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Part I

NOTCH SENSITIVITY OF AIRCRAFT STRUCTURAL AND ENGINE ALLOYS

Part I Preliminary Studies with A-286 and 17-7 PH (TH 1050) Alloys

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FOREWORD

This report was prepared by The University of Michigan under USAF Contract No. AF 33(616)-3380. The contract was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques," Task No. 73,605, "Design Data for Metals." The research was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Dr. A. J. Herzog as project engineer.

This report covers a period of work from January 1956 to January 1957.

Original data for this investigation are indexed in data book No. 1869, located in files of The Engineering Research Institute of The University of Michigan under the heading "Project 2475."

The A-286 alloy stock tested was furnished without charge by The Allegheny Ludlum Steel Corporation.

ABSTRACT

This program was designed to extend previous analyses of the creep-rupture behavior of notched test specimens held under steady axial load. Experimental studies have also been planned and carried out in an effort to clarify the factors controlling rupture life in the presence of a non-uniform complex stress.

Vacuum melted A-286 alloy produced by the consumable electrode process was chosen for this investigation with the expectation that a range of notch sensitivity could be developed by increasing the temperature of solution treatment. Extensive tests had been planned to study changes in smooth-bar properties corresponding to marked differences in notched-bar strength, in hopes of isolating all the major factors associated with notch sensitivity. For solution temperatures ranging from 1650° to 2300°F, the lot of material studied exhibited strong notch strengthening at 1200°F for nearly all specimens tested with K_t's of 1.8, 3.0 and 4.1, despite elongation at fracture as low as 1% or less for certain solution temperature near 2200°F.

Additional smooth- and notched-specimen data were obtained for 17-7PH (TH 1050) sheet material at test temperatures of 600°, 800° and 900°F, and for two small lots of Waspaloy at 1350°F. The 17-7PH alloy exhibited a high degree of freedom from notch sensitivity. The Waspaloy was notch weakened for nominal stresses where yielding occurred at the notch root during load application. For lower nominal stresses, notch strengthening was indicated.

Results obtained indicate that reduction of an alloy's inherent strength by prior plastic deformation may be a prominent factor in notch sensitivity. Examination of all available data discloses no case of notch weakening without accompanying loss of life in smooth bars which are prestrained at the test temperature. Conversely, in no known case of marked notch strengthening has the material been found to be weakened by plastic prestrain.

Prestrain effects alone may not be able to explain all notch behavior, but response of the material to plastic strains appears to be a necessary part of any complete analysis of notch effects.

PUBLICATION REVIEW

This report has been reviewed and is approved

FOR THE COMMANDER:

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[a]INTRODUCTION

Current trends in design and operation of aircraft presage ever higher working stresses and operating temperatures for engine and airframe components. To meet the needs with existing alloys requires maximum utilization of their inherent strength by minimizing unessential safety factors. In particular, the unknown effects under creep conditions of two- and three-dimensional stressing and of concentrated stresses at notches, openings and section changes assume a more critical role in design.

The study reported on here is part of a continuing investigation sponsored by the Materials Laboratory, Wright Air Development Center, to analyze the creep-rupture response of metal structures in the presence of stress concentrations. Previous work under Contract AF 18(600)-62 resulted in a method for predicting creep-rupture life of a notched test specimen held under steady axial load, using data determined with unnotched specimens. (See Reference 1). The current program was designed to clarify questions raised by the earlier studies and to seek a more general analysis of the behavior of aircraft structural materials subject to creep under non-uniform complex stresses.

The past considerations of notch sensitivity of heat-resistant alloys at elevated temperatures indicated that notched-bar rupture strength should be explainable in terms of three major factors:

1.) The initial stress pattern, determined by the geometry of the specimen, the applied load and the stress-strain properties of the alloy for the conditions of the test.

2.) The rate of redistribution of initial stress gradients, as controlled by a creep relaxation process.

