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TENTH PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

by

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SUMMARY

This research under Task No. 73605 of Contract AF 18(600)-62 is part of a study into factors affecting notch sensitivity of alloys at elevated temperatures. Emphasis has been placed on creep properties as a measure of the ability of an alloy to reduce stress concentrations near the notch root and thus extend the rupture life of the notched specimen.

Past experiments on round smooth and notched specimens of three super-alloys are now being supplemented by tests with flat notched specimens of two of those same alloys (S-816 and Inconel X-550 at 1350°F) and with two other alloy types (a Cr-Mo-V steel and an aluminum alloy).

Incomplete results indicate rupture life for flat notched bars to be moderately to slightly lower than for comparable round notched specimens for S-816 and for the low-alloy steel. For the aluminum alloy no difference between flat and round notched specimens was apparent in the few tests completed to date.

Notched and smooth bars from three heats of Waspaloy have been under study in search for properties other than creep or relaxation which influence response to notches. Material from one heat, sampled from stock as supplied by the producer and not re-rolled at the University of Michigan, shows marked effects upon notch rupture life when the 1550°F aging step is omitted from the conventional heat treatment. Tests are planned to seek an explanation for the observed notch behavior. It is anticipated that metallurgical changes promoted by plastic deformation near the notch during loading may complicate analysis of results.

During the coming quarter it is hoped to complete experimental work at 1100°F for the low-alloy steel and at 400°F for the aluminum alloy.

NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

INTRODUCTION

This report presents test results obtained between April 1 and June 30, 1955 under Task No. 73605 of Air Force Contract Number AF 18(600)-62. The research reported here is part of a study into factors affecting notch sensitivity of alloys at elevated temperatures.

It has been indicated previously for round specimens of three heat-resistant alloys that notch-rupture behavior was associated with the rate of relaxation of stresses concentrated initially near the notch root. A mathematical analysis was developed to explain observed notch rupture life in terms of smooth-bar properties.

To check the generality of past findings, experiments are now being extended to two additional materials and to flat specimens notched at the edges. Available results of rupture tests for these new conditions are included herein.

The previous progress report (Ref. 1) compared rupture lives of smooth and notched specimens from three different heats of Waspaloy with two different heat treatments. (Stock from all three lots of the alloy received a common final rolling at the University of Michigan before heat treatment.) In these studies it was sought to learn whether other factors than creep and relaxation exert major influence on notch sensitivity. Differences in relative notch strength for the conditions examined were too small for firm conclusions. It was suggested in a private communication from Dr. E. E. Reynolds of the Allegheny Ludlum Steel Corporation that larger variation in notch strength might be obtained if the stock were not re-rolled. Initial results reported here support this belief. Further tests are therefore planned, using specimen blanks sampled from the bar-stock as supplied by the manufacturer.

All original data for this entire research are summarized and indexed in Engineering Research Institute data book Number 2708.

CURRENT STATUS OF THE EXPERIMENTAL PROGRAM

Superalloys

All experimental work originally planned for the three superalloys (S-816, Waspaloy, Inconel X-550) has been completed. The Waspaloy bar stock has been completely used up and nearly so for the other two alloys. A few specimens of the Inconel X-550 to be notched outside the University of Michigan by special techniques designed to give low residual machining stresses have still not been received for testing here.

Limited rupture results at 1350°F were obtained with flat notched bars of S-816 and Inconel X-550, but none of the original stock of Waspaloy remained for similar tests with that alloy.

Small amounts of Waspaloy from other heats are still being tested in search of other properties than creep or relaxation which affect notch-rupture behavior. The amounts of these materials on hand are insufficient to permit comparison of notch effects in cylindrical and flat specimens.

Cr-Mo-V Low-Alloy Steel ("17-22-A"S)

Rupture life at 1100°F for this alloy has been established over a wide range of steady stresses for both round and flat notched specimens, as well as for conventional smooth bars. These results are included in the present report along with short-time tensile data at 1100°F. Tests in progress on addibility of rupture life and on creep rates under variable-stress operation are expected to be completed in the coming quarter.

2024-T4 Aluminum Alloy

Preliminary tests at 500° and 400°F indicated the latter temperature to satisfy needs of this program. To date, five (5) smooth-bar rupture tests have been completed at 400°F, along with six (6) tests on notched specimens. Further tests at this temperature are scheduled for July and August to complete the data for steady-load conditions. In view of the tendency for 2024-T4 to over-age under test conditions, considerable testing may be required to establish creep and rupture behavior for the variable-stress history to be found in fibers near the root of a notch. A few multiple-stress tests for such a study have been started, but no results are yet ready to report.

EXPERIMENTAL RESULTS

Round vs Flat Specimens - S-816 and Inconel X-550 at 1350°F

Results of rupture tests on two smooth and six notched bars with a flat gauge section were included in the previous report (See Table 4, Ref. 1). Additional data obtained since on flat bars of S-816 and Inconel X-550 are listed in Table 1. All rupture values obtained to date at 1350°F for S-816 with conventional heat treatment are shown in Figure 1. Figure 2 compares rupture life at 1350°F of round and flat unnotched specimens of Inconel X-550. Also shown are results for three tests on flat notched bars with theoretical stress concentration factor of 3.1.

In both plots life of smooth bars appears to be independent of whether the test section is round or flat, a result which might be anticipated in the absence of surface deterioration under test conditions.

Notch strengthening was obtained with S-816 at all stress levels and all notch geometries studied. Points for all round notches, with theoretical stress concentrations from 2.0 to 6.6, seemed to fall on a common curve somewhat higher than the corresponding curve for flat bars with a range of K_t between 2.4 and 7.2.

