 1, show the uniformity of precipitated carbides. Figure 2 shows the alloy in the solution treated and aged condition with precipitation at the grain boundaries caused by aging. The grain size corresponds to ASTM Standards No. 5.

The static properties of the heat treated material are listed in Table I. The hardness of the specimen was 26.6 - 28.6 Rockwell "C".

3.2 Specimen Type and Preparation

3.2.1 Specimen Type. Three types of specimens were used to obtain a range of stress concentration. The fatigue specimens are illustrated in Figure 3, the creep and stress rupture specimens in Figure 4. The only difference between fatigue specimens and creep specimens are the threaded ends; the test sections are alike. All the specimens have the same diameter at the test section or at the root of the notch respectively.

The theoretical stress concentration factor shown for each specimen in Figures 3 and 4 was computed from Neuber's charts.

3.2.2 Specimen Preparation. The specimens were machined in three steps: (1) rough machining, (2) finish machining, and (3) finish polishing.

In the first step the specimens were roughed out to 13/32 inch diameter at the test section and the threads ground. In the second step, the test section was finished with a 3/4 inch square carbide tool bit using an emulsified oil in water solution as lubricant on the first cuts. The initial depth of cut was 0.025 inch, whereas the final cuts were somewhat less than this. The test section was finish turned to 0.255 - 0.254 inch diameter by this procedure. In the final operation, step 3, the finish polishing of the specimens was performed in a specially adapted tool grinder with an adjustable belt sander. The angle of contact between the specimen and the belt can be changed to produce the desired direction of the polishing scratches. The final operation consists of two steps, a roughing and a finishing operation.

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In the roughing operation a 240 grit, 1/4 inch wide silicon carbide belt was used at a belt speed of 300 feet per minute with the specimen rotating at approximately 260 rpm. Approximately eight to ten passes of this belt were used, producing polishing marks in a circumferential direction. In this operation, all the rough tool marks resulting from the finish machining operation are removed. The finish polishing operation was performed with a 400 grit, 1/4 inch wide silicon carbide belt using the same belt speed as in the previous polishing procedure but a slightly lower specimen speed. Furthermore, the angle of the belt to the specimen was changed so that the final polishing scratches were parallel to the specimen axis (perpendicular to the expected fatigue cracks). In this procedure approximately 0.0005 inch is removed from the diameter by approximately six passes. Kerosene was used as a coolant.

The notched specimens received the same machining operation as outlined in step 1 and step 2 for the unnotched specimens. The notches are then cut with a carbide tool to an oversize of 0.020 inch in diameter. This oversize is taken off by grinding. Finally the roots of the notches were lapped in nearly axial directions to avoid marks and microcracks caused by machining in the direction of the expected fatigue cracks. In this lapping process the specimen was rotated at approximately 30 rpm. A cylindrical copper rod having a diameter slightly less than that of the notch was mounted on a chuck at right angles to the axis of the specimen and rotated by the motor spindle at about 600 rpm. A polishing compound was used consisting of one part of 600 grit Alumina in 5 parts of 10W lubricating oil and 4 parts kerosene. A force of approximately 0.5 pounds between the lap and specimen was used in all cases. The notches were lapped until all circumferential scratches were removed. This procedure produced a surface finish of about 10 micro-inches.

SECTION IV. TESTING EQUIPMENT AND TEST PROCEDURE

4.1 Testing Equipment

The testing equipment used in this investigation consists of the axial stress fatigue testing machine and a temperature controller-creep recorder.

The axial stress fatigue machines used in this project are similar to those described in a previous publication (1). These machines have been

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developed for fatigue, dynamic creep, and stress rupture tests at elevated temperatures. Alternating force up to ± 5000 pounds is produced by a 3600 rpm centrifugal force type of mechanical oscillator, and preload up to 10,000 pounds can be applied by means of calibrated springs which are kept at a constant force during the test by an automatic follow-up system. Seven machines of this type were used in this project; each S-N curve generally represents data from more than one machine.

The specimen was heated in a long electrical resistance furnace which is a modification of that described in (1). The method of shunting for maintaining a temperature gradient of less than ± 5° F over the entire test length was the same as described previously. The Brown "Electroline" temperature control system was used to maintain constant temperature. This system consists of a Brown "Electronik" circular chart recorder-controller which actuates a "Modutrol" motor geared to an autotransformer.

Both static and dynamic creep were measured by motion of the lower grip relative to a machine column. A linear variable differential transformer was used to measure this extension. For the first hour of the test, creep recording was taken continuously with a separate recorder. Thereafter the output of the transducer was recorded on the temperature controller-recorder by using a time clock and switching unit which samples the transducer output periodically (30 minute intervals) during the course of the test.

4.2 Testing Procedure

Two thermocouples were attached in close contact with the specimen surface at the test section with a 24 gage chromel wire.

After the specimen had been at the test temperature for one hour and the grip assembly tightened, the following loading sequence was used. In tests under combined static and alternating stresses (ratios A = 0.25, 0.67, and 2.0), the static or mean stress component was applied first at a loading rate of about 17,000 psi per minute. The alternating stress component was applied gradually by increasing the motor speed slowly in seven seconds. However, when large damping was encountered at the higher stress levels the time required to reach full speed (3600 rpm) was extended to 15 to 30 minutes so as to avoid specimen overheating. In reporting the data, time to failure is defined from the instant when full load (static plus alternating) is reached.

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SECTION V. RESULTS AND DISCUSSION

The fatigue data obtained are listed in Tables II, III, IV, and V plotted in Figures 5, 6, and 7. The S-N fatigue diagrams shown in these figures are plotted on the basis of the logarithm of the maximum or crest stress S_c during the stress cycle versus the logarithm of the number of cycles and hours to failure, one curve being plotted for each ratio A . The crest stress S_c is used in these plots instead of the alternating stress S_a or mean stress S_m in order to permit inclusion of both static and reversed stress data.

In plotting the data for the S-N curves only those tests which had fatigue failure in the test section and which had no previous stress history were plotted in order to preserve clarity and readability of the graphs. Therefore, not all the data listed in the tables are plotted in the S-N figures.

From the S-N curves the effect of stress concentration, temperature, and alternating-mean ratio on the fatigue behavior can readily be observed. With the exception of the figures at 1500° F and alternating-mean ratio of 0.67, the S-N curves of the notched specimens begin with a larger gradient than those of the unnotched specimens. In a certain range of the specimen life the gradient decreases rapidly and from thereon the curve continues relatively flat and does not exhibit a definite fatigue limit. S-N curves of unnotched specimens exhibit this knee after a larger number of cycles than those of the notched specimens. For reversed stress the knee in the S-N curve of the notched specimens shifts to a smaller number of cycles with increasing temperature. In most cases the S-N curve is in the flat range after 2×10^7 cycles or 100 hours at 3600 rpm.

The difference in ordinate between the S-N curve of the unnotched specimens and that of the notched specimens decreases with decreasing alternating-mean ratio A. At an alternating-mean ratio of 0.25 the S-N curve of the notched specimens may even lie above that of the unnotched specimens. This tendency can be explained by the fact that with decreasing alternating-mean ratio the static creep effects become increasingly dominant over fatigue effects, and at a ratio of 0.25, failure occurs primarily due to creep. However, creep is very much reduced by the three dimensional stress condition in the notched specimens which results in the higher strength of the notched specimens with respect to the unnotched ones. This behavior is even more significantly illustrated by the following stress range diagrams.

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Figure 8 shows the effect of temperature on the fatigue strength under reversed stress at 1.08×10^7 cycles (50 and 100 hours life) for the three types of specimens. The effect of temperature is smaller for the severely notched specimens than for the unnotched specimens.

Some of the creep curves of the unnotched specimens at 1350° and 1500° F which were obtained by the Materials Laboratory of the Wright Air Development Center are shown in Figure 9. The stress-rupture data for unnotched and notched specimens at 1350° and 1500° F are plotted in Figure 10. This diagram indicates the higher strength of the notched specimens with respect to the unnotched ones. The difference in strength is larger at 1350° F than at 1500° F. Since in the logarithmic plot the lines for unnotched and notched specimens are nearly parallel, the difference in life decreases with increasing lifetime. Furthermore, both types of notched specimens exhibit the same lifetime for a given stress which means that the severity of notches has no effect on the creep strength within a range of $K_t = 2.4$ to $K_t = 3.4$.

The fatigue data diagramed in Figures 5, 6, and 7 are replotted on a stress range basis in Figure 11. The ordinate indicates the alternating stress and the abscissa, the mean stress. Each curve indicates the combinations of alternating and mean stress which results in failure after a definite number of cycles in the range from 2.16×10^5 to 2.16×10^7 (1, 50, and 100 hours of specimen life). The series of inclined lines which pass through zero indicate the ratio A of alternating-to-mean stress used.

Comparison of the stress-range diagrams for the unnotched and notched specimens show that stress concentration causes a decrease in fatigue strength and an increase of stress-rupture strength. This can be explained by the fact that fatigue failure can occur in localized regions where the stress concentration is a maximum. However, for creep failure, creep deformation must occur over the entire cross section of the specimen, which in the notched section is very much reduced by the nonuniform stress distribution and the three dimensional stress state inside the specimen. The confinement of reduction in cross sectional area preceding fracture is also a factor in notch strengthening under static force.

These stress-range diagrams also show that the mean stress reaches a maximum at an intermediate stress ratio A. In other words, the allowable mean stress first increases with increasing stress ratio and then decreases beyond a certain value. This indicates that superposition

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of an alternating load on a static preload reduces creep damage and thereby increases the life of the specimen. This effect can only occur in the region where failure occurs primarily due to creep, and fatigue has only a secondary effect. In the transition region, two separate S-N curves occur at the same mean stress; in other words, two different fatigue strengths for a given time are possible at the same mean stress. This effect is more likely to be apparent in tests at constant ratio A than in tests under constant mean stress and variable alternating stress. If the S-N curves are investigated for a given constant mean stress only, a wide scatterband would appear in the transition region described above and no definite S-N curve could be drawn even if statistical approaches were applied.

The effect described above is more pronounced at higher temperatures where creep becomes more dominant and increases the transition region. For the same reasons this effect increases with increasing number of cycles, or increasing time respectively. The stress-range diagram in Figure 11, shows that the same effect tends to occur in notched specimens, but is shifted to higher temperatures.

The reduction of creep damage in S-816 by superimposed alternating stress was reported by Lazan (1); it can also be observed in other high strength materials such as for example in SAE 4340 (2) or B50R 207 alloy (3).

In Figure 12 the stress-range data of Figure 11 are replotted on a dimensionless basis. In this diagram the abscissa is the ratio of mean stress to rupture strength at 100 hours and the ordinate scale is the ratio of alternating stress to fatigue strength at 2.16×10^6 cycles (100 hours). The curves in Figure 12 show trends similar to those shown in Figure 11. The effect of superimposing alternating stress on mean stress at low ratios A is quite apparent.

In order to show the effect of ratio A and temperature on the maximum stress, S_c, the fatigue data have been replotted in Figures 13 and 14. In these figures the abscissa is the ratio R, which is trough (or minimum) stress S_t divided by crest (or maximum) stress S_c. Ratio R is used to avoid infinities. The relationship between the ratio R and the ratio A is $R = (1-A) / (1 + A)$, the values of ratio A being given along the upper abscissa. The curves for unnotched specimens at 1350° F in Figure 13 and those for unnotched and notched specimens at 1500° F in Figure 14 show a definite maximum. This maximum separates the influence zone of the fatigue from that of creep. With decreasing ratio A the maximum allowable stress increases at first, indicating the greater prominence of "fatigue" over "creep" in controlling rupture life. After

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reaching the maximum, the inverse effect is obvious. The effect of temperature on the ranges is apparent by comparing both figures.

The two types of diagrams shown in Figures 11 and 12, and in Figures 13 and 14 are combined and shown in Figure 15 in the form of modified Goodman diagrams. In this type of diagram the abscissa indicates the mean stress and the ordinate maximum (crest) and minimum (trough) stresses. The stresses in the abscissa and ordinate are plotted to the same scale. In this diagram the locus of steady stress (A=0) is at 45° to the mean stress axis. This type of diagram shows not only the relationships of alternating stress to mean stress, and crest (or maximum) stress to mean stress, but also the effect of stress ratio on crest stress and stress amplitude.

The dip in the curves indicates the prominence of creep over fatigue. This effect of creep damage increases with increasing temperature. It is also present in notched specimens but occurs in a smaller degree at the test temperatures of 1350° and 1500° F. The slenderness of the diagrams for the notched specimens demonstrates the notch effect in the fatigue range for the various stress ratios. Comparison of the diagram for the unnotched specimens with that for the notched ones also shows the increase of the rupture strength by the stress concentration effect.

The effect of temperature on the fatigue strength reduction factor K_f and the notch sensitivity index q under reversed stress condition ($A = \infty$) is shown in Figure 16. The index q is defined in the figure. The curves indicate that the notch sensitivity of the specimens with $K_t = 2.4$ decreases continuously with increasing temperature while the notch sensitivity of the specimens with $K_t = 3.4$ has a minimum at 1350° F.

The three dimensional plots of Figures 17 and 20 are an attempt to show how the notch sensitivity is affected by the number of cycles to failure and the ratio R for temperatures of 1350° and 1500° F. Figures 17 and 18 show the fatigue strength reduction factor and Figures 19 and 20, the notch sensitivity index q . These diagrams indicate that the number of cycles have a rather small effect on the notch sensitivity. In the stress rupture region (R = 1.0, or A = 0) the fatigue strength reduction factor K_f may even become smaller than one (and the notch sensitivity index q negative) showing again the increase of creep strength associated with the inhomogeneous stress distribution and the three dimensional stress state.

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At the stress ratio of approximately R = 0.33 or A = 2.0 and at 1350° F the notch sensitivity index and the fatigue strength reduction factor have a peak. This results from the superposition of the effect of fatigue and that of creep and indicates that the effect of fatigue is dominant over a wider range of stress ratios than at 1500° F.