3.) Rupture characteristics of the material under the prevailing stresses and for the prior history experienced by each metal fiber.

In the method of Reference 1, the stress-time history of the material at the base of notch was determined by a step-wise calculation based on the smooth-bar creep and rupture data. The shear stress invarient theory was used to compute the creep under the complex stresses. As creep occurs, differences in principal stresses are reduced and the peak effective stress near the notch is reduced through creep relaxation. A basic assumption was that the fraction of rupture life used up at any stress level is the length of time at the stress in relation to the total available rupture time in a constant load test at that stress. Furthermore the increments of life used up at successive levels of stress were assumed addible. The rupture life of the notched specimen was thus computed by finding the time when the sum of the life expended under the changing stress level at any location reached 100%.

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a) Manuscript released by the author on 4 January 1947 for Publication as a WADC Technical Report.

The method was found to work reasonably well for metallurgically stable materials. Two types of metallurgical instability have been identified. Thermally induced structural changes alter properties with time so that computations for various stress levels in the changing stress history of a fiber in a notched bar are no longer valid when based on data from constant load tests on smooth specimens.

The other type of metallurgical change found was that initiated by yielding. Certain notch sensitive alloys were found to undergo a severe loss in rupture life from yielding. Thus notched specimens which yielded near the notch, due to the stress concentration there, were much weaker at the base of the notch than a smooth specimen under like nominal stress. Calculations of rupture life based on the altered strength came quite close to the test values for notched specimens.

The only test of the calculation method has been to check the agreement between calculated and observed values. Even though prior experience has been very promising, the conclusions should be carefully examined in view of the number of assumptions involved. The data previously obtained were often fragmentary results of exploratory tests devised to find general trends. The present investigation was undertaken to obtain sufficiently complete data to define the effects using one alloy, A-286, with variable notch sensitivity introduced by altering the heat treatment.

Additional data were to be obtained for 17-7 PH sheet material in the TH 1050 condition. (This latter alloy was chosen to typify the heat-treatable stainless steels being used increasingly for stressed-skin applications in aircraft for supersonic flight.)

Work was also to continue with any additional lots of Waspaloy which could be obtained, to learn if trends indicated by past studies are general for the material and, if they are not, to seek the factors which alter response to notches of different lots of the alloy.

Substantially all tests performed under Contract AF 16(600)-62 with notched specimens involved a steady tensile load imposed at the start and maintained until fracture. Before resulting findings are applied to analysis of aircraft components, behavior of notched specimens should be examined under conditions typifying those of operational service. The present program considers briefly two such types of history: namely, notched specimens alternated between two levels of applied stress and the introduction of a notch into a specimen after prior creep service of the unnotched material.

A SURVEY OF EFFECTS OF SOLUTION TEMPERATURE ON NOTCH SENSITIVITY OF A-286 ALLOY AT 1200°F

During the current program creep and rupture properties for smooth specimens and notched-bar rupture life for several notch acuities were established at 1200°F for A-286 solution treated at temperatures covering the range from 1650° to 2300°F.

Specimen preparation methods and testing procedures followed standard practice used at the University of Michigan. Notches were rough ground and then finish lapped, by procedures developed during the course of the work reported in WADC TR 54-175, Part 3. (Ref. 1).

Test Material and Specimens

The A-286 stock, donated by the Allegheny Ludlum Steel Corporation, was 3/4 inch diameter bar from their Heat No. 21,030. This material, produced by the vacuum "Consutrode" process, was chosen as representing the most advanced form of the alloy available and a probable production method for future severe-service applications. The chemical analysis supplied by the producer was:

C	Mn	Si	Cr	Ni	Mo	Ti	V	Al	S	P	Fe	*B
0.06	1.35	0.47	14.58	25.30	1.38	2.00	0.21	0.17	0.014	0.018	Bal	0.004

The bars were processed by the producer from a 20-inch diameter ingot in the following manner:

1. Pressed and cogged to 4-1/4 inch square from 2150°F
2. Recogged to 2-7/8 inch square from 2100°F
3. Rolled to 3/4 inch diameter round from 2100°F.