For K_t = 3. 1, the data presented for flat bars of Inconel X-550 show notch weakening at 1350°F. Similar results were reported by Carlson, et al (Ref. 2) with the same stress concentration (0. 020-inch root radius) in round specimens. Because the method of notch preparation differed for these two sets of data and apparently influences results, check tests on round bars notched by grinding and then lapping are planned to afford a better comparison between flat and round notched specimens of this alloy. This apparent close agreement between the two sets of data is subject to question.

Change in Notch Behavior of One Heat of Waspaloy Upon Re-Rolling

In results given previously (Fig. 3 of Ref. 1) for a rather sharp notch, omission of the 1550°F aging step from the conventional heat treatment had little effect on notch rupture life for Waspaloy from three different heats, all re-rolled at 1950°F to 1/2-inch squares before sampling specimens. Only for Heat No. 63613 did any deviation appear between specimens with and without the intermediate aging step.

Further studies on this particular heat have employed a less sharp notch (K_t = 3.1) and have compared notch behavior for specimens sampled both from the original 1-3/4 inch round supplied by the manufacturer and from the 1/2 inch squares rolled at the University of Michigan from that stock. (Rolling procedure was outlined on page 5 of Ref. 1).

Test results are illustrated in Figure 3 and listed in Table 2. Smooth-bar rupture life for the re-rolled material was unaffected by omission of the intermediate age. No smooth specimens cut from the 1-3/4 inch stock have yet been run from this same heat, but data for specimens sampled from 7/8 inch rounds of Heat 44036 without re-rolling show a common curve with the re-rolled material from Heat 63613. Notch rupture behavior exhibited strong effects of the re-rolling. Notch weakening resulted for the 1/2-inch square stock with both heat treatments. In contrast, the original 1-3/4 inch stock was notch strengthened with conventional heat treatment and was very decidedly weakened when the 1550°F aging step was left out. This difference in behavior appears sufficient to warrant further investigation with the remaining meager stock of 1-3/4 inch round in an attempt to explain the observed notched-bar results.

"17-22-A"S Alloy Steel at 1100°F

The "17-22-A"S Cr-Mo-V steel was furnished by the Timken Roller Bearing Company from their Heat No. 31158. The 144 lineal feet of 1-inch round supplied had been hot rolled, annealed, pickled and machine straightened before shipment. Chemical analysis was as follows:

C	Mn	P	S	Si	Cr	Ni	Mo	V
0.32	0.60	0.011	0.017	0.70	1.32	0.14	0.48	0.22

Specimen blanks received the following conventional heat treatment at the University of Michigan:

1725°F, 1 hr, Air Cool + 1200°F, 6 hr, Air Cool

Summary results of eight (8) creep-rupture tests at 1100°F with smooth specimens, and for 21 additional rupture tests with both round and flat notched specimens are given in Table 3 and Figure 4.

For the range of stresses investigated, notched specimens with a theoretical stress concentration factor less than 2 showed slight notch strengthening for both round and flat specimens with values for the flat bars slightly lower than for round.

Results for notches with K_t = 3.1 fell close to those for smooth bars. At stresses above 60,000 psi notch strengthening appeared, with the curve for round specimens higher than for flat. At longer test times, mild notch weakening set in and the curve for round notched specimens seemed to fall below that for flat notches.

A short-time tensile test at 1100°F gave the properties:

Tensile Strength:	80,600 psi
0.2% Yield Stress:	71,600 psi
Elongation/2 inches:	25%
Reduction of Area:	74.5%
Elastic Modulus (E):	20.8 x 10^6 psi/in/in

Early portions of the stress-strain curve are included in Figure 5.

2024-T4 Aluminum Alloy

This material was purchased from the Aluminum Company of America as cold-finished rod. The 209 feet of 3/4-inch round obtained was from lot No. 130875 with the following nominal composition, percent by weight:

	Cu	Fe	Si	Mn	Mg	Zn	Cr	Other Elements Each	Other Elements Total	Al
Max.	4.9	0.50	0.50	0.9	1.8	0.10	0.10	0.05	0.15	Balance
Min.	3.8			0.3	1.2					

Specimens were machined from the as-received stock and heat treated later. The following conventional heat treatment was employed:

Hold 1 hour in a (Na,K) NO_3 salt bath at 920°F, Water Quench

Age 4 days in a controlled-temperature room at 75-80°F

A specimen to be tested was removed from the controlled-temperature room at 96 ($\pm$1) hours and immediately prepared for loading into a furnace at test temperature. The load was applied not less than two nor more than four hours later, depending on how quickly proper temperature distribution could be attained.

Choice of a test temperature for this alloy required a compromise between desire for a low temperature to give relative stability of structure and a high enough temperature to give 100 to 1000 hour rupture strengths somewhat below the proportional limit. This latter requirement was to limit plastic deformation at the root of a notch, so as to permit evaluation of initial stresses near the notch when the load is first applied.

Preliminary tests at 500° and 400°F presented in Table 4 and Figure 6 indicated the latter temperature to be satisfactory. In a 1000-hour test with a notch having K_t near 2 the maximum stress would still be less than the 0.2% offset yield strength. The known greater tendency for over-aging at 500°F appeared to more than offset any advantage of a lower ratio of rupture strength to yield strength. No further tests at that temperature are planned.

The few notch tests completed for 2024-T4 alloy show a uniform notch strengthening, apparently independent of limited differences in notch root radius or whether the specimen is round or flat. Only two test points for flat bars are yet available and more data will be required before these results may be firmly established.