It should be emphasized that the low notch sensitivity results are based on the rupture stress and not on a deformation limit. In the fatigue tests at a stress ratio of A = 0.25, deformations of over 25 per cent at 1350° F and over 30 per cent at 1500° F have been measured at fracture. Even at a ratio A = 0.67 the specimen exhibited a deformation of 14 per cent and more at 1500° F and 100 hours life. If total creep were used as criteria for defining notch sensitivity then a different conclusion than that listed above would result. Although specimen creep was recorded, only the rupture data are reported in this paper, the analysis of the creep data under fatigue conditions being planned for a future report.

SECTION VI. SUMMARY AND CONCLUSIONS

A series of axial stress tests were undertaken on S-816 alloy to determine the effect of stress concentration at various combinations of alternating and mean stress on the fatigue, stress-rupture, and creep properties at 75°, 1350°, 1500°, and 1650° F. The stress range from static tension to reversed stress was covered in five alternating-to-mean ratios A, and stress combinations were varied to produce rupture in the range from 10^4 to 2.8×10^7 cycles (0.5 to 130 hours).

The basic fatigue data are presented in S-N curves and stress range diagrams to show the effect of stress concentration and temperature on fatigue life. The relative effect of creep and fatigue on rupture and how these factors are affected by temperature is shown in diagrams and discussed.

The following conclusions are based on the fatigue and notch sensitivity data presented in this report.

1. The knee in the S-N curve occurs at a smaller number of cycles for the notched specimens than for the unnotched ones. With increasing temperature the knee in the S-N curves for reversed stress moves to the left (to smaller number of cycles). In most cases the S-N curve is reasonably flat after 2×10^7 cycles or 100 hours life.

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2. The difference in stress for a given number of cycles between the S-N curves of the unnotched and that of the notched specimens decreases with decreasing alternating-mean ratio A.

3. The fatigue properties are reduced as the temperature is increased for all ratios A . The fatigue strength under reversed stress decreases continuously with increasing temperature. The effect of temperature decreases with increasing stress concentration of the notches.

4. The severity of notches within a range of $K_t = 2.4$ to $K_t = 3.4$ has no effect on the static creep strength.

5. The notched specimens exhibit a smaller strength at high ratios A and a higher strength at small ratios A than the unnotched ones at the same temperature. The reason for this behavior is that at the high ratios A fatigue damage is predominant and determines the life of the specimen; whereas at small ratios A creep damage is primarily the cause of failure.

6. Under certain conditions at small ratio A the superposition of alternating stress on mean stress increases the life of the specimen. This effect is smaller in notched specimens than in unnotched ones and increases with increasing temperature.

7. The role of fatigue and creep as factors in rupture is a function of temperature, alternating-to-mean stress ratio and stress concentration factor. As the temperature increases, fatigue considerations become less important and creep factors predominate. The ratio A at which the dominating role changes from creep to fatigue depends on the test temperature and the stress concentration factor.

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3. "Static and Dynamic Creep-Rupture Properties of B50R 207 and B50R 311 Alloys," Department of Mechanics and Materials, University of Minnesota, Report to General Electric, June 1954.

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TABLE I

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF TEST MATERIAL

CHEMICAL COMPOSITION 1/

C	Mn	Si	Cr	Ni	Mo	S	P	Cb	W	Fe	Co	Ta
.397	1.12	.50	19.42	20.62	4.1	.018	.012	2.86	4.03	2.99	42.9	1.03

MECHANICAL PROPERTIES (Room Temperature)

Specimen Number	Mod. E 10^6 psi	Tensile Strength ksi	Yield Strength ksi	Elongation %
AO 2751	32.4	145.50	79.1	22
AO 2752	34.1	149.00	69.5	25

1/ Determination made by the Allegheny Ludlum Steel Corporation.

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TABLE II

TEST DATA FOR S-816 ALLOY AT 75° F

Specimen Number AO--AK	Ratio $S_a/S_m = A$	Applied Stress, KSI S_m	S_a	S_c	Time to Rupture Hours	Kilocycles	
3059	∞	0	55.0	55.0	143.6	31,020.	
2884	∞	0	55.0	55.0	53.8	11,620.	B.T.
2880	∞	0	58.0	58.0	51.6	11,150.	T.S.
2872	∞	0	58.0	58.0	51.3	11,080.	
2870	∞	0	60.0	60.0	15.4	3,326.	T.S.
2869	∞	0	60.0	60.0	10.6	2,290.	T.S.
2873	∞	0	62.0	62.0	29.9	6,458.	
2878	∞	0	62.0	62.0	9.2	1,987.	
2877	∞	0	64.0	64.0	23.0	4,968.	
2876	∞	0	66.0	66.0	8.4	1,814.	
2875	∞	0	66.0	66.0	0.67	144.7	
2874	∞	0	68.0	68.0	0.67	144.7	
2879	∞	0	68.0	68.0	0.02	4.32	
AO--AL							
2716	∞	0	27.0	27.0	239.4	51,810.	
2712	∞	0	30.0	30.0	29.6	6,394.	
2711	∞	0	40.0	40.0	4.0	864.0	
2720	∞	0	50.0	50.0	1.0	216.0	
2719	∞	0	60.0	60.0	0.35	75.6	
AO--AM							
2991	∞	0	23.0	23.0	123.8	26,741.	T.S.
2987	∞	0	24.0	24.0	71.0	15,340.	
2986	∞	0	27.0	27.0	9.1	1,966.	
2984	∞	0	30.0	30.0	10.8	2,333.	
2982	∞	0	34.0	34.0	2.8	604.8	
2977	∞	0	36.0	36.0	2.8	604.8	
2983	∞	0	45.0	45.0	0.83	179.3	

T.S. - Test Stopped.
B.T. - Broke in Threads.

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TABLE III

TEST DATA FOR S-816 ALLOY AT 1350° F

Specimen Number	Ratio $S_a/S_m = A$	Applied Stress, KSI S_m	S_a	S_c	Time to Rupture Hours	Kilocycles	
AO--AK							
2855	∞	0	40.0	40.0	140.9	30,430.	T.S.
2863	∞	0	41.5	41.5	145.6	31,450.	T.S.
2859	∞	0	42.0	42.0	0.019	4.10	T.R.
2861	∞	0	42.5	42.5	0.025	5.40	T.R.
2857	∞	0	45.0	45.0	0.01	2.16	T.R.
AO--AL							
2676	∞	0	25.0	25.0	112.8	24,370.	T.S.
2690	∞	0	26.5	26.5	100.0	21,600.	T.S.
2678	∞	0	28.0	28.0	2.6	561.6	
2677	∞	0	32.0	32.0	0.3	64.8	
2687	∞	0	34.0	34.0	0.15	32.4	
2688	∞	0	38.0	38.0	0.1	21.6	
AO--AM							
2978	∞	0	19.0	19.0	143.5	30,996.	T.S.
2980	∞	0	20.0	20.0	3.0	648.	
2990	∞	0	21.0	21.0	140.3	30,348	T.S.
2975	∞	0	21.0	21.0	3.7	799.2	
2511	∞	0	22.0	22.0	100.1	21,622.	T.S.
2972	∞	0	23.0	23.0	0.95	205.2	
3007	∞	0	23.0	23.0	0.54	116.6	
2974	∞	0	24.0	24.0	0.84	391.0	
2973	∞	0	24.0	24.0	0.67	144.7	
2507	∞	0	25.0	25.0	4.6	993.6	
2510	∞	0	27.5	27.5	0.42	90.7	
2509	∞	0	29.0	29.0	0.24	51.8	
2970	∞	0	31.0	31.0	0.11	23.7	
2508	∞	0	34.0	34.0	0.11	23.7	
AO--AK							
3084	2.0	20.0	40.0	60.0	90.4	19,526.	
3645	2.0	21.0	42.0	63.0	15.8	3,413.	
3643	2.0	21.7	43.3	65.0	1.6	345.6	
3667	2.0	23.3	46.7	70.0	0.09	19.4	
3083	2.0	25.0	50.0	75.0	0.01	2.16	T.R.

T.S. - Test Stopped.
T.R. - Temperature Rise at Load Application.

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TABLE III (cont.)

TEST DATA FOR S-816 ALLOY AT 1350° F

Specimen Number	Ratio $S_a/S_m = A$	Applied Stress, KSI S_m	S_a	S_c	Elong. %	Red. Area %	Time to Rupture Hours	Kilocycles	
AO--AK									
3061	0.25	40.0	10.0	50.0	18.0	24.5	142.6	30,802.	T.S.
3096	0.25	42.4	10.6	53.0	-	-	57.4	12,398	
3072	0.25	45.6	11.4	57.0	16.9	19.2	52.9	11,426	
3078	0.25	48.0	12.0	60.0	-	-	56.3	12,161	
3062	0.25	52.0	13.0	65.0	26.8	31.6	49.8	10,757	
3053	0.25	56.0	14.0	70.0	24.5	22.7	4.5	972.	T.S.
3076	0.25	56.0	14.0	70.0	23.8	22.5	7.5	1,620.	
3091	0.25	60.0	15.0	75.0	18.7	24.8	4.3	928.8	
3058	0.25	68.0	17.0	85.0	26.0	26.9	1.2	259.92	T.S.
3051	0.25	80.0	20.0	100.0	30.8	28.6	0.12	25.92	
3088	0.25	80.0	20.0	100.0	26.4	21.3	0.05	10.80	T.S.
AO--AM									
2997	0.25	48.0	12.0	60.0			164.8	35,597.	T.S.
3003	0.25	49.6	12.4	62.0			140.4	30,326	T.S.
3002	0.25	49.6	12.4	62.0			23.6	5,097.	
2994	0.25	52.0	13.0	65.0			22.7	4,903.	
3000	0.25	54.4	13.6	68.0			10.0	2,160.	T.R.
2996	0.25	57.6	14.4	72.0			5.2	1,123.	
3014	0.25	60.0	15.0	75.0			5.4	1,166.	
3021	0.25	64.0	16.0	80.0			2.1	453.6	
3020	0.25	68.0	17.0	85.0			0.17	36.7	
AO--AS									
3155	0	40.0	0	40.0	41.5	52.60	159.0	-	
3154	0	45.0	0	45.0	29.5	33.19	47.9	-	
3153	0	55.0	0	55.0	32.0	31.59	11.5	-	
3152	0	60.0	0	60.0	31.5	35.57	4.3	-	
AO--AT									
3199	0	56.5	0	56.5			196.7	-	
3150	0	56.5	0	56.5			72.1	-	
3147	0	60.0	0	60.0			82.6	-	
3148	0	67.5	0	67.5			25.0	-	
3197	0	82.5	0	82.5			5.0	-	
AO--AU									
3133	0	50.0	0	50.0			452.0	-	
3135	0	55.0	0	55.0			233.1	-	
3138	0	60.0	0	60.0			76.4	-	
3140	0	67.5	0	67.5			24.5	-	
3142	0	82.5	0	82.5			4.1	-	

T.S. - Test Stopped.
T.R. - Temperature Rise at Load Application.

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TABLE III (cont.)

TEST DATA FOR S-816 ALLOY AT 1350° F

Specimen Number AO--AM	Ratio S_a/S_m = A	Applied Stress, KSI S_m	S_a	S_c	Time to Rupture Hours	Kilocycles	
3207	2.0	8.0	16.0	24.0	97.2	20,995	
3209	2.0	8.33	16.66	25.0	5.1	11,016	
3017	2.0	9.33	18.66	28.0	0.52	112.3	
3016	2.0	11.0	22.0	33.0	0.28	60.5	
3015	2.0	12.33	24.66	37.0	0.13	28.1	
3019	2.0	12.5	25.0	37.5	0.05	10.8	
AO--AK							
3648	0.67	36.0	24.0	60.0	105.2	22,723.	
3048	0.67	39.0	26.0	65.0	49.1	10,606.	
3646	0.67	39.0	26.0	65.0	19.4	4,190.	
3052	0.67	42.0	28.0	70.0	17.8	3,845.	
3081	0.67	42.0	28.0	70.0	2.0	432.0	
3056	0.67	44.91	30.09	75.0	23.8	5,140.8	
3082	0.67	46.5	31.0	77.5	20.6	4,449.6	
3060	0.67	48.0	32.0	80.0	1.1	237.6	
3090	0.67	51.0	34.0	85.0	0.43	92.9	
3087	0.67	54.0	36.0	90.0	0.04	8.64	
AO--AM							
3018	0.67	26.9	18.1	45.0	113.8	24,581.	T.S.
3012	0.67	27.0	18.0	45.1	14.8	3,197.	
3009	0.67	28.1	18.9	47.0	58.2	12,570.	
3008	0.67	29.9	20.1	50.0	2.4	518.4	
3010	0.67	31.14	20.86	52.0	0.25	54.0	
3001	0.67	32.9	22.1	55.0	0.2	43.2	
3013	0.67	35.9	24.1	60.0	0.09	19.44	
3004	0.67	38.9	26.1	65.0	0.03	6.48	
3005	0.67	41.9	28.1	70.0	0.05	10.80	T.R.

T.S. - Test Stopped.
T.R. - Temperature Rise at Load Application.