The stock was shipped as rolled and was neither straightened nor annealed prior to receipt by the University of Michigan. This procedure was followed in order to minimize the possibility of non-uniform response during heat treatment as a result of variable strains from point to point which can occur during cold straightening.

Before machining, specimen blanks were heat treated by a one-hour solution at the selected temperature, oil quenched and then aged at 1325°F for 16 hours, air cooled. The ASTM grain size after this treatment ranged from a uniform number 8 or finer for the 1650°F solution temperature to number 1 and coarser when the solution took place at 2300°F. Representative photomicrographs

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* Analysis for boron in this range is difficult and imperfectly standardized. A check analysis made without change by the Universal-Cyclops Steel Corp. indicated a boron content of 0.0019%.

are arranged in Figure 1 to show these changes in grain size with solution temperature. At 1800° and 1900°F the grain size was mixed but at 2000°F and above all grains were near the same size for any particular solution temperature.

All A-286 specimens tested in this program had a cylindrical gauge section about two inches long and either 0.350 or 0.400 inch diameter. Notched bars were designed to give theoretical stress concentration factors (K_t) of 1.8, 3.0 and 4.1, employing a single circumferential groove with 60° included angle and a circular root radius. The notch with $K_t = 4.1$ corresponds to the most common specimen used in commercial practice for acceptance testing of alloys for aircraft turbine applications. Dimensions were chosen so that the cross section of the specimen in the plane of the notch equalled half the shank cross section.

Experimental Results for A-286

Comparative creep and rupture tests for different solution temperatures were all run at 1200°F and at stresses of 60,000, 65,000 or 70,000 psi. Notched rupture specimens were tested at conditions to survey notch sensitivity trends for K_t's between 1.8 and 4.1 for the range of solution temperatures at 70,000 and 65,000 psi, plus two tests at 60,000 psi with the sharpest notch. Table 1 summarizes all the rupture data obtained. In Figure 2 rupture times are plotted separately for each test stress and are shown as a function of the solution temperature employed. Figure 3 shows the data for the 1650°, 1800° and 2225°F solution temperatures in the more usual form of log stress versus log rupture life.

Rupture times for unnotched specimens increased rather uniformly with rising solution temperature up to about 2000°F, reached a peak approximately ten times the corresponding life for the 1650°F solution treatment, and then declined rather rapidly when solution temperatures approached 2200° or 2300°F. Notched specimens tested with theoretical stress concentration factors between 1.8 and 4.1 all had considerably longer rupture life than did smooth specimens under like load for solution temperatures up to at least 2000°F. For any given stress level and solution temperature, the maximum notched specimen life was found for $K_t = 1.8$ and the least for $K_t = 4.1$. The same relative strengths for the different stress concentration factors held for specimens with higher solution temperatures, but the limited number of tests completed for these conditions indicated borderline to moderate notch sensitivity for specimens solution treated around 2200°F.

This 2200°F solution temperature corresponds to a smooth-bar elongation at rupture of around one per cent, compared with 8 per cent or higher for 1650° and around 4 per cent for 2300°F solution temperature. Trends for reduction of area of smooth specimens with different solution temperatures are similar, though the absolute values are higher. Both measures of smooth-bar ductility seem to be independent of test stress for the narrow range investigated. (See Fig. 4).

W. F. Brown, Jr. and his associates at the NACA Lewis Laboratory have reported several instances in which curves of notch rupture strength ratios (notched-bar life / smooth-bar life) versus rupture time bear a striking similarity to comparable curves of ductility versus rupture time. (See Ref. 2) In the present case where variable smooth-bar ductility results from differences in heat treatment, the pattern of falling and then rising ratio of notched-bar life to smooth-bar life also closely parallels the accompanying changes in elongation for different solution temperatures. (Compare Figures 4 and 5.).