Tensile data for 400°F were found as follows (See also Figure 5):

Tensile strength:	53,500 psi
0.2% Offset Yield Strength:	47,000 psi
Elongation in 2 inches:	15%
Reduction of Area;	40%
Elastic Modulus:	9.6×10^6 psi/in/in

DISCUSSION OF RESULTS

Comparative Notch Effects in Flat vs Round Specimens

Studies on flat notched specimens are still too incomplete for broad generalization. Results to date on S-816 are extensive enough to establish that for conditions studied a flat notch gives a moderate to slight decline in rupture strength below that for a round bar with the same stress concentration factor. This result agrees with the slight higher effective stress found in a notched flat bar than in a round notched bar with the same K_t.

It should be noted, however, that for all the S-816 tests the stress at the notch root exceeded the yield point during loading to the test stress. The same is true for the few tests completed for 2024-T4 alloy. Tests at lower stresses, where elastic conditions were still present on loading, would be easiest to analyze but the test time would be at least several thousand hours for most conditions under study. It is anticipated that approximate methods will permit satisfactory handling of calculations when only small plastic strains are present on loading.

The effect on notch strength to be expected from plastic strain at the start of a test is difficult to appraise, especially when the structure present tends to be unstable at test temperature and so is more sensitive to differences in metallurgical condition. Analysis of the problem is made particularly difficult by the fact that any strain hardening or other metallurgical changes usually result in simultaneous increase in rupture strength and in creep strength, or in simultaneous lowering of both. Resultant effects on life in the presence of a stress raiser oppose one another so that the net effect may be either an increase or decrease in notched-bar rupture life, and indeed may show opposite effects for different stress levels or notch geometries.

Such responses to initial localized strain may be involved in the different notch behavior observed for Waspaloy in Figure 3. It is possible that no corresponding difference would be found for smooth-bar properties under similar conditions. In such a case some insight could perhaps be obtained by determining in detail creep and rupture properties for a range of stresses after prior overloading at temperature to initial strains of the magnitude estimated to occur at a notch during loading.

FUTURE WORK

Experimental work for the coming quarter will center on completion of steady-load notched-bar data and of smooth-bar tests under variable load for the two alloys introduced into the program this year. Efforts will also be made to complete tests on the 1-3/4 inch round Waspaloy stock from Heat 63613 in hopes of determining the causes of noted wide variation in notch behavior for specimens with and without the 1550°F intermediate age. Response to initial strain at the notch will be investigated insofar as time and material permit.

Analysis of notched-bar results in terms of smooth-bar properties is to continue. When the remaining tests are completed, the entire mass of data are to be reviewed for possible general relations between notch behavior and smooth-bar properties.

BIBLIOGRAPHY

1. Voorhees, H. R. and Freeman, J. W. Ninth Progress Report on Notch Sensitivity of Heat-Resistant Alloys at Elevated Temperatures., University of Michigan Engineering Research Institute, Report No. 2024-7-P, March 31, 1955

2. Carlson, R. L., MacDonald, R. J., and Simmons, W. F. Investigation on Notch Sensitivity of Heat-Resistant Alloys at Elevated Temperatures, WADC TR 54-391, October 1954.

TABLE 1

Rupture Properties at 1350°F for Flat Specimens of S-816 and Inconel X-550

Spec. No.	Alloy	Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (inches) W	w	t	r	K_t	How Notch was Finished
				Smooth Specimens					
FS-S(B)27	S-816	30,000	802.3	0.400		0.100			
FS-X563	Inconel X-550	40,000	563.4	0.400		0.100			
				Notched Specimens					
FN-S95	S-816	40,000	171.0	0.620	0.310	0.100	0.025	3.1	Ground, lapped
FN-S96	S-816	60,000	6.0	0.620	0.310	0.100	0.025	3.1	Ground, lapped
FN-X559	Inconel X-550	40,000	169.0	0.620	0.310	0.100	0.025	3.1	Ground, lapped

(a) W = Width of unnotched gauge length
w = Minimum width (at notch)
t = Thickness of bar
r = Notch root radius
K_t = Theoretical stress concentration factor (in axial direction).

TABLE 2

Notch Rupture Tests at 1350°F for Waspaloy Heat 63613 With and Without Re-Rolling

Before Heat Treatment

Spec. No.	Stress (psi)	Rupture Life (hours)	Remarks
Specimens Sampled from 1-3/4 inch Round Stock Rolled by Supplier			
LN- W351	42,000	1086.2	Conventional Heat Treatment
LN- W352	52,000	208.5	Conventional Heat Treatment
LN- W353	42,000	1.5	1550°F Age Omitted
LN- W354	52,000	0.75	1550°F Age Omitted
Specimens from 1/2 inch Squares Rolled at U. of M. from 1-3/4 inch Round			
LN- W319	50,000	18.4	Conventional Heat Treatment
LN- W321	50,000	1.5	1550°F Age Omitted
LN- W322	40,000	9.4	1550°F Age Omitted

All Notches Ground and Lapped

Notch Geometry (In): D = 0.500
d = 0.350
r = 0.018
60° Angle

TABLE 3

Rupture Properties at 1100°F for Smooth and Notched Bars of "17-22-A"S Cr-Mo-V Alloy Steel Normalized and Tempered

Smooth Bars

Spec. No.	Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
-L701	70,000	0.6	15.5	66.5
-L707	65,000	4.5	17	43
-L702	60,000	9.7	8.5	25
-L708	55,000	19.6	6	14
-L703	50,000	32.2	5	8.5
-L704	40,000	87.2	4.5	6.5
-L705	30,000	213.9	3	3.5
-L706	20,000	873	2.5	3.5