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TABLE IV

TEST DATA FOR S-816 ALLOY AT 1500° F

Specimen Number AO--AK	Ratio $S_a/S_m = A$	Applied Stress, KSI S_m	S_a	S_c	Time to Rupture Hours	Kilocycles	
2490	∞	0	30.0	30.0	120.0	25,920.	T.S.
2488	∞	0	35.0	35.0	115.9	25,034.	T.S.
2493	∞	0	37.5	37.5	58.0	12,528.	
2497	∞	0	38.25	38.25	30.6	6,609.	
2495	∞	0	39.0	39.0	1.4	302.4	
2489	∞	0	40.0	40.0	0.1	21.6	
2491	∞	0	42.0	42.0	0.47	102.0	
AO--AL							
2722	∞	0	18.0	18.0	160.0	34,560.	T.S.
2702	∞	0	20.0	20.0	20.3	4,384.	
2703	∞	0	21.0	21.0	3.5	756.0	
2697	∞	0	22.0	22.0	0.78	168.5	
2699	∞	0	24.0	24.0	0.55	119.0	
2696	∞	0	24.0	24.0	0.25	54.0	
2691	∞	0	25.0	25.0	10.8	2,333.	
2698	∞	0	27.3	27.3	0.15	32.4	
2693	∞	0	30.0	30.0	0.12	25.9	
2710	∞	0	35.0	35.0	0.04	8.64	
AO--AM							
2502-1	∞	0	15.0	15.0	18.0	3,888.	T.S.
2505	∞	0	18.0	18.0	95.9	20,714.	
3235	∞	0	19.0	19.0	6.8	1,468.	
2991	∞	0	20.0	20.0	4.9	1,058.	
2502-2	∞	0	20.0	20.0	2.0	432.0	P.S.
2506	∞	0	22.0	22.0	0.57	123.1	
AO--AK							
3647	2.0	16.0	32.0	48.0	135.5	29,268.	T.S.
3658	2.0	17.3	34.7	52.0	17.8	3,845.	
3050	2.0	18.0	36.0	54.0	28.7	6,199.	
3085	2.0	19.0	38.0	57.0	6.1	1,317.	
3047	2.0	20.0	40.0	60.0	1.3	280.8	
3644	2.0	22.0	44.0	66.0	0.04	8.64	
AO--AM							
3219	2.0	9.0	18.0	27.0	140.6	30,370.	
3232	2.0	9.3	18.7	28.0	140.0	30,240.	T.S.
3230	2.0	9.33	18.66	28.0	6.51	1,406.	
3215	2.0	10.0	20.0	30.0	4.1	885.6	
3231	2.0	10.66	21.33	32.0	1.25	270.0	
3213	2.0	11.66	23.33	35.0	0.18	38.88	

T.S. - Test Stopped.
P.S. - Prior Stress History.

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TABLE IV (cont.)

TEST DATA FOR S-816 ALLOY AT 1500° F

Specimen Number AO--AK	Ratio $S_a/S_m = A$	Applied Stress, KSI S_m	S_a	S_c	Elong. %	Red. Area %	Time to Rupture Hours	Kilocycles	
3098	0.67	30.0	20.0	50.0	14.5	20.4	107.2	23,155.	T.S.
3070	0.67	31.8	21.2	53.0			18.1	3,909.	
3055	0.67	32.9	22.1	55.0			12.6	2,721.	
3054	0.67	36.0	24.0	60.0			4.0	864.0	
3089	0.67	38.9	26.1	65.0			3.9	842.4	
3095	0.67	41.9	28.1	70.0			0.48	103.7	
3094	0.67	44.9	30.1	75.0			0.1	21.6	
AO--AM									
3211	0.67	22.8	15.2	38.0			137.8	29,765.	T.S.
3212	0.67	23.4	15.6	39.0			116.6	25,186.	
3224	0.67	24.0	16.0	40.0			137.7	29,743.	T.S.
3223	0.67	24.0	16.0	40.0			10.3	2,225.	T.S.
3208	0.67	24.0	16.0	40.0			3.2	691.2	
3220	0.67	25.2	16.8	42.0			138.4	29,849.	T.S.
3221	0.67	25.2	16.8	42.0			13.2	2,851.	
3217	0.67	26.1	17.4	43.5			14.6	3,153.	
3222	0.67	26.1	17.4	43.5			14.3	3,089.	
3210	0.67	27.0	18.0	45.0			0.47	101.5	
AO--AK									
3068	0.25	26.4	6.6	33.0	34.1	41.9	110.1	23,782.	T.S.
3660	0.25	27.2	6.8	34.0	-	-	136.8	29,549.	T.S.
3093	0.25	32.0	8.0	40.0	33.4	45.8	14.8	3,197.	
3073	0.25	36.0	9.0	45.0	36.5	41.6	10.1	2,186.	
3071	0.25	36.0	9.0	45.0	32.0	28.3	9.5	2,052.	T.S.
3077	0.25	40.0	10.0	50.0	32.3	41.1	3.0	648.0	
3063	0.25	40.0	10.0	50.0	-	-	2.3	496.8	
3066	0.25	44.0	11.0	55.0	30.5	30.5	1.6	345.6	
3086	0.25	52.0	13.0	65.0	37.3	34.1	0.48	103.7	

T.S. - Test Stopped.

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TABLE IV (cont.)

TEST DATA FOR S-816 ALLOY AT 1500° F

Specimen Number	Ratio S_a/S_m = A	Applied Stress, KSI S_m	S_a	S_c	Elong. %	Red. Area %	Time to Rupture Hours	Kilocycles	
AO--AM									
3229	0.25	28.0	7.0	35.0			136.3	29,441.	T.S.
3218	0.25	36.0	9.0	45.0			164.5	35,532.	
3228	0.25	38.4	9.6	48.0			56.3	12,161.	
3216	0.25	40.0	10.0	50.0			32.2	6,955.	
3227	0.25	42.4	10.6	53.0			13.5	2,916.	
3225	0.25	44.0	11.0	55.0			6.8	1,469.	
3226	0.25	46.4	11.6	58.0			3.7	799.2	
3234	0.25	51.2	12.8	64.0			0.86	185.8	
AO--AS									
3191	0	26.0	0	26.0	36.2	48.81	144.3	-	
3194	0	30.0	0	30.0	34.0	32.01	38.9	-	
3151	0	35.0	0	35.0	41.3	34.83	19.6	-	
3192	0	40.0	0	40.0	48.2	48.33	3.1	-	
3193	0	45.0	0	45.0	42.5	48.23	1.25	-	
AO--AT									
3149	0	36.0	0	36.0			155.0	-	
3146	0	40.0	0	40.0			57.0	-	
3196	0	45.0	0	45.0			23.5	-	
3198	0	60.0	0	60.0			2.1	-	
AO--AU									
3134	0	30.0	0	30.0			501.0	-	
3137	0	40.0	0	40.0			56.0	-	
3136	0	45.0	0	45.0			185.0	-	
3139	0	47.5	0	47.5			17.0	-	
3141	0	60.0	0	60.0			1.6	-	

T.S. - Test Stopped.

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TABLE V

TEST DATA FOR S-816 ALLOY AT 1650° F

Specimen Number	Ratio	Applied Stress, KSI			Time to Rupture	
AO--AK	$S_a/S_m = A$	S_m	S_a	S_c	Hours	Kilocycles
2856	∞	0	28.0	28.0	86.7	18,727.
2860	∞	0	29.0	29.0	57.3	12,377.
2865	∞	0	31.0	31.0	13.3	2,873.
2858	∞	0	31.0	31.0	7.7	1,663.
2862	∞	0	33.0	33.0	15.0	3,240.
2864	∞	0	34.0	34.0	3.7	799.2
2866	∞	0	36.0	36.0	0.79	170.6
AO--AM						
2989	∞	0	19.0	19.0	60.8	13,133.
2992	∞	0	19.0	19.0	46.2	9,979.
2971	∞	0	20.0	20.0	72.1	15,574.
2988	∞	0	21.0	21.0	20.2	4,363.
2976	∞	0	21.0	21.0	0.91	196.5
2985	∞	0	22.0	22.0	0.35	75.6
2993	∞	0	25.0	25.0	0.11	23.76

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APPENDIX

DEFINITION OF TERMS AND SYMBOLS

The terms and symbols used in this report are defined below. In general, they are the same notations as used in the ASTM Manual on Fatigue Testing with a few minor deviations and some extensions.

S_u - Static Ultimate Strength.

S - Instantaneous Principal Stress (tensile stresses considered positive, compressive negative).

S_c - Crest Stress - the highest algebraic value of stress in the stress cycle = $S_m + S_a$.

S_t - Trough Stress - the lowest algebraic value of stress in the stress cycle = $S_m - S_a$.

S_a - Alternating Stress - the amplitude of the cyclic stress = $(S_c - S_t)/2$.

S_m - Mean Stress - the algebraic mean of the maximum and minimum stresses = $(S_c + S_t)/2$.

A - Alternating-to-Mean Stress Ratio - the ratio of alternating to the mean stress = S_a/S_m .

R - Trough Stress Ratio - the ratio of the trough stress to the crest stress = S_t/S_c .

N - Fatigue Life - the number of cycles of stress which may be endured without failure for a given test condition.

K_t - Theoretical Stress Concentration Factor.

K_f - Fatigue Strength Reduction Factor - the ratio of the fatigue strength of an unnotched specimen or member to that of a notched specimen or member at the same life and stress ratio.

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q - Notch Sensitivity Index - a measure of the degree of agreement between K_f and K_t for a particular specimen or member of given size and material = $(K_f - 1) / (K_t - 1)$.

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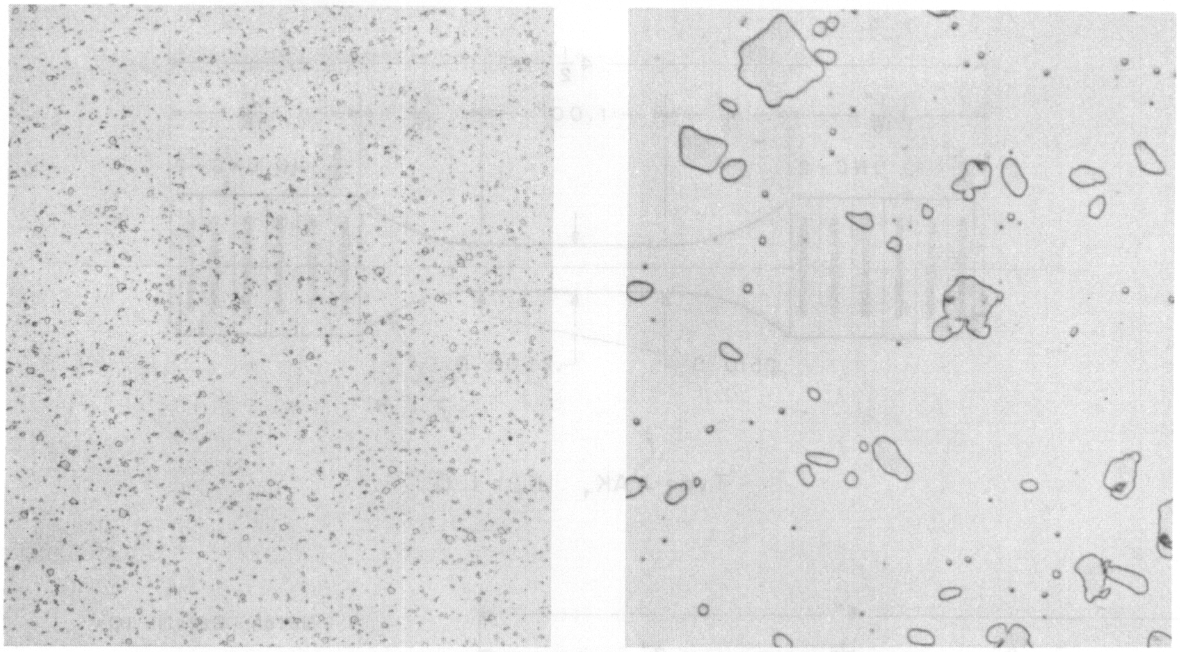
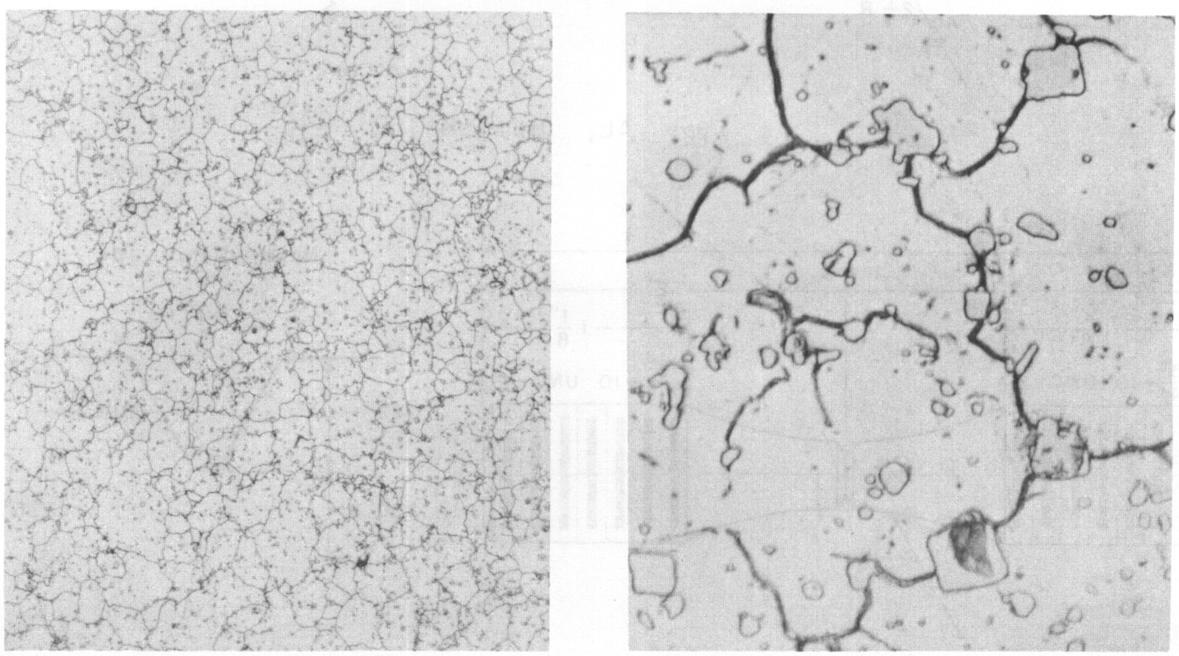


X 100 X 1000

Electrolytically Etched with 5% Oxalic Acid

Fig. 1 S-816 Alloy Solution Treated at 2300° F with Subsequent Water Quenching.



X 100 X 1000

Electrolytically Etched with 5% Oxalic Acid

Fig. 2 S-816 Alloy Solution Treated and Aged at 1400° F for 16 Hours.

