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Part 3

NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

Part 3. Final Data and Correlations

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FOREWORD

This report was prepared by the University of Michigan under USAF Contract No. AF 18(600)-62. The contract was initiated under Project No. 7360. "Materials Analysis and Evaluation Techniques", Task No. 73605, "Design Data for Metals". The research was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center. Dr. A. Herzog acted as project engineer.

This report covers work performed during calendar year 1955. Original data for this entire research are summarized and indexed in data book No. 2708, located in files of the Engineering Research Institute of the University of Michigan under the heading "Project 2024".

The "17-22-A"S low alloy steel used in this research was supplied without cost by the Timken Roller Bearing Company. Material for study of variable notch effects in Waspaloy was furnished, also without charge, by the Allegheny Ludlum Steel Corporation and by the Pratt and Whitney Aircraft Corporation.

ABSTRACT

Earlier parts of this report summarized rupture lives for smooth and notched round specimens of three heat-resistant alloys, together with pertinent experimental data on tensile stress-strain properties and creep-relaxation characteristics for these alloys. Similar types of data have now been obtained for flat specimens, and for two other types of material (a Cr-Si-Mo-V steel and an age-hardening aluminum alloy).

Results gathered during the over-all program lead to the following conclusions:

1. Elevated-temperature rupture characteristics of notched specimens under a steady tensile load appear to depend on three major factors:

    a. The distribution and level of the initial stress pattern, determined by the notch configuration and tensile characteristics of the alloy.

    b. The rate at which variable creep rates at different locations in the cross section are able to relax the peak stress originally concentrated near the notch. Under multiaxial stressing the effective stress can easily become less than the nominal value for alloys with low creep resistance.

    c. Rupture characteristics of the material at the prevailing stresses and for the prior history experienced by different fibers in the notched bar. If too large a portion of the total life is used up at the initial high stresses, the remaining service will be short even if the final stress is low.

2. It appears that rupture life of a structure in the presence of a concentrated complex stress involves no new factors beyond those which determine rupture under simple stress. If one can predict the stress-strain-time history at points throughout a body, the time until rupture at any point seems amenable to calculation from data obtained with smooth specimens. The major uncertainty is choice of the proper criterion for initiation of rupture following creep under variable complex stresses.

3. For some alloys a small amount of plastic deformation near the notch when the load is added may radically alter subsequent creep-rupture characteristics. This may be the major factor in notch weakening under some conditions.

PUBLICATION REVIEW

This report has been reviewed and is approved

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
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1.) INTRODUCTION

As modern high-performance aircraft demand higher working stresses and operating temperatures in both engine and airframe components, the design engineer must strive to reduce "factors of ignorance" so as to make fullest use of the inherent strength of available alloys. Increasing use is being made of rupture tests on notched specimens to evaluate ability of aircraft materials to withstand the presence of concentrated complex stresses. In such tests, normally conducted with steady axial load and constant temperature, the life of a notched specimen may be either longer or shorter than that for a smooth bar under the nominal stress, depending on the particular alloy, the test temperature and the notch configuration. To date, use of notch rupture data has been largely for qualitative comparison between materials.

This investigation was initiated under Air Force Contract No. 18(600)-62 to study the basic mechanism causing the different types of notch response observed in tests on heat-resistant alloys at elevated temperatures. Special attention was to be directed to the relative significance of stress redistribution by a creep-relaxation mechanism.

The entire investigation has been built around a desire to explain notch rupture characteristics in terms of alloy properties as ordinarily measured in simple tension. It was not sought to establish why a smooth rupture specimen behaves as it does, but only to apply the usual creep-rupture data to analyze alloy behavior in the presence of a complex concentrated stress.

It was reasoned that a notch per se should introduce no new properties, but merely modify stress-strain histories of fibers in the notched bar. Under the restraint imposed by surrounding portions at lower stress, the highly-stressed material near the notch root would be subject to creep relaxation of the stress. Unless this reduction of stress level is quite rapid, the critical fibers near the notch exist under high-stress creep conditions throughout the test, corresponding to a short rupture life. In order for notch strengthening to occur, the stress promoting rupture in these fibers must drop quickly to a value considerably below the level of the nominal stress which compares to the uniform axial stress in the corresponding smooth specimen.

By the time the axial stress of the fibers near the notch root reaches the nominal stress level, further relaxation should be much reduced in rate. Moreover, the average axial stress component must still equal the applied load divided by the cross section at the notch regardless of how far stress redistribution proceeds. Under these limitations, it appears that notch strengthening can only be explained if the rupture life in any fiber is controlled not by the largest principal stress component but by some combination of differences

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between stress components. Numerous experimenters have established that behavior of ductile metals under complex stressing (biaxial or triaxial stress patterns) at room temperatures as well as occurrence of creep and short-time fracture at elevated temperatures can all be satisfactorily correlated by the shear-stress invariant theory. This theory, generally attributed to von Mises, gives the effective stress ($\overline{S}$) governing yielding or creep in terms of the principal stresses ($S_1 > S_2 > S_3$) according to the following expression:

$$2\,\overline{S}^2 = (S_1 - S_2)^2 + (S_1 - S_3)^2 + (S_2 - S_3)^2 \quad (1).$$

This effective stress has been assumed in this investigation to also control rupture under creep conditions, although no positive proof of this has been found.

Relaxation is fastest in the direction of the largest stress component, so that the difference between two principal stresses decreases faster than does either stress itself. The effective stress across the entire notched section can therefore easily fall below the nominal axial stress in alloys of low creep resistance. The occurrence of notch strengthening is then easily explained.

The initial stress pattern in a notched specimen is a function of the notch geometry and can be calculated by elasticity theory when the effective stress in all fibers remains below the proportional limit. If localized yielding occurs, the resulting initial stress pattern depends also on the stress-strain properties of the particular alloy at the test temperature.

Starting with a given distribution of initial stress, the actual life of a notched specimen is controlled by creep and rupture properties of the alloy concerned. Limiting conditions would be: (1) negligible stress redistribution, giving a minimum life corresponding to that for the maximum stress present on loading, and (2) complete, rapid redistribution to a uniform creep rate throughout. In the latter case, the actual life could approach the rupture life corresponding to the integrated average of the initial effective stress levels across the notched section.

For a specific material the rate of stress leveling is dependent on the creep-rate gradient between different fibers, and on the elastic modulus. The extension of life resulting from lowering of the initial peak stress depends in turn on the slope of the stress-rupture life curve for the alloy and temperature involved.

Part 1 of this report (See Ref. 1) presented results of preliminary studies with three heat-resistant turbine-blade alloys. Notch strengthening appeared to accompany conditions of rapid relaxation and notch weakening was found when smooth-bar tests indicated slow relaxation even at stresses where rupture life was quite short.

The major contribution of the early tests toward a workable quantitative treatment came out of tests on smooth specimens in which one steady load was maintained for a portion of the test and then a different steady load was used for a succeeding period. For the materials studied, life fractions were found to be additive; i.e., the portion of total rupture life used up during a period of time at any particular stress in a variable-stress test equals the fraction:

$$\frac{\text{actual time at the given stress}}{\text{rupture life for that stress}}$$

In Part 2 (See Ref. 2) a step-wise analysis based on addibility of life fractions was developed to compare notch behavior more quantitatively in terms of smooth-bar properties. Indications were that widely-differing rates of stress redistribution by creep relaxation could satisfactorily explain variations in notch behavior. Notch strengthening was found to be associated with rapid relaxation of high initial stresses. For conditions where relaxation was slow, a large portion of the total life was postulated to be used up quickly at the high stress near the notch, resulting in early fracture there and lowering life of the specimen below that for a smooth bar.

This third and final part of the total report includes experimental work on flat specimens, both smooth and notched at the edges, and for two additional materials, an air-hardening Cr-Si-Mo-V steel designated as "17-22-A"S and an age-hardened aluminum alloy (2024-T4). Search for factors affecting notch behavior, other than creep and rupture properties, was also continued.

Comparative rupture properties for smooth and notched specimens are assembled in the present report for all alloys studied in the entire program, and attempts have been made to show how notch behavior is related to smooth-bar data.

SECTION I

EXPERIMENTAL RESULTS OBTAINED DURING 1955

Earlier studies employed cylindrical specimens, both smooth and notched, of three heat-resistant alloys. Experimental investigation for the year 1955 was extended to include testing of flat specimens prepared from bar stock, and to include two additional types of alloys. Work has continued in search for other factors than tensile, creep and rupture properties which affect notch behavior for a given notch geometry. In particular, a limited available supply of Waspaloy stock was tested to determine why it exhibited different notch behavior depending on whether an intermediate aging step was included or omitted from the conventional heat treatment.

Notches Employed in Tests During the Past Year

Extremely-small notch root radii are difficult to produce accurately and permit only approximate calculation of actual stress levels near the notch. To permit closer evaluation of initial stress patterns, the sharper notches used in many earlier tests (root radii of 0.004 to 0.010 inch) were eliminated from most specimens studied during the past year. For most of the round specimens, a root radius of either 0.020 or 0.080 inch was adopted. The corresponding theoretical stress concentration factors (K_t) are, respectively, about (3.2) and (1.9) when the shank diameter is 0.600 inch and the cross section at the notch half that of the shank.

Routine notch preparation followed the sequence sketched in Figure 1. First the notch was rough turned to the final diameter plus twice the desired root radius, r. A shaped grinding wheel with flood cooling was next used to finish the 60° included angle and to form a flat $r\sqrt{3}$ inches wide at the final aim diameter plus r. A sharp wheel then made a shallow circumferential groove in the center of the flat to guide the wire used in the final lapping step. If the wire employed had a diameter slightly less than 2r, a few minutes of hand lapping with a fine lapping compound was usually sufficient to remove the remaining metal and to give a notch with the root circle closely blended into the side angles. This lapping step was interrupted from time to time and progress checked by visual observation, using a 50X optical comparator.

Round specimens were rotated in a lathe during lapping. For flat specimens with edge notches, the special fixture illustrated in figure 2 was devised to maintain alignment between the specimen and the wires during lapping.

Tests on Flat Specimens of Two of the Original Alloys Studied

It appeared very desirable to test some flat notched specimens to ascertain whether indications found for triaxial stressing of notched round bars applied equally to the biaxial case. A few rupture tests were also run on smooth bars with flat rectangular cross section for comparison purposes.

From the original three heat-resistant materials only sufficient stocks of S-816 and Inconel X-550 remained to permit testing of flat specimens. These specimens were machined from the same round bar used to make the cylindrical specimens since the desirability of obtaining all types of specimens from the same heats of metal and with a common fabrication history prior to machining seemed to more than outweigh limitations of specimen geometry imposed by the small diameter of the bar stock. The specimen (See Figure 3) adopted also eliminated many of the difficulties often encountered with gripping and alignment of strip specimens.

Heat treatment of the specimen blanks, machining of threaded ends and rough notching followed identical steps as preparation of round test bars. Two flats, each about 0.125 inch wide, were ground on opposite sides of the round bar to serve as edges for the final flat gauge section. These flats were used to line up the bar in a shaper when the bulk of the surplus material was being removed from the sides of the center portion of the specimen. The threaded ends of the specimen were next centered in a pair of matched steel jig blocks shown in figure 3.

The jig blocks were designed to hold the specimen onto a magnetic base plate so that after a light grinding pass was made on one surface and the specimen was flipped over, the same grinder setting would finish the opposite face of the specimen to the same distance from the specimen axis. To avoid bowing of the flat section as material with residual stresses from the shaping operation was removed, light cuts of a few thousandths of an inch were ground from alternate sides. Final grinding passes were of the order of 0.0005 inch. Flood cooling was employed at all times during grinding to minimize residual surface stresses of thermal origin.

After the gauge-section surface was finish ground, the notch was lapped until the notch of desired root radius extended straight across the specimen normal to the sides of the flat.

Design of suitable specimens to be prepared in this manner involved compromise among several often-conflicting factors:

(1). To approach truly biaxial stressing, specimen thickness should be small in comparison to its width. A width/thickness ratio of 4/1 is considered about the minimum acceptable value, with 8/1 preferred.

(2). For the 3/4-inch diameter round stock on hand the resulting flat specimen must be quite thin. However, a thickness less than about 0.100 inch is difficult to machine.

(3). It might be desirable from the standpoint of later interpretation to have the notched cross section the same fraction of the shank section in both round and flat notched specimens.

Starting with 3/4-inch round stock, a flat 0.100-inch thick and 0.740-inch wide can be obtained. A shallow notch would permit an increase in width/thickness ratio for a given stress concentration, but the resultant localization of the stress makes the shallow notch more prone to variability from minor deviations in specimen geometry and makes analysis of stress changes more critical. Using the borderline width/thickness ratio of 4/1, a 0.030-inch root radius is required for K_t = (3.3) and 0.100-inch for K_t = (2.0). These dimensions were adopted as "standard" for the majority of the current series of tests. However, the tests on

S-816 and Inconel X-550, listed in Table 1, used specimens with somewhat different geometry, prepared before specifications for flat notched specimens had been finalized.

Rupture strengths for flat specimens of S-816 with conventional heat treatment are shown in Figure 4 along with round-bar data presented in earlier reports. The data include results for three smooth and three notched round specimens of the same lot of alloy tested at Battelle Memorial Institute under another contract with wright Air Development Center. (See Ref. 3.)

The two test points for smooth flat specimens show no apparent significant deviation from results for round smooth specimens. This result 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 2.1 to 6.6 seemed to fall on a common curve somewhat higher than corresponding curves for flat bars with a range of K_t between 2.4 and 7.2. These results suggest less effect from different theoretical stress concentration factors than from type of stress, biaxial or triaxial.

Experimental results for Inconel X-550 (Figure 5) lead to similar conclusions; namely, that the shape of the gauge section has little effect on smooth-bar life and that flat notched specimens appear to have lower rupture strength than round notches with the same theoretical stress concentration.

Further Studies on Notch-Preparation Effects

The method of notch preparation has been demonstrated to have a large effect on notched-bar life for some conditions. Figure 6, a revision of Figure 7 of Ref. 2, shows the wide spread of results obtained at 1350°F for Inconel X-550 specimens with the same quite-sharp notch. These results have been explained by the variable extent and character of residual stresses in the critical fibers near the notch left from the notching operations. Residual compressive stresses near the surface left from machining operations can be expected to offset part of the tensile stress at the notch root and thereby tend to extend notch life. Results presented later indicate, however, that for some materials small amounts of cold work can severly reduce rupture strength. Therefore, the trends depicted in Figure 6 may not be applicable to other alloys or temperatures.

If the residual stress hypothesis is adopted, specimens heat-treated after notching should give results most nearly typical of a notch free from initial machining stresses.

Three notched specimens of Inconel X-550 were finished by grinding in the as-received condition to a nominal gauge diameter of 0.600-inch, 0.424-inch diameter at the notch, and 0.005-inch notch root radius. The specimens then received a conventional heat treatment after being sealed in individual Vycor glass tubes under high vacuum. The Vycor tubing collapsed around the specimen and showed pronounced devitrification during the four-hour solution treatment at 2150°F, but the vacuum was retained throughout the treatment.

Rupture data obtained at 1350°F follow:

Stress (psi)	Rupture Life (Hr.)
60,000	3.4
50,000	7.6
40,000	55.9

These rupture times fall near, but slightly lower than, the values previously found for similar specimens treated in a raw helium atmosphere after turning the notch on a lathe. In the present specimens no evidence was seen of the surface alteration and preferential orientation of grain boundaries perpendicular to machined surfaces noted in the earlier specimens.

For the sharp notch studied, agreement is only fair between a notch finish-lapped after rough grinding and a notch heat treated after notch preparation. For notches with larger root radius, the two methods should give more nearly equal results, because a greater depth of worked material is removed by lapping in the case of a larger root radius.

This expectation appears to be borne out by tests to be reported in a later section on "17-22-A"S Cr-Si-Mo-V steel at 1100°F. Most of a group of notched specimens with a 0.020-inch root radius received a conventional normalizing + temper prior to notching, while two were heat treated in vacuum after the notch was made. (All notches were rough ground and then lapped). Comparative rupture times listed in Table 2 and included on Figure 7 indicate a nearly identical degree of notch weakening for the two procedures.

In the case of S-816 at 1350°F, any residual stresses from machining should quickly relax out with but a small consumption of rupture life. For that alloy, three flat notches were merely finished in a shaper, while three others were ground and lapped. Still no effect from this source can be identified in the results on Figure 4. Similar results can be anticipated for other alloys showing a large degree of notch strengthening.

Attempts were made to obtain specimens notched by a method employing supersonic vibration, but efforts to date have been unsuccessful.

In the notch-finishing procedure used at the University of Michigan, the notch root receives a final lapping with movement of abrasive particles in the circumferential (transverse) direction. At the University of Minnesota Department of Mechanics and Materials a more refined lapping technique employs a rotating wire so that abrasive movement at the root of the notch is in the axial direction. Comparable specimens with K_t of about 3 were prepared at the two laboratories from the same lot of Inconel X-550, with heat treatments, rough machining and testing all performed at the University of Michigan.

NOTCHED BARS OF INCONEL X-550 AT 1350°F, $K_t = 3$

Laboratory Where Notch was Finished	Stress (psi)	Rupture Life (hours)
Michigan	55,000	31.5
Michigan	35,000	523.1
Minnesota	50,000	134.8
Minnesota	40,000	185.4
Minnesota	35,000	568.4

These test findings plotted on Fig. 5 show considerable scatter, but no particular trend is apparent to indicate any consistent effect from the differences in the two lapping techniques.

Five specimens of the same alloy from another lot were heat treated, rough machined and tested at the Department of Mechanics and Materials at the University of Minnesota. The notches for these five bars were lapped to final dimension at the University of Michigan by the technique normally employed there.

The University of Minnesota obtained close agreement between specimens finished at Michigan and at Minnesota for one case each of rupture at 1350°F and 1500°F and fatigue at 75°F and 1350°F under reversed stress. The fifth specimen tested to rupture at 1350°F broke at a much shorter time than comparison specimens machined at either laboratory.

Test Results for "17-22-A"S Alloy Steel at 1100°F

The 1-inch round of "17-22-A"S steel 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)

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):	20.8×10^6 psi/in/in

Early portions of the stress-strain curve are included in Figure 8.

Summary results of constant load creep-rupture tests at 1100°F with smooth, round specimens, and for rupture tests with both round and flat notched specimens are given in Table 2 and Figure 7. For the range of stresses investigated, notched specimens with a theoretical stress concentration factor of about 2 showed notch strengthening for both round and flat specimens, with values for the flat bars slightly lower than for round. (See Fig. 9). At higher notch acuities, the notched-bar life increases, so that for notches with K_t = 3.2 to 3.3 results fell close to those for smooth bars.

At nominal stresses above 60,000 psi, notch strengthening appeared for all notch geometries studied. At longer test times, mild notch weakening set in and the curve for round notched specimens seemed to fall below that for flat notched specimens. As for previous alloys, flat smooth specimens showed substantial agreement with results for round smooth bars.

Five specimens of this alloy subjected to multiple-stress rupture tests gave the results listed in the top half of Table 3. Agreement with the life-fraction rule was only fair. Deviations from quantitative addibility of life fractions are probably chiefly due to metallurgical changes during extended creep. In support of this belief, it might be noted that the greatest discrepancy occurred when the stress level was increased after a prior period of 100 to 200 hours at lower stress. For a high initial stress and low later stress, the life-fraction rule appears to be essentially correct. The decided "break" in the smooth-bar stress-rupture life curve of Figure 7 also indicates probable structural alteration in service.

To simulate the stress-time history near the root of a notched specimen, a step-down relaxation test was run and the specimen carried to rupture after a residual stress of 20,000 psi had been reached. The initial stress was chosen to give about 0.1% plastic strain on loading. During the 30.9 hours required for relaxation to 20,000 psi an estimated 10.4% of a total rupture life was expended. The specimen lasted an additional 778.5 hours at the 20,000 psi to give a total calculated life at rupture of 97.9%.

Creep data obtained from the various tests were cross plotted to give curves of stress versus creep rate. (See Figure 10). Separate curves show the creep rate measured immediately after loading, the minimum creep rate, and the third-stage creep rate after certain percentage of the total rupture life had been expended.

Test Results for 2024-T4 Aluminum Alloy

This material was purchased from the Aluminum Company of America as cold-finished rod. The 3/4-inch round obtained was from lot No. 130,875 with the following nominal composition, percent by weight:

	Cu	Fe	Si	Mn	Mg	Zn	Cr	Other Elements		Al
								Each	Total	
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 (± 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.

The analysis proposed in this report employs results of constant-stress smooth-bar tests to predict creep and rupture characteristics under the variable stress histories of fibers in notched tension specimens. The validity of such a procedure is questionable when material properties are not identical for fibers under consideration in the smooth specimens and in the notched specimens. In particular, alloys which are prone to over-age at service temperatures exhibit time and stress-dependent changes in creep and rupture strength, so that the existing properties after a given fraction of life has been expended depend on the particular stress history experienced by a fiber of metal. Creep and rupture properties for material subjected to prior plastic strains are also expected to differ from these of material not so pre-strained.

In preliminary tests with 2024-T4 alloy at 500°, a change in slope of the curve of stress versus rupture time at about 20 to 30 hours suggested structural instabilities were probably greater than could be tolerated for the analysis proposed. (See Figure 11). At 400°F a similar break in the stress rupture time curve did not occur until much longer times. Still lower temperatures would be preferred from a stability standpoint, but the yield strength would be very near smooth-bar rupture strengths of interest. Then, for the same nominal stresses as used in smooth bars, notched specimens would suffer extensive plastic deformations at the notch root as the load was applied, making analysis of subsequent creep and rupture characteristics difficult or even impossible.

The 400°F temperature appeared to be a reasonable compromise. In a 1000-hour test with a notch having K_t near 2, the maximum stress of 35,000 to 40,000 psi would be less than the 0.2% offset yield strength. Yielding would occur with sharper notches or higher nominal stresses. Unless the actual creep and rupture properties of the material are known, as affected by initial plastic deformations and by progressive aging, any analysis such as used in this report cannot reasonably be expected to hold quantitatively.

Tensile data for 400°F were determined as follows (See also Figure 8):

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

Constant-load rupture tests for smooth and notched specimens are summarized in Table 4 and Figure 11. All notch tests conducted with 2024-T4 alloy showed notch strengthening. Round notched specimens with theoretical stress concentration factors of 1.9 and 3.2, and flat notches with $K_t = 2.0$ all seemed to have about the same rupture lives, whereas points for flat bars with a sharper notch ($K_t = 3.3$) fell about midway between the curves for smooth bars and round notched specimens.

Stress-creep rate properties at 400°F are presented on Figure 12.

The 2024 alloy in the T-4 condition (room-temperature age) can be expected to over-age progressively during prolonged exposure to a temperature of 400° or 500°F, with resultant loss in strength. By the end of a long-time test, the material is in the weakened condition, while in a short-time test the material may actually show an initial increase in strength as precipitation continues and detrimental over-aging effects should be limited. As a consequence, the life-fraction rule, based on data from constant-stress tests, should give a low result from step-up tests, and high results when the acting stress falls during the tests.

Experimental findings listed in the lower part of Table 3 demonstrate that these trends are very real. A period of 100 or 200 hours at 400°F appears to result in a 30 to 50 fold reduction in rupture life at a subsequent stress of 30,000 psi, compared with the original rupture strength at this stress. Minimum creep rate during the 30,000 psi stress period after prior exposure for 95 hours at 10,000 psi and 400°F was 0.1095 in/in/hour, contrasted with 0.0004 in/in/hour for material kept at 30,000 psi during the entire test.

For alloys exhibiting such marked property changes as the one under consideration, the simple life-fraction rule which agrees with experimental results for stable alloys may be far in error. It might be noted, however, that in one test where 36% of the life was estimated to be used up during step-wise relaxation from 40,000 psi to 18,000 psi the simple life-fraction rule was apparently adequate.

Relaxation Properties of 2024-T4 and "17-22-A"S Alloys

Summary report WADC TR 54-175, Part 2, showed a qualitative relationship between relaxation rate and notch rupture properties. At 1350°F, the respective times required for relaxation from the 10-hour rupture stress to the 1000-hour rupture stress were 0.5, 20, and 150 hours for the alloys S-816, Waspaloy and Inconel X-550. The first of these alloys was found to be strengthened by a variety of notches, Inconel X-550 was weakened by most notches tested and Waspaloy showed intermediate notch sensitivity.

At 1500°F, Waspaloy with conventional heat treatment exhibited notch strengthening and the corresponding relaxation from the 10-hour to the 1000-hour rupture stress required 8 hours. For the same testing temperature, S-816 rolled 13.5% at 1200°F after solution treatment at 2325°F was notch weakened and Waspaloy rolled between conventional solution and aging steps was neither strengthened nor weakened by the notch employed. In the latter conditions, the times for relaxing from the 10-hour to the 1000-hour rupture stress were about 9 and 10 hours, respectively.

A single relaxation test each has also been run for 2024-T4 aluminum alloy at 400°F and for "17-22-A"S low alloy steel at 1100°F, with initial stress in each case roughly midway between the proportional limit and the 0.2% offset yield strength. This stress level appeared to be about the value near the root of typical notched bars studied. The aluminum alloy required about 21 hours relax from the 10-hour rupture stress to that corresponding to 1000-hour life. The low alloy steel took roughly twice as long (38 hours) to relax between its 10-hour and 1000-hour rupture stresses. (See Figure 13.)

Effect of Plastic Strains on Creep, Relaxation and Rupture Properties

It might be noted that for all notch tests with S-816 (fig. 4) the stress at the notch root exceeded the yield point during loading. The same is true for most of the tests with the 2024-T4 alloy.

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 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 even opposite effects for different stress levels or notch geometries.

Limited tests have been run on the several alloys in this program to ascertain the order of magnitude of effects on creep, relaxation and rupture characteristics resulting from initial plastic strains:

S-816 at 1350°F

Early in this program it was noted that a small amount of plastic strain seemed to promote more rapid creep in S-816 tested at 1350°F. These effects have been studied more critically with the stock remaining. Five specimens of S-816 were pre-strained at 1350°F by amounts ranging from zero to 9.2% after they had received a conventional heat treatment. Each was then reloaded to an initial stress of 37,500 psi at 1350°F test temperature and relaxation characteristics obtained, as presented in Figure 14.

In all cases, plastic working produced more rapid relaxation during the first hour than was found for a specimen not pre-strained. But, after a few hours of relaxation, the residual stress for material with initial plastic strain was noticeably higher than for the material never stressed above the proportional limit.

Relaxation characteristics were obtained to rather low stresses in test times of several hundred hours. In every case, the calculated portion of rupture life consumed in the entire relaxation period was still less than one percent. The stress on each specimen was later raised and the test allowed to proceed at this new stress until rupture occurred. Table 5 lists the time required for relaxation to 15,000 psi and life expenditure during that initial period of relaxation, along with rupture life during the subsequent higher-stress period.

Plastic pre-straining of more than a few percent delays relaxation at the lower stresses. When life fractions were calculated from rupture properties of unstrained material, specimens with 6 to 9 percent initial plastic strain were found not to be weakened by the plastic deformation or by a prolonged relaxation period following it. In fact, a total life of more than 100% was indicated by the life-fraction rule.