Round Notched Bars

Spec. No.	Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (Inches)			
			D	d	r	K_t
N-L731	65,000	22.5	0.600	0.424	0.086	1.8
N-L735	55,000	45.4	0.600	0.424	0.086	1.8
N-L732	50,000	63.5	0.600	0.424	0.086	1.8
N-L733	45,000	34.7	0.600	0.424	0.086	1.8
N-L736	35,000	195.0	0.600	0.424	0.086	1.8
N-L734	25,000	600.0	0.600	0.424	0.086	1.8
N-L718	65,000	14.1	0.600	0.424	0.020	3.1
N-L713	60,000	17.8	0.600	0.424	0.020	3.1
N-L714	50,000	36.5	0.600	0.424	0.020	3.1
N-L715	40,000	73.5	0.600	0.424	0.020	3.1
N-L716	30,000	172.3	0.600	0.424	0.020	3.1
N-L717	20,000	699.6	0.600	0.424	0.020	3.1

Flat Notched Bars

Spec. No.	Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (Inches)				
			W	w	t	r	K_t
N-L737	55,000	39.6	0.740	0.400	0.100	0.100	1.9
N-L738	45,000	74.5	0.740	0.400	0.100	0.100	1.9
N-L739	35,000	146.3	0.740	0.400	0.100	0.100	1.9
N-L740	25,000	430.0	0.740	0.400	0.100	0.100	1.9

(Continued on next page)

TABLE 3 (continued)

pec. No.	Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (Inches) W	w	t	r	K_t
N-L719	65,000	7.0	0.740	0.400	0.100	0.031	3.1
N-L720	55,000	16.5	0.740	0.400	0.100	0.031	3.1
N-L721	45,000	39.0	0.740	0.400	0.100	0.031	3.1
N-L722	35,000	137.5	0.740	0.400	0.100	0.031	3.1
N-L723	25,000	387.5	0.740	0.400	0.100	0.031	3.1
N-L724	20,000	606.8	0.740	0.400	0.100	0.031	3.1

a) All notches ground and lapped; notch angle 60°;
K_t = Theoretical stress concentration factor (in axial direction)

Round Notched Specimens: D = Diameter of unnotched gauge length
d = Diameter of notch
r = Notch root radius

Flat Notched Specimens: W = Width of unnotched gauge length
w = Minimum width (at notch)
t = Thickness of bar
r = Notch root radius

TABLE 4

Rupture Properties at 400° and 500°F for Smooth and Notched Bars of 2024-T4

Aluminum Alloy

pec. No.	Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
SMOOTH BARS				
500°F				
-A603	20,000	2.83	14.	54.5
-A605	15,000	24.3	12	44.5
-A609	10,000	167.2	14.5	38.5
400°F				
-A613	45,000	0.825	7	33.5
-A616	40,000	2.3	15	44.5
-A611	35,000	6.2	7	37
-A607	25,000	73.6	9.5	37
-A610	20,000	434.9	8.5	32

ROUND NOTCHED BARS

			[a]Nominal Specimen Geometry (inches)			
			D	d	r	K_t
500°F						
-A618	15,000	88.9	0.600	0.424	0.020	3.1
400°F						
-A619	35,000	50.1	0.600	0.424	0.020	3.1
-A617	30,000	133.9	0.600	0.424	0.020	3.1
-A626	25,000	412.3	0.600	0.424	0.020	3.1
-A631	35,000	42.3	0.600	0.424	0.075	1.85
-A633	25,000	384.9	0.600	0.424	0.075	1.85

FLAT NOTCHED BARS

			[a]Nominal Specimen Geometry (inches)				
			W	w	t	r	K_t
400°F							
N-A643	35,000	48.9	0.740	0.400	0.100	0.098	1.9
N-A642	30,000	168.45	0.740	0.400	0.100	0.098	1.9