Other factors investigated for possible influence on the apparent decline of notch strengthening of A-286 solution treated at or near 2200°F include plastic strains during load application or during early creep periods and the alteration of subsequent creep-rupture properties by plastic strains introduced into the metal at the start of a test.

Even the unnotched specimens tested at 70,000 psi stress exhibited some initial plastic strain when the load was applied. The amount of this plastic loading strain for solution temperatures between 1650° and 2225°F was small, averaging around 0.04%. The few specimens treated at 2300°F exhibited variable degrees of yielding, but two tests loaded to 70,000 and 65,000 psi had plastic strains of 0.86% and 0.33%, respectively, indicating a sharp fall-off in yield strength at 1200°F after solution at the extreme treating temperature.

These unnotched specimens solution treated at 2300°F were also singular in their creep behavior. For all other specimens, the primary creep rate declined typically and gradually during the first five per cent or so of the test duration, passed through a minimum rate, and then began a gradual acceleration starting from a creep strain of 0.1 - 0.2% or less. The specimens solution treated at 2300°F crept exceedingly fast at first and then the creep rate dropped sharply. At 70,000 psi stress over one per cent of creep strain was measured for the first three minutes. The next hour and a quarter saw only 0.165% additional creep. At 65,000 psi the creep curve rose rapidly to slightly over 0.4% strain and then nearly leveled off, in a manner similar to that at the higher stress. In contrast, the specimen tested at 60,000 psi, with negligible plastic strain from loading, followed a creep pattern similar to specimens solution treated at the lower temperatures.

These trends are illustrated by curves in Figure 6 of cumulative creep strain versus solution temperature for each of the three stress levels studied. Curves are sketched for the creep in 10, 25 and 50% of the rupture life for each test. For 60,000 psi stress the measured creep strain at any given stage in the several tests shows a steady drop with increasing solution temperature over the entire range from 1650° to 2300°F. The 65,000 psi stress curves fall to a minimum as solution temperature is increased to 2100° or 2200°F and then rise again. At 70,000 psi the minimum creep appears to occur for a solution temperature around 2000°F and then the curves sweep sharply upward to high amounts of early creep if higher solution temperatures are employed.

Seven experiments were completed in which a smooth specimen was prestrained by momentary overloading at the start of a creep test. Since these exploratory tests were also used to obtain the yield characteristics for the different solution temperatures, the required load to give exactly the desired final stress after plastic straining could not be calculated in advance. Neither could the exact amount of prestrain be controlled as closely as might be desired, but ranged from 0.72 to 2.03% for the seven tests. In only five instances were comparable combinations of solution temperature and nominal stress obtained for pairs of prestrained and non-prestrained specimens. Results for these five pairs are tabulated below:

EXPLORATORY TESTS WITH A-286 AT 1200°F ON EFFECT OF PLASTIC PRESTRAIN

Solution Temp., °F	Stress (psi)	Initial Plastic Strain, %	Rupture Life, hr.	Creep Strain at 25% of the Life, %
1800	70,560	0.80	17.9	0.74
1800	70,000	0.03	20.3	0.37
1800	60,540	0.90	59.8	0.50
1800	60,000	-	79.9	0.18
1950	65,870	1.33	90.0	0.40
1950	65,000	-	103.	0.21
2200	60,790	1.31	99.8	0.085
2200	60,000	-	307.8	0.07
2300	60,940	1.56	17.6	0.045
2300	60,000	-	50.8	0.017

Solution temperatures of 1800° and 1950°F produced nearly identical rupture times whether or not the specimens were prestrained, provided due allowance is made for the one per cent or so difference in stress levels actually present in the tests compared. With solution at 2200° and 2300°F the prestrains obtained were greater than for the lower solution temperatures. However, the proportionally greater loss in life for the specimens prestrained after solution at 2200° and 2300°F cannot be explained by the resulting slightly greater difference in stress level present in these tests. The data for the higher solution temperatures scatter considerably even without deliberate plastic strain at loading, but the points added to Figure 2 for the 60,000 psi tests with prior plastic strain at test temperature appear to fall below the probable band of such scatter.