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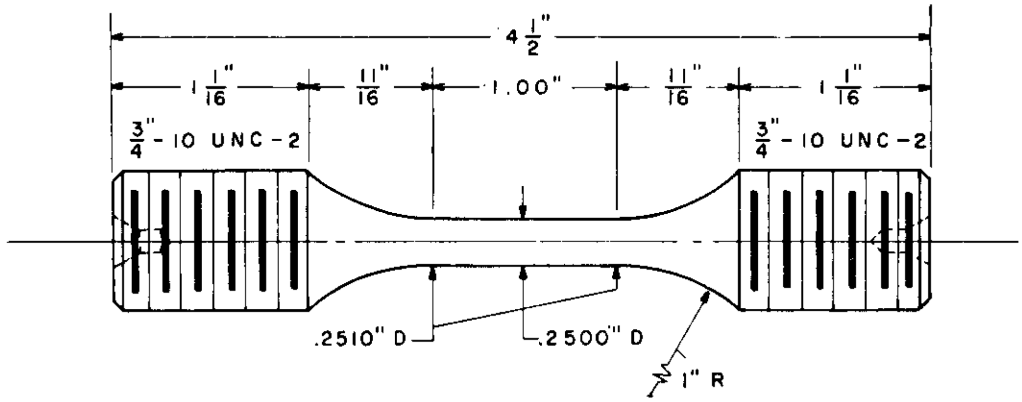
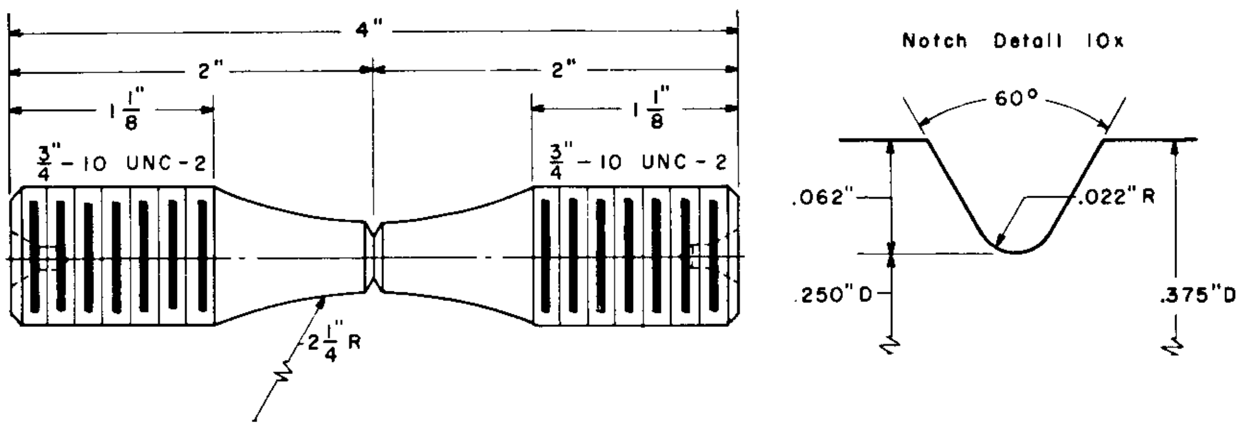
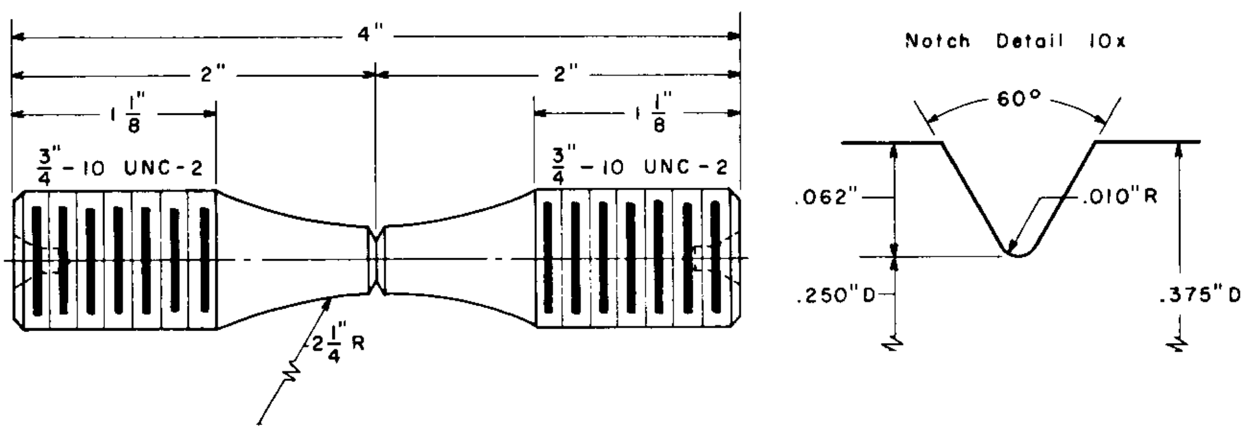


Type AK, $K_t = 1.0$



Type AL, $K_t = 2.4$



Type AM, $K_t = 3.4$

Fig. 3 Unnotched and Notched Fatigue Specimens Types AK, AL, and AM.

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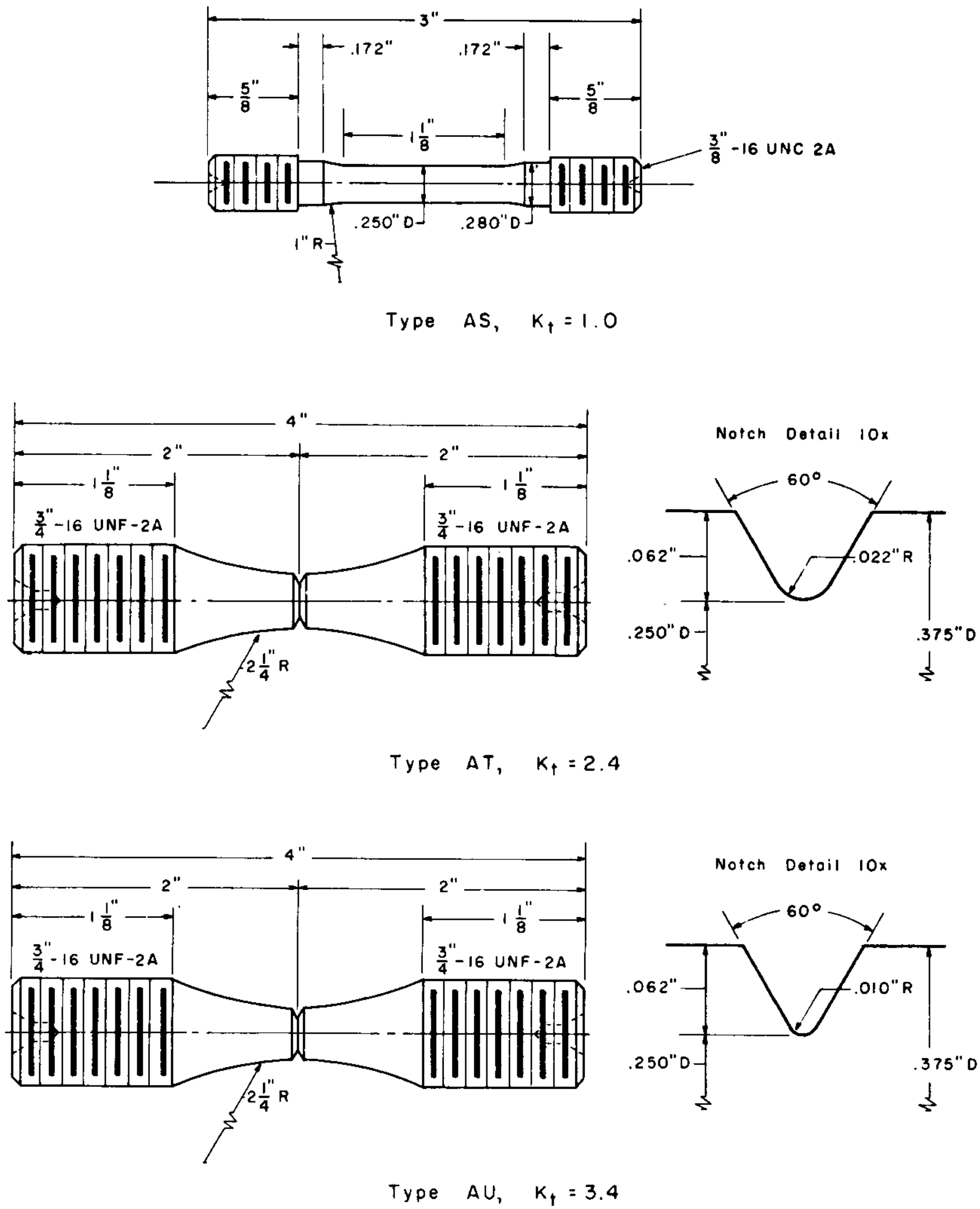

Fig. 4 Unnotched and Notched Creep Specimens Types AS, AT, and AU.

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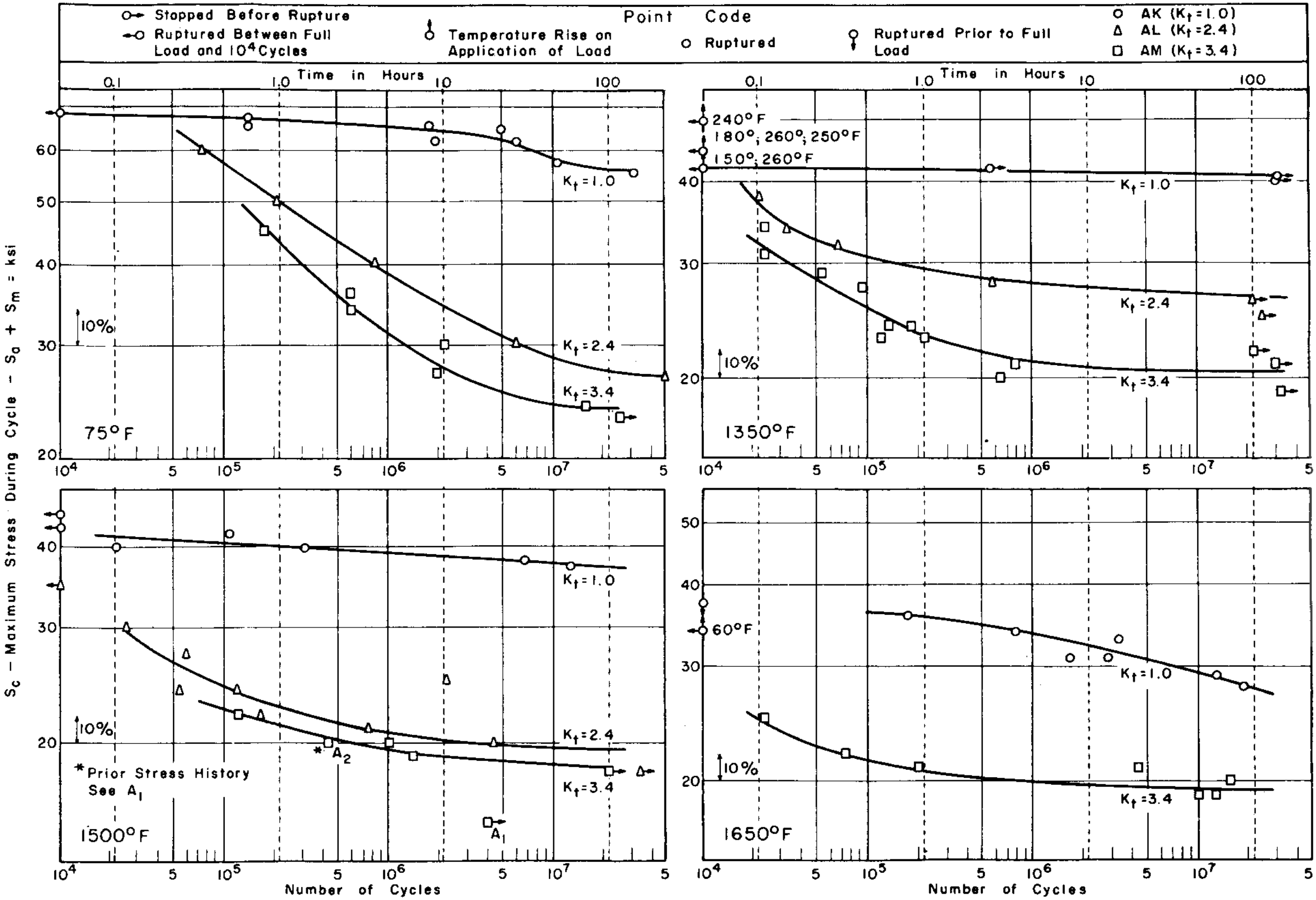

Fig. 5 S-N Fatigue Diagrams for Unnotched and Notched Specimens of S-816 Alloy at 75°, 1350°, 1500°, and 1650°F Under Reversed Stress (A=∞).