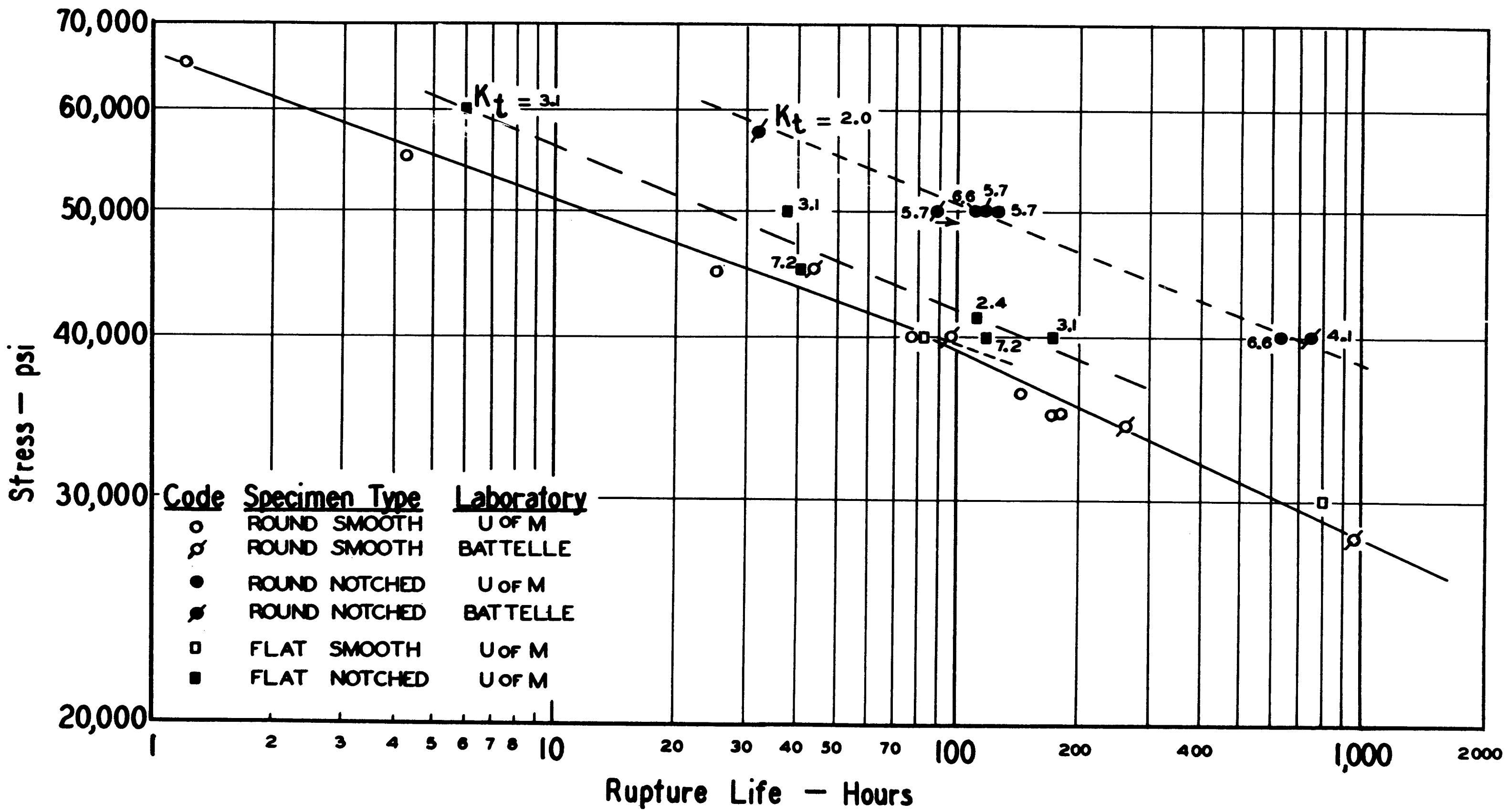

FIG. 1 - STRESS VERSUS RUPTURE LIFE OF S-816 AT 1350°F FOR SMOOTH AND NOTCHED BARS, BOTH ROUND AND FLAT.

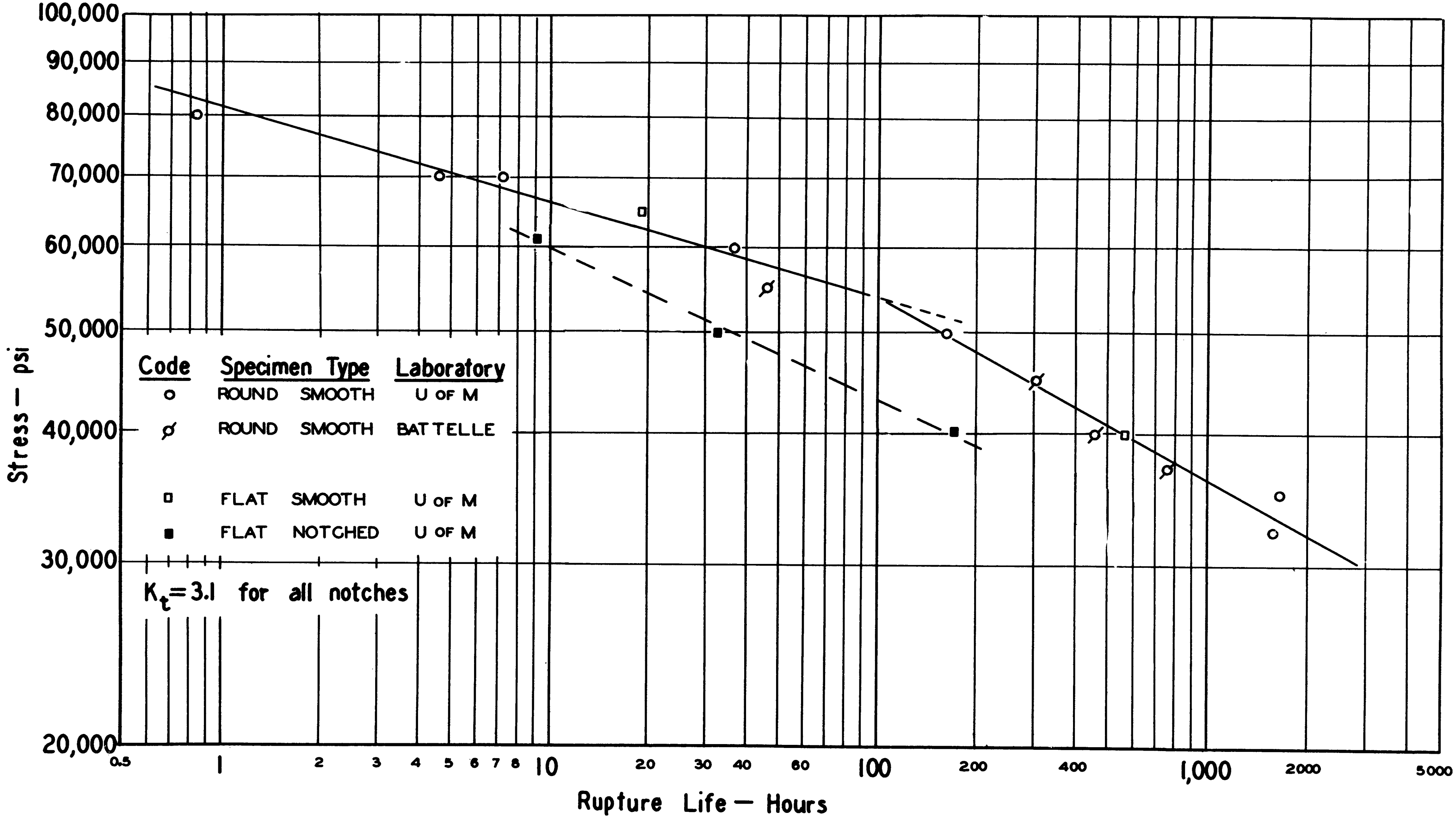

FIG. 2 - STRESS VERSUS RUPTURE LIFE OF INCONEL X-550 AT 1350°F FOR SMOOTH AND NOTCHED BARS.