By comparing the cumulative creep at the end of a given percentage of the rupture life for each particular test, one should eliminate effects of the small stress difference between specimens with and without prestrain. In all curves studied, prior short-time straining was found to result in higher subsequent creep rates. Of possible significance is the finding that the cumulative creep at 25% of the rupture life was increased two or three times by prestraining specimens solution treated at 1800°, 1950° and 2300°F, while for the 2200°F solution temperature prestrain seems to have resulted in a gain in creep strain of only about twenty per cent over specimens not prestrained.

Analysis of the A-286 Test Results.

The most evident feature of these studies is the freedom from notch sensitivity at 1200°F for this vacuum-melted A-286 made by the consumable electrode method and then heat treated in the usual solution temperature range of 1650° to 1800°F.

Failure of the material to exhibit marked notch weakening with moderate increase in solution temperature was both a surprise and a disappointment from the standpoint of its projected use to clarify expected large differences in notch response with variable heat treatments.

Some possible cause-effect relationship may be demonstrated by the similarity between curves of Figures 4 and 5, but more probably the ductility and the notch strength ratio are but two reflections of a more basic change in the material's properties when different solution temperatures are used. The most fruitful lead for future investigation is the apparent lowering of rupture life without simultaneous large acceleration of creep after plastic prestrain for specimens which had been solution treated at the 2200°F temperature for which the only tendency for notch sensitivity was found. The observed variations with solution temperature in the creep-rupture response to prestrain were admittedly not large, but neither were the corresponding differences in notch behavior.

EXPERIMENTAL RESULTS FOR 17-7PH AND WASPALOY

During the past year, efforts with 17-7PH sheet specimens and with two small lots of Waspaloy stock were secondary to those on A-286. Experimental results have, however, been carried to a point where definitive tests might be planned with these materials to test hypotheses suggested by studies on A-286 and other materials.

Test Data for 17-7PH:

The 17-7PH material was supplied from Armco Steel Corporation's Heat No. 55,651 as annealed sheets 36 x 120 x 0.063 inches, with a 2D surface finish. Chemical analysis was certified by the supplier to be as follows:

C	Mn	P	S	Si	Cr	Ni	Al
0.072	0.55	0.018	0.011	0.33	17.03	7.25	1.28

Specimen blanks one inch wide by 22 inches long were all oriented transverse to the direction of rolling of the sheets, with care being taken to randomize the sampling location across the width of the sheet and between sheets. The specimen blanks were heat treated in air for 1-1/2 hours at 1400°F, air cooled for 10 minutes (to about 500°F), then quenched in water at 60°F. After an 8 to 12 hour period at 60°F, the specimens were aged 1-1/2 hours at 1050°F and air cooled.

Preliminary machining to within about 0.050 inch on the gauge width was done with a milling cutter. The gauge section for smooth specimens was then ground to final dimensions of 2 inches long by 0.500 inches wide. The width of specimens to be run in creep and then notched was made 0.600 inch. This latter width was used for all notched specimens of 17-7PH tested to date, with a 0.300 inch width at the base of the edge notch and a 0.024-inch root radius to give a theoretical stress concentraction factor of 3.1.

For all tests on the 17-7PH material, specimens were placed into a preheated creep furnace and brought to the required temperature level and distribution within approximately four hours, after which the load was applied and the test period started. Rupture data for smooth and notched specimens are summarized in Table 2 and Figure 7. The rupture strengths determined in this investigation show reasonable agreement with the following values reported by the producer as typical for the alloy. (See Ref. 3):

Temp., °F	1000 Hour Rupture Strength, psi	Elongation at Rupture, %	1000 Hour Rupture Strength, psi	Elongation at Rupture