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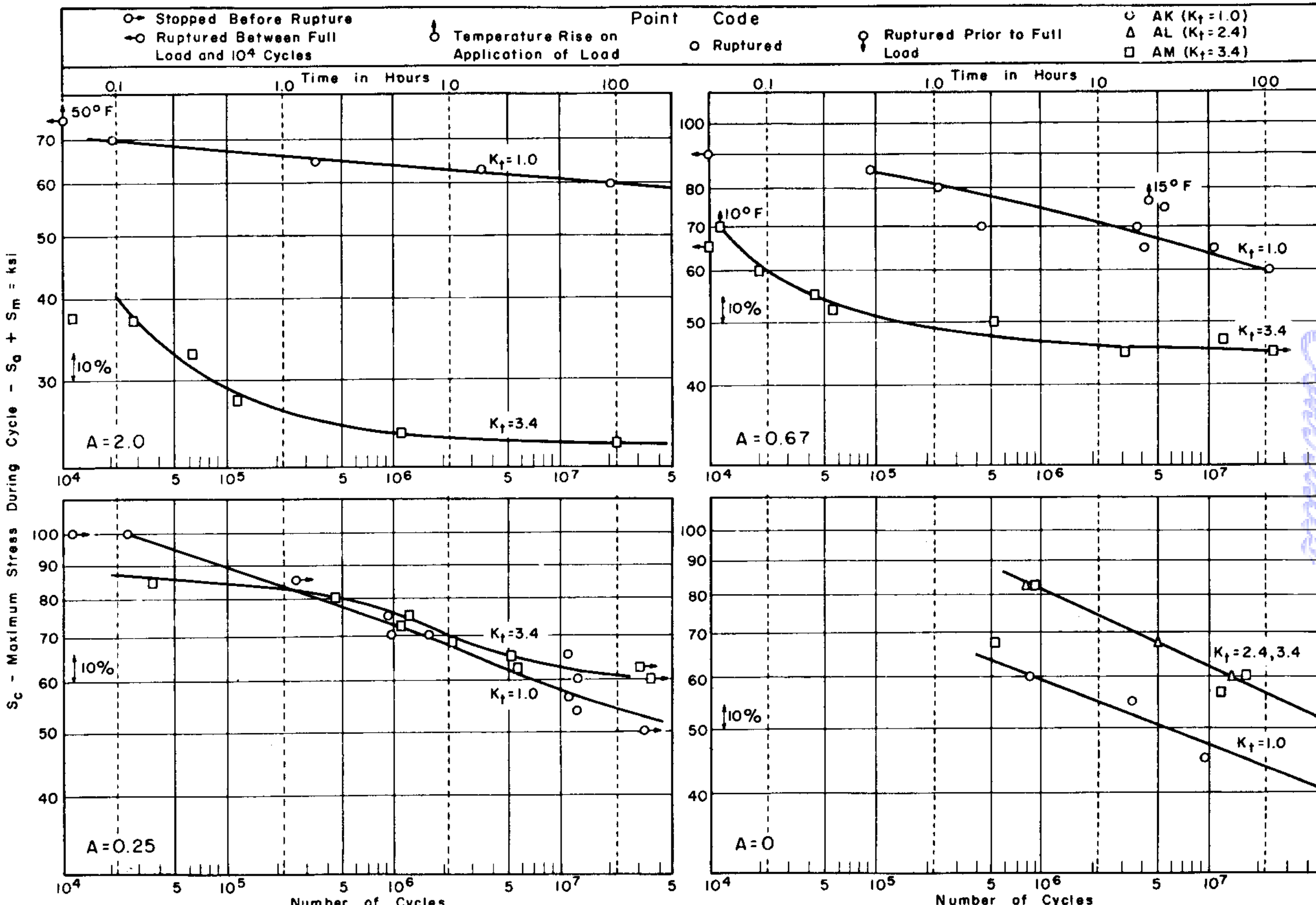

Fig. 6 S-N Fatigue Diagrams for Unnotched and Notched Specimens of S-816 Alloy at 1350°F and at Alternating-Mean Ratios A = 2.0, 0.67, 0.25, and 0.

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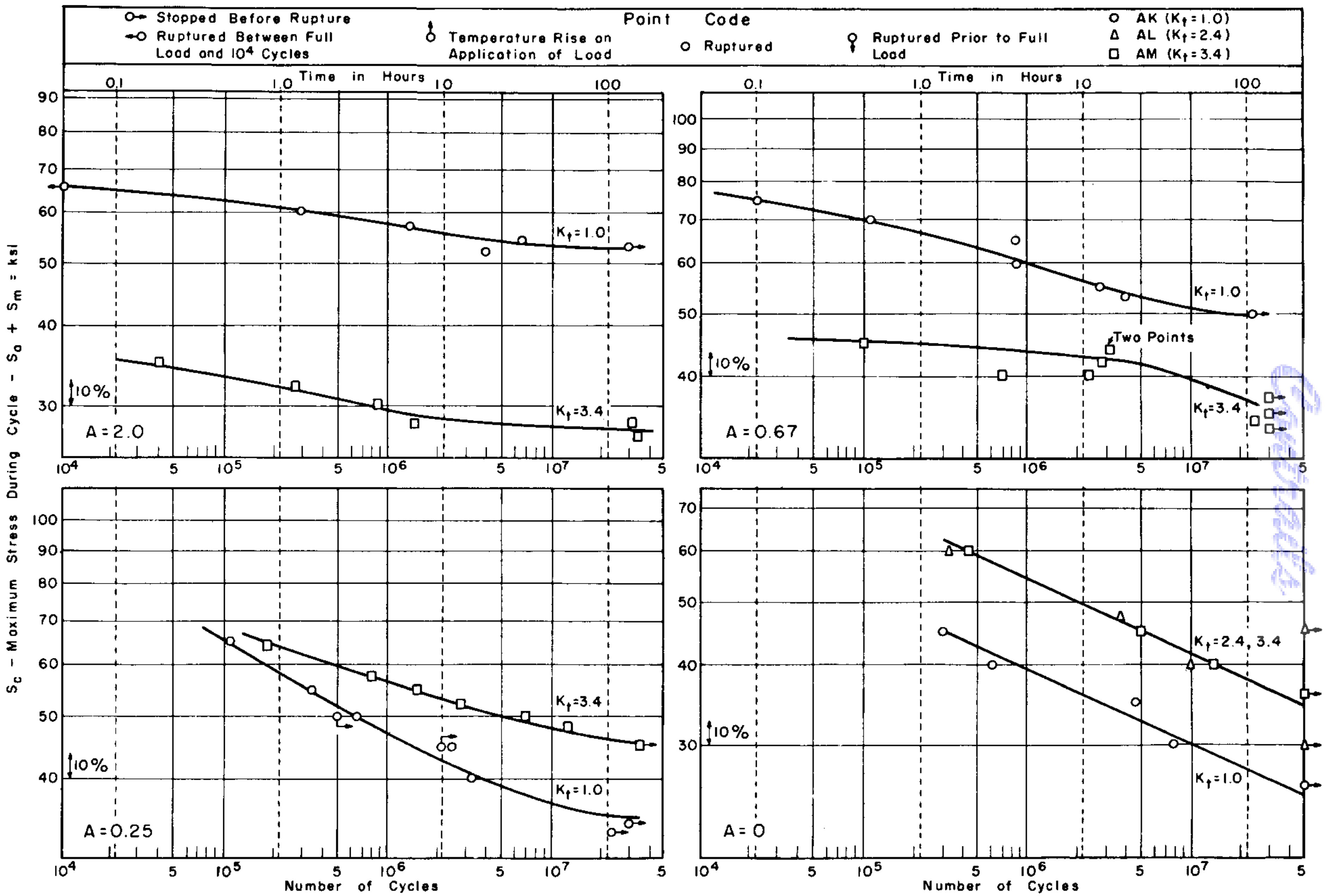

Fig. 7 S-N Fatigue Diagrams for Unnotched and Notched Specimens of S-816 Alloy at 1500°F and at Alternating-Mean Ratios A=2.0, 0.67, 0.25, and 0.

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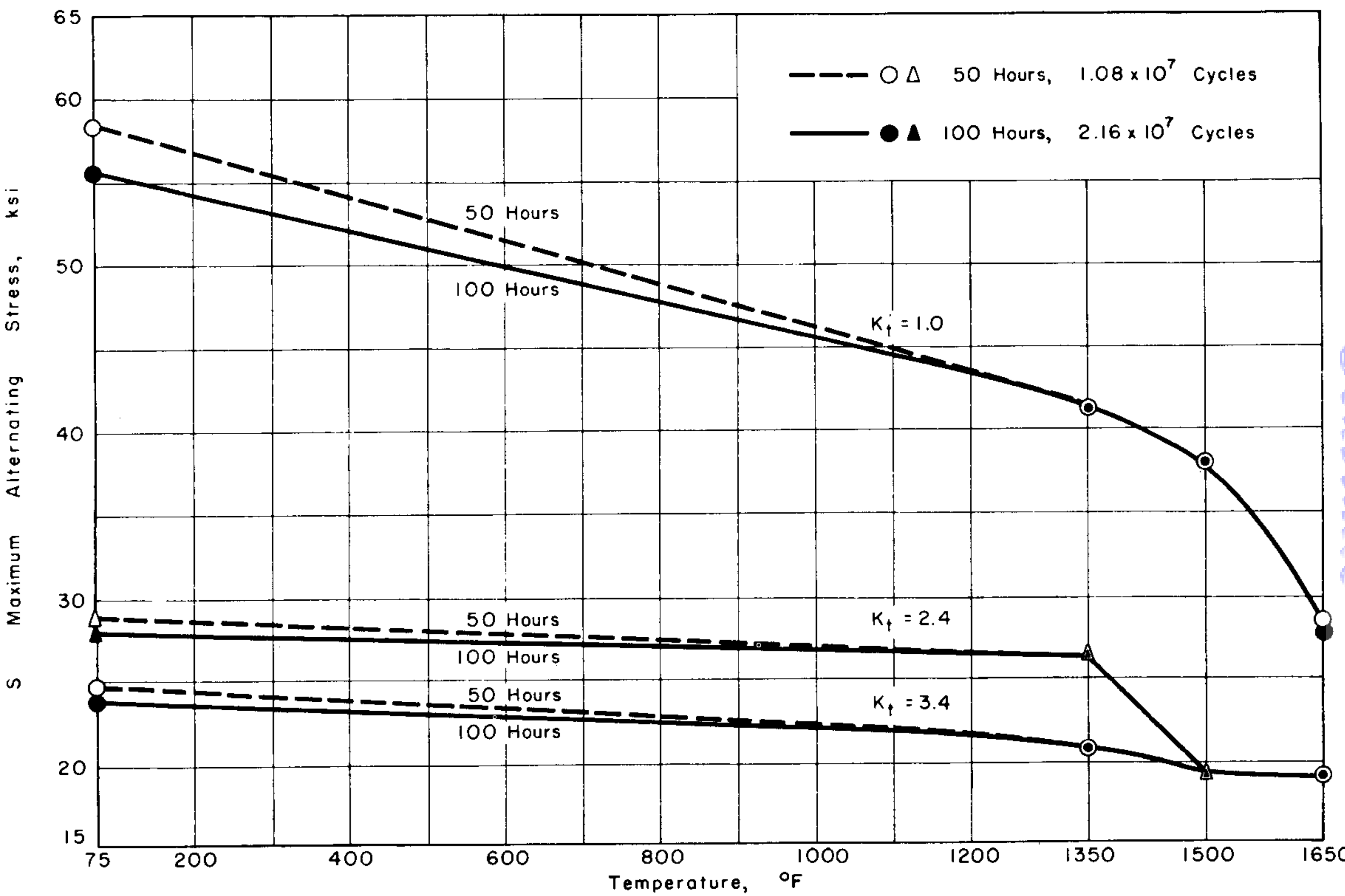

Fig. 8 Effect of Temperature on Fatigue Strength of S-816 Alloy for Type AK (K_t=1.0), AL (K_t=2.4), and AM (K_t=3.4) Specimens Under Reversed Stress.

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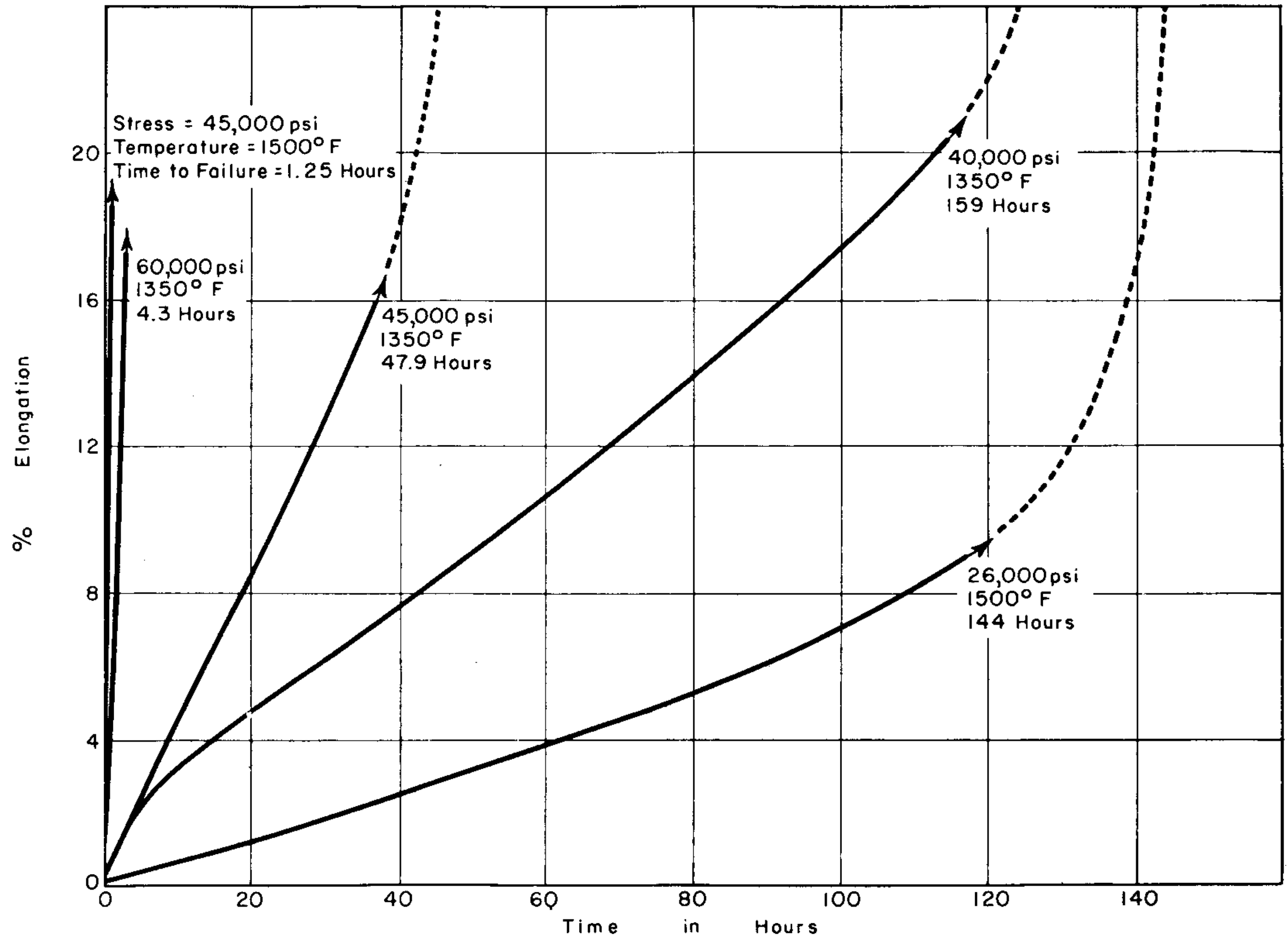

Fig. 9 Creep Curves of S-816 Alloy for Various Stresses at 1350° and 1500° F.