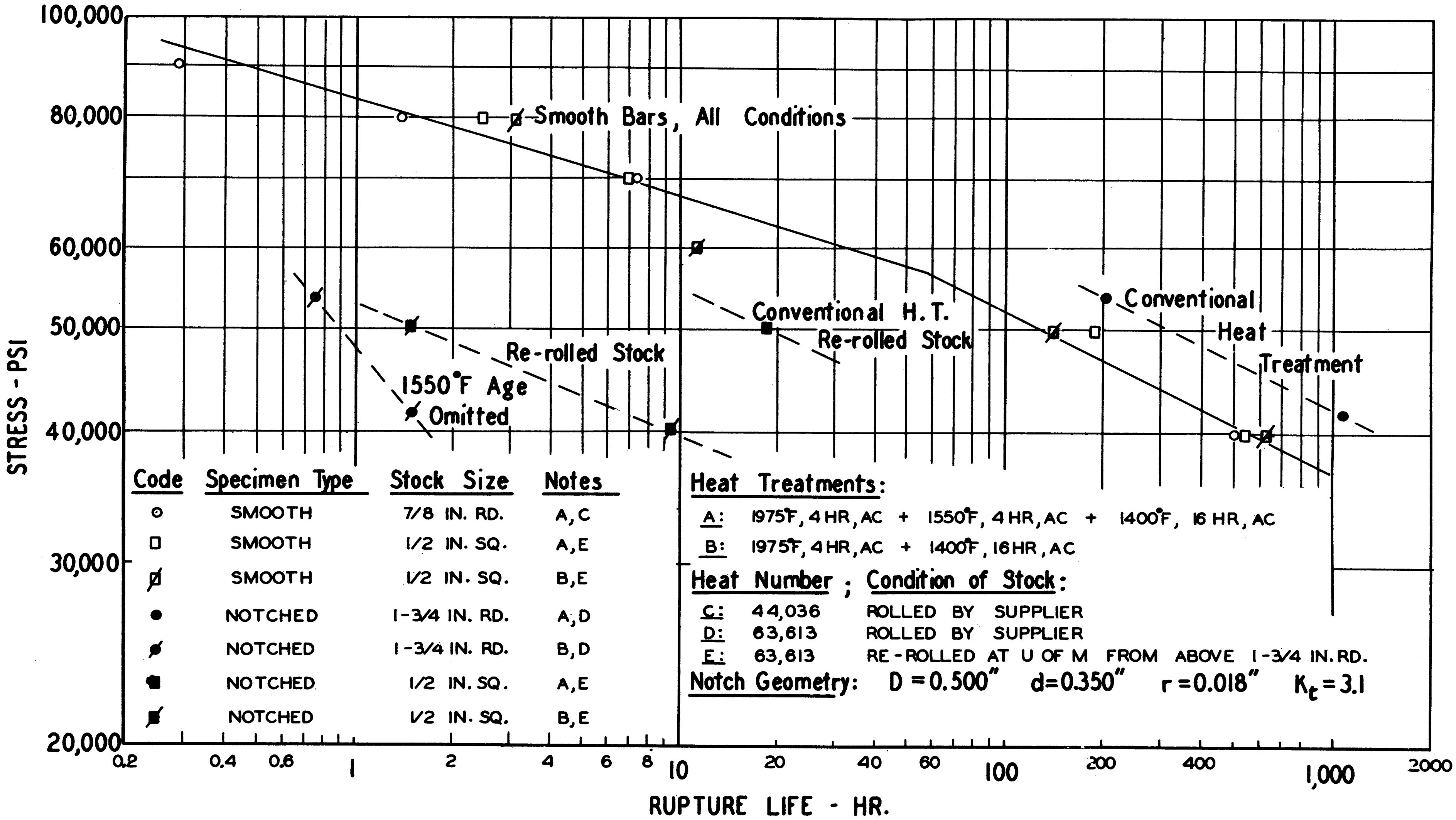

FIG. 3 - STRESS VERSUS RUPTURE LIFE AT 1350°F FOR WASPALOY HEAT 63,613 WITH AND WITHOUT RE-ROLLING BEFORE HEAT TREATMENT.