Inconel X-550 at 1350°F

Corresponding tests on Inconel X-550 with initial plastic strains up to 2.6% exhibit quite different behavior. Increasing amounts of pre-strain shortened relaxation times (See Figure 15) but when the specimen was then held at constant stress following the relaxation, specimens with initial strains of more than between 0.25 and 0.85% had but a fraction of life to be expected from calculations based on properties of unstrained material (See Table 5).

"17-22-A"S at 1100°F

Three creep tests are available for this low alloy steel, with two specimens pre-strained by momentary overloading to 74,000 psi and 79,800 psi, respectively.

Plastic Pre-strain (%)	Stress (psi)	Creep Strain During first 20 mins. (in/in)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
0	40,000	0.0052	87.2	4.5	6.5
0.11	40,000	0.0041	81.4	4.	4.5
0.22	39,750	0.0036	78.9	2.5	5.5

Small prior plastic strains appear to result in a slight loss of rupture life and ductility, and in a moderate drop in creep rate at least up to the secondary creep stage.

2024-T4 at 400°F

One smooth specimen of this alloy was plastically strained 1.9% at temperature by momentary loading to 50,000 psi. Subsequent relaxation from 40,000 psi to 20,000 psi required only 3.4 hours, compared with 9.7 hours for the comparable test reported in an earlier section. Without prior loading to a stress above the yield point, life consumption during the relaxation was 36% based on constant-stress creep data; pre-straining reduced the calculated life consumption during the relaxation to 23.7%. When the pre-strained specimen was allowed to creep to rupture at the 20,000 psi residual stress, the sum of life fractions for the entire test was 1.04. Reduction of area (29%) was almost the same as the 32% for a specimen tested at a constant 20,000 psi stress.

A second smooth specimen of this alloy was similarly pre-strained about 1% at temperature and then run to rupture at a 35,000 psi stress. A life of 7.3 hours was obtained compared to about 6 hours shown by the smoothed curve for specimens not pre-strained (Fig. 11). For both conditions, measured reduction of area after rupture was 37%, but the pre-strained material showed a consistently higher creep rate. (At the end of 3.8 hours, the comparative creep strains were 0.006 and 0.0035 inches/inch.)

These fragmentary data indicate a possible slight increase in rupture strength at 400°F by pre-straining 2024-T4, with concurrent increase in creep rate.

Waspaloy at 1350°F

None of the original lot of Waspaloy stock was left to evaluate effects of initial plastic strains, but data presented later for another heat of this alloy suggest an important loss in rupture life following plastic deformations at 1350°F.

Studies of Reported Variable Notch Response in Some Lots of Waspaloy

Earlier work showed a definite qualitative relationship between notch behavior and creep or relaxation properties, but possible influence of other factors was not evaluated. A series of experiments has been carried out since to learn whether other properties than those considered previously must be included to explain reported variable notch sensitivity with slight variations in heat treatment of certain lots of alloy.

In particular, results cited by Carlson, et. al. (Pages 9 and 11 of Reference 3) suggest that some heats of Waspaloy show differing sensitivity at 1350°F to the same notch according to whether or not an intermediate age (1550°F, 4 Hr, AC) is included between a 4-Hour solution at 1975°F and 16 hours aging at 1400°F.

A limited amount of material was located from one heat of Waspaloy melted under vacuum and from two heats melted in air. It was decided to compare smooth-bar and notched-bar properties for the three lots, with and without the 1550°F aging step, and to seek to correlate any devious behavior.

Chemical compositions for the three heats of alloy, listed in Table 6, showed the materials to be rather comparable, except that the titanium content of vacuum-melted material was some half-percent above either of the other heats. (Air melted heat 44,036 was from the same stock as used in earlier work at 1500°F reported in references 1, 2 and 3).

To minimize effects of difference prior treatments, and to stretch the short supply of stock, all of the available material from Heats 3-260 and 44,036 and half of the supply of Heat 63,613 was rolled to 1/2-inch squares at the University. Initial break-down to one-inch squares was at 2150°F. All further rolling was at 1950°F. Reduction to 5/8 inch squares was in 10 steps, with reheat after each step. The final 14 percent reduction (5/8-inch to 1/2-inch squares) was from 1950°F in four steps without reheat.

Test results obtained on these re-rolled materials are presented on Figures 16 through 21 and in Tables 7 and 8. The most evident finding was a uniformly higher strength for the single vacuum-melted heat tested (Heat 3-260) compared with the two air-melted materials.

Heat 3-260 not only had yield and tensile strengths some 20,000 to 30,000 psi above the other heats, but also exhibited nearly twice as high an elongation and reduction of area in the tensile test. Smooth-bar rupture strength for the Heat 3-260 were about 14,000 psi higher at 100 hours and 8,000 to 10,000 psi higher at 1000 hours than for the other heats. No consistent difference was noted in rupture ductility either among materials or between the two heat treatments. In both air-melted materials, conventional heat treatment seemed to give a higher tensile strength than when the 1550°F age was omitted. Omission of the intermediate age also seems to have lowered the yield strength of Heat 63,613 about 5,000 psi.

Omission of the 1550°F age did appear to result in slightly lowered rupture strength, but the spread in data from this source was so small that a single curve was used for each alloy to show smooth-bar rupture properties.

Notch weakening was found in all cases where rupture occurred for a notch with 0.004-inch root radius in a bar with shank and notch diameters of 0.500 and 0.350-inch, respectively. These specimens were heat treated in an atmosphere of raw helium after turning on a lathe. Except for Heat 63,613, no effects on notch rupture life from omitting the 1550°F aging step was detected in the tests run and the relative position of rupture curve for notched and unnotched specimens was about the same for the three heats. It is difficult to say whether a real spread exists in the notched-bar data for Heat 63,613 with the two different heat treatments.

Later tests run with a duller notch (0.018-inch root radius) are too sparse to permit broad conclusions, but the same general shape is suggested for the stress-rupture life curves for both notches. For this notch, the material with conventional heat treatment seemed to have longer rupture life than material with the 1550°F age omitted.

One trend does seem to be consistent for all conditions studied: at high nominal stress, a relatively large change in stress level causes but a small change in notch rupture life, but below some critical stress range a quite moderate drop in nominal stress results in very prolonged life.

Little effect on creep properties resulted when the intermediate (1550°F) aging step was omitted from the conventional heat treatment. Where differences were found, the conventional heat treatment resulted in the higher creep for any given stress level. Figure 18 illustrates about the largest differences noted between creep curves for the two treatments. For like stress levels, and with conventional heat treatment, Heat 44,036 showed more creep than Heat 63,613 at 80,000 and 70,000 psi, but the reverse was noted at 60,000 and 40,000 psi.

Comparative creep properties for the three Waspaloy heats are more easily visualized from Figures 19 through 21, where the creep rates are shown as a function of stress level. Besides the minimum creep rate, initial creep rate and the creep rate at either 80% or 90% of the rupture life are shown by separate curves.

The 1550°F aging step had no apparent effect on the creep rate for Heat 3-260 at any portion of the tests, from initial loading until rupture (Fig. 19). For the other two heats, omitting the intermediate age appeared to result in slower creep at higher stress levels, but variation in creep rates for the two heat treatments is probably too small to have recognizable effects on results calculated by an analysis such as that proposed in Reference 2.

Comparison of Figures 19, 20 and 21 shows that the minimum creep rate for Heat 3-260 occurred rather early (from 5 to 15 percent of the life) and that the creep rate after about 50 percent of the life exceeded the initial rate. For both air-melted heats, the minimum rate occurred somewhat later (12 to 25 percent of life expired) and the creep rate remained below the initial rate until very near rupture.

In all the data gathered, no large difference was measured in any smooth-bar property for specimens with and without the 1550°F aging step. This agrees with the apparent lack of any marked difference in notch rupture strength for the two heat treatments involved, at least in tests with $K_t = 6.8$.

The consistently-higher tensile and rupture strengths exhibited by the vacuum-melted material may be due to higher titanium content but may be at least partly the result of different prior history. Heat 3-260 was rolled to final size directly from a 10-pound ingot, whereas, the other materials were from large commercial heats and had been submitted to a rolling and annealing schedule before final rolling at the University of Michigan. The magnitude of effect to be expected from this difference in prior history is hard to estimate.

Variable Notch Behavior of Waspaloy Heat 63,613 Rolled by the Supplier

Rupture data listed in Table 8 included fragmentary results for specimens with 0.018-inch root radius ($K_t = 3.2$) prepared from 1/2-inch squares of Waspaloy Heat 63,613 rolled at the University of Michigan from 1-3/4 inch round. With conventional heat treatment, rupture life was 18.4 hours at 50,000 psi nominal stress at 1350°F. When the 1550°F age was omitted, rupture times at 50,000 and 40,000 psi were only 1.5 and 9.4 hours, respectively.

This may not be a significant indication in view of the few test results involved, particularly when consideration is given results previously reported for $K_t = 6.8$, in which if anything the heat-treatment effects were reversed. To check for reported pronounced increased notch sensitivity for this heat when the 1550°F age was omitted, repeat tests were performed on the material rolled by the supplier:

NOTCH RUPTURE TESTS AT 1350°F FOR WASPALOY
TAKEN FROM 1-3/4 INCH ROUND ROLLED FROM HEAT 63,613 BY SUPPLIER

Stress (psi)	Rupture Life (hours)	Remarks
60,000	3.0	Conventional heat treatment
52,000	208.5	Conventional heat treatment
42,000	1086.2	Conventional heat treatment
52,000	0.75	1550°F Age omitted
42,000	1.5	1550°F Age omitted
30,000	1650.9+(Disc.)	1550°F Age omitted

All notches ground and lapped after heat treatment

Notch Geometry, Inches: Shank diameter, D = 0.500
Diam. at notch, d = 0.350
Notch root radius, r = 0.018

These test results indicated a definite difference in notch rupture strength, depending on whether or not an intermediate aging for 4 hours at 1550°F was included between solution treating and the 1400°F age of the conventional heat treatment. Such a difference in notch sensitivity could be explained by any of at least three factors:

1. Different stress-strain properties for the two conditions, resulting in different degrees of relief by plastic straining of initial high stressed at the notch.

2. Different inherent creep-relaxation properties or rupture properties for material with the two treatments.

3. Variable response in the two conditions to initial plastic strains at the notch, resulting in unequal metallurgical alterations and therefore in different strength properties during much of the life of fibers near the notch root.

Since only enough material from this particular lot was available to make a total of sixteen smooth bars, complete testing of all variables was impossible.

Two pairs of smooth specimens were allocated to learn whether any large differences in inherent rupture strength exist for the two heat treatments. Findings included in Table 9 suggest no significant deviations in rupture life or ductility which would explain variation in notch strength.

A more fruitful approach appears to have been made in other tests where a smooth specimen was first overloaded momentarily to cause an initial plastic strain approximating conditions at a notch root. Loading curves obtained during this initial overload period provided satisfactory stress-strain data, so that separate specimens were not allotted for tensile tests.

Specimens with the full conventional heat treatment exhibited somewhat higher yield strength than did those for which the 1550°F age was omitted. Figure 22 shows stress-strain curves obtained by averaging values from the several loading curves obtained in the pre-strain tests.

Specimens with both heat treatments suffered a drop in rupture strength after plastic pre-straining by momentary overloading. (See Table 9 and Figures 23 and 24.) The available data for the two conditions are not completely comparable in that the pre-strain obtained for specimens with conventional heat treatment varied from 0.45 to 0.9%, whereas, for the other treatment, the lowest pre-strain was 0.9% and all other values were 1.3% or higher. Moreover, the shortage of material limited the range of creep stresses tested after pre-strain.

At high stresses (short rupture times) the curves for pre-strained material should approach the extension of the usual zero pre-strain curve since the two should coincide near the tensile strength of the material at the test temperature.

Despite obvious limitations in the data, at lower test stresses the character of the stress-rupture life curves after pre-strain seems to differ significantly for the two heat treatments. With conventional treatment, rupture curves for differing degrees of pre-strain appear to consist of a family of nearly straight lines of different slope, at least for the first 50 or 100 hours. Test points for 1.3 to 1.7% pre-strain for the alloy without the 1550°F intermediate age do not permit the same pattern, but seem to demand either a continuous curvature or else a "break" in the curve above 60,000 psi. Curves drawn for 0.9% and 0.4-0.5% pre-strain are necessarily approximate.

In any case, the few data on hand suggest a 10 to 100-fold decline in rupture life for test stresses between 40,000 and 60,000 psi after the material without the 1550°F aging step is pre-strained about 1.5%.

Notched-bar life for a cylindrical specimen with theoretical stress concentration factor of 3.2 was much lower at 40-50,000 psi for the material without the 1550°F age than when the complete conventional heat treatment was used. For higher or lower nominal stress, notch rupture curves for the two conditions give indication of possible intersection.

Plots of stress versus creep rate for the two heat treatments employed exhibit considerable disparity. An immediate parallel is evident between the linearity of the stress-rupture life and stress-creep rate curves for the conventional heat treatment, and the marked upward concavity in the corresponding curves for material lacking the intermediate age.

The magnitude of differences in these properties established for this lot of Waspaloy with the two heat treatments appears adequate to explain observed differences in notch properties for the two conditions. This matter will receive more quantitative consideration in a later section.

Notch Rupture Tests with Step-Up Stressing

On several occasions, the test stress chosen for a notched specimen was so low that rupture had not occurred at times in excess of 1000 hours. Rather than to turn these tests off and to report them simply as discontinued, it was decided to raise the stress level to where rupture should occur in another few days, to obtain some measure of the life remaining in the specimen.

Contrary to expectations, long-time exposure of a notched specimen to a low initial stress resulted in greatly extended rupture life at later high stress, compared with notch strength under constant high stress throughout the test. Data assembled in Table 10 show several instances where notched specimens of Waspaloy at 1350°F became decidedly notch strengthened when subjected to step-up stress history, whereas, with constant application of the final stress they would be severely notch weakened.

The last two tests listed in Table 10 demonstrate that a short-period at the lower stress did not increase life at later high stress, and may even have reduced the total life for the entire test in the case of "17-22-A"S at 1100°F.

Experimental Measurement of Plastic Strains from Loading and Creep of Flat Notched Bars

To check methods to estimate initial conditions near a notch loaded beyond the elastic range, measurements of actual plastic strains were attempted using flat notched specimens of 2024-T4 alloy. A square grid with 0.010-inch spacing was lightly scribed on opposite faces. Photomicrographs were prepared on glass plates at approximately five diameters magnification, using vertical illumination. Grid distances on the glass plate could be measured to about 0.0002 inch using an optical comparator with micrometer stage. A single grid distance could thus be determined to a precision of about $\left(\frac{0.0002 \text{ inch}}{5 \times 0.010 \text{ inch}}\right)(100\%) = 0.4\%$ of plastic strain. Since higher magnification only made it more difficult to locate the edge or center of the scribed grid lines, higher precision was achieved by measuring the average strain over several grid units. Resort to this latter expedient ruled out the hoped-for determination of localized strain within a few thousandths of an inch of the notch root, so long as the specimens were to be made from the 3/4-

inch diameter stock on hand.

Relative magnification of photographs obtained before and after stressing was determined by comparing the distance between corresponding points in the shank portion of the specimen where the low stress level would cause no plastic deformation on loading and little creep deformation at the applied load.

Specimens tested had a theoretical stress concentration factor of 3.3 in a bar with 0.400 inch minimum width. A specimen loaded to 40,000 psi nominal stress at 400°F and unloaded immediately exhibited 0.3% longitudinal strain at a distance of about 0.005 inch in from the notch root. No longitudinal plastic strain could be detected in material near the axis, either from the initial load application or for one hour of creep at 40,000 psi. Near the notch, 1.2% of strain was measured for the first hour of creep and 2.9% for 4.1 hours at 40,000 psi. By the end of the 4.1 hours, approximately 0.5% of permanent longitudinal strain was also evident at the axis. It will be shown later (Table 11) that these measurements, and corresponding measurements of transverse strains, are of the magnitude required by assumptions employed to correlate data in this report.

FACTORS AFFECTING RUPTURE LIFE OF NOTCHED SPECIMENS

Evidence gathered in this program seems to verify the general soundness of the original premise that rupture life under conditions of initial stress concentration should be explainable in terms of the changing stress pattern and rupture strengths at existing conditions. It appears that all types of notch behavior encountered in these studies involve the following major factors:

1. Initial stress pattern upon loading. The stress levels depend, in turn, on the notch geometry (degree of triaxiality) and the stress-strain properties of the alloy in the condition tested.

2. Stress-creep rate characteristics, which control the rate of redistribution of initial stress gradients by creep-relaxation.

3. Stress-rupture life properties at each stage of stress-strain-time history.

Sharp notches or high nominal stresses may cause plastic deformation at the notch root when the load is applied. Under the subsequent decreasing stress, creep or rupture behavior in the deformed portion of the specimen may differ from that anticipated from usual tests on unnotched specimens. Furthermore, creep and rupture strengths may change during testing as a result of metallurgical instabilities. Due allowance for such property changes is implied under items (2) and (3) above.

Ductility seems to be involved to the extent that the material must be able to yield sufficiently during loading to prevent the stress at the notch from reaching the tensile strength and must be capable of from one to three percent of total creep calculated to be required for complete leveling of the stress gradients in a typical notched specimen, if notch strengthening is to be obtained.

Initial Stress Patterns in Notched Bars

A characteristic feature of a notched-bar rupture test is the initial stress gradient present. For low nominal stresses where elastic strains are absent at all points in a notched bar, stress patterns may be computed from relationships presented by Neuber for various types of specimen. (See Ref. 5.)

When initial stresses near the notch exceed the proportional limit, theoretical stress distributions based on elasticity theory no longer apply directly. For such cases, an approximate method to estimate actual levels of effective stress was suggested in reference 2 and illustrated by Figure 34 of that report. In this method the total strain energy (area under the stress-strain curve from zero to the actual stress) is assumed to equal the elastic strain energy (area under the elastic modulus line) which would have been expended had the material remained elastic and reached the theoretical elastic stress level corresponding to the load applied and the initial notch configuration.

The experimental measurements of strains in a flat notched specimen mentioned earlier were performed in hopes of establishing the degree of validity of the suggested estimation of local yielding during load application, as well as to determine whether creep distribution in a notched specimen shows the change from largely localized strains at first to general creep throughout near the end of the test as predicted by the analysis employed in this work.

Longitudinal strains were determined at the midplane of the specimen and at a distance of about 0.005-0.010 inch from the notch root. Average transverse strains were also found for a 0.040-inch width at the center of the specimen and for a like width near the notch.

Values for the same strains were calculated from smooth-bar properties for comparison. No particular problems arose in computations for longitudinal strains, but to calculate the transverse strains required that allowance be made for the large variation in stress over the width for which measurements were made. The 0.400-inch width at the notch was imagined to be divided into "bands" of nearly-uniform stress level. Each band consists of two parts located symmetrically from the specimen axis. The bands were proportioned for close spacing near the notch root where stress varied greatest with position and wide spacing near the axis of the bar. This was accomplished by making each band half the area of the adjacent band toward the axis.

Under elastic loading the initial stress pattern for the centroids of the bands considered would be as shown in Table 11. (Band 6 is the outermost and band 1 at the center). The four outer bands, 6 through 3, cover the 0.040-inch depth over which the transverse strains were determined on the gridded specimen.

Table 11 includes listings of ratios of the principal stress components, deviator stress components and the effective stress in comparison with the nominal stress level. The deviator component (S'_i) is defined as the total component less the average of the three principal stresses. The ratio of plastic strain in any direction to the effective strain (corresponding to the effective stress level present) equals 3/2 times the deviator stress in that direction, divided by the effective stress. The second part of Table 11 presents values of this ratio. Other columns list the estimated plastic deformations on loading and cumulative creep strain at 40,000 psi nominal stress, calculated during the course of computations to be discussed later.

Longitudinal strains for the two locations where measurements were made can be calculated directly from values in Table 11 for bands 5 and 1. Calculation of the average transverse plastic strain for the combined bands 6 through 3 can be illustrated by the following computations for this strain during 4.1 hours creep at 40,000 psi:

Band No.	$(3/2)\left(\frac{S'_{transverse}}{\bar{S}}\right)$ (Total Effective Creep (%))		Fraction of Total Cross Section		
6	(3/2)(-0.46)(2.68)	x	1/63	=	-0.0294
5	(3/2)(-0.39)(2.34)	x	2/63	=	-0.0434
4	(3/2)(-0.19) (1.78)	x	4/63	=	-0.0322
3	(3/2)(+0.01)(1.17)	x	8/63	=	+0.0022
				(15/63)	-0.1028
					-0.43%

Calculated values and experimental measurements obtained are as follows:

	Plastic Strain, percent							
	Near Notch Root				Near Specimen Axis			
Stress-Time History	Longitudinal		Transverse		Longitudinal		Transverse	
	Calc.	Expt.	Calc.	Expt.	Calc.	Expt.	Calc.	Expt.
Stress to 40,000 psi and unload	0.65	0.3	-0.12	-0.3	0	<0.1	0	<0.1
1 hr. at 40,000 psi and unload	1.35	1.2	-0.22	-0.2	0.11	<0.1	-	-
4.1 hrs. at 40,000 psi and unload	2.55	2.9	-0.43	-0.7	0.74	0.5	0.30	-0.1

Considering the probable error in the experimental results, the comparative strain measurements and computed values indicate that the proposed calculation methods probably give an answer of the proper order of magnitude for strain during loading. Agreement is sufficiently close for creep strains, and the precision adequate, to leave little doubt that creep strains are quite localized near the notch root during early stages of a notch rupture test.

Influence of initial stress pattern and of other factors on notch rupture life can be better visualized by comparing data assembled in Table 12 for representative notched bars. Data chosen were all for conventional heat treatments unless otherwise indicated in the table. Conditions listed were selected to illustrate different patterns of initial stress, different magnitudes of stress-redistribution rates, and different response of alloys to initial plastic deformation on loading.

Table 12 lists the initial effective stress for fibers at the notch root and near the axis of the specimen. Major attention is directed to the effective stress since that stress controls yielding and creep. Because some experimenters (4) have found that rupture after creep may depend on the largest (axial) principal stress component, this value on loading is also tabulated for the notch-root and axis locations.

In cylindrical notched specimens the tangential stress (in the hoop direction) is between the longitudinal (axial) stress and the radial stress in value. When these component stress values are substituted into Eq. 1, the effective stress at the notch root is less than the axial component there. For flat specimens sufficiently thin that the stress in the direction of the thickness is essentially zero, the effective stress and the axial stress are equal at the notch root.

With flat specimens the principal stress in the thickness direction is assumed to remain at zero over the entire cross section, whereas for round specimens all three components are finite and become nearly equal as the axis is approached. For high notch acuities (K_t of about 3 or greater) the effective stress at the center of a flat notched bar is several times the effective stress at the center of a comparable round notched specimen. At low K_t's, the distribution of either the effective stress or the axial component becomes more nearly equal for the two types of specimen.

Effect of Stress-Strain Properties on Notch Rupture Strength

S-816 illustrates the important contribution to notch strengthening possible from yielding alone in the presence of complex stress. For the relatively-dull notch of Item 1 ($K_t = 2.1$) the effective stress on loading was below the nominal stress at all locations in the plane of the notch. If no redistribution of stress at all were to occur in the ensuing period of test, notch life would still be more than double that of a smooth specimen at the nominal stress.

Stress-strain properties affect notch behavior in at least two ways:

1. The general shape of the stress-strain curve above the proportional limit controls the effective stress for fibers loaded beyond the elastic range. In the case of 2024-T4 at 400°F, and more especially of S-816 at 1350°F, the plastic strain required for a further stress increase is relatively large (See Figures 8 and 27).

With "17-22-A"S alloy steel at 1100°F (Figure 8), the tensile curve exhibits a long gradual sweep from the proportional limit into the yield range. For such a material, progressively higher applied nominal stresses or higher notch acuities are reflected as a relatively-large rise in stress level near the notch.

The significance of this effect is borne out for a flat notch with $K_t = 3.2$ loaded to approximately the proportional limit in each case, the initial maximum effective stress for S-816 is one-third higher than the nominal stress, while for "17-22-A"S the stress near the notch on loading is more than double the nominal.

2. Tensile properties also contribute to notch rupture behavior according to the relative rupture life of the particular alloy at stresses in the yield range. This factor plays a part in the decided notch strengthening apparent for S-816 at 1350°F. Rupture life of this alloy at the 0.2% offset yield stress is about 19 hours; for other materials tested, rupture life at the yield strength is but a fraction of an hour.

Stress Redistribution by Creep under a Stress Gradient

If no subsequent stress redistribution were to occur, rupture at the notch root should correspond to the life at the peak stress obtained upon loading. But the high stress level near the notch root demands an accompanying high initial creep rate. Under proper conditions the localized creep can reduce the concentration of stress and thereby extend the life of the notched specimen. In a sharp notch the small region of concentrated stress is surrounded by a much larger volume of metal at low stress and consequent low initial rate of creep deformation. The situation is not unlike contained plastic deformation in an elastic-plastic body at room temperature, where the plastic strain can exceed the magnitude of elastic strains only after the plastic zones merge to make unrestricted flow possible.

In a conventional smooth tensile creep bar, all fibers are subjected to the same simple axial stress until necking occurs. The entire plastic creep strain results in elongation of the bar with no stress interaction between fibers. In contrast, had the specimen been stressed elastically to the same initial stress and temperature, and the heated portion then clamped rigidly against axial movement, all plastic creep strain would have to be accommodated within the specimen itself by replacing some of the initial elastic strain. The stress level in the specimen must perforce fall or "relax".

How the total plastic strain at any point in a structure splits between creep and relaxation depends on the geometry (degree of restraint) and the extent of stress gradients between adjacent fibers of material.

At any stage of a notch rupture test the specimen as a whole may be imagined to creep at some average over-all rate of deformation which is slower than the creep rate near the notch root and faster than that near the axis. Much of the rapid creep in fibers near the notch root results in elastic relaxation of the stress level there at early times, while the drag of the core material against faster-moving regions is reduced by rising elastic strains, and therefore rising stress level and creep rate near the axis.

Progressive leveling of the stress gradient at slower and slower rate can be expected as a state of uniform creep rate across the entire specimen is approached.

Relative Notch Strengths of Flat and Round Specimens

All other things being equal, the initial peak effective stress for a notched flat specimen of given notch acuity should be higher than for a round bar with the same K_t. In addition, the stress gradient which can be redistributed is less for the flat specimen. The combined effect of these factors should result in shorter rupture life for a flat specimen than for a round specimen at like nominal stress and stress concentration factor. A major effect can not be expected for K_t's much below 2. Such, indeed, was the experimental observation in the majority of tests in this research.

For S-816 at 1350°F, where a 10,000 psi lower strength was obtained with flat notches than with round, K_t was relatively high (3.2 to 7.2 for eleven of thirteen total tests). The differential between the two types of notch specimens was only about half as great for the 2024-T4 alloy of Figure 10 at $K_t = 3.2$ to 3.3. This same alloy showed no apparent effect of notch-bar shape at low stress concentration factor ($K_t = 1.9$ to 2). Results for Inconel X-550 (Fig. 5) show a lowering of notch rupture life with flat bars at $K_t = 3.2$ to 3.3, similar to that for 2024-T4, even though one is an example of notch weakening and the other of notch strengthening.