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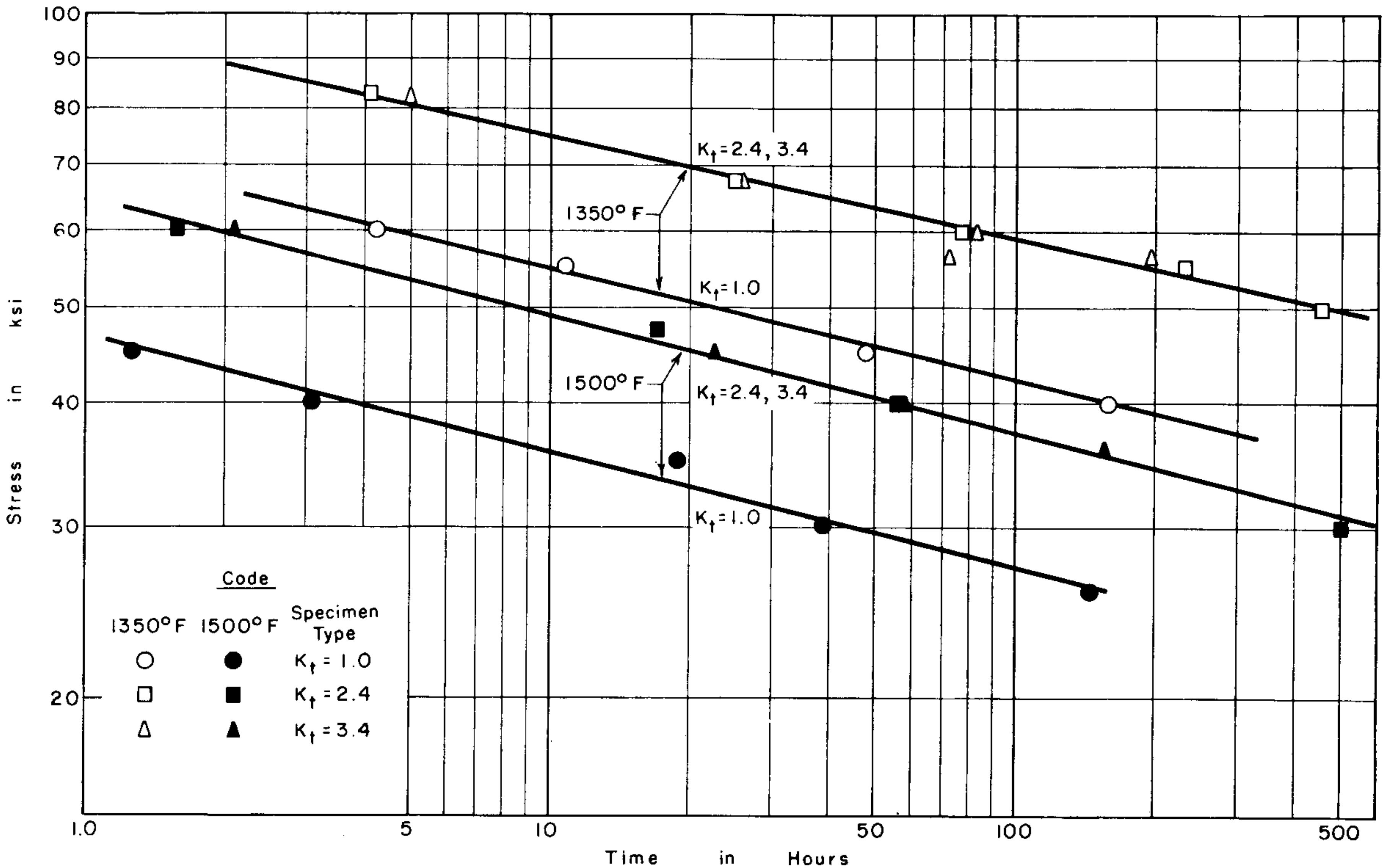

Fig. 10 Stress – Rupture Diagram for Various Specimen Types of S-816 Alloy at 1350° and 1500° F.

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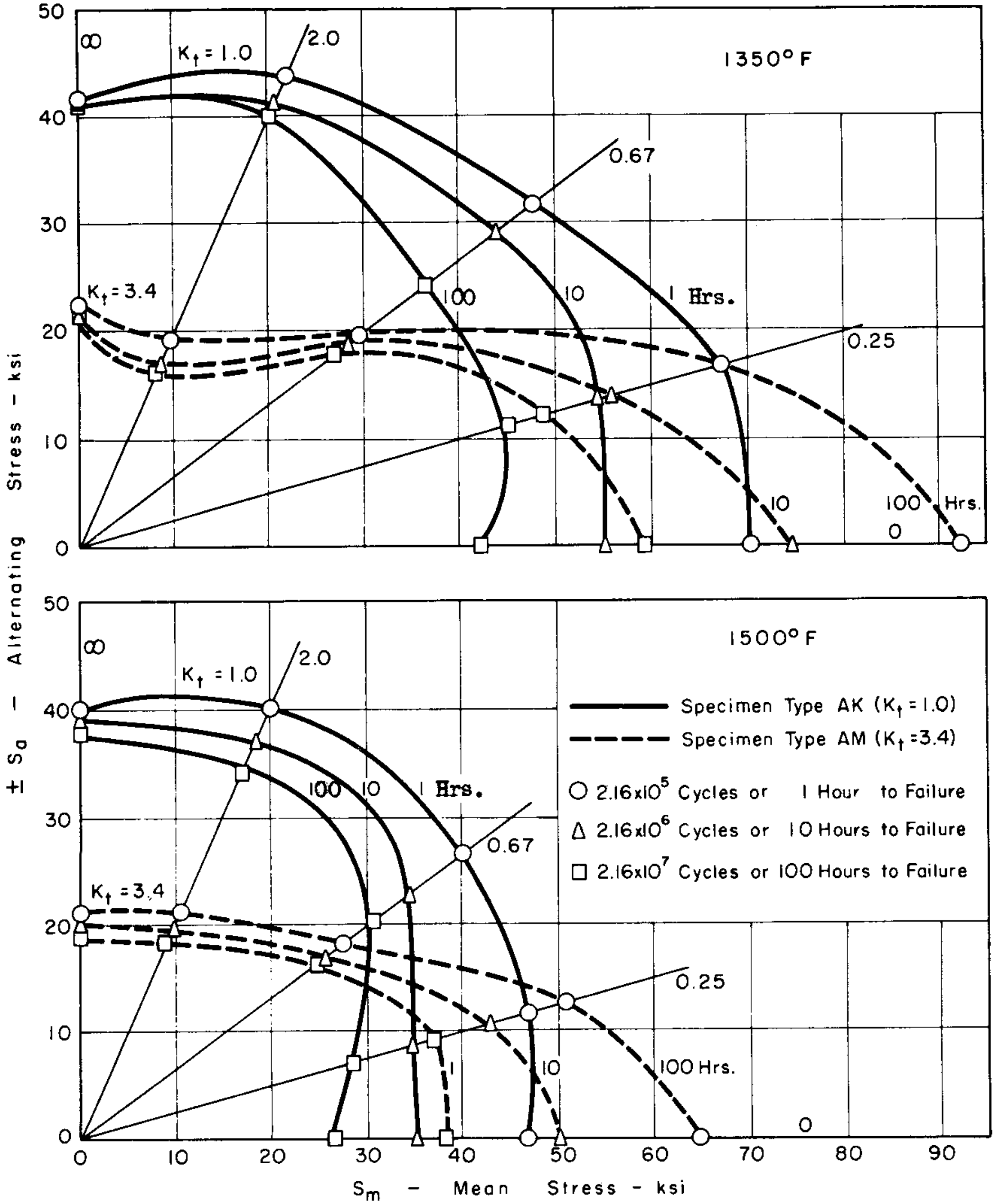

Fig. 11 Stress Range Diagrams for Unnotched and Notched Specimens of S-816 Alloy at 1350° and 1500° F.

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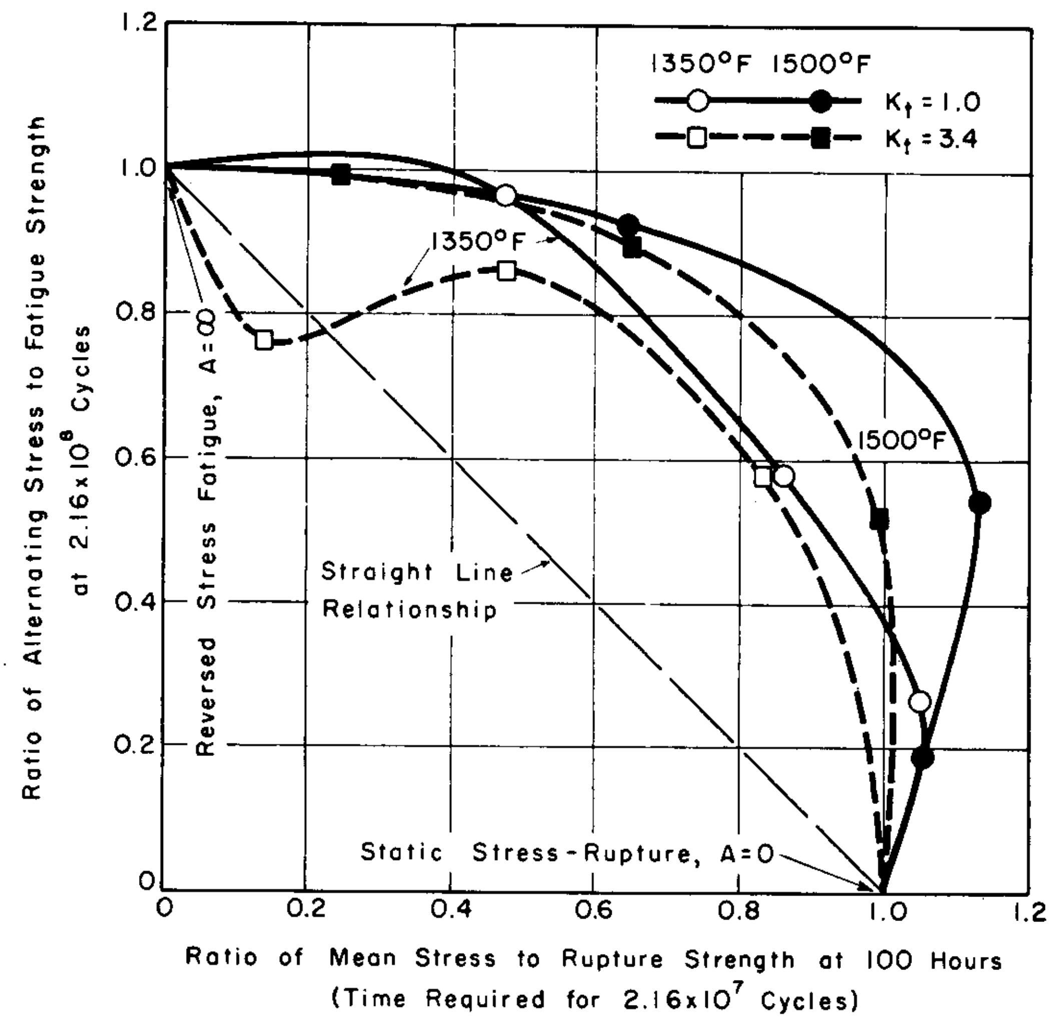

Fig. 12 Fatigue Stress-Range Diagrams for Unnotched and Notched Specimens of S-816 Alloy at Temperatures of 1350° and 1500° F Using Unitless Ratios.