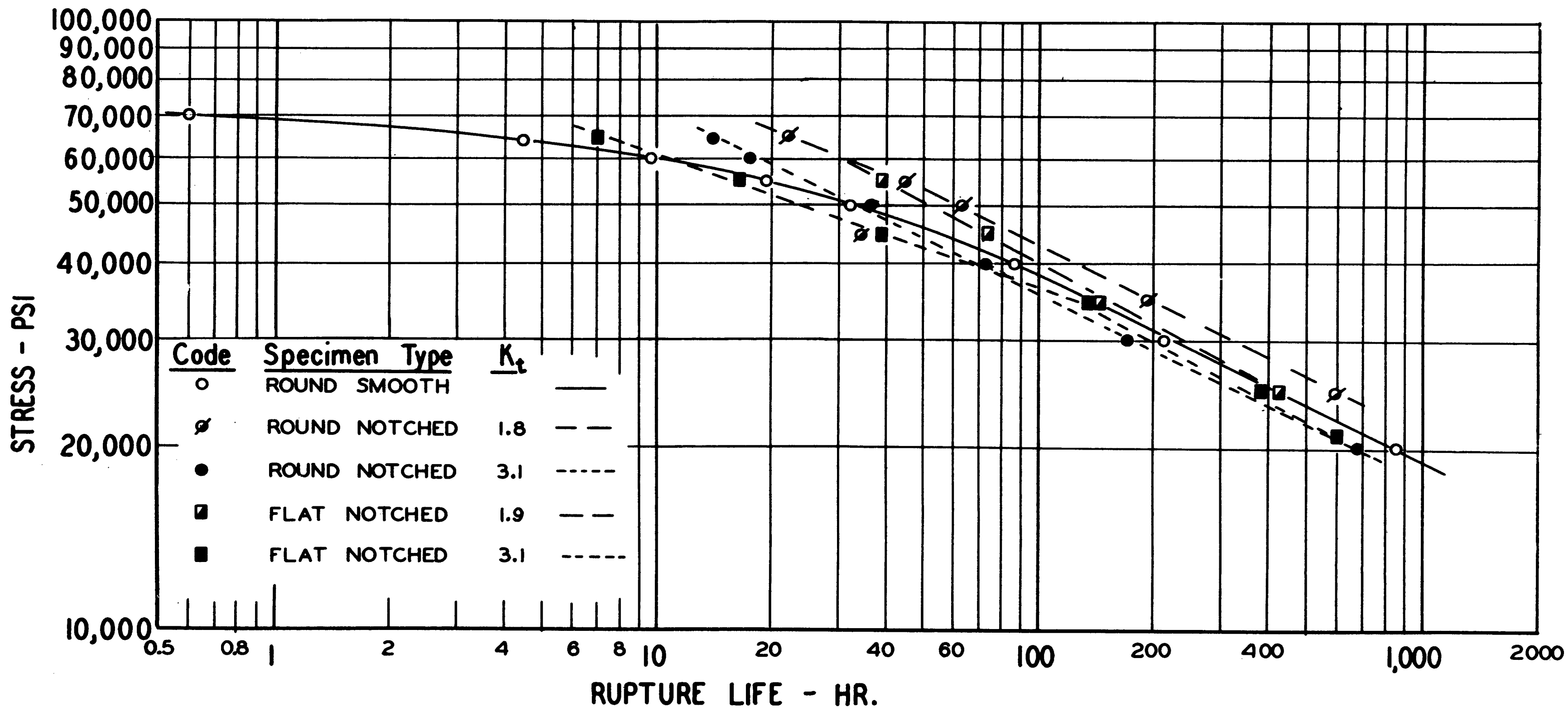

FIG. 4 - STRESS VERSUS RUPTURE LIFE AT 1100°F FOR SMOOTH AND NOTCHED BARS OF "17-22A"(S) Cr-Mo-V STEEL.