Trends for "17-22-A"S (Fig. 7) are in the same direction, but the shorter life for flat specimens with $K_t = 3.3$ seems to hold only at high nominal stresses. At 30,000 psi nominal stress and below even the flat notch with K_t of 2.0 appears to have a shorter rupture life than a round specimen with essentially the same notch acuity. Table 12 includes data for two pairs of "17-22-A"S specimens at 30,000 psi and one pair at 60,000 psi nominal stress. In each pair one specimen was flat and the other round, with roughly equal theoretical stress concentration factors.

At 60,000 psi and $K_t = 3.2$, material near the notch yields about 1%, carrying the peak effective stress in the two specimens to nearly equal values. But near the axis the high degree of triaxiality in the round specimen keeps the effective stress low (11,630 psi) compared with the 39,000 psi calculated to be present near the center of the flat specimen. The resulting difference in creep-rate gradients and in the total amount of stress leveling possible for the two cases easily accounts for the two-fold difference in experimental rupture lives for the two specimens.

Initial effective stresses and experimental notch rupture lives bear similar relations for a nominal stress of 30,000 psi and $K_t = 1.9$ to 2.0. In contrast, the pair at this stress with sharper notches ($K_t = 3.1$ and 3.3) appear to be in disagreement. The effective stresses initially present in these two bars are not far different at the notch root and creep rates near the axis are low in either case. Differences which do exist favor longer life in the round bar. If one considers not the relative effective stresses but rather the axial components for the two specimens, the relative experimental notch rupture lives appear more reasonable.

Effective Stress Versus Maximum Principal Stress As Controlling Rupture Life

Examination of initial stress patterns and observed notch rupture lives for other pairs of flat versus round bars should be useful to help judge relative significance of the effective stress and the largest principal stress in determining rupture properties after creep under complex stressing.

Inconel X-550 specimens, items 11 and 13 of Table 12, favor effective stress over the axial component as an explanation of notch rupture behavior. Initial effective stress values at the notch root for the two bars should promote slightly longer life in the round specimen. This trend is helped by the somewhat steeper creep gradient in the round specimen. On the other hand, if axial stresses are considered, the 10,000 psi difference in initial peak stress should cause the flat notch to last the longer. The same conclusion can be drawn for the 2024-T4 data with K_t = 3.2 to 3.3 (Items 20 and 21).

The other pair of 2024-T4 specimens (items 22 and 23) agree better with the axial stress as the determinator of rupture, but the results may be equally capable of explanation under the effective-stress criterion of rupture if allowance is made for probable higher strength and more rapid relaxation caused by the small amount of yielding near the flat notch on loading.

The latter explanation can also be offered for anomalous results with S-816 at 1350°F, listed as the first two items in Table 12. Notch acuity and nominal stress differed for the two cases, but the particular conditions used resulted in nearly equal gradient of effective stress across the two notches. The small differences in effective stress are in the wrong direction to give the notch results obtained, while a cursory examination shows the relative axial stresses to be in the proper order for the observed notch rupture lives.

Closer study of the tabulated values for item 1 provides strong evidence against principal stress as the factor controlling rupture life. Any stress redistribution under creep-relaxation will lower the effective stress at the notch root, including a drop in the axial component. Simultaneously the axial component near the axis should rise, especially since the highest axial stress on loading is approximately midway out from the center in this particular example. As creep-rate gradients tend to level, the axial stress across the notched cross section will approach the nominal value of 58,000 psi. But even at the initial stress of 45,470 psi, material near the axis has only about 30 hours life by the principal-stress theory. With the further rise of this axial stress with time, it is difficult to reconcile the measured life of 32.5 hours with predictions based on the maximum principal stress criterion of rupture.

The effective stress appears to control creep for all stress patterns. The majority of data examined in this program suggest that the effective stress is also a valid measure of rupture strength for the triaxial tension of notched bars. However, this may not still be the case for other types of materials, or particularly, for structures with types of stress patterns markedly different from those investigated.

Qualitative Effect of Relaxation Characteristics on Notch Behavior

In a specimen with sharp notch, the small volume of material at high stress near the notch root is so completely restrained by the larger mass of surrounding material at low stress and consequent negligible creep rate that nearly all the creep near the notch results in stress relaxation in the early parts of the test. At later times, the proportion of total creep going to reduce elastic strains becomes less and the material near the notch acts in a manner equivalent to a relaxation test with elastic follow-up. In the notched specimen the amount of "follow-up" depends on the notch geometry and the material properties, and varies throughout the test. Due to these complications relaxation tests performed were restricted to the condition of zero follow-up or complete restraint.

For each material in the program one or more relaxation test was conducted with initial stress near the yield strength, since this should correspond with conditions near the root for many of the notch tests run. Time to relax from the yield stress to the 100-hour and 1000-hour rupture strengths is compared in the following tabulation with the qualitative notch sensitivity observed.

QUALITATIVE NOTCH BEHAVIOR AS RELATED TO RELAXATION TIMES

Alloy and Temp.	Notch Characteristics	Relaxation Time from Yield Stress to: 100-hour Rupture Stress	Relaxation Time from Yield Stress to: 1000-hour Rupture Stress
S-816 at 1350°F	Strengthened by a wide variety of notches	0.05 hr	0.5 hr
Waspaloy at 1500°F	"	0.6	3.4
2024-T4 at 400°F	Moderate strengthening for several notches	3	20
Waspaloy at 1350°F	Borderline, depending on notch geometry	1.8	15
"17-22-A"S at 1100°F	"	1.2	38
S-816 at 1500°F (2325°F soln + 13.5% reduction at R.T.)	Weakened by sharp notch	1.5	15
Inconel X-550	Weakened by most notches at 30,000 to 50,000 psi nominal stress	4	95

Although ability to relax out initial stress concentration is surely an important criterion for notch strengthening, relaxation properties alone are probably inadequate to explain notch behavior. They can furnish a measure of stress changes under restraint corresponding to initial stress and strain levels, but they still must be supplemented by data telling how fast rupture life is consumed during and after the relaxation.

The above comparisons relate only to relaxation rates for different alloys, but ignore the amount of stress redistribution possible for specific notches. It should be obvious that a high uniform rate of creep per se does not help to create a longer time until rupture if it does not result in a more favorable stress pattern. On the other hand, when a large reduction in stress level near the notch root would result from extended relaxation, the life of the bar can be greatly lengthened.

It is assumed that under prolonged relaxation the effective stress across the entire notched section should approach a state of uniform effective stress. The longitudinal stress component is the major contributor to the effective stress level. Moreover, the requirement of constant axial load demands that a drop in axial stress for one fiber require an increase in axial stress elsewhere.

Combining these considerations, the final effective stress approached in any specimen can be approximated by an integrated average of the initial effective stress levels across the notch. Values of this average stress (S*) and rupture life corresponding to it have been included in Table 12. In some instances, for example, Items 18 and 19 of Table 12, complete relaxation could result in but a ten-fold increase in life above that corresponding to the initial peak stress. At other times, as for Items 6 and 7, a very great extension of life would have been obtained if relaxation had been at all rapid but fracture occurred before much leveling of initial stress gradients took place. Any adequate treatment of relaxation effects on notch-bar behavior must reflect both the rate and the amount of relaxation for the conditions present.

A Mathematical Calculation of Notch Rupture Life, Using Creep and Rupture Data from Smooth Specimens

Reference 2, pages 26 to 33, proposed a method to calculate notch behavior from smooth-bar properties. The cross section in the plane of the notch was divided into imaginary concentric rings and the initial stress and creep rate determined for the centroid of each such ring. For a short time interval the effective creep rate and the principal creep components were assumed to remain essentially constant. Creep strain in each principal direction during this interval was calculated as though the ring were free to creep at its centroid conditions. Next, the difference in creep strain between adjacent rings was considered to be replaced by an equivalent elastic strain and the required stress changes to bring this about were computed. The net change in stress for any one ring during the time interval was taken as the sum of the changes calculated for the separate interactions with adjacent rings at either side. With the new stress level now determined, the life fraction consumed during the first time interval could be found, new creep rates evaluated and the process repeated. The start of rupture for the specimen is considered to be the time when any ring reaches a calculated 100% of total life consumed.

This analysis yielded results close to experiment for two examples cited in Reference 2, but the original proposal had some apparent faults. Modifications have since been made in the procedure to correct these and also to reduce the tedium of the calculations.

In the original method the cross section in the plane of the notch was divided into nine concentric rings chosen arbitrarily to give four small bands of equal area near the notch. The next four rings toward the axis each had an area four times that of the outermost rings. A central ring covered half the total cross section.

With the above division of the area a somewhat abrupt change in calculated stress redistribution occurred at the change from the group of rings with one area to the group with the other area. Moreover, the fractions of total stress interaction at any interface which should be applied to the separate rings varies from one pair of rings to another.

More recent calculations have employed only six concentric rings, with each half the area of the next ring toward the axis. For such a pattern, elastic stress changes at any interface are always distributed in the ratio 2/1 between the two rings involved. Under the new distribution the outermost ring is 1/63 of the total area, so that the stress at its centroid is very near the value at the surface of the specimen near the notch root. (For flat notched specimens, bands with the same area ratios were employed. Each "band" except the one at the center consisted of two halves, one toward each notch root.)

When the notch problem was first analyzed, attention was focused on changes in the separate component stresses and relaxation was assumed to proceed independently for the three principal deviator stress components. Such an approach may not be valid since any elastic change in one stress component will result in accompanying elastic strains in other directions. In any case, it appears unnecessary to deal with stress components so long as the effective stress and effective creep in adjacent areas have essentially the same direction.

Calculations were repeated for the conditions of the first example cited under the Sample Calculation in Reference 2. (Waspaloy at 1500°F under a nominal stress of 25,000 psi with a notch acuity of 1.75.) In the new procedure, after the effective creep rate is found corresponding to the initial effective stress at the centroid of each ring, the difference in effective creep rate between rings is multiplied by a time interval and the shear modulus to get the stress interaction at each interface.

By the modified method, stress changes for initial calculation steps were somewhat smaller than for the method originally proposed, but conditions calculated for the end of fifty hours elapsed time by the two methods indicated nearly identical patterns of stress and of life expenditure for corresponding locations.

Apparently, the self-correcting tendency pointed out in the Discussion of Reference 2 is such that the final calculated result is rather insensitive to minor discrepancies. The important factors seem to be the general magnitude of the creep or relaxation rates exhibited by the material and the slope of the stress-rupture life curve, which determines the proportion of life increase caused by any particular reduction of the initial stress gradient.

Notch life calculated by the modified correlation procedure is included in Table 12 for the 14 examples completed. Results are also shown graphically in Figure 28. Agreement between test results and calculations is only fair but some of the disagreements in Figure 28 can be explained in terms of prior-strain and instability effects.

It was shown earlier that Inconel X-550 and Waspaloy at 1350°F and "17-22-A"S steel at 1100°F suffer loss in rupture strength from small plastic strains at temperature, whereas 2024-T4 aluminum alloy is made stronger. Of the materials weakened by plastic pre-strain, Inconel X-550 exhibited a simultaneous acceleration of creep rates while the other two alloys creep more slowly in the strained condition. The combined detrimental effects of shortened inherent life and slower relaxation of initial stress peaks should be sufficient to explain the short life actually obtained for "17-22-A"S (item 14) with 0.9% initial plastic strain, compared with life calculated from properties of material not pre-strained.

The position of points for Inconel X-550 may be explained by a greater effect of increased relaxation rate than of decrease in rupture strength with prior strains of about 0.5%. On the other hand, the fact that these results parallel the line representing equality between calculated and measured lives may signify a consistent error in the calculation method or may reflect some discrepancy in the stress-creep rate or stress-rupture life curves employed.

Plastic strain on loading does not appear to be a key factor in the higher-than-calculated notch rupture lives obtained in tests with 2024-T4 alloy. The specimen with largest initial strain (1.62% in item 24) shows the closest agreement of all the tests, and item 22 with a mere 0.04% initial strain lies on a common curve with points for specimens with much higher strains. Of probable significance is the close parallel between prediction and experiment at short rupture life and increased deviation at longer test times. Some of this effect is undoubtedly tied to failure of the life-fraction rule to predict long enough life under conditions of falling stress, which observation was mentioned earlier.

Another element favoring too low a calculated notch life is the continuing precipitation process taking place during testing at elevated temperature of the naturally-aged alloy. Measurable contraction in volume during precipitation would result in too low a measured creep. Consequently, the creep data used may have indicated slower leveling of stress gradients than actually occurred. Investigation of the magnitude of volume change in this alloy under zero load appears desirable.

Curves used in calculations for Waspaloy at 1350°F were corrected for prior strain effects as best they could be, limited by meagerness of test data. More detailed examination of the findings for Waspaloy Heat 63,613 should be useful at this point.

Explanation of Variable Notch Effects in Some Heats of Waspaloy at 1350°F

Some heats of Waspaloy have been reputed to show variable notch properties at 1350°F, especially when the 1550°F intermediate age is omitted from the conventional heat treatment. Figures 23 and 24 illustrate the magnitude of deviation possible. In the first place, omission of the 1550°F age resulted in a 10,000 to 20,000 psi drop in notch rupture life at rupture times between 1 and 1000 hours for a theoretical stress concentration of 3.2. At shorter or longer times, notch rupture curves for the two treatments tended to approach one another, resulting in a second peculiarity: At nominal stresses above about 35,000 psi the slope of the stress-rupture life curve was quite steep for notched specimens without the intermediate age, and rupture lives were but a few hours. When the nominal stress was lowered to 30,000 psi, rupture life was extended to several thousand hours.

Both of these behavior patterns become quite understandable when reasonably complete smooth-bar properties are available for conditions existing at the notch root.

Maximum deviation in notch behavior between the two heat treatments is typified by Items 6 and 7 of Table 12. Nominal stress of 50,000 psi produced stress patterns that were not significantly different for the two conditions and any differences present would of themselves promote longer life for the specimen without 1550°F age. The key to the superior strength of the notch with conventional heat treatment lies in its ability to relax quickly. Creep at the initial peak stress is 50 or 100 times faster than the rate found when the 1550°F age is omitted, if the curves of Figures 25 and 26 are reliable. For the specimen without the intermediate age, stepwise calculations indicate rupture at 0.53 hours in the outer ring considered, with a total creep in that ring of only 0.2% at rupture. The calculated ductility at fracture is less than 1% even when the strain on loading is included. This reflects the loss in ductility often observed under triaxial stressing. By the time fracture occurred, the stress in the outer ring could drop only to 81,400 psi. The specimen with conventional heat treatment exhibits so much faster creep relaxation that only about 0.005 hours time was indicated to be necessary for the effective stress in the outer ring to reach 81,000 psi. At a time equal to rupture in the preceding instance, the present bar was calculated to have used up less than one-fifth of the total life of the outer ring and the stress level there was already down to 67,000 psi. Completed calculations predicted a rupture life of 28.8 hours. Experimental life was 85 hours. Both these values are a different order of magnitude from the 0.75-hour experimental and 0.53-hour calculated life for the specimen without the 1550°F intermediate age in its heat treatment.

There can be little doubt about the different character of the stress-creep rate curves for these two heat treatments or of the effect of this difference on notch behavior. However, the exact shape and best location for the particular curves is subject to considerable interpretation in view of the paucity of data points around which they were constructed. Considerable leeway in placement of stress-creep rate curves appears to be permissible before calculations of the type performed are markedly affected. For example, duplicate sets of computations were performed for one "17-22-A"S specimen, Item 14 of Table 12, using the different curves on Figure 9 marked "a" and "b" for the creep-rate properties at 0% life expired. Despite rather large differences in calculated stress redistribution at early times, the completed calculations agreed quite closely (112 hours life predicted using curve "a"; 125 hours using "b".)

Returning to the tests on Waspaloy, Heat 63,613, inspection of its smooth-bar properties reveals why this lot of Waspaloy without the intermediate age exhibits but a small change in notch rupture life with a large change in nominal stress above 40,000 psi. At a notch acuity of K_t = 3.2 the rather flat stress-strain curve results in initial peak stresses differing by only 10% for nominal stresses of 40,000 and 70,000 psi. Then, with the sharp upturn of the stress-creep rate plots above about 60,000 psi stress, initial relaxation near the notch root occurs at the same order of magnitude for this entire range of nominal stress.

Conventional heat treatment produced stress-creep rate curves which seem to continue in a straight line at the higher stresses, or which may even exhibit a slight concavity downward. A small variation in applied stress is accompanied by a large change in ability of the material to relieve initial stress concentrations and, therefore, a large change in rupture life. Experimental results confirm these expectations.

Reasons for the different response to plastic strain for the two heat treatment is not understood, but prior history-especially rolling practice-appears to be involved. At least, none of the material re-rolled at the University of Michigan seemed to display the sensitivity to plastic deformation so evident in the 1-3/4 inch stock of Waspaloy, Heat 63,613.

Extended Notch Life of Waspaloy at Low Nominal Stress

The specimen identified as Item 8 of Table 12 had still not failed after 1651 hours at 30,000 psi. The load was then raised to a nominal stress of 50,000 psi for an additional 294.8 hours without failure, and finally to 70,000 psi at which level rupture occurred after 47.9 more hours. Prolonged life at 30,000 psi nominal stress can be in part attributed to the fact that the maximum stress obtained was barely above the proportional limit so that plastic strain did not lower rupture strength. Furthermore, this specimen did not operate in the upper region of Figure 26 where creep rates are disproportionately slow for the prevailing rupture life.

Calculations covering the first 1651 hours of service at 30,000 psi indicated total life consumption in the outer fibers was slightly more than 40% and that the existing stress there would then be down near the 10,000 hour rupture stress. With no further stress leveling, a life in excess of 7000 hours should result.

Neglecting any lessening of notch acuity from the creep at 30,000 psi, addition of 20,000 psi nominal stress to the specimen at 1651 hours test time would result in a higher peak stress than was originally present at 30,000 psi, but the stress would still hardly exceed the proportional limit and would in any case be less than the peak stress for a like specimen loaded to 50,000 psi at the start of the test.

Continuing the calculations for the new stress pattern, rupture is predicted after 2.1 hours at the 50,000 psi nominal stress. This is far short of experimental observations, but is some three times the life determined for a specimen loaded to 50,000 psi from the start.

The calculation procedure used appears incapable of exact prediction of notch behavior under variable load, but the results do support a finding that under some conditions long-time exposure at temperature to a low stress may make a notched member more capable of withstanding a high load later. To be of much value, this initial time at low stress must result in substantial lowering of stress concentrations without using up a large portion of the total life.

SUMMARIZED EXPLANATIONS OF NOTCHED-SPECIMEN RUPTURE-TEST RESULTS FOR ALLOYS INVESTIGATED

Factors involved in notched-specimen rupture tests are interrelated in a fairly complicated manner. The various factors were considered in a general way in previous sections but they were not applied to specific alloys. This section of the report summarizes results for each particular alloy and discusses specific reasons for observed behavior of each.

S-816 Alloy at 1350°F: In all tests, S-816 showed notch strengthening. The major reason for this was the relatively-low yield strength of S-816 alloy and its relatively-high rupture strength for its yield strength. Under the state of triaxiality near the root of a sharp notch in a round specimen, yielding caused sufficient stress redistribution that the effective stress was below the nominal stress at all points in the notched cross section. At the same time, the rupture life at the yield stress was relatively long. Rather rapid creep quickly redistributed the initial stress and further reduced the effective stress so that rupture life was additionally prolonged.

Test results for round notched specimens were on the same stress-rupture time curve, independent of the notch severity. This was due to the yield characteristics causing the initial stresses to be about the same in all cases, and subsequent stress redistribution to about the same final stress level. To obtain an effect from notch acuity, very dull notches would be required with insufficient triaxiality to reduce the effective stress as much as for the notches studied. As one goes to lower and lower theoretical stress concentration factors, by using duller and duller notches, the notch rupture strength must eventually fall to the limiting value represented by the smooth bar curve. Very dull notches would give a small increase in strength. As sharper notches were used the increase in rupture life from the notch triaxiality would eventually reach the saturation point observed.

In flat specimens notched at the edges, rupture times were less than for round specimens with notches of the same stress concentration factor. This was due to the effective stress in the flat specimens being higher than for the round specimens after yielding or creep. The zero stress in the thickness direction of a flat specimen leaves the effective stress much higher, so that the initial effective stress after loading was above the nominal stress. Only the rapid rate of creep caused the rupture times to be prolonged beyond those for smooth specimens.

The flat specimens with K_t between 3 and 7 appear to have attained a level of effective stress rather independent of stress concentration factor under the extensive yielding and rapid creep for this alloy. More data would be desirable to establish behavior for notches with $K_t<2$ and to check the possibility indicated by the data that beyond a certain point the sharper notch gives shorter rupture time than the duller notch. This effect, if real and not due to data scatter, can be explained by the flatter gradient of effective stress obtained between the notch root and the axis in specimens with higher K_t.

Under the biaxial stresses in the flat notched S-816 bars, the effective stress at the notch root continued to go up with notch acuity for the range studied. For these same specimens, the effective stress near the center of the bar was nearly the same for variable K_t. The sharper notch thus started out with higher peak stress and could not relax to as low a final level of effective stress no matter how rapidly the redistribution took place. Therefore, a decrease in rupture life appears reasonable for K_t above some critical value, but the data are insufficient to delineate the ranges of stress concentration factor at which this might occur.

It is not certain to what extent plastic flow at the base of the notch changes creep-rupture properties. It is well known that hot-cold working increases rupture strength of S-816. It has been assumed that the one or two percent of plastic flow at the base of the notches would have an insignificant effect. It was noted, however, in relaxation tests that small amounts of plastic flow accelerated relaxation rate at high stress levels. Such evidence as is available therefore indicates that any effects of plastic flow at the base of the notch would contribute slightly to longer life in the rupture test.

Inconel X-550 at 1350°F

The yield strength at 1350°F is relatively high causing the initial stresses at the base of a notch to be high. For any test where the load is sufficiently high for the stress concentrating effect of the notch to cause yielding, the initial stress at the base of the notch would cause rupture in a fraction of an hour unless creep-relaxation occurred rapidly. Creep relaxation in relation to the rate at which rupture life is used up is thus a controlling factor.

Most published data show notch strengthening for high nominal stresses and short rupture times. Apparently, a major factor in such published results has been residual stresses from machining the notches offsetting the stress concentration of the notch. Notch strengthening at high nominal stresses was greatly reduced by notch preparation methods minimizing residual stress effects. There is still some tendency for less notch sensitivity at high nominal stresses. This probably arises from the more rapid increase of the nominal stress than of the effective stress, and from the increased creep rates observed for material which has yielded, compared to the creep of unyielded material. The indicated loss in rupture life from yielding would have an opposing effect tending to reduce rupture life when higher notch acuities increased local yielding. More detailed data on these two effects of prior strain are required before the notch rupture test results can be explained with certainty.

When the nominal stress is reduced to the point where little yielding occurs at the base of the notch, the rupture times for the notched specimens begin to approach the smooth bar values. At this condition, there is no loss in life from yielding and creep allows the stress concentration to relax to the point where little life is lost and presumably would eventually cause notch strengthening.

Flat specimens had slightly lower rupture strength than round specimens for stress concentrations of $K_t = 3.2$ because the effective stress was not reduced as much by biaxial stresses as by triaxial stresses. The combination of more yielding with greater loss in life as well as a higher effective stress resulted in somewhat shorter rupture times.

Waspaloy at 1350°F

The major reason why Waspaloy with a standard heat treatment is notch sensitive at high to intermediate nominal stresses and relatively sharp notches is the loss of rupture life resulting from yielding at the base of the notch. If this did not occur, the initial stress, creep and rupture characteristics are such that most of the notches studied should increase life. When the nominal stress was sufficiently low that little or no yielding occurred, the rupture life was always longer in the notched specimens than in smooth.

Plastic yielding of the order of 0.5% reduced rupture times below those of smooth bars by a factor of 1/3 to 1/2. Strains of the order of 0.9% reduced life to from 1/4 to 1/5 that of smooth bars.

Relatively dull notches with restricted amount of yielding showed increases in rupture life due to the reduction of effective stress by creep under the triaxial stress interaction. Only when notches were sufficiently sharp to cause substantial yielding was life reduced.

The studies of varying notch sensitivity due to the inclusion or omission of the intermediate age at 1550°F showed that the balance between rate of effective stress reduction by creep and the rate at which rupture life is used up can be very critical when yielding occurs. The one case where omission of the intermediate age caused reduced rupture life in relation to the fully aged material could only be explained by the much higher creep resistance of the single aged material at high stress levels.

It should also be noted that the creep characteristics at high stress levels governing notched specimen rupture life were influenced by prior processing history. When re-rolled, the material which underwent increased notch sensitivity due to omission of the 1550°F age no longer showed this characteristic. In fact, if anything, the relationships were reversed.

Waspaloy did not show as much of a tendency for notch strengthening at high nominal stresses and short rupture times which seemed characteristic of Inconel X-550. Apparently, this was mainly due to the damage from yielding predominating over other factors. In particular, Waspaloy did not undergo appreciable increased creep rate at high stress levels as the result of yielding, as was the case for Inconel X-550. Consequently, the rate of stress reduction after loading was not increased and life was shortened due to lowered rupture strength.

"17-22-A"S Cr-Si-Mo-V Steel at 1100°F

At high nominal stress, "17-22-A"S was strengthened by all notches studied, due to the rapid creep at effective stresses above 60,000 psi. (At the yield stress of this alloy the creep rate is about twenty times as fast as for Waspaloy at its 1350°F yield stress, while rupture life for these two conditions is nearly the same).

At lower nominal stress the rate of relaxation is sufficiently slow that for sharper notches mild notch weakening results.

The gradual curvature of the stress-strain curve for "17-22-A"S from the proportional limit to the relatively high yield stress means that, unlike the case of S-816 at 1350°F, different notch shape and acuities, and different nominal stresses produce a wide range of effective stress at the notch root. Notch acuity affects the peak stress level more than does notch shape, round or flat. Consequently, a substantial difference in notch strength is evident between $K_t = 1.9$ to 2.0 and $K_t = 3.2$ and 3.3.

A second factor promoting a high degree of notch strengthening at high nominal stress, relative to that for lower nominal stress, is the decided change in slope of the stress-rupture life curve near 50-60,000 psi. At effective stresses above 60,000 psi, a given reduction of stress level by relaxation causes a proportionally greater prolongation of rupture life than does a comparable relaxation in the range of effective stress below 50,000 psi.

2024-T4 Aluminum Alloy at 400°F

In most of the notches studied for this alloy, the initial effective stress at the notch root was quite near the yield stress as a result of stress-strain properties similar to those already discussed for S-816. The 2024-T4 has a creep rate at its yield stress higher than did any other alloy in this program except "17-22-A"S, thus favoring rapid relaxation at early times.

The lower modulus value for the aluminum alloy (with consequent small stress change for a given amount of creep) is more than offset by the much lower initial stress present and, more particularly, by the relatively-flat curve of stress versus rupture life. In the critical range of stress from 50,000 to 40,000 psi, 2024-T4 exhibits a larger gain in rupture life for a given stress drop than did the other alloys except for S-816 which also showed pronounced notch strengthening.