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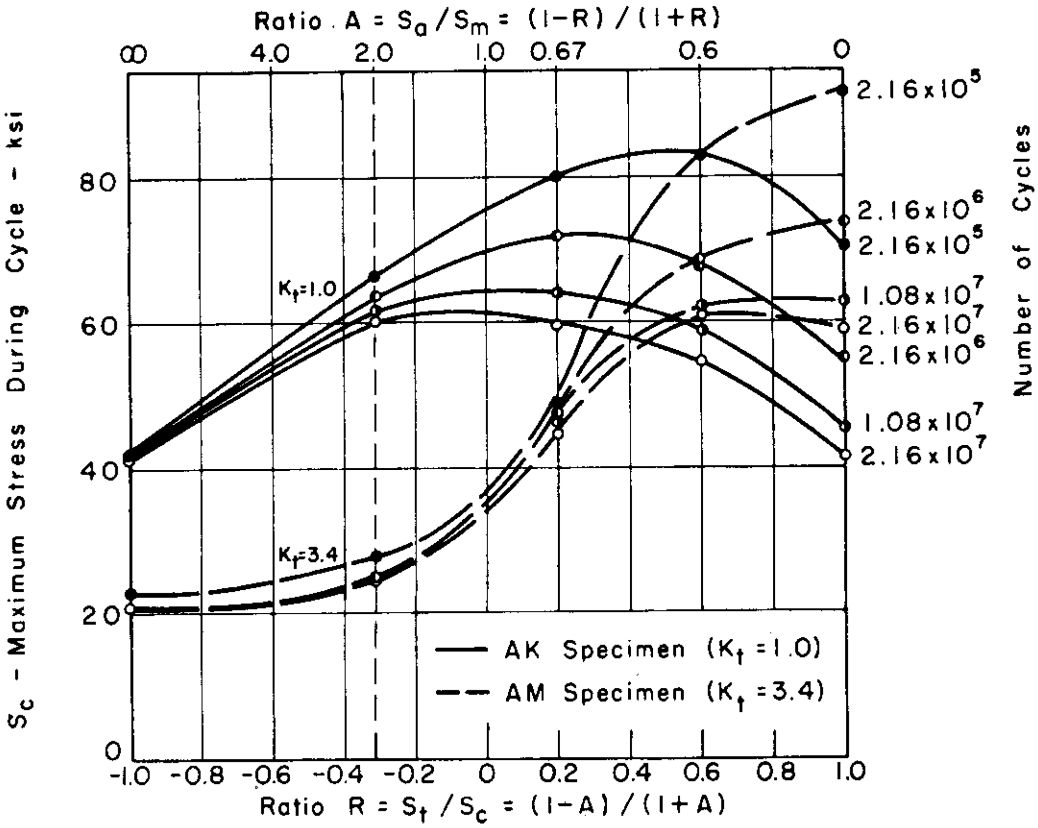

Fig. 13 Effect of Stress Ratio on the Maximum Stress of Unnotched and Notched (K_t=3.4) Specimens at 1350° F for Various Fatigue Lives of S-816 Alloy.

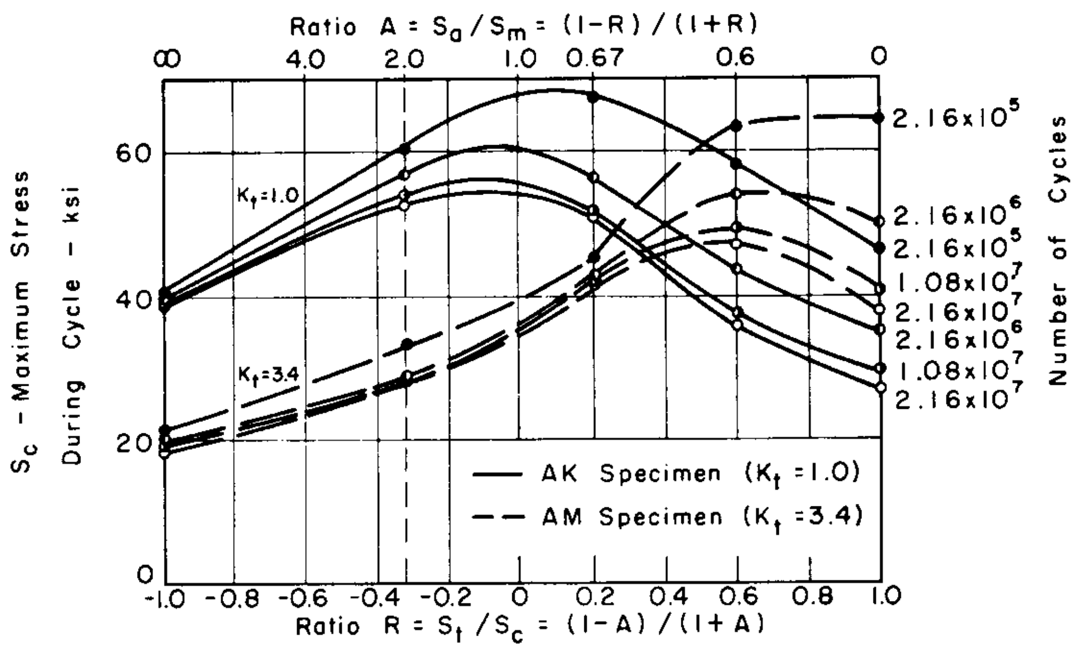

Fig. 14 Effect of Stress Ratio on the Maximum Stress of Unnotched and Notched (K_t=3.4) Specimens at 1500° F for Various Fatigue Lives of S-816 Alloy.

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Contrails

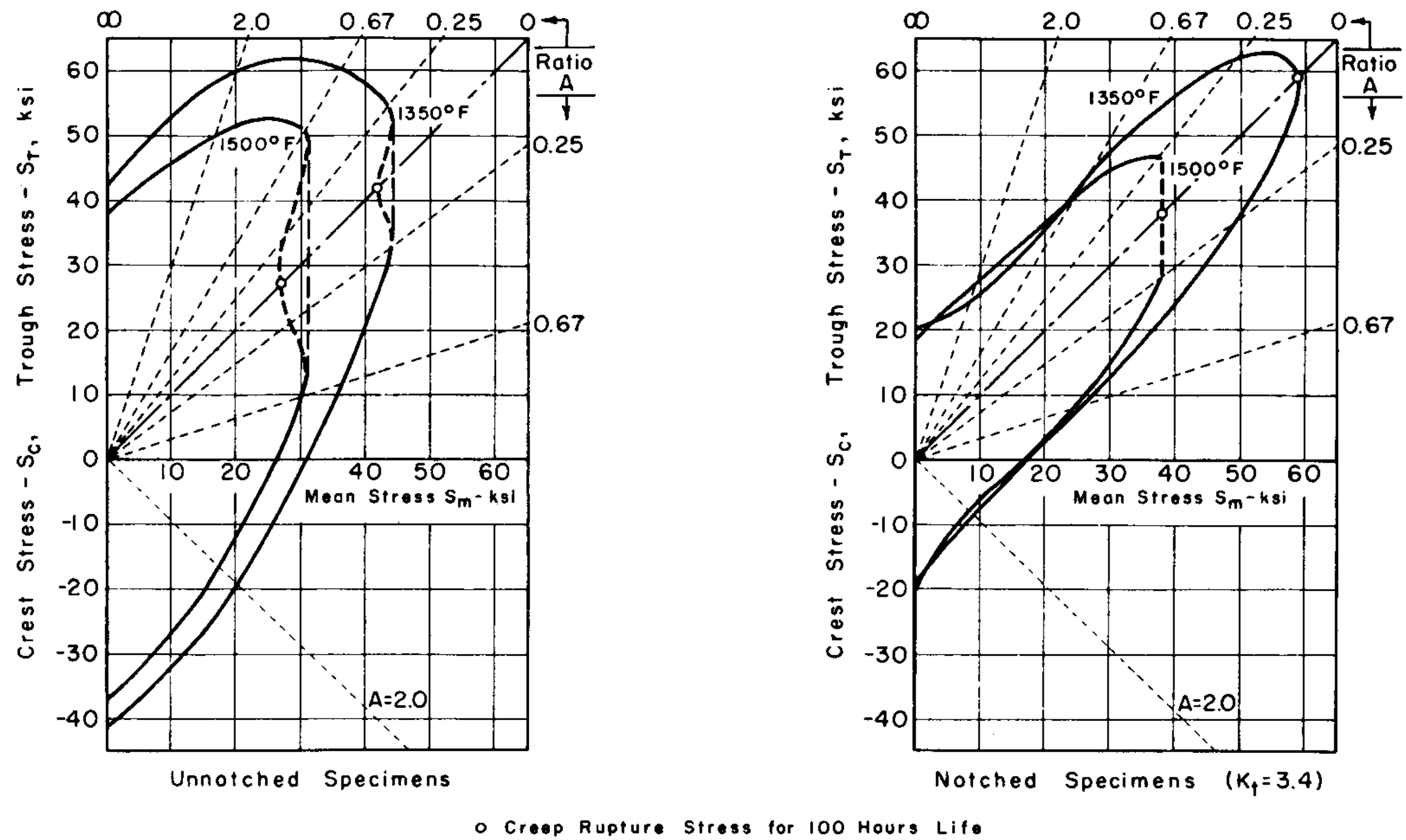

Fig. 15 Modified Goodman Diagrams of S-816 Alloy for Unnotched and Notched Specimens at 1350° and 1500°F (Fatigue Strength at 2.16×10^7 Cycles).

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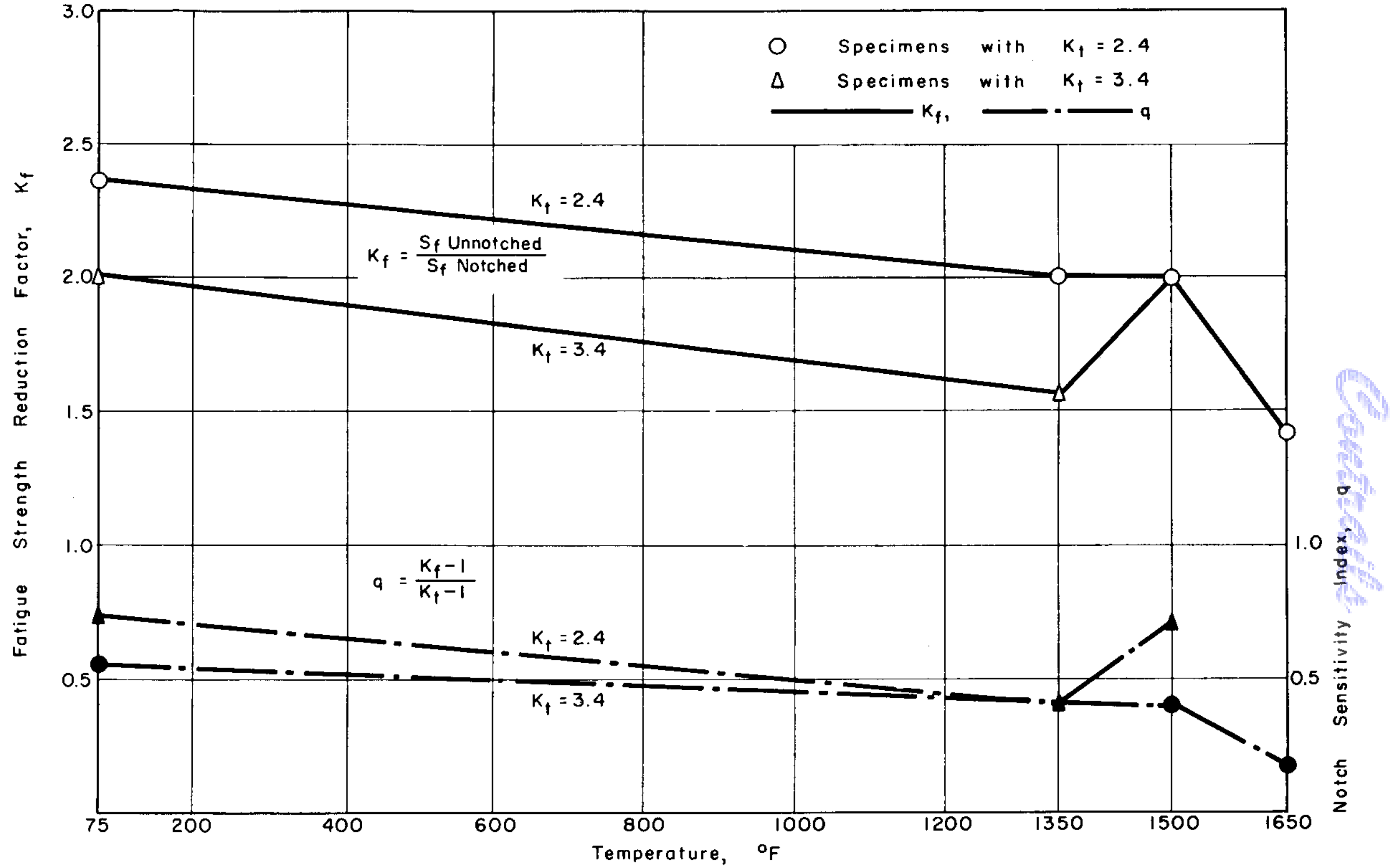

Fig. 16 Effect of Temperature on Notch Sensitivity of S-816 Alloy Under Reversed Stress. Fatigue Strength Determined at 2.16×10^7 Cycles.

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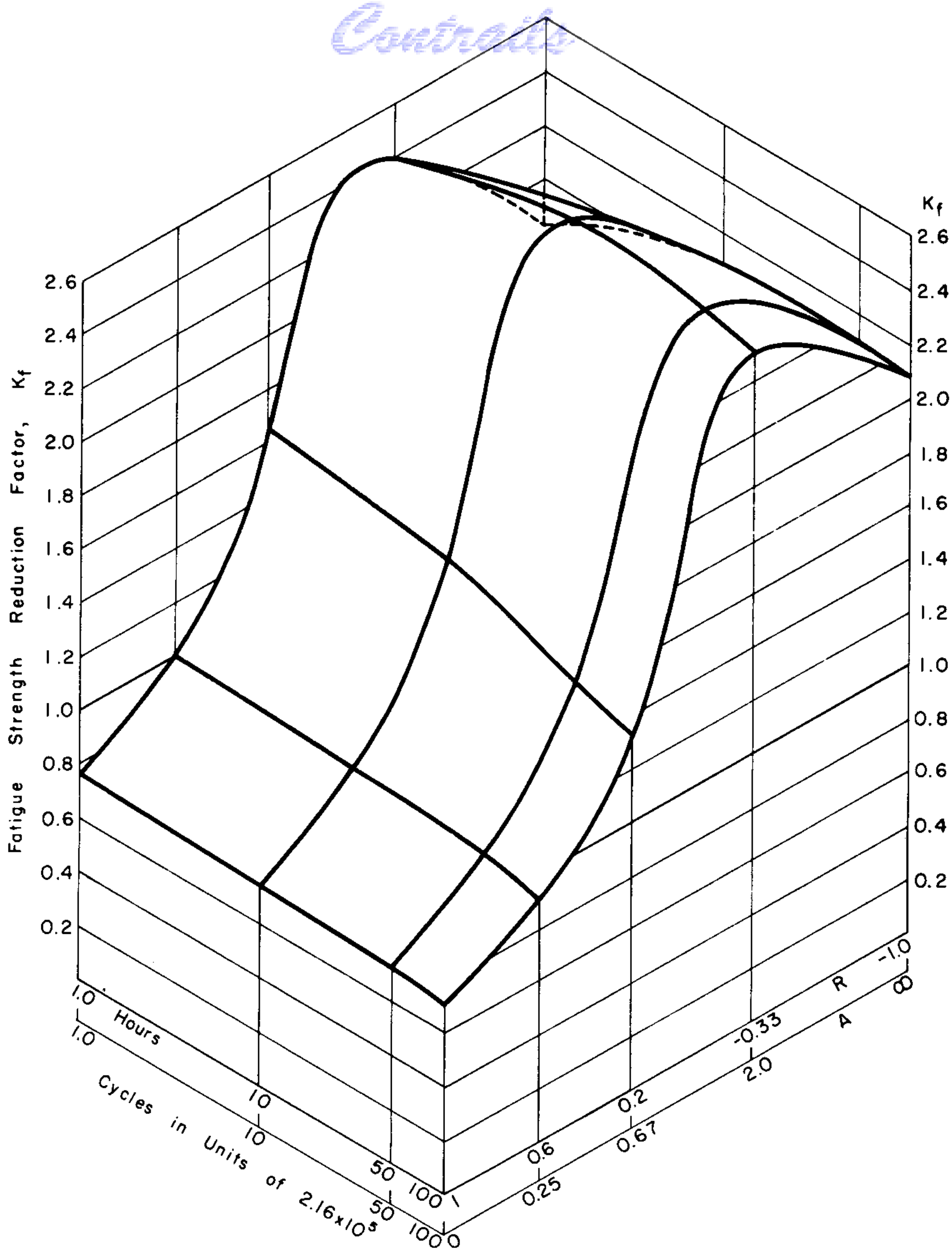

Fig. 17 Fatigue Strength Reduction Factor of S-816 Alloy for Type AM (K_t=3.4) Specimens at 1350° F as a Function of Alternating - Mean Ratio and Number of Cycles.