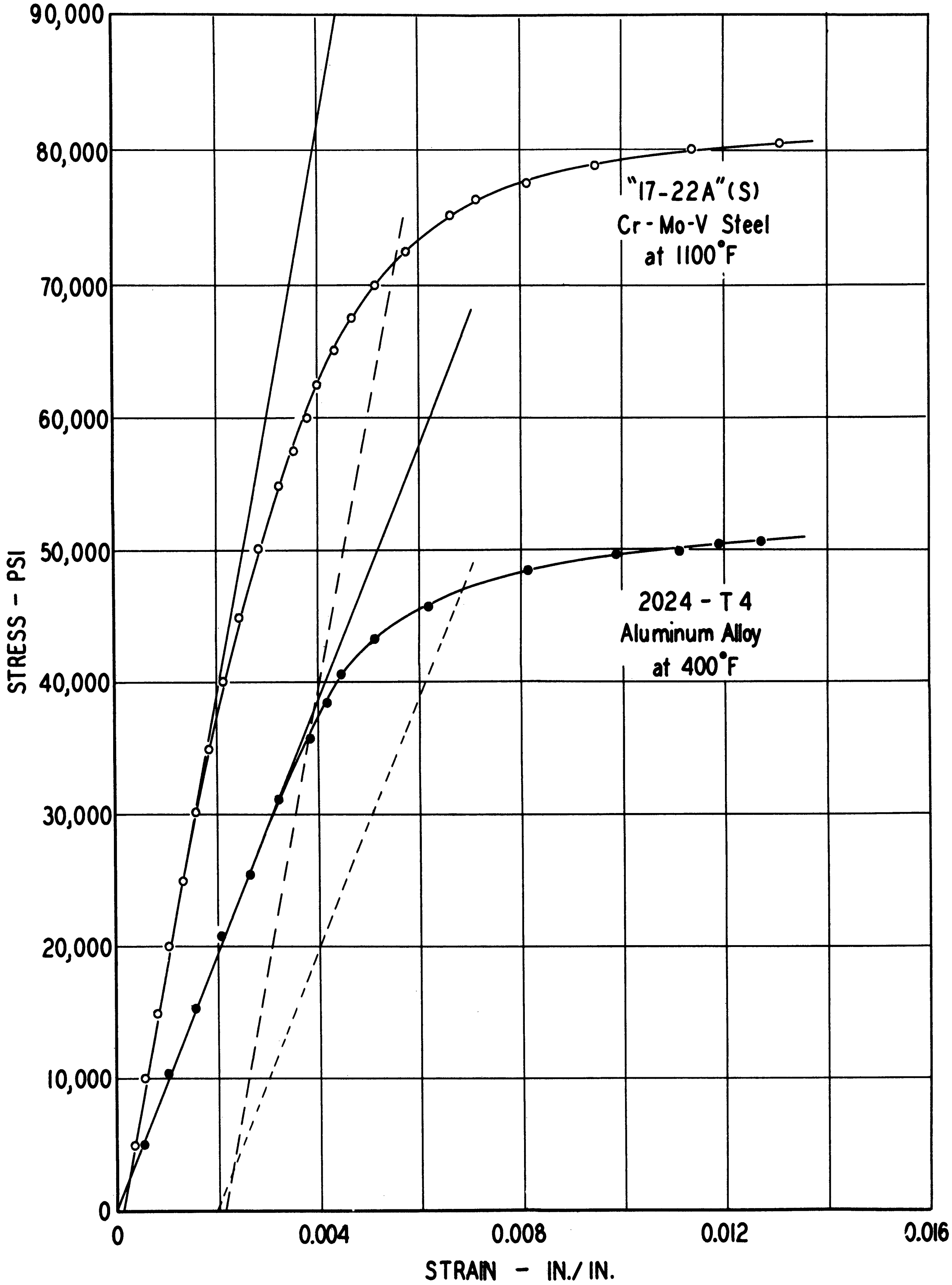

FIG. 5 - STRESS-STRAIN CURVES FOR TWO OF THE ALLOYS STUDIED.

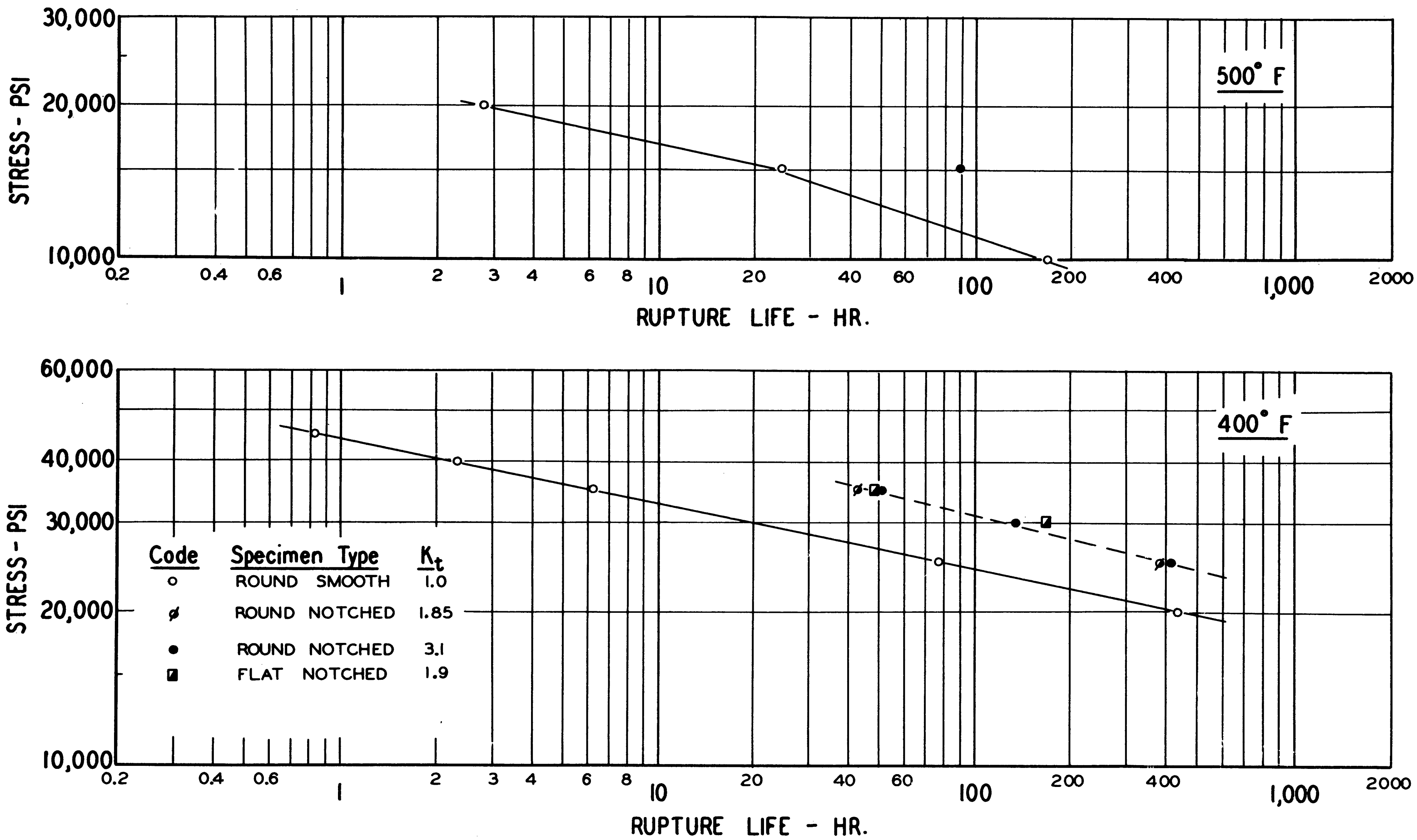

FIG. 6 - STRESS VERSUS RUPTURE LIFE FOR SMOOTH AND NOTCHED BARS OF 2024-T4 ALUMINUM ALLOY