Round specimens of 2024-T4 with K_t's of 1.9 and 3.2 should be expected to have nearly the same degree of notch strengthening since the slightly lower effective stress near the root of the duller notch is offset by its higher effective stress near the axis, with consequent smaller stress gradient that can be leveled by relaxation.

Flat specimens with the sharper notch have slightly higher stress near the notch and much higher stress near the axis than do corresponding round notches, accounting for the observed lower rupture lives for the flat bars with $K_t = 3.3$.

From the data on hand, no satisfactory explanation was found for the flat specimens with $K_t = 2.0$ giving rupture times as high as those for round specimens.

CONCLUSIONS

Analysis of the comparative results of rupture tests on notched and regular specimens of five alloys, in relation to their tensile stress-strain, tensile creep-relaxation and tensile rupture properties, showed the following factors to govern rupture time of notched specimens:

1. For the five materials, the controlling factor was the rate at which the stress concentration from the notch was reduced by yielding during loading and by subsequent time-dependent creep-relaxation, compared to the rate at which rupture life was used up.

Relatively low yield strengths, allowing considerable plastic flow to reduce effective stresses at the base of notches, prolong rupture time. Relatively rapid creep at the high stresses initially existing at the base of notches promotes increased rupture time. Both factors, particularly low yield strength in relation to the rupture strength, combine to make S-816 practically insensitive to notches.

2. Yielding and creep relaxation reduce the effective stresses at the base of notches through interaction of the complex stresses. The extent of both processes in the three principal directions is distributed in proportion to the relative magnitude of the individual principal stresses. This reduces differences between principal stresses. The effective stress causing rupture apparently is a function of these differences between the principal stresses, according to shear-stress invariant theory. The process of relaxation of a stress concentration by yielding and creep can therefore reduce the effective stress below the nominal and prolong life. The actual rupture time is governed by the rate of such relaxation processes in relation to the rate at which rupture life is used up.

A given extent of stress relaxation causes a proportionally-larger increase in rupture life for materials with a flatter curve of stress versus rupture life at the conditions of interest.

3. It has been found that some alloys lose considerable rupture life from small amounts of yielding during loading. This was the primary cause for notch sensitivity in Waspaloy at 1350°F and probably was involved in the notch weakening of Inconel X-550 at 1350°F. Apparently, this factor should be checked for many other alloys.

4. The geometry of test specimens is important to test results in that it controls the initial stress patterns after loading for the rupture tests. This, in conjunction with the stress-strain yield characteristics, determines the magnitude of the initial effective stress distribution across the specimen. The distribution of stress in turn influences the reduction of effective stress by creep relaxation.

5. A triaxial stress from circumferential notches in round specimens is less damaging than a biaxial stress from notches in the edges of flat specimens. For the same theoretical stress concentration factor in both types of specimens, the effective stress is higher at the center of the flat specimens. This limits the degree to which stress-relaxation can reduce the effective stress. Secondly, the effective stress is also higher at the notch root in the flat specimen so that tests on flat specimens are inherently carried out under higher effective stresses than in triaxial round specimens.

6. Sufficiently-low yield strengths and rapid stress relaxation by creep result in prolonged rupture times in comparison to smooth specimens. Because reduction of effective stress by yielding or creep is dependent on the extent of triaxiality, it follows that rupture life increases with severity of stress concentration up to a maximum.

Increasing yield strengths and creep resistance reduce the stress concentration at which the maximum strengthening occurs. Materials with high yield strengths and high creep resistance in relation to the rupture strengths can suffer loss in rupture life from all degrees of stress concentration.

7. Residual stresses from notch preparation can apparently influence performance of specimens which are resistant to stress relaxation. The usual compressive residual stress from turning a notch offsets part of the axial tensile stress, reducing the effective stress. Minimizing the residual stress by refining notch preparation reduces rupture time. If procedures are used which leave a tensile stress, such as result from overheating during grinding, the residual stress will be added to the stress concentration and abnormally short rupture times will result.

8. Attempts have been made to calculate rupture times for notched specimens from consideration of the stress-strain and creep-relaxation characteristics, as measured in simple tension tests. The degree of success was almost wholly dependent upon the degree to which the effect of prior stress-strain-time effects on properties could be estimated as the effective stress was lowered by the stress-relaxation properties. It worked quite well for Waspaloy at 1500°F without any corrections. In the other alloys involved in the investigation, the prior history effects were more influential. In the case of Waspaloy at 1350°F, a limited amount of data for the effect of prior strain allowed corrections of properties which gave calculated lives quite close to the experimental values. The calculations tend to support the contention that stress relaxation by yielding and creep, in relation to the rate of expenditure of rupture life, governs rupture time of notched specimens. There are many assumptions in the calculation method which lower the degree of reliance as a proof of the theories presented. There seems little doubt, however, that the basic concepts are correct and general. More proof of the validity of the assumption that rupture under complex stresses is governed by the effective stress and not by the maximum principal stress would be reassuring. In addition, the investigation points out a very strong need for detailed information on the effect of prior history on subsequent properties as the stress concentration relaxes, if rigorous computations of expected performance are to be carried out. There is also need to better understand the interaction effects along the stress gradients as relaxation occurs.

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TABLE 1

RUPTURE PROPERTIES AT 1350°F FOR FLAT SPECIMENS OF S-816 AND INCONEL X-550

Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (inches) W	w	t	r	K_t	How Notch was Finished
		S-816, Smooth Specimens					
40,000	83.5	0.400	--	0.100	--	-	
30,000	802.3	0.400	--	0.100	--	-	
		S-816, Notched Specimens					
45,000	40.7	0.724	0.468	0.125	0.005	7.2	Shaped
40,000	119.3	0.724	0.468	0.125	0.005	7.2	Shaped
42,000	110.6	0.724	0.468	0.125	0.060	2.4	Shaped
60,000	6.0	0.620	0.310	0.100	0.025	3.2	Ground, Lapped
50,000	37.9	0.620	0.310	0.100	0.025	3.2	Ground, Lapped
40,000	171.0	0.620	0.310	0.100	0.025	3.2	Ground, Lapped
		Inconel X-550, Smooth Specimens					
65,000	19.2	0.400	--	0.100	--	-	
40,000	563.4	0.400	--	0.100	--	-	
		Inconel X-550, Notched Specimens					
61,400	9.2	0.620	0.310	0.100	0.025	3.2	Ground, Lapped
50,000	32.5	0.620	0.310	0.100	0.025	3.2	Ground, Lapped
40,000	169.0	0.620	0.310	0.100	0.025	3.2	Ground, Lapped

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

TABLE 2

RUPTURE PROPERTIES AT 1100°F FOR SMOOTH AND NOTCHED BARS OF "17-22-A"S Cr-Si-Mo-V ALLOY STEEL NORMALIZED AND TEMPERED

Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
	Round Smooth Bars		
73,000	0.47	23	71
70,000	0.6	15.5	66.5
65,000	4.5	17	43
60,000	9.7	8.5	25
55,000	19.6	6	14
50,000	32.2	5	8.5
40,000	87.2	4.5	6.5
30,000	213.9	3	3.5
20,000	873	2.5	3.5
	Flat Smooth Bars		
60,000	8.1	-	-
45,000	50.5	-	-
30,000	183.3	-	-

Round Notched Bars

		[a]Nominal Specimen Geometry (Inches)			
Stress (psi)	Rupture Life (hours)	D	d	r	K_t
65,000	22.5	0.600	0.424	0.086	1.9
55,000	45.4	0.600	0.424	0.086	1.9
50,000	63.5	0.600	0.424	0.086	1.9
45,000	34.7	0.600	0.424	0.086	1.9
35,000	195.0	0.600	0.424	0.086	1.9
25,000	600.0	0.600	0.424	0.086	1.9
65,000	14.1	0.600	0.424	0.020	3.2
50,000	17.8	0.600	0.424	0.020	3.2
50,000	36.5	0.600	0.424	0.020	3.2
40,000	73.5	0.600	0.424	0.020	3.2
30,000	172.3	0.600	0.424	0.020	3.2
20,000	699.6	0.600	0.424	0.020	3.2
[b]40,000	68.6	0.600	0.424	0.020	3.2
[b]25,000	368.6	0.600	0.424	0.020	3.2

TABLE 2 (continued)

Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (Inches) W	w	t	r	K_t
		Flat Notched Bars				
55,000	39.6	0.740	0.400	0.100	0.100	2.0
45,000	74.5	0.740	0.400	0.100	0.100	2.0
35,000	146.3	0.740	0.400	0.100	0.100	2.0
25,000	430.0	0.740	0.400	0.100	0.100	2.0
20,000	764.6	0.740	0.400	0.100	0.100	2.0
65,000	7.0	0.740	0.400	0.100	0.031	3.3
55,000	16.5	0.740	0.400	0.100	0.031	3.3
45,000	39.0	0.740	0.400	0.100	0.031	3.3
35,000	137.5	0.740	0.400	0.100	0.031	3.3
25,000	387.5	0.740	0.400	0.100	0.031	3.3
20,000	606.8	0.740	0.400	0.100	0.031	3.3

(a) All notches ground and lapped except where otherwise stated; 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

(b) Heat treated in vacuum after notch was ground and lapped.

TABLE 3

MULTIPLE-STRESS RUPTURE TESTS ON SMOOTH SPECIMENS

Stress (psi)	Fraction: Time at Stress / Rupture Life at Stress			Sum of Life Fractions	Rupture Ductility	
					Elongation (%)	Reduction of Area (%)
"17-22-A"S at 1100°F						
25,000	197/430	=	0.458			
60,000	0.66/9.9	=	0.067			
				0.525	8.	30.
60,000	5.5/9.8	=	0.562			
25,000	238.35/430	=	0.554			
				1.116	5.	4.
25,000	131.3/430	=	0.305			
60,000	0.085/9.8	=	0.009			
				0.314	12.5	47.
60,000	1.1/9.8	=	0.112			
50,000	3.9/35	=	0.112			
30,000	40.0/220	=	0.182			
20,000	114.7/880	=	0.131			
				0.537	9.	22.
60,000	3.67/9.8	=	0.375			
25,000	130/430	=	0.305			
60,000	3.0/9.8	=	0.306			
				0.986	15.5	32.5
2024-T4 at 400°F						
20,000	173.3/460	=	0.376			
30,000	0.4/18	=	0.022			
				0.398	18.7	17.5
10,000	95/(10,000)	=	0.01			
30,000	0.375/18	=	0.02			
				0.03	13.	51.
30,000	10/18	=	0.556			
20,000	287.25/460	=	0.625			
				1.18	8.5	30.
2024-T4 at 500°F						
15,000	10.5/24.5	=	0.428			
10,000	168.75/165	=	1.023			
				1.45		

TABLE 4

RUPTURE PROPERTIES AT 400° and 500°F FOR SMOOTH AND NOTCHED BARS OF 2024-T4 ALUMINUM ALLOY

Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
		Round Smooth Bars	
		500°F	
20,000	2.83	14.	54.5
15,000	24.3	12.	44.5
10,000	167.2	14.5	38.5
		400°F	
45,000	0.825	7	33.5
40,000	2.3	15	44.5
35,000	6.2	7	37
25,000	73.6	9.5	37
20,000	434.9	8.5	32
18,500	421.4	20	28
17,500	476.2	11.5	36.5
		Flat Smooth Bars	
		400°F	
30,000	13.2	-	25.5
20,000	401.8	-	30.5

Round Notched Bars

Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (inches)			
		D	d	r	K_t
		500°F			
15,000	88.9	0.600	0.424	0.020	3.2
		400°F			
40,000	13.2	0.600	0.424	0.020	3.2
35,000	50.1	0.600	0.424	0.020	3.2
30,000	133.9	0.600	0.424	0.020	3.2
25,000	412.3	0.600	0.424	0.020	3.2
20,000	1154.8	0.600	0.424	0.020	3.2
35,000	42.3	0.600	0.424	0.075	1.9
25,000	384.9	0.600	0.424	0.075	1.9
20,000	1703.9	0.600	0.424	0.075	1.9

TABLE 4 (continued)

Stress (psi)	Rupture Life (hours)	[a]Nominal Specimen Geometry (inches) W	w	t	r	K_t
		Flat Notched Bars				
		400°F				
40,000	6.3	0.740	0.400	0.100	0.031	3.3
30,000	37.9	0.740	0.400	0.100	0.031	3.3
20,000	637.4	0.740	0.400	0.100	0.031	3.3
35,000	48.9	0.740	0.400	0.100	0.100	2.0
30,000	168.45	0.740	0.400	0.100	0.100	2.0
25,000	546.25	0.740	0.400	0.100	0.100	2.0

(a) All notches ground and lapped before heat treatment; 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 5

EFFECT OF PLASTIC PRE-STRAINING ON RELAXATION AND RUPTURE OF S-816 AND OF INCONEL X-550 TESTED AT 1350°F

S-816

Plastic Pre-Strain (%)	Relaxation Time 37,500 psi to 15,000 psi (hr)	Life used in Relaxing to 15,000 psi (%)	Subsequent Creep to Rupture	
			Stress (psi)	Fraction: Time at Stress / Rupture Life at Stress of Material Not Pre-Strained
0	5.25	0.25	40,000	61.9/87 = 0.71
1.35	5.5	0.17	40,000	70.15/87 = 0.81
3.15	6.0	0.15	40,000	60.3/87 = 0.69
6	14.9	0.33	37,500	190.75/135 = 1.41
9.2	61.8	0.58	40,000	90.9/87 = 1.05

INCONEL X-550

Plastic Pre-Strain (%)	Relaxation Time 60,000 to 40,000 psi (hour)	Life used in Relaxing to 40,000 psi (%)	History of Stress and Life Consumed	
			Stress (psi)	% of Total Life Consumed
0	100	34.6	Relax 60,000 to 22,360 psi Relax 60,000 to 38,060 psi (Ruptured at 38,060)	77.2 3.1 80.3%
0.25	93.9	42.2	Relax 60,000 to 14,600 psi 35,000 psi to Rupture	70.0 1.3 71.3%
0.85	32.3	14.1	Relax 60,000 to 11,690 psi 35,000 psi to Rupture	34.0 4.0 39.0%
1.4	21.6	9.5	Relax 60,000 to 40,000 psi 40,000 psi to Rupture	9.5 24.4 33.9%
2.6	5.7	2.4	Relax 60,000 to 40,000 psi 40,000 psi to Rupture	2.4 19.5 21.9%

TABLE 6

CHEMICAL COMPOSITIONS OF THREE HEATS OF WASPALOY TESTED

Melting Atmosphere:	Vacuum	Air	Air
Heat Number:	3-260	44,036	63,613
Element	Chemical Composition, Percent by Weight		
C	0.08	0.08	0.04
Mn	0.27	0.80	0.73
Si	0.60	0.61	0.66
P		0.01	0.014
S	0.005	0.017	0.014
Cr	19.7	18.72	20.16
Ni	Bal.	Bal.	Bal.
Co	14.0	13.44	14.25
Mo	3.90	2.93	3.15
Fe	0.74	1.17	1.33
Al	1.11	1.29	1.00
Ti	3.10	2.29	2.54
Cu	0.1	0.1	0.06
Mg	0.1		

TABLE 7

SHORT-TIME TENSILE PROPERTIES AT 1350°F FOR THREE HEATS OF WASPALOY
(Material Re-rolled at University of Michigan)

	Heat 3-260		Heat 44,036		Heat 63,613	
	[a]Conv. H. T.	[b]No 1550° Age	Conv. H. T.	No 1550° Age	Conv. H. T.	No 1550° Age
0.2% Y. S. (psi)	112,500	118,000	91,400	91,000	95,000	90,200
Tensile Strength (psi)	135,000	135,000	115,000	102,000	117,000	106,200
Proportional Limit (psi)	92,000	85,000	67,500	77,000	75,000	73,000
Elongation (%/1.4 in.)	16.	16.	4.5	3.5	7.5	4.5
Reduction of Area (%)	17.5	16.	7.5	11.5	9.	9.

(a) 1975°F, 4 Hr., Air Cool + 1550°F, 4 Hr., Air Cool + 1400°F, 16 Hr., Air Cool

(b) 1975°F, 4 Hr., Air Cool + 1400°F, 16 Hr., Air Cool

TABLE 8

RUPTURE DATA AT 1350°F FOR THREE HEATS OF WASPALOY
(Material Re-rolled at University of Michigan)

SMOOTH SPECIMENS

Stress (psi)	Heat 3-260 Rupt. Life (hours)	Heat 3-260 Red. of Area (%)	Heat 3-260 Elong. (%)	Heat 44,036 Rupt. Life (hours)	Heat 44,036 Red. of Area (%)	Heat 44,036 Elong. (%)	Heat 63,613 Rupt. Life (hours)	Heat 63,613 Red. of Area (%)	Heat 63,613 Elong. (%)
A. Conventional Heat Treatment (1975°F, 4 Hr., AC + 1550°F, 4 Hr., AC + 1400°F, 16 Hr., AC)									
100,000	2.32	11.	7.5	-	-	-	-	-	-
90,000	5.25	6.5	4.	-	-	-	-	-	-
80,000	21.7	9.	5.5	1.23	8.5	3.	2.48	6.5	3.5
70,000	36.6	7.5	3.	5.35	7.	2.5	7.0	7.	3.
60,000	155.4	6.5	4.	42.9	5.5	3.5	11.4	6.5	2.5
50,000	-	-	-	108.5	3.	3.5	189.9	4.5	1.5
40,000	-	-	-	820.95	5.	4.	550.8	4.	4.
B. 1550°F Aging Step Omitted (1975°F, 4 Hr., AC + 1400°F, 16 Hr., AC)									
100,000	1.28	8.	2.	-	-	-	-	-	-
90,000	2.75	8.5	3.	-	-	-	-	-	-
80,000	16.1	5.5	3.5	0.55	-	-	3.15	11.	2.5
70,000	46.4	6.	5.5	4.0	10.5	2.5	7.0	8.	3.
60,000	49.1	6.5	3.5	25.05	8.5	2.	11.3	6.5	3.
50,000	-	-	-	41.9	1.5	1.5	142.5	4.	3.
40,000	-	-	-	865.6	5.	4.5	634.5	7.	4.5

TABLE 8 (continued)

NOTCHED SPECIMENS

Stress (psi)	Heat 3-260		Heat 44,036		Heat 63,613	
	Conv. H. T.	No. 1550°Age	Conv. H. T.	No 1550° Age	Conv. H. T.	No 1550° Age
			(Rupture Lives - Hours)			
^{a}70,000	1.0	-	-	-	-	-
^{a}60,000	-	2.6	-	-	-	-
^{a}55,000	11.3	-	-	-	-	-
^{a}50,000	-	2.2	0.45	-	0.6	1.5
^{a}45,000	9.0	-	-	-	-	-
^{a}40,000	-	^{b}2281+	1.2	1.3	1.25	29.6
^{a}35,000	-	-	-	2.6	-	1477.8
^{a}32,500	-	-	^{b}2064+	-	^{b}2136+	-
^{a}30,000	-	-	-	^{b}2490+	-	-
^{c}50,000	^{b}3179+	-	-	-	18.4	1.5
^{c}40,000	-	-	604.8	-	-	9.4
^{c}35,000	-	-	-	-	-	^{b}1301+

(a) Notch geometry: Shank diameter, D = 0.500 inch
Diameter at notch, d = 0.350 inch
Notch root radius, r = 0.004 inch
Notch Angle, 60°

Heat treated in raw helium atmosphere after notch machined on lathe.

(b) Discontinued

(c) Notch geometry: Same as (a) but Notch root radius, r = 0.018 inch
Notch ground and lapped after heat treatment

TABLE 9

SMOOTH-BAR RUPTURE TESTS AT 1350°F FOR WASPALOY
(Heat 63,613; Specimens Taken from 1-3/4" Stock Rolled by Supplier)

Momentary Overload Stress (psi)	Measured Plastic Strain from Overload (%)	Test Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
		Conventional Heat Treatment			
-	0	75,000	1.6	3	3.5
-	0	40,000	587.3	-	3.5
98,000	0.765	69,820	1.1	4.	6.5
98,000	0.88	64,900	2.4	2.	6.5
98,000	0.515	59,670	9.85	-	4.5
98,000	0.93	52,140	16.0	2.5	3.5
98,000	0.44	44,730	174.85	1.5	2.
		1550°F Age Omitted			
-	0	75,000	2.4	2.5	8.5
-	0	45,000	579.6	5.	3.5
100,000	2.2	70,240	0.12	4.	8.
98,000	0.93	64,940	4.35	3.5	6.
98,000	1.33	60,210	3.85	2.5	4.5
98,000	1.27	52,300	5.3	3.5	3.5
98,000	1.72	45,340	9.7	2.5	3.5

TABLE 10

NOTCH RUPTURE TESTS WITH STRESS INCREASED AFTER A PROLONGED PERIOD AT LOWER STRESS

Stress History	Rupture Life for Stress (hours)		Remarks
	Notched	Smooth	
	Waspaloy at 1350°F		
40,000 psi, 2280.0 hr +	-	4,000	Heat 3-260, re-rolled
50,000 psi, 1029 hr +	10	700	Conventional heat treatment
60,000 psi, 584.6 hr	2	160	K_t = 6.8
50,000 psi, 3179.1 hr +	10	700	Heat 3-260, re-rolled
70,000 psi, 64.3 hr	0.9	47	Conventional heat treatment
			K_t = 3.2
32,500 psi, 2064 hr +	-	6,000	Heat 44,036, re-rolled
40,000 psi, 1030.3 hr +	1.25	850	Conventional heat treatment
50,000 psi, 51.1 hr	0.45	94	K_t = 6.8
30,000 psi, 2490.3 hr +	-	15,000	Heat 44,036, re-rolled
40,000 psi, 1073.5 hr +	1.25	850	1550°F age omitted
50,000 psi, 10.8 hr	0.45	94	K_t = 6.8
30,000 psi, 1650.9 hr +	-	>10,000	Heat 63,613;1-3/4 inch
50,000 psi, 294.8 hr +	0.75	185	stock; 1550°F age omitted
70,000 psi, 47.9 hr	0.37	4.4	K_t = 3.2
35,000 psi, 1301.4 hr +	-	2,000	Heat 63,613, re-rolled
50,000 psi, 5.95 hr	1.6	115	1550°F age omitted
			K_t = 3.2
32,500 psi, 2136.3 hr +	-	4,200	Heat 63,613, re-rolled
40,000 psi, 162.8 hr	1.5	700	Conventional heat treatment
			K_t = 6.8
	Inconel X-550 at 1350°F		
24,500 psi, 1343.7 hr +	>10,000	>10,000	K_t = 6.7
35,000 psi, 270.9 hr	200	1,400	
35,000 psi, 103.25 hr +	150	1,400	K_t = 3.2
45,000 psi, 22.3 hr +	50	250	
55,000 psi, 12.7 hr	25	60	
	"17-22-A"S at 1100°F		
20,000 psi, 216.5 hr +	690	870	K_t = 3.2
40,000 psi, 32.0 hr	74	88	

TABLE 11

INITIAL STRESS PATTERN AND PATTERN OF PLASTIC STRAIN ON LOADING AND DURING CREEP FOR A FLAT NOTCHED SPECIMEN

(2024-T4 at 400°F under 40,000 psi stress; Width at notch root 0.400 inch; $K_t = 3.3$)

Band No.	Fraction of Total Cross Sectional Area	Distance of Centroid from Notch Root	Stress ratio at centroid, fraction of nominal stress						
			Principal Components			Deviator Components			Effective Stress
			Longitudinal	Transverse	Thickness	Longitudinal	Transverse	Thickness	
6	1/63	0.0016 in.	2.995	0.149	0	1.947	-0.899	-1.048	2.924
5	2/63	0.0064	2.389	0.400	0	1.459	-0.530	-0.930	2.218
4	4/63	0.0159	1.760	0.582	0	0.979	-0.199	-0.781	1.554
3	8/63	0.0350	1.253	0.636	0	0.623	0.006	-0.630	1.085
2	16/63	0.0730	0.905	0.596	0	0.405	0.096	-0.500	0.797
1	32/63	0.1492	0.712	0.534	0	0.297	0.119	-0.415	0.642

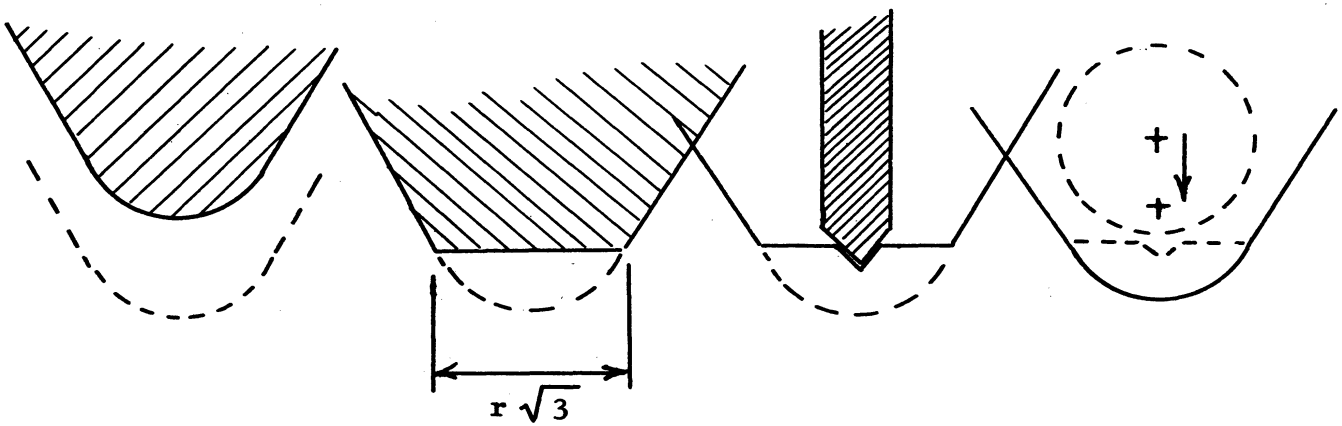
Band No.	$(3/2)(S'_i/\overline{S})$		Calculated Plastic Strain on Loading (%)	Calculated Cumulative Effective Creep $(\overline{e^P})$ (percent)	
	Longitudinal	Transverse		After 1.0 hour	After 4.1 hour
6	1.00	-0.46	1.17	1.46	2.68
5	1.08	-0.39	0.60	1.25	2.34
4	0.95	-0.19	0.22	0.87	1.78
3	0.86	0.01	0.04	0.49	1.17
2					
1	0.69	0.28	0	0.11	0.71

TABLE 12

REPRESENTATIVE NOTCHED-BAR DATA FOR THE FIVE ALLOYS STUDIED

Item Number	Material	Test Temp. (°F)	Type Specimen	K_t	Nominal Axial Stress (psi)	Initial Stress Pattern on Loading (psi)				Experimental Notch Rupture Life (hours)	Initial Plastic Strain at Notch Root (%)	Integrated Avg. of Initial Effective Stresses at Notch ($\overset{*}{S}$)	Rupture Life (hours) Corresponding to the Effective Stresses Indicated			Calculated Results	
						At Notch Root		Near Axis of Bar					Initial Value on Loading				
						Effective Stress	Axial Component	Effective Stress	Axial Component				At Notch Root	Near Axis of Bar	$\overset{*}{S}$	Notch Life (hours)	Maximum Creep at Rupture (%)
1	S-816	1350	Round	2.1	58,000	50,700	57,050	22,990	45,470	32.5	0.43	32,900	6.9	3300	320	-	-
2	S-816	1350	Flat	3.2	40,000	52,700	52,700	28,200	31,370	180	0.60	33,770	7.1	860	275	-	-
3	Waspaloy, Heat 44036	1500	Round	3.2	25,000	68,000	76,610	4,660	15,860	>550	0.06	11,470	0.16	-	12,500	-	-
4	Waspaloy, Heat 44036	1500	Round	1.75	25,000	39,270	43,520	12,150	19,280	550	0	18,060	12.15	9000	920	780	-
5	Waspaloy, Heat 44036	1350	Round	3.2	50,000	91,400	103,100	9,400	32,000	125	0.41	21,800	0.32	-	22,000	-	-
6	[a] Waspaloy, Heat 63613	1350	Round	3.2	50,000	92,500	104,300	9,060	30,840	85	0.32	20,630	0.19	-	(1,000,000)	28.8	1.4
7	[b] Waspaloy, Heat 63613	1350	Round	3.2	50,000	89,500	100,900	9.000	30,630	0.75	0.35	20,520	0.26	-	(1,000,000)	0.53	0.2
8	[b] Waspaloy, Heat 63613	1350	Round	3.2	30,000	79,000	89,000	5,400	18,390	>1651	0.03	12,700	1.2	-	-	[c]>7300	[c]>1.21
9	Waspaloy, Heat 3-260 Re-rolled at U. of M.	1350	Round	6.8	50,000	125,000	141,000	5,560	28,870	10	3.3	14,900	0.42	-	(10,000,000)	-	-
10	Waspaloy, Heat 63613 Re-rolled at U. of M.	1350	Round	6.8	40,000	112,000	126,400	4,590	23,830	1.5	2.1	12,490	0.17	-	(9,000,000)	-	-
11	Inconel X-550	1350	Round	3.2	40,000	89,000	100,300	7,470	25,450	240	0.19	18,090	0.35	-	(55,000)	58	1.0
12	Inconel X-550	1350	Flat	3.25	40,000	90,000	90,000	26,130	29,070	165	0.22	35,140	0.3	6600	1250	34	1.15
13	Inconel X-550	1350	Round	6.7	30,000	96,100	109,100	3,250	17,850	500	0.52	9,250	0.14	-	-	109	0.8
14	"17-22-A"S	1100	Round	3.2	60,000	80,040	90,000	11,630	39,600	18	0.90	24,540	0.086	5600	425	112	3.0
15	"17-22-A"S	1100	Flat	3.2	60,000	80,600	80,600	39,000	43,300	10	1.06	47,200	0.078	88	46	-	-
16	"17-22-A"S	1100	Round	3.1	30,000	69,700	78,600	5,620	19,160	195	0.17	13,390	0.88	-	3450	-	-
17	"17-22-A"S	1100	Flat	3.3	30,000	71,600	71,600	19,480	21,610	220	0.20	25,950	0.59	940	350	-	-
18	"17-22-A"S	1100	Round	1.9	30,000	44,500	49,310	14,610	23,480	330	0.02	21,500	56.5	2550	670	339	2.4
19	"17-22-A"S	1100	Flat	2.0	30,000	51,600	51,600	20,800	24,000	245	0.04	26,950	28.3	745	310	-	-
20	2024-T4	400	Round	3.2	30,000	50,500	56,940	5,730	19,550	140	0.66	13,130	0.39	-	2580	30	2.9
21	2024-T4	400	Flat	3.3	30,000	50,800	50,800	19,750	21,900	40	0.77	25,450	0.38	285	75	9.3	2.7
22	2024-T4	400	Round	1.95	30,000	41,450	45,930	14,650	23,530	140	0.04	21,540	1.8	1400	176	18.9	-
23	2024-T4	400	Flat	2.0	30,000	46,200	46,200	20,960	24,190	140	0.16	26,900	0.78	205	48	11.8	-
24	2024-T4	400	Flat	3.3	40,000	51,500	51,500	27,060	30,000	6.4	1.62	32,900	0.34	44	10.2	3.7	2.7

a. Conventional Heat Treatment
b. 1550°F Age Omitted
c. Test stress raised after 1651 Hours at 30,000 psi



(1) Rough turn

(2) Grind flat bottom

(3) Grind groove in flat

(4) Lap with wire of diameter slightly under $\underline{2r}$

Fig. 1.- Steps Employed in Routine Notch Preparation.

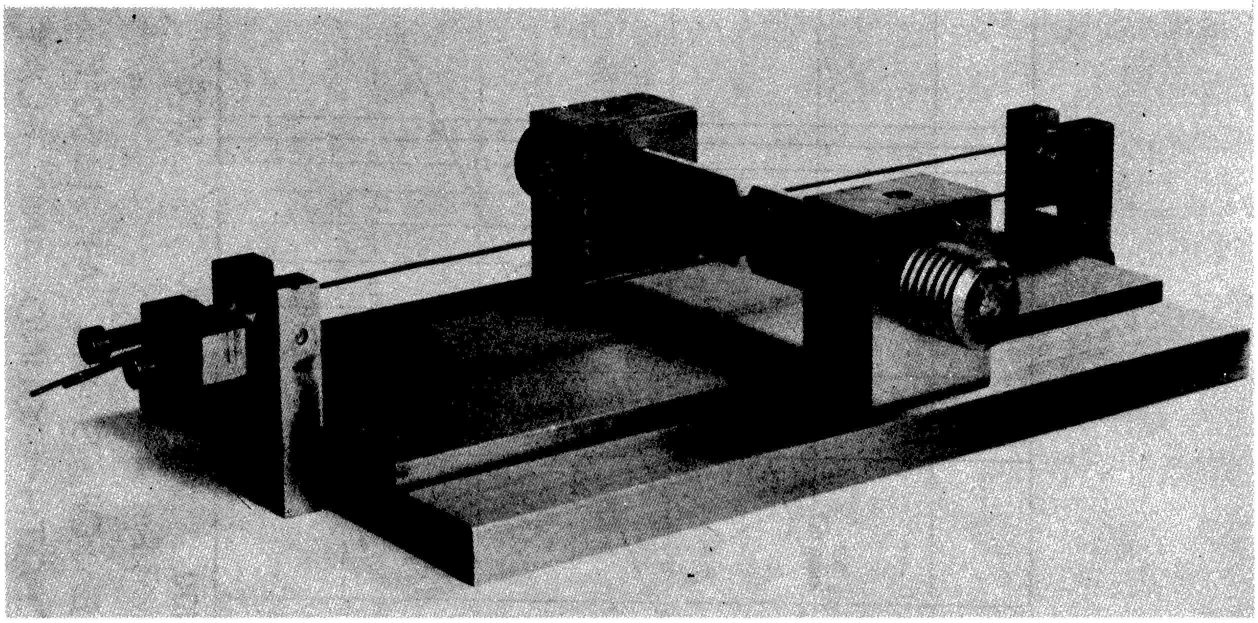


Fig. 2. - Fixture to Maintain Alignment During Lapping of Flat Notched Specimens.

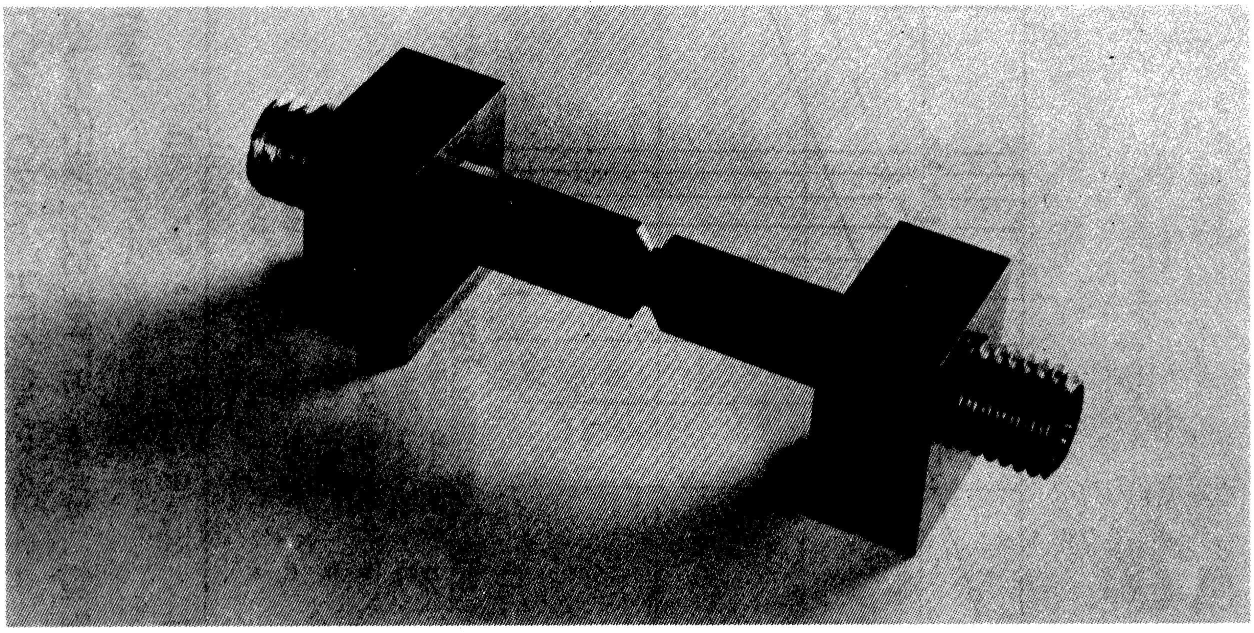


Fig. 3. - Flat Notched Specimen Machined from Round Bar Stock, Shown with Jig Blocks Used During Specimen Preparation.

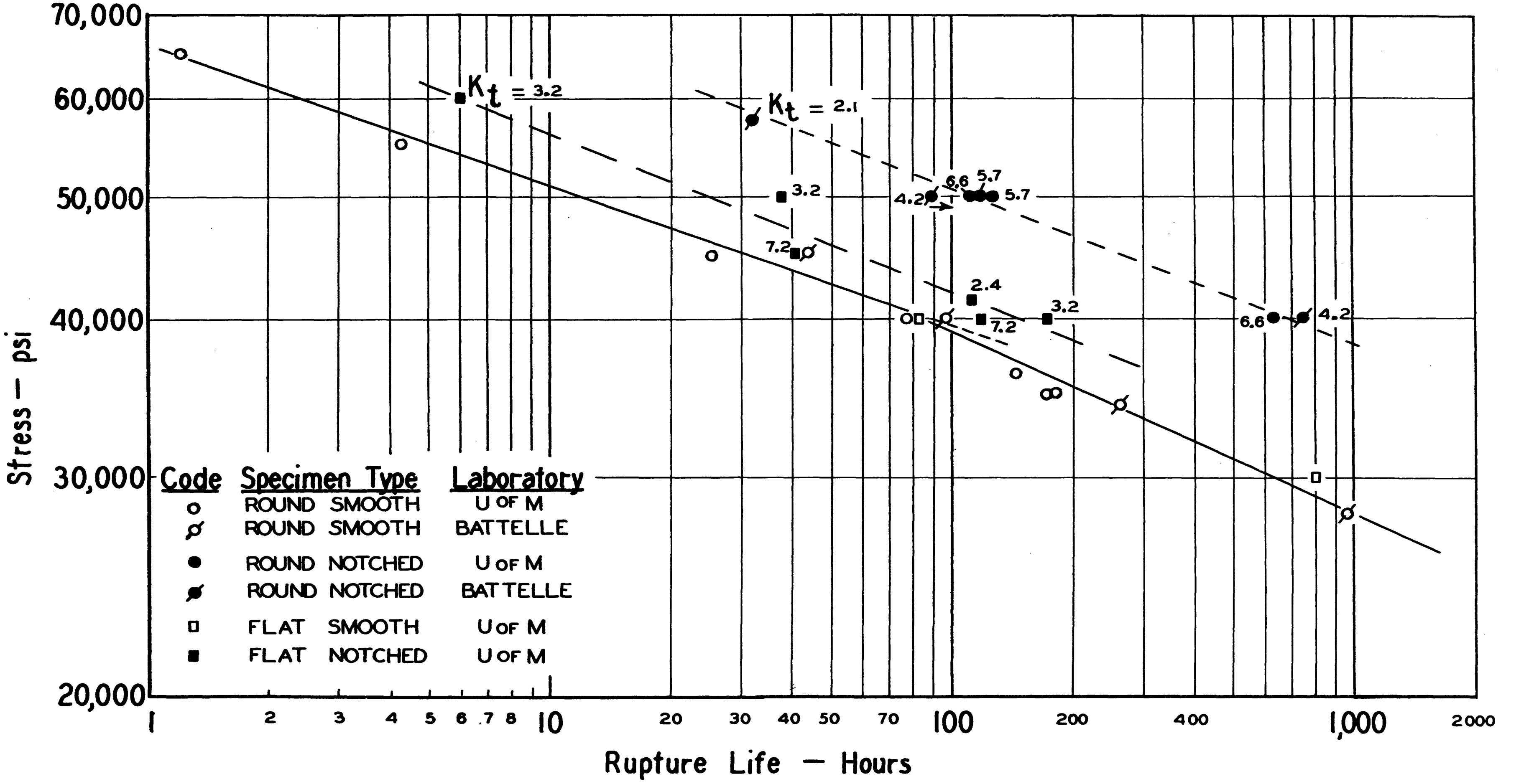


FIG. 4 - STRESS VERSUS RUPTURE LIFE OF S-816 AT 1350°F FOR SMOOTH AND NOTCHED BARS, BOTH ROUND AND FLAT.

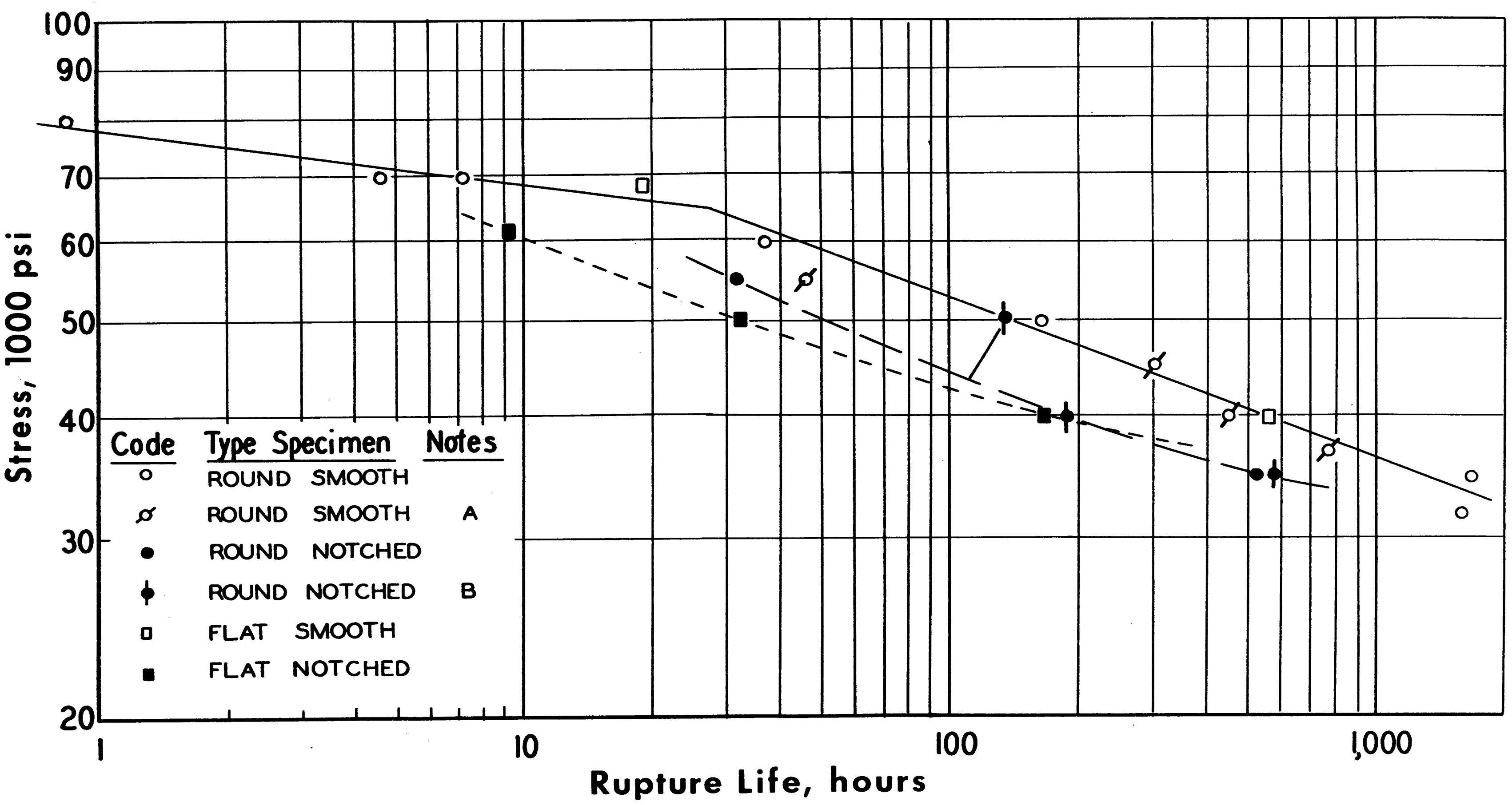


FIG. 5 — COMPARATIVE RUPTURE LIVES AT 1350°F FOR ROUND AND FLAT SPECIMENS OF INCONEL X-550.

NOTES: All notches ground & lapped; $K_t = 3.2 - 3.3$

A: Data of Carlson, et.al.

B: Notch lapped at Univ. of Minnesota

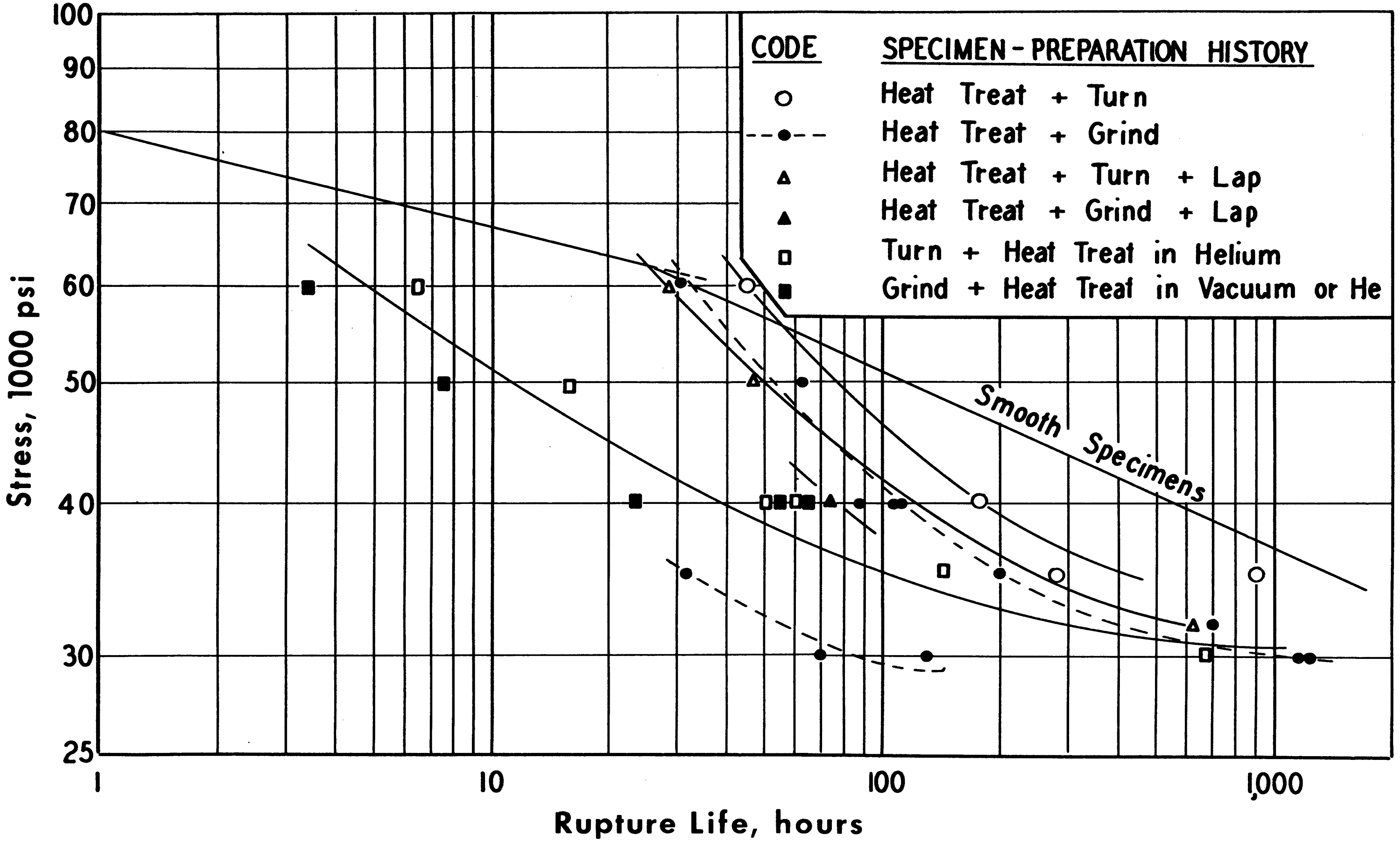


FIG. 6 – EFFECT OF NOTCH PREPARATION PROCEDURE ON RUPTURE LIFE OF INCONEL X-550 AT 1350 °F.

NOTCH GEOMETRY, INCHES: D=0.600, d=0.424, r=0.005

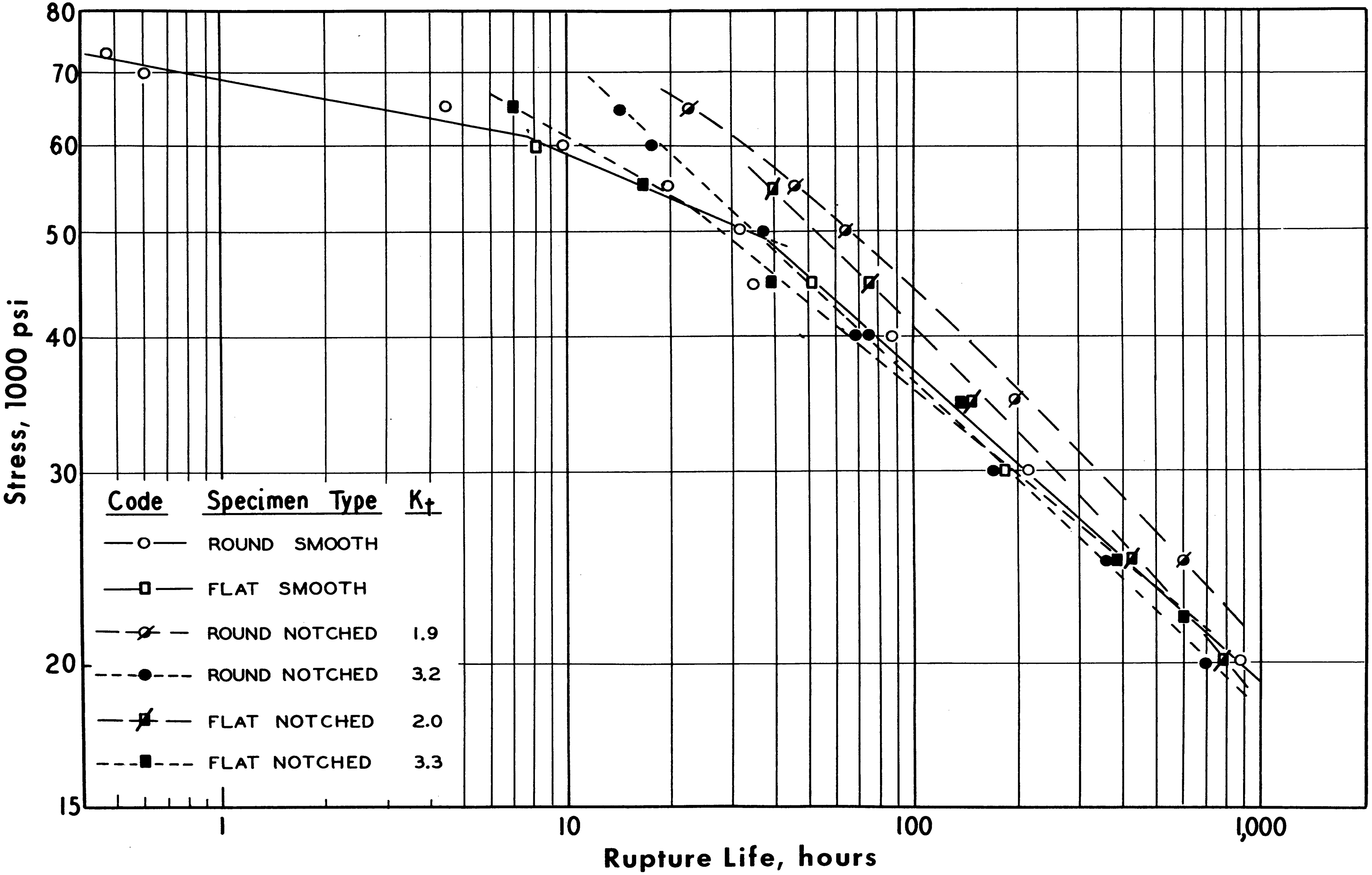


FIG. 7 — STRESS VERSUS RUPTURE LIFE AT 1100°F FOR SMOOTH AND NOTCHED BARS OF "17-22A"S Cr-Si-Mo-V STEEL.

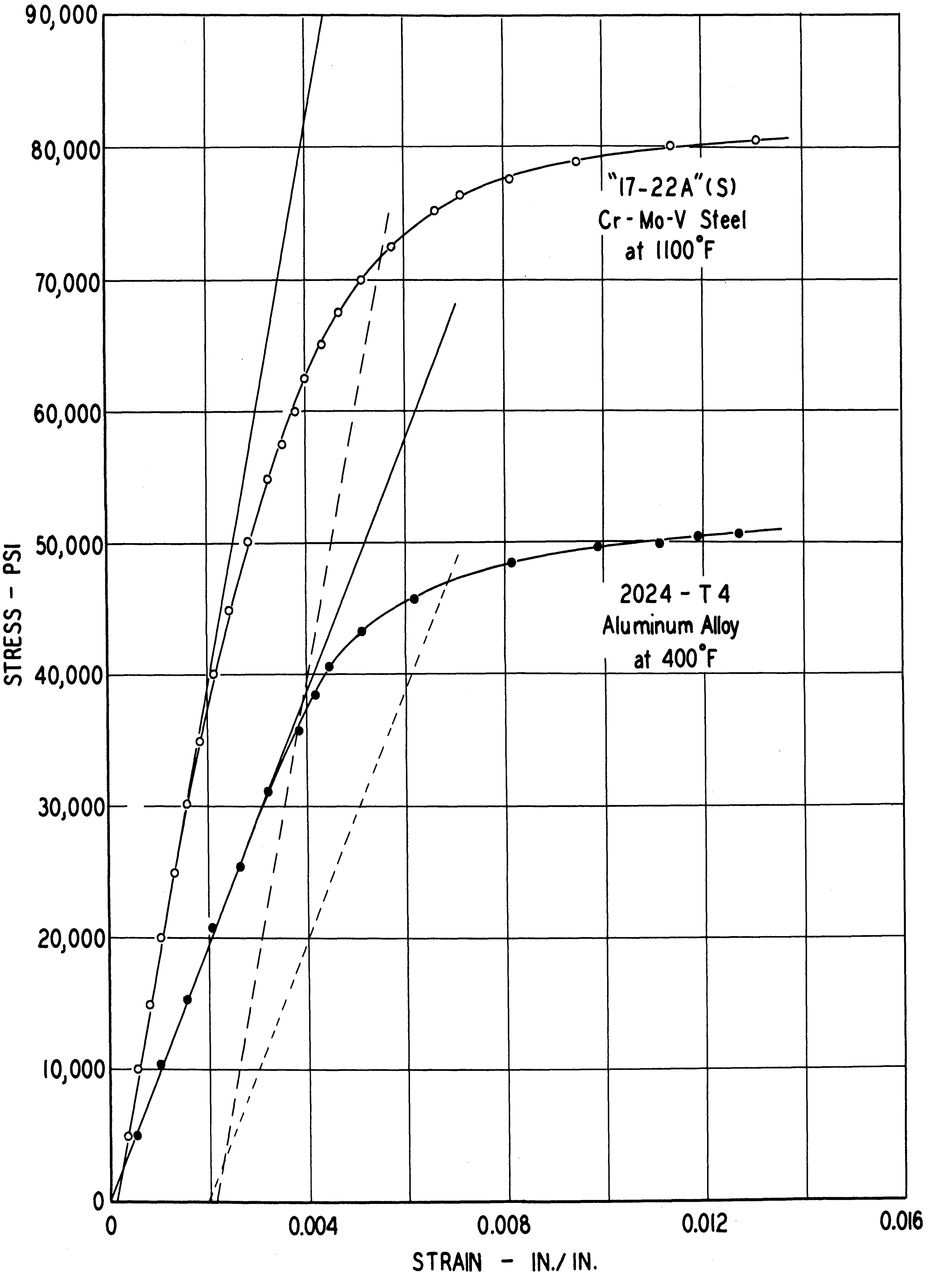
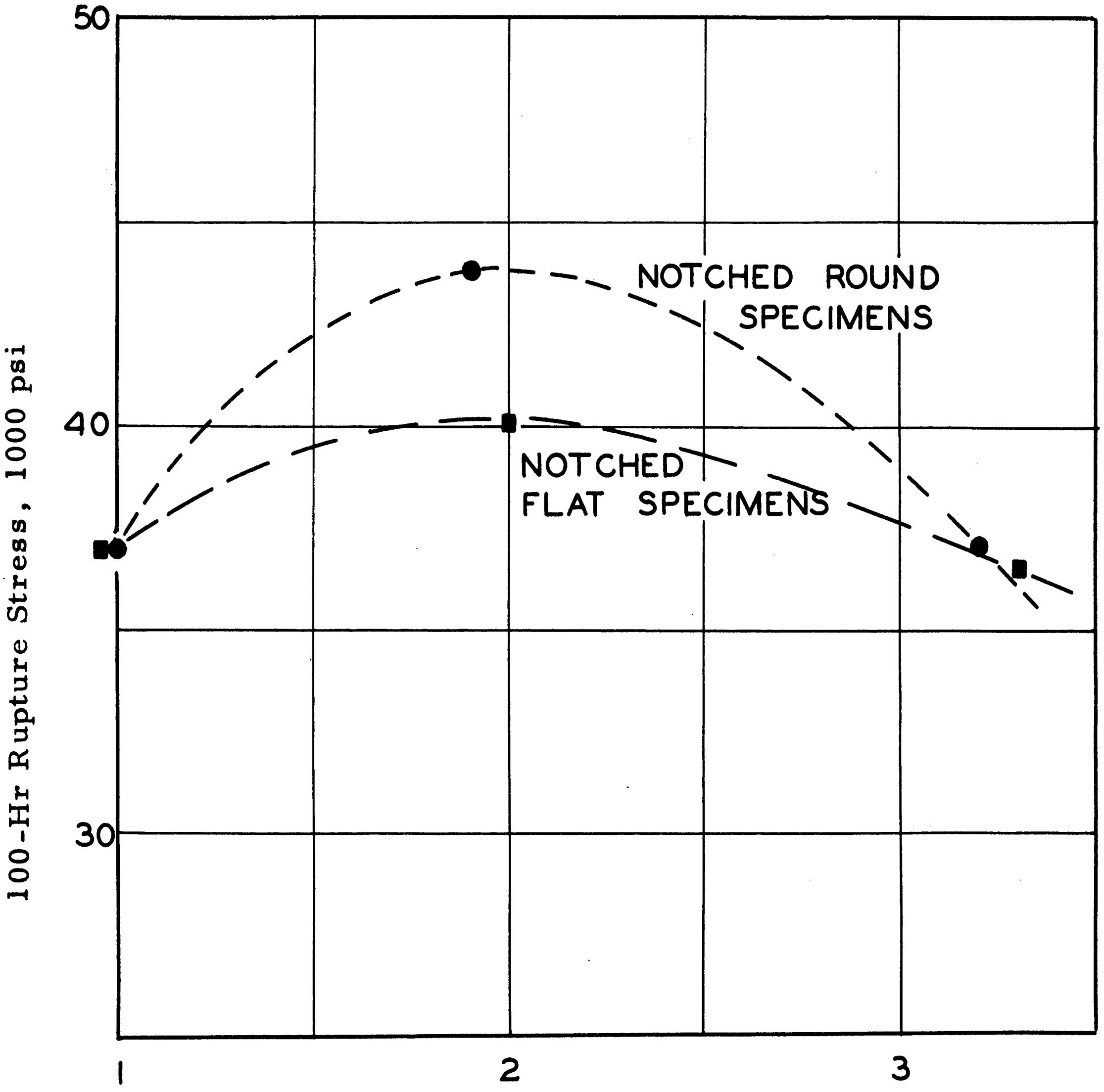


FIG. 8 - STRESS-STRAIN CURVES FOR TWO OF THE ALLOYS STUDIED.



Theoretical Stress Concentration Factor, K_t

Fig. 9 - Variation of the 100-hour rupture stress with notch acuity for 17-22A(S) steel at 1100°F.

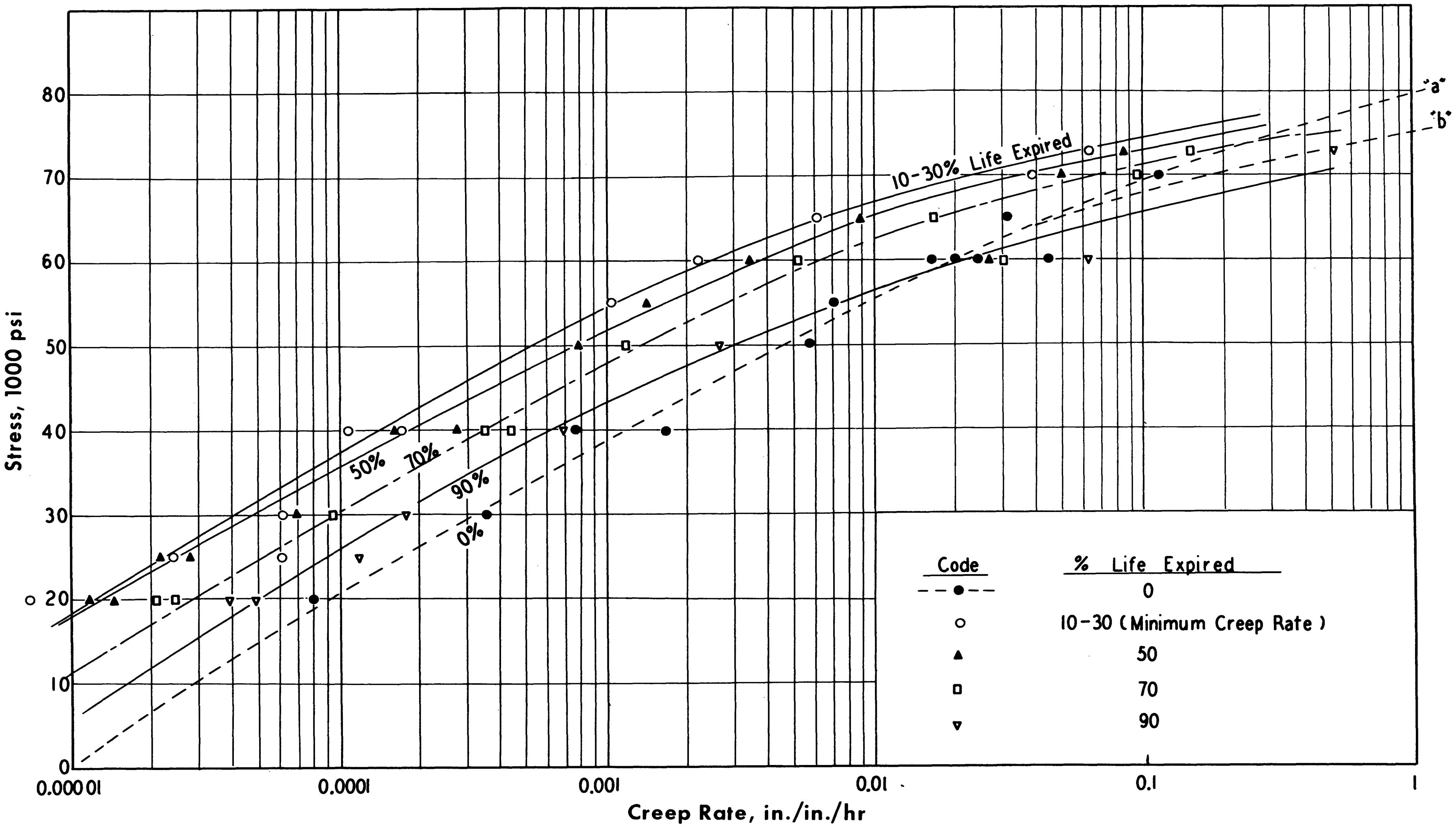


FIG. 10 — STRESS VERSUS CREEP RATE AT 1100°F FOR "17-22A"S Cr-Mo-Si-V STEEL, NORMALIZED PLUS TEMPERED.

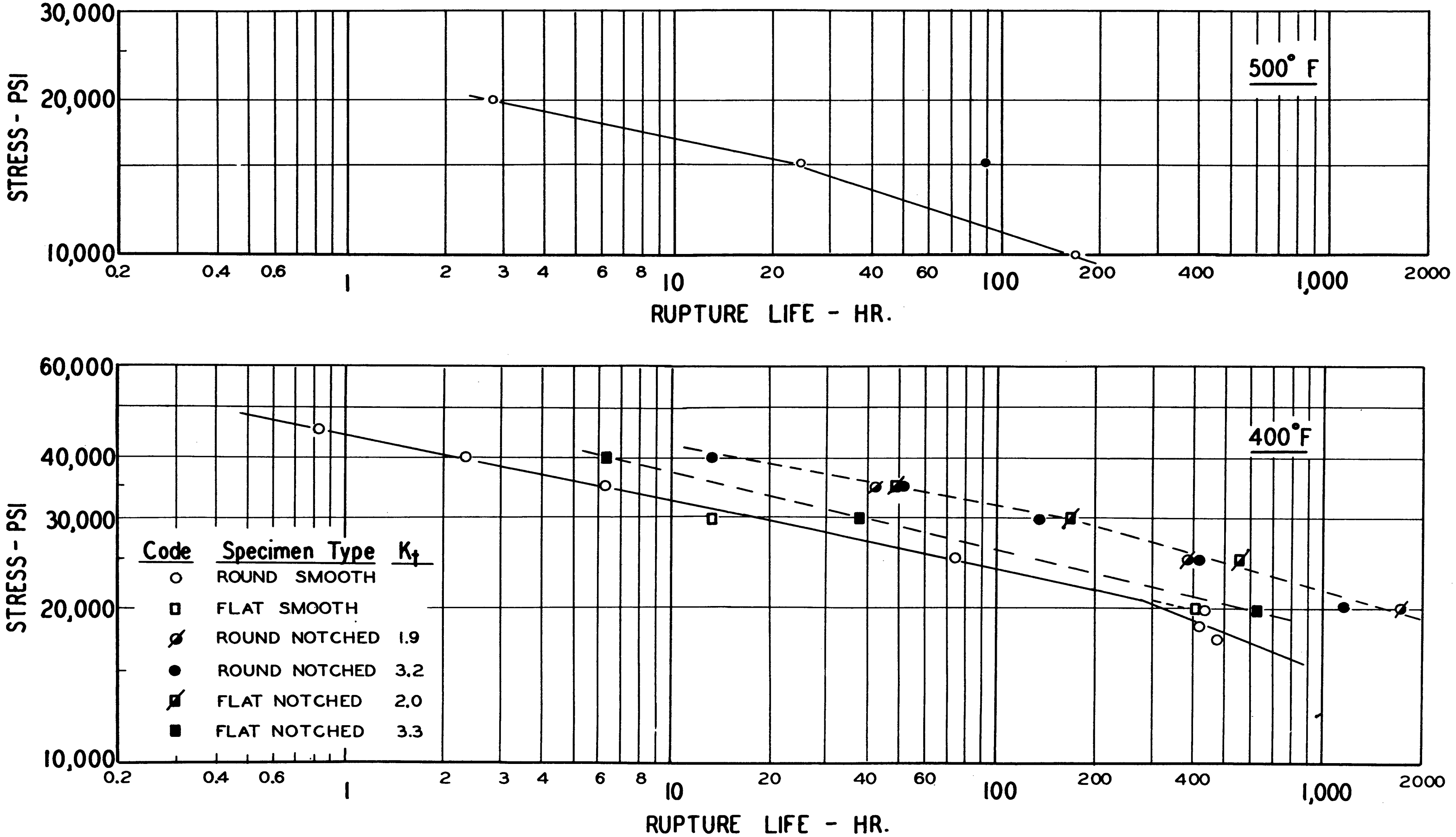


FIG. 11 – STRESS VERSUS RUPTURE LIFE FOR SMOOTH AND NOTCHED BARS OF 2024 - T4 ALUMINUM ALLOY

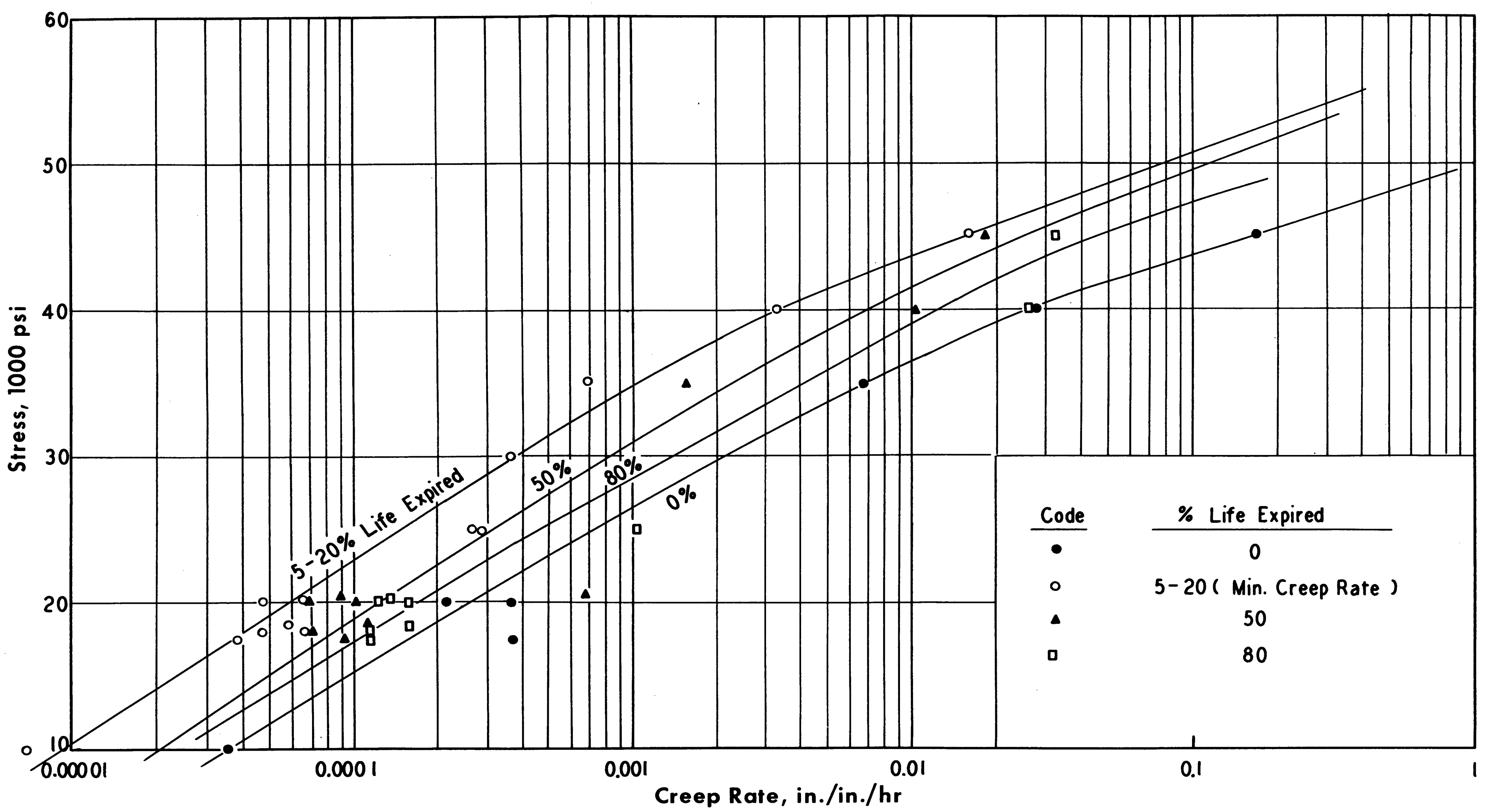


FIG. 12– STRESS VERSUS CREEP RATE AT 400°F FOR 2024 -T4 ALLOY.

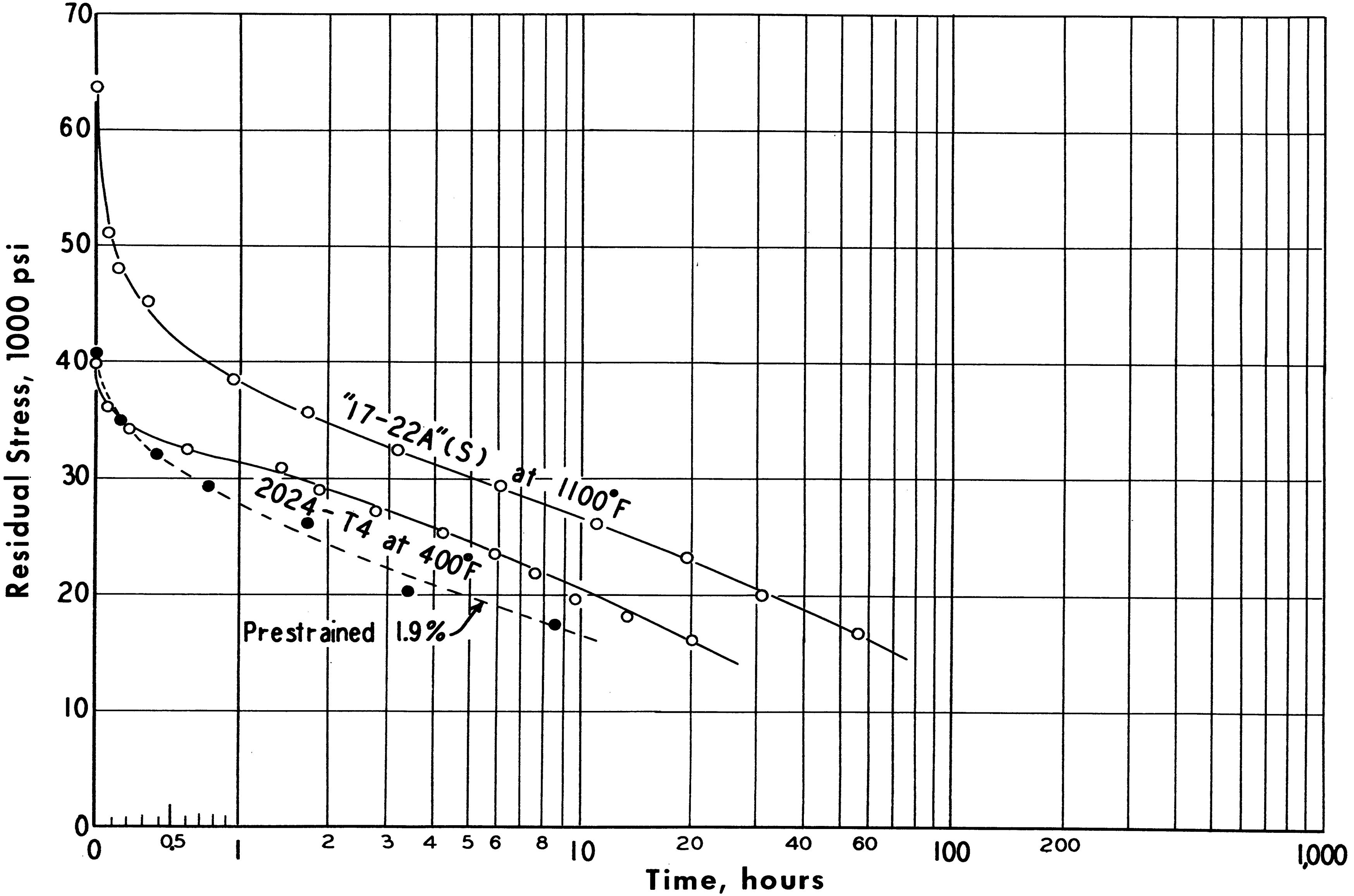


FIG. 13 – RELAXATION DATA OBTAINED FOR "17-22A" S AND 2024 - T4 ALLOYS.

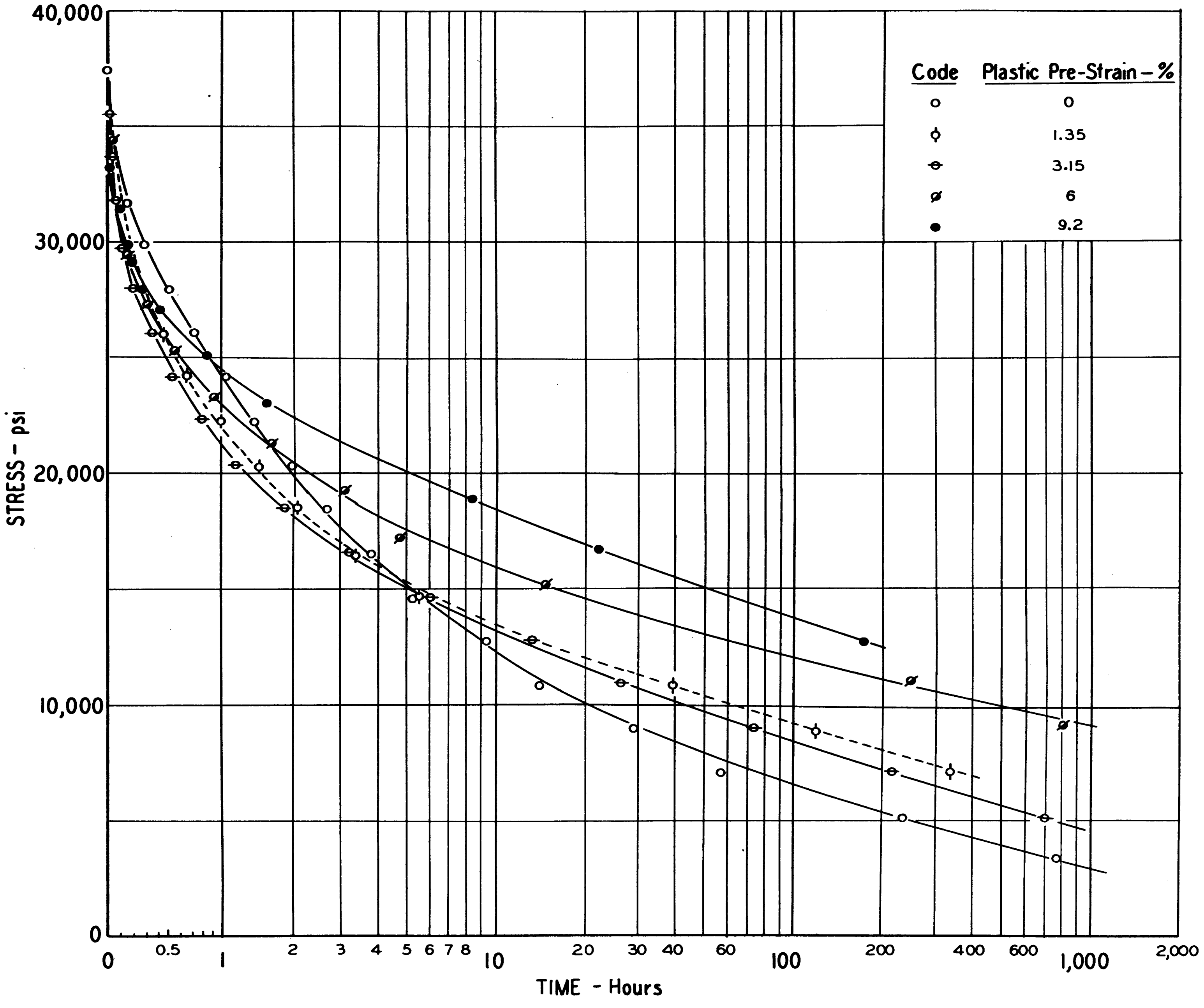


FIG. 14 – EFFECT OF PLASTIC PRE-STRAIN AT TEMPERATURE ON RELAXATION OF S-816 AT 1350 °F.

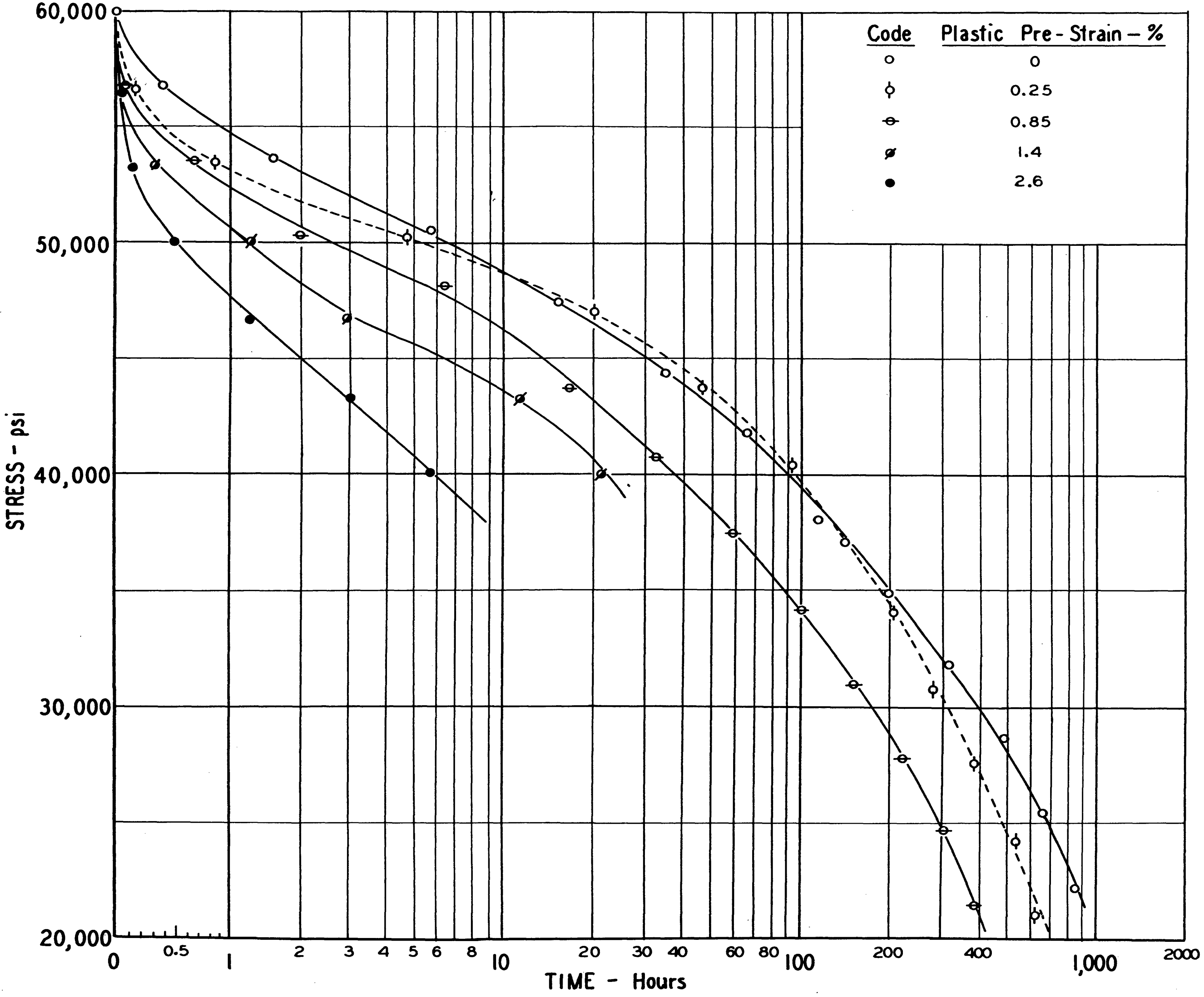


FIG. 15 - EFFECT OF PLASTIC PRE-STRAIN AT TEMPERATURE ON RELAXATION OF INCONEL X-550 AT 1350°F.

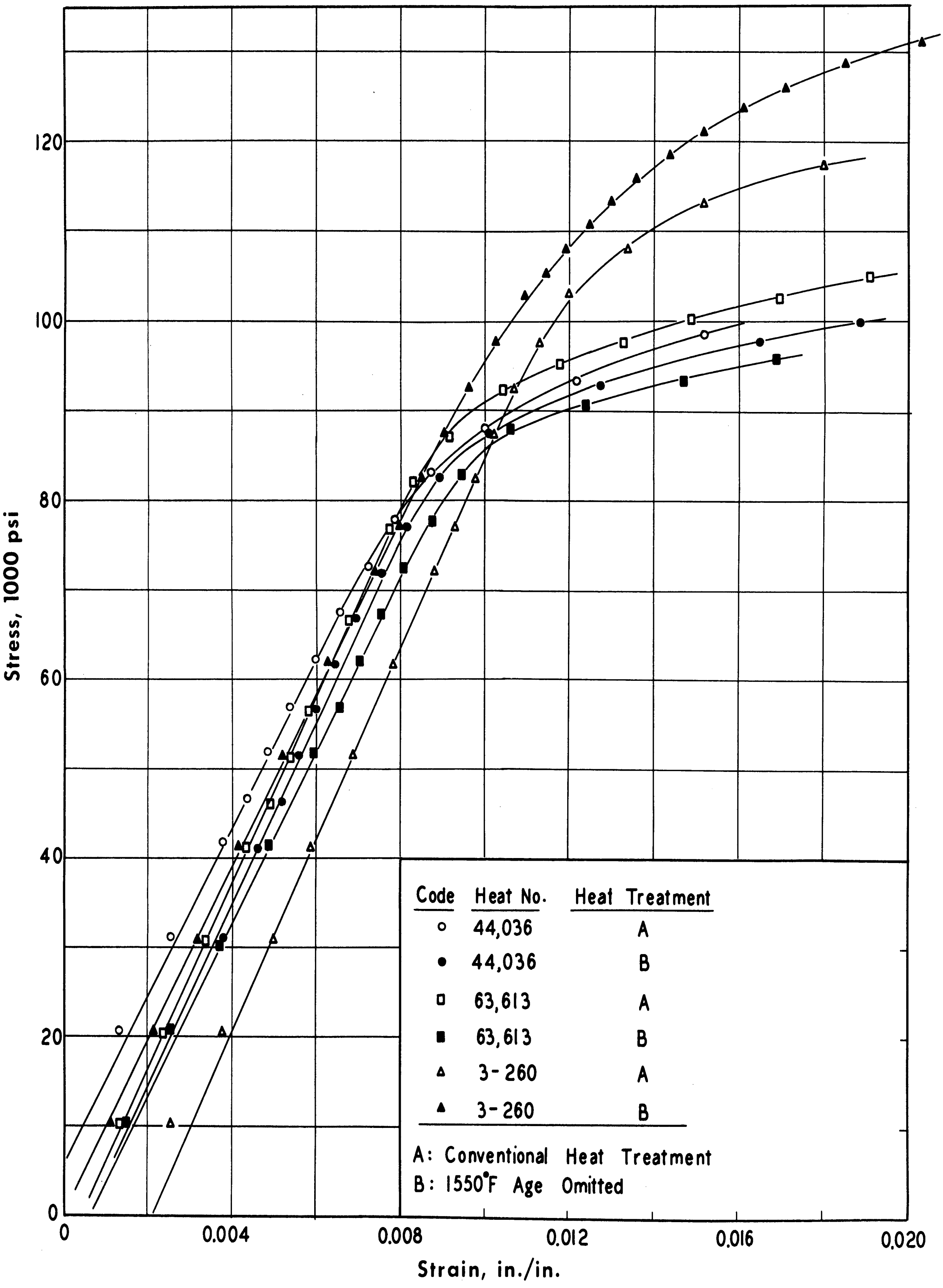


FIG. 16 — INITIAL PORTION OF LOADING CURVES AT 1350°F FOR THREE HEATS OF WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS. (ALL STOCK RE-ROLLED AT THE UNIVERSITY OF MICHIGAN).

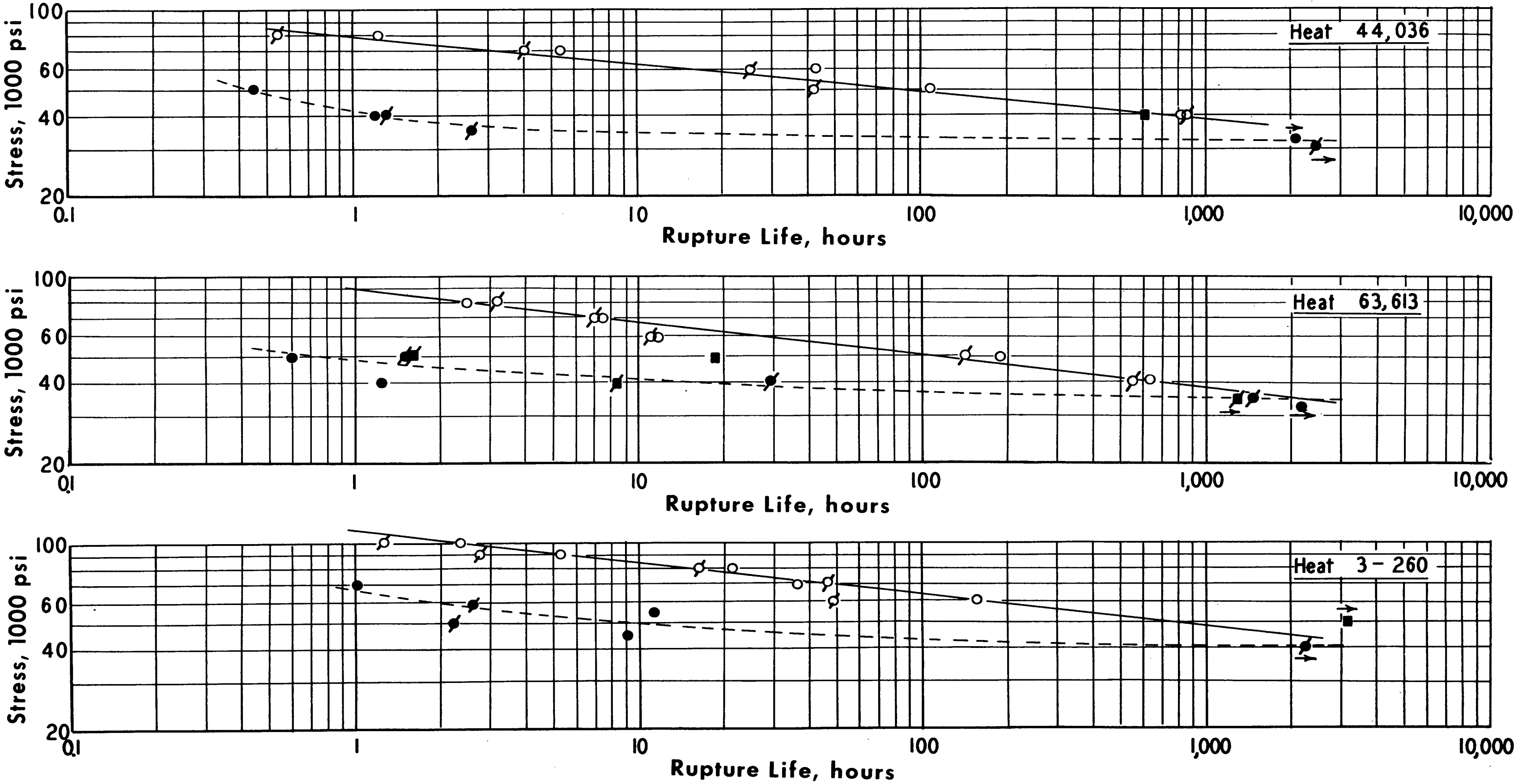


FIG. 17 – STRESS VERSUS RUPTURE LIFE AT 1350°F FOR SMOOTH AND NOTCHED ROUND SPECIMENS FROM THREE HEATS OF WASPALOY. (MATERIAL RE-ROLLED AT THE UNIVERSITY OF MICHIGAN).

Smooth Specimens	Notched Specimens $K_t = 6.8$	Notched Specimens $K_t = 3.2$	
—○—	- -●- -	■	Conventional Heat Treatment
—ø—	- -ø- -	■	1550°F Age Omitted

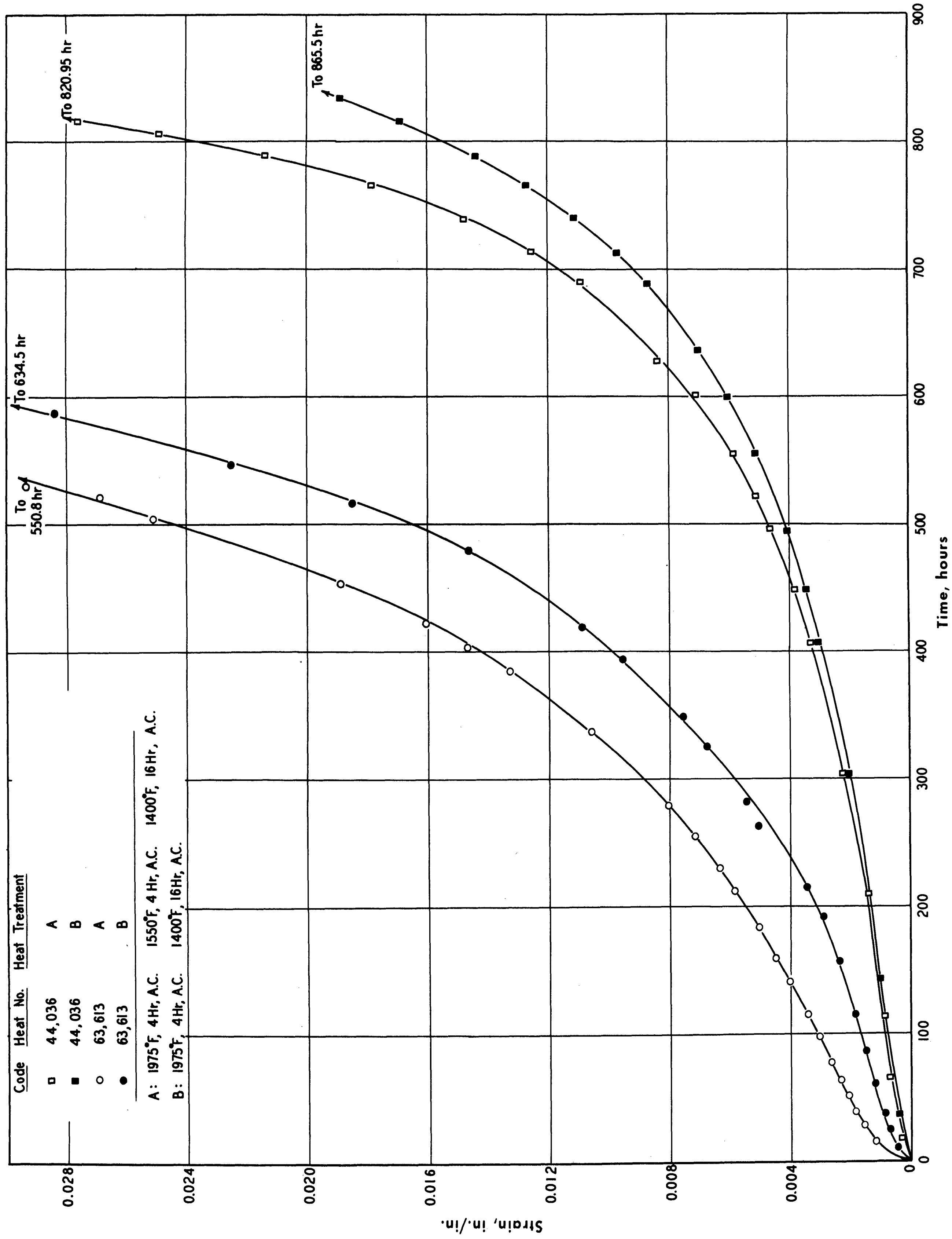


FIG. 18 - CREEP CURVES AT 1350°F AND 40,000 PSI STRESS FOR WASPALOY WITH TWO DIFFERENT HEAT TREATMENTS.

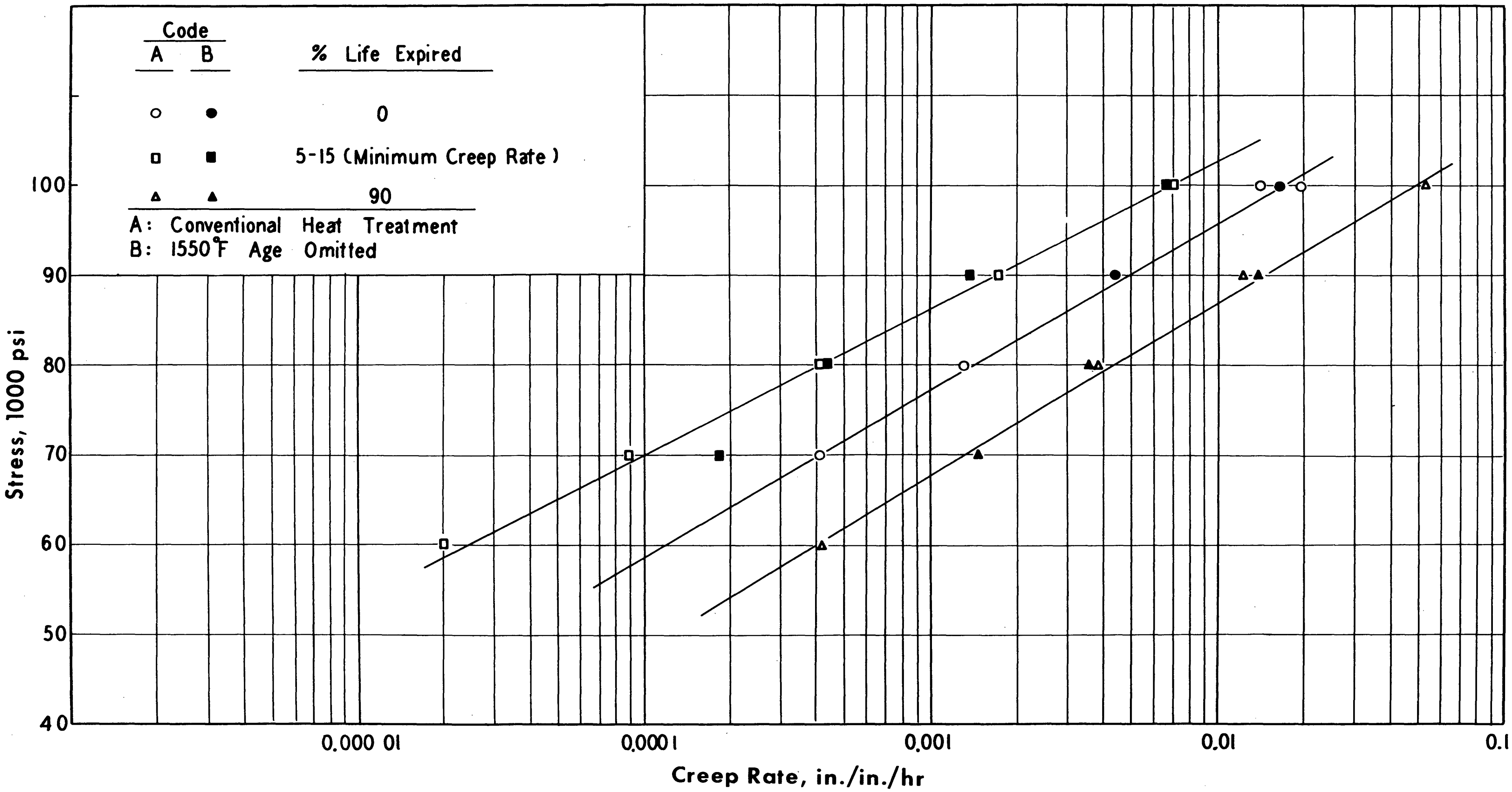


FIG. 19 – STRESS VERSUS CREEP RATE AT 1350°F FOR RE-ROLLED WASPALOY (HEAT NO. 3-260).

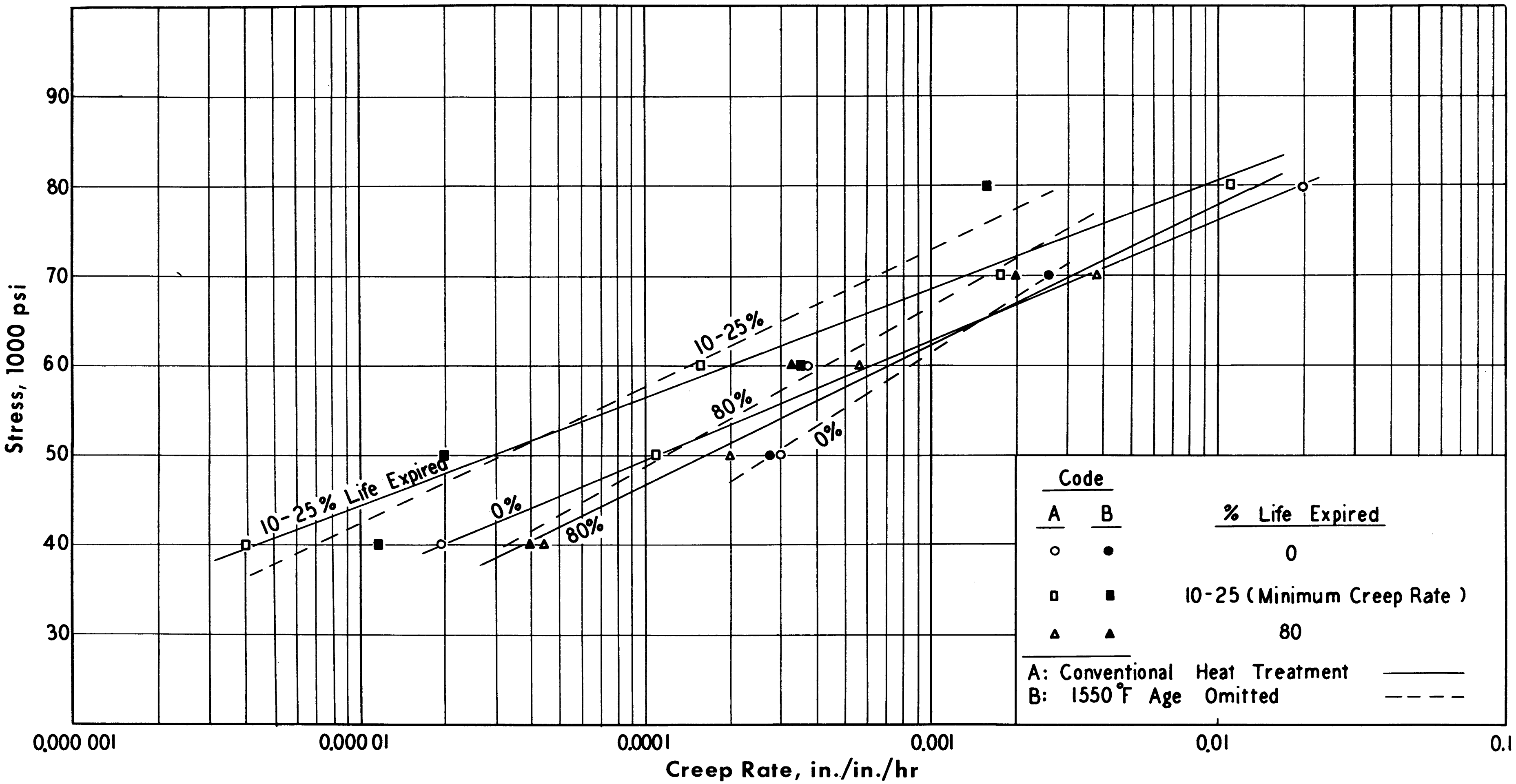


FIG. 20 — STRESS VERSUS CREEP RATE AT 1350°F FOR RE-ROLLED WASPALOY (HEAT NO. 44,036).

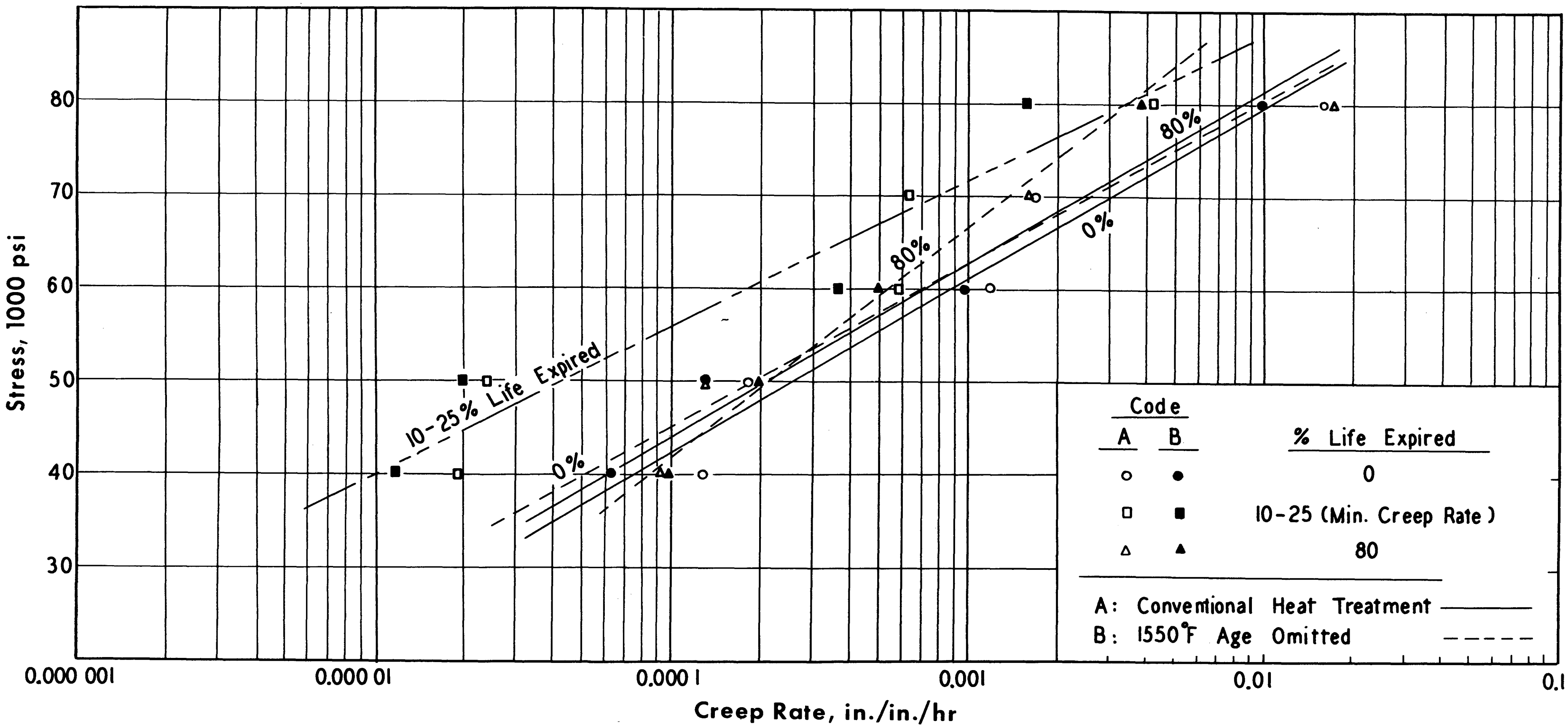


FIG. 21 – STRESS VERSUS CREEP RATE AT 1350°F FOR RE-ROLLED WASPALOY (HEAT No. 63 613).

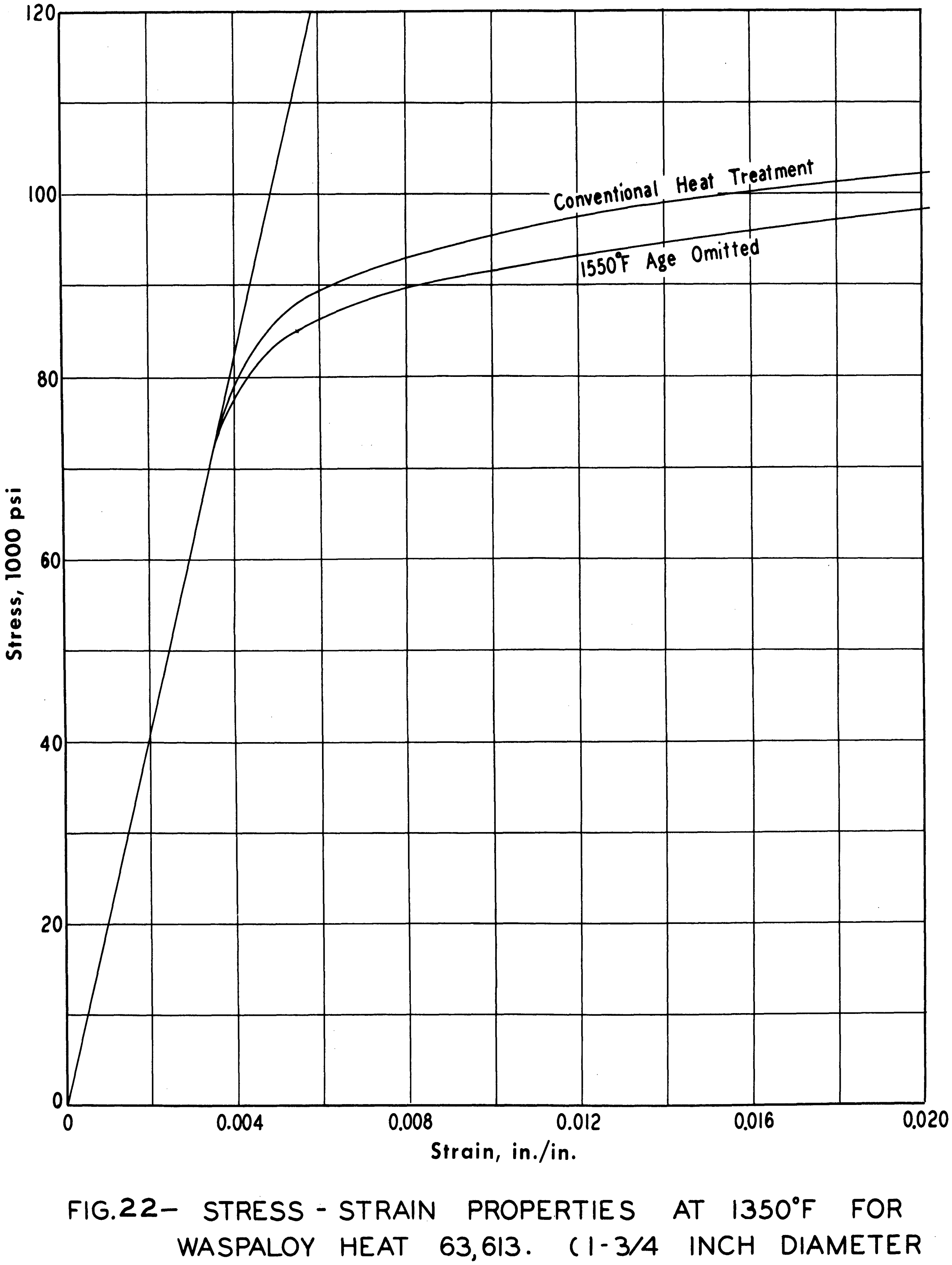


FIG.22— STRESS - STRAIN PROPERTIES AT 1350°F FOR WASPALOY HEAT 63,613. (1-3/4 INCH DIAMETER STOCK ROLLED BY SUPPLIER.)

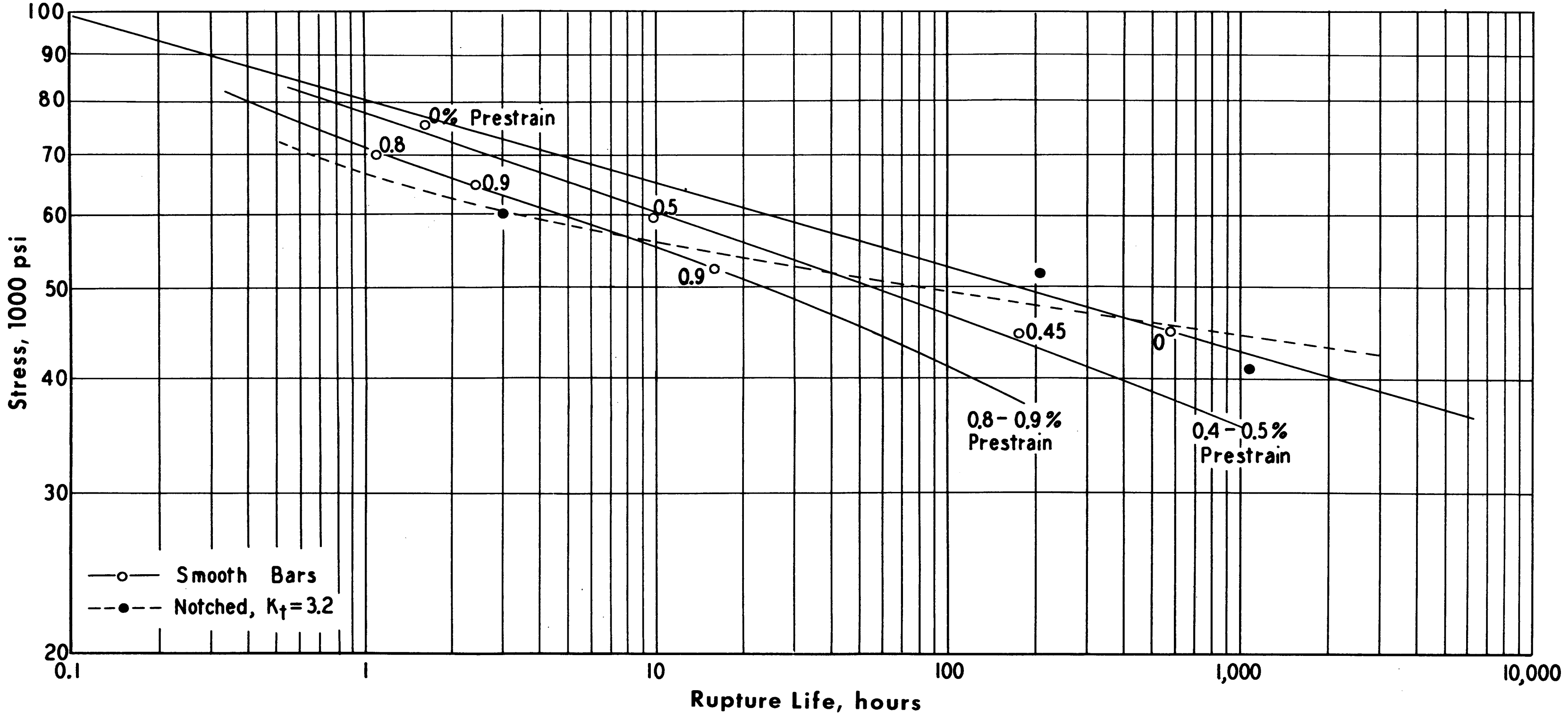


FIG. 23 - RUPTURE PROPERTIES AT 1350°F FOR WASPALOY HEAT 63,613 WITH CONVENTIONAL HEAT TREATMENT, SHOWING EFFECT OF PLASTIC PRE-STRAIN ON LIFE OF SMOOTH BARS. (1-3/4 INCH DIAM. STOCK ROLLED BY SUPPLIER)

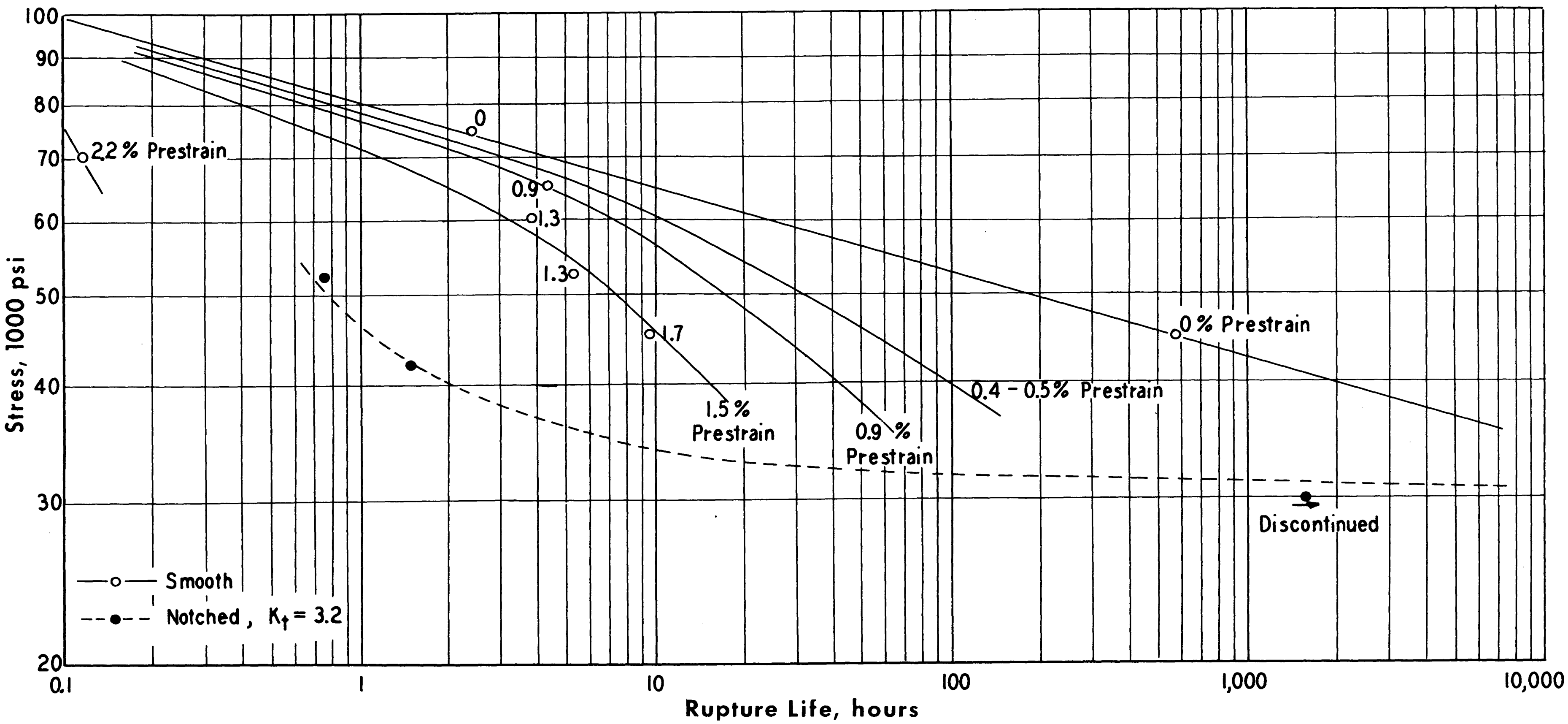


FIG. 24 — RUPTURE PROPERTIES AT 1350°F FOR WASPALOY HEAT 63,613 WITH THE 1550°F AGE OMITTED, SHOWING EFFECT OF PLASTIC PRE-STRAIN ON LIFE OF SMOOTH BARS. (1-3/4 INCH DIAM. STOCK ROLLED BY SUPPLIER)

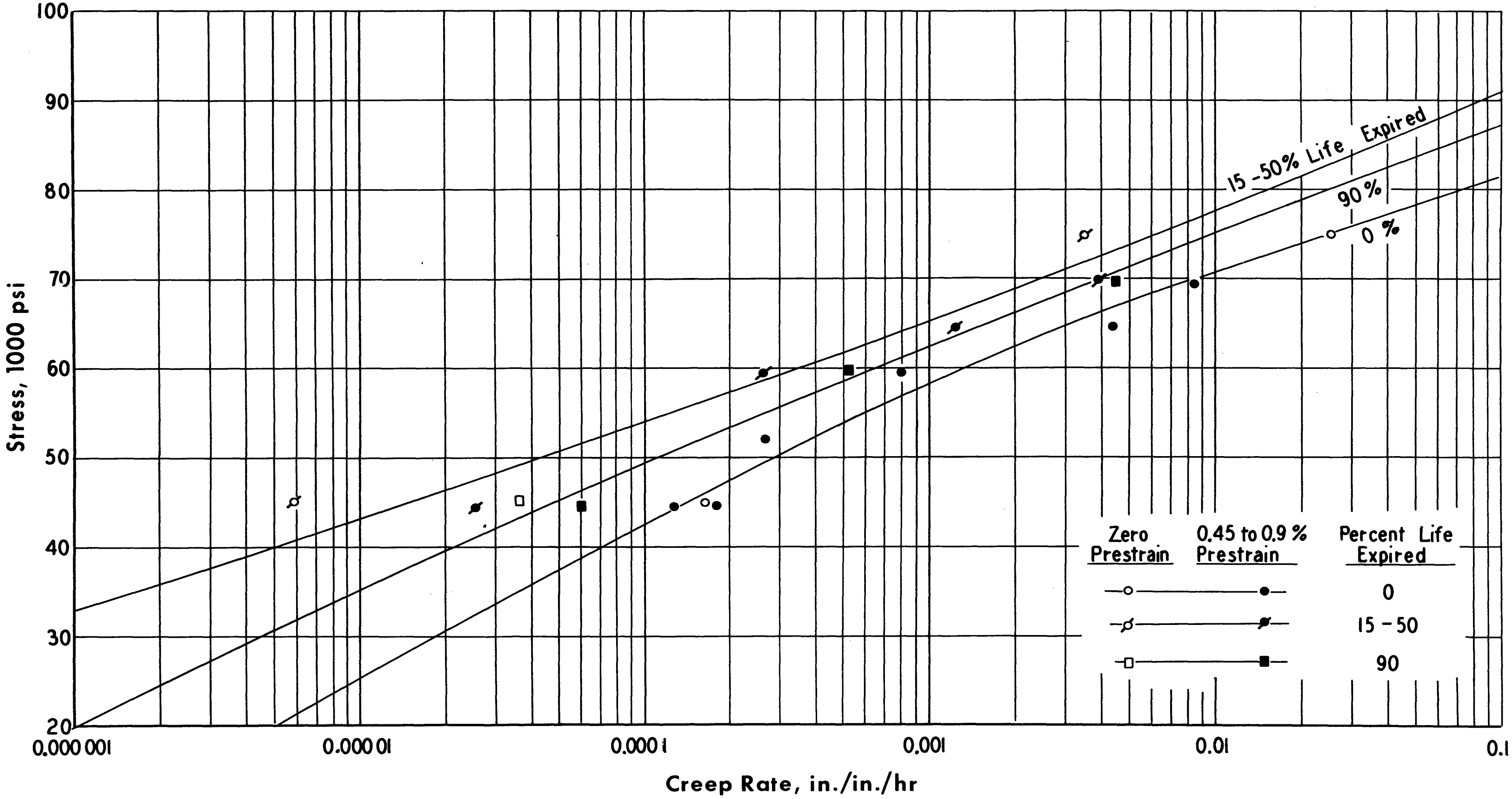


FIG. 25 - STRESS VERSUS CREEP RATE AT 1350°F FOR WASPALOY, HEAT 63,613 WITH CONVENTIONAL HEAT TREATMENT.

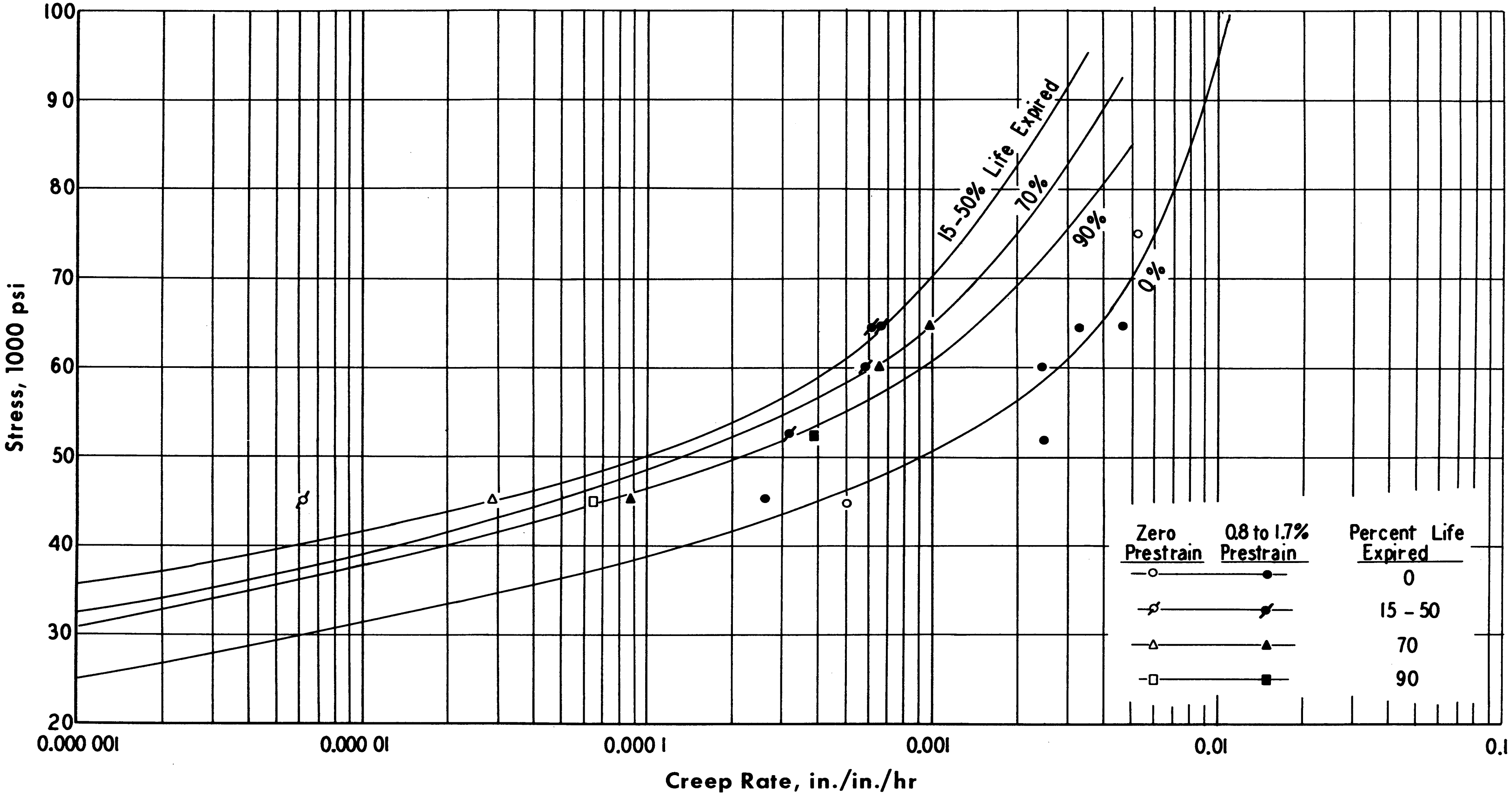


FIG. 26 - STRESS VERSUS CREEP RATE AT 1350°F FOR WASPALOY HEAT 63,613 WITH THE 1550°F AGE OMITTED FROM THE HEAT TREATMENT

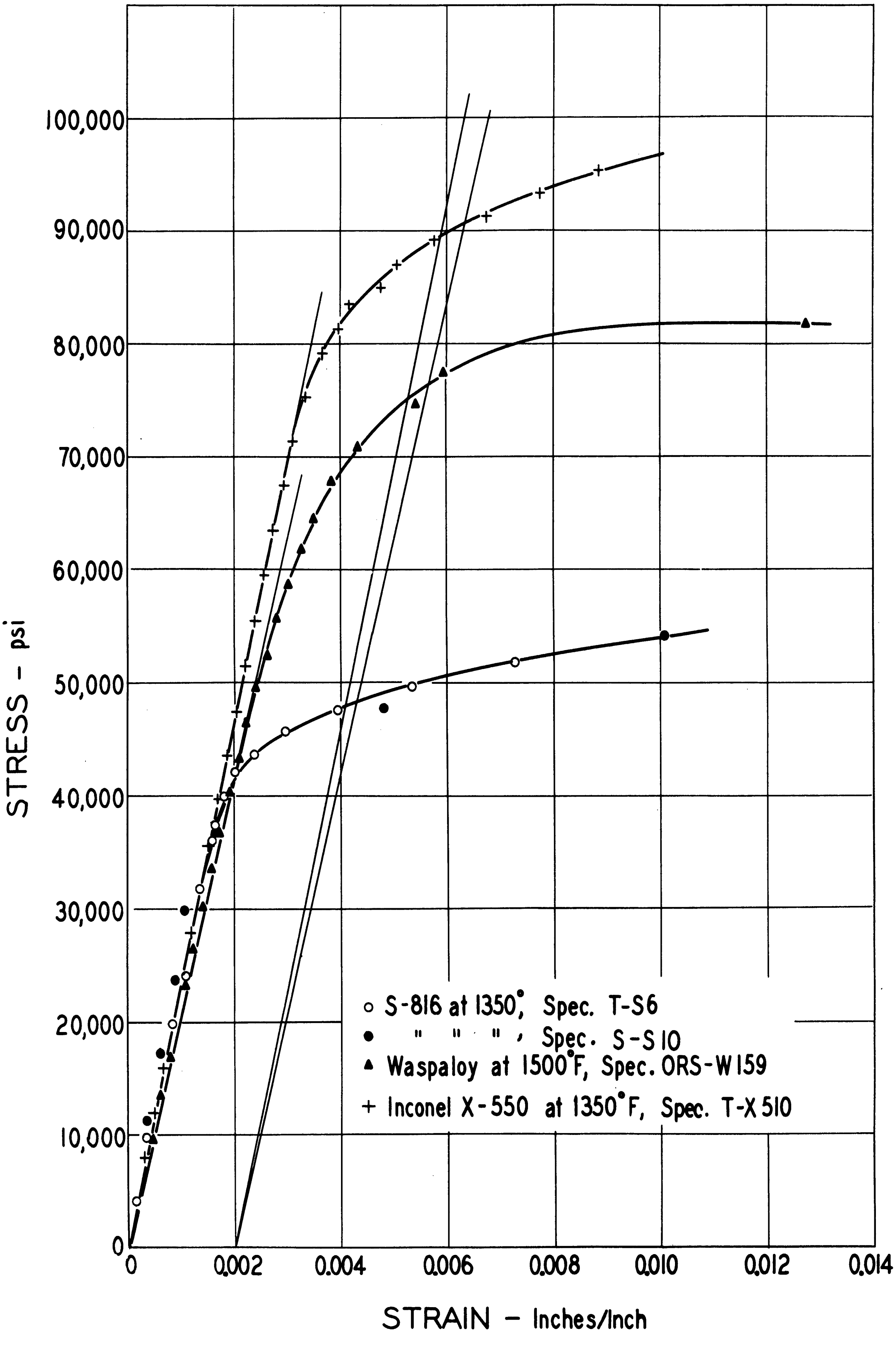


FIG. 27- SHORT-TIME TENSILE CHARACTERISTICS OF ALLOYS STUDIED.

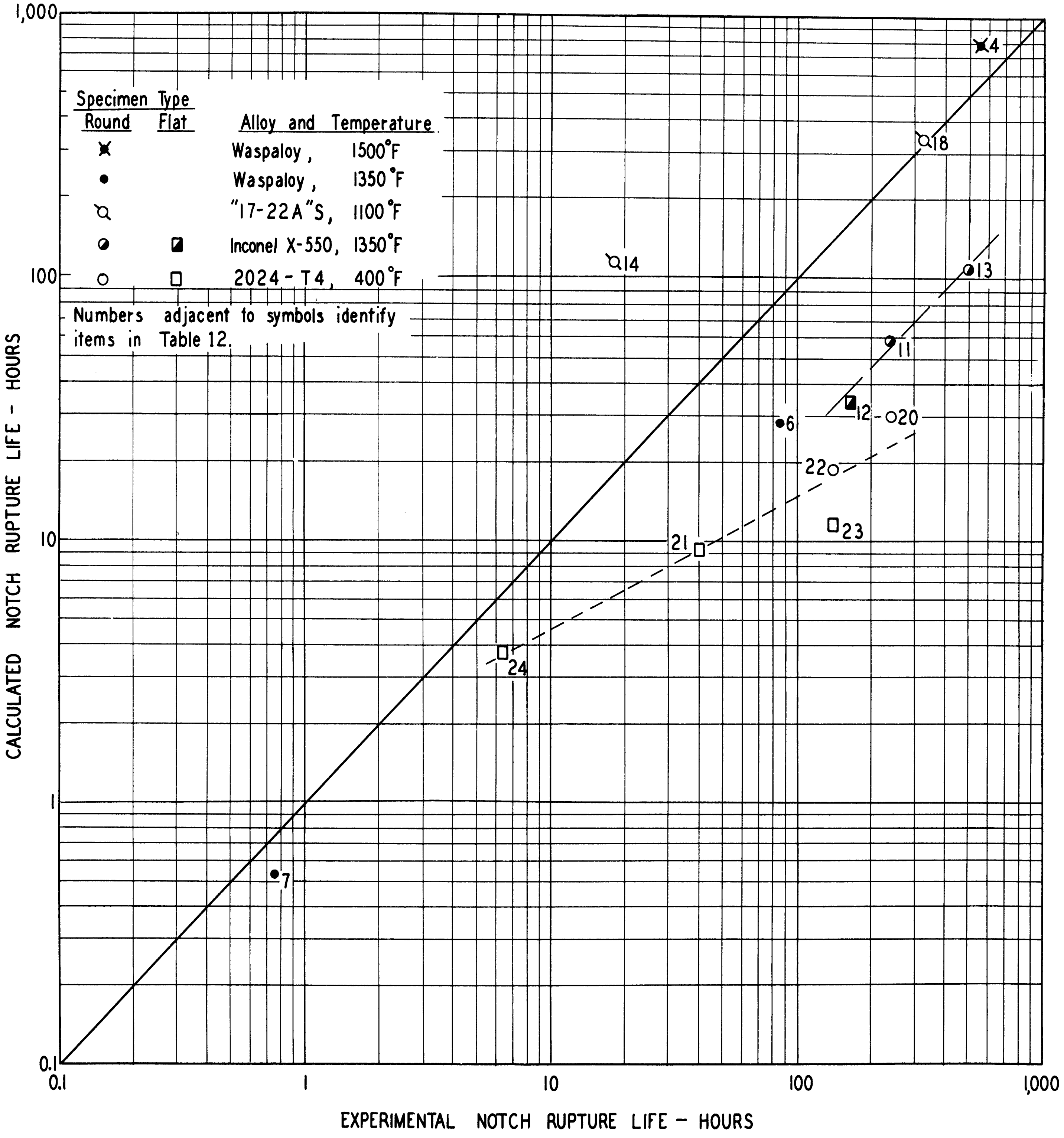


FIG. 28 – COMPARISON OF CALCULATED AND EXPERIMENTAL NOTCH RUPTURE LIVES.