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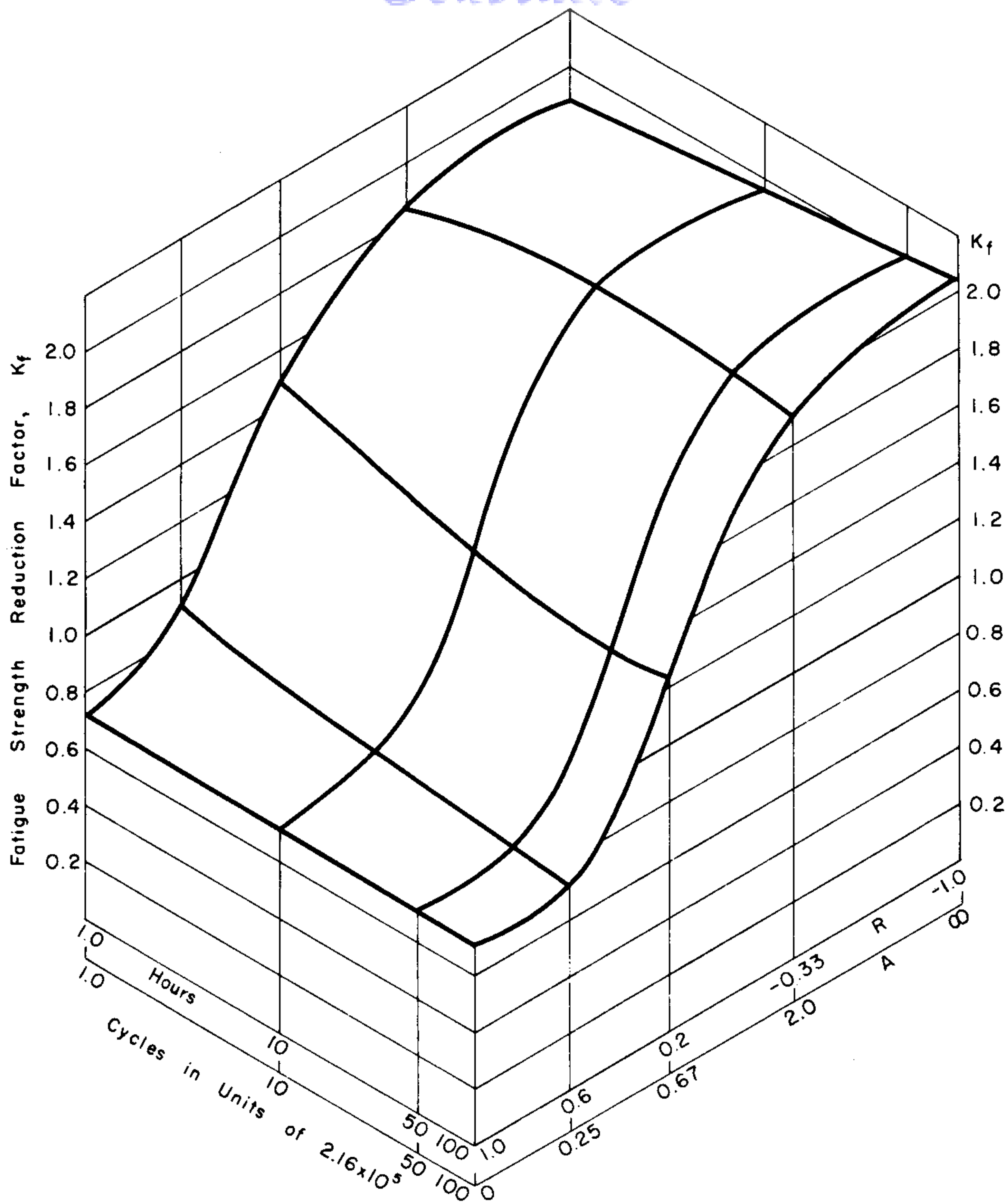

Fig. 18 Fatigue Strength Reduction Factor of S-816 Alloy for Type AM ($K_t = 3.4$) Specimens at 1500° F as a Function of Alternating - Mean Ratio and Number of Cycles.

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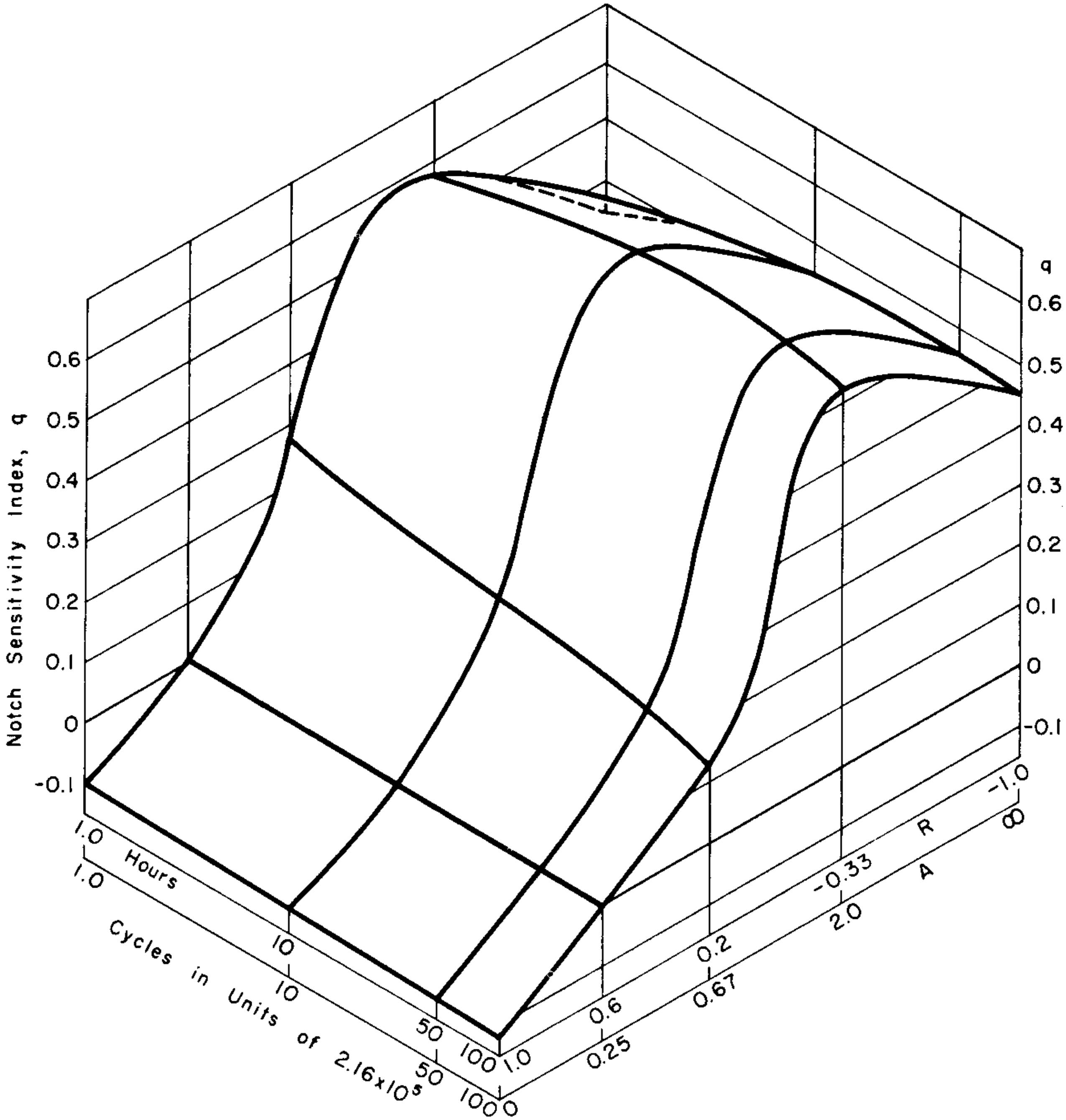

Fig. 19 Notch Sensitivity of S-816 Alloy for Type AM (K_t = 3.4) Specimens at 1350° F as a Function of Alternating - Mean Ratio and Number of Cycles.

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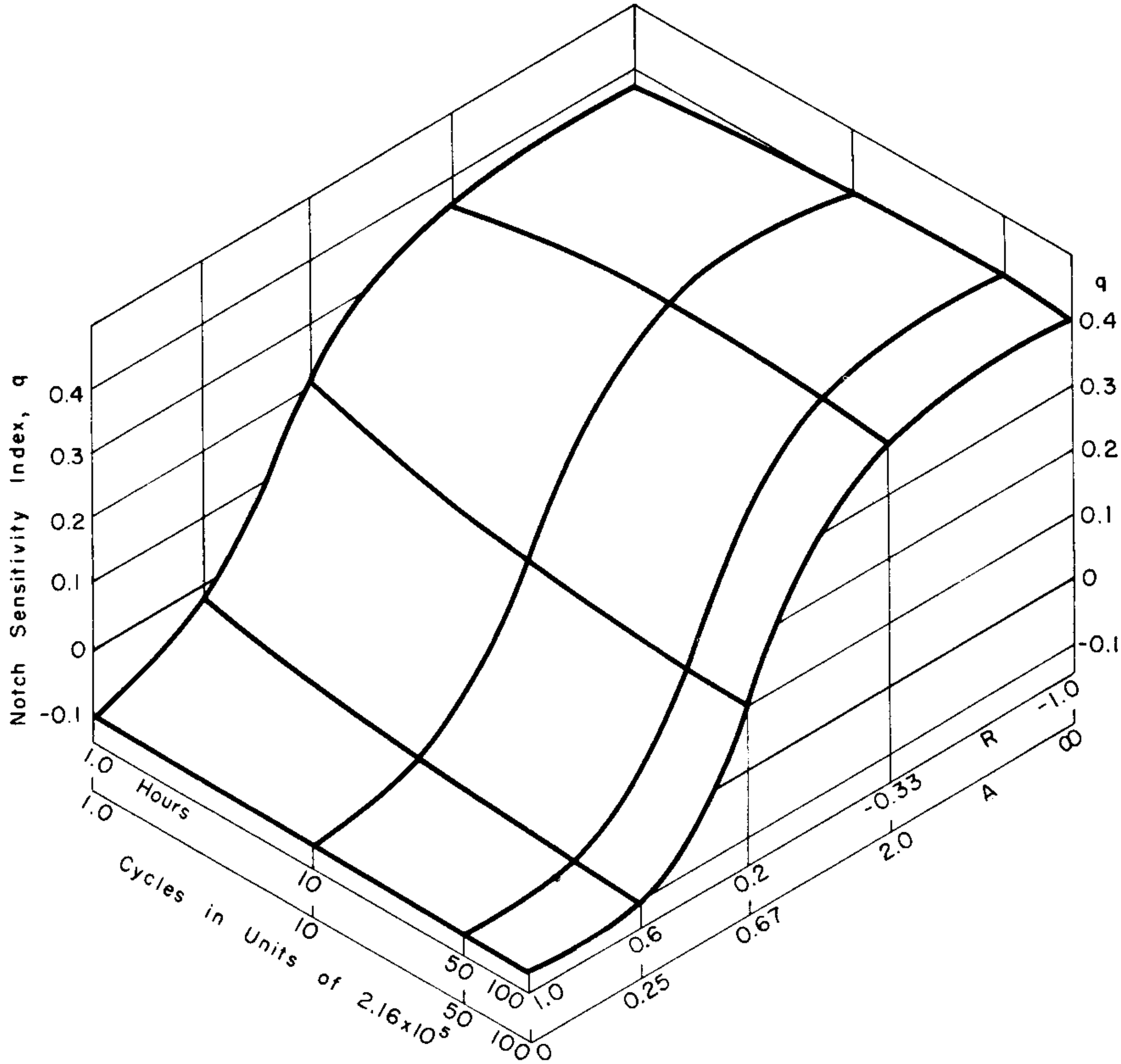

Fig. 20 Notch Sensitivity of S-816 Alloy for Type AM (K_t = 3.4) Specimens at 1500° F as a Function of Alternating - Mean Ratio and Number of Cycles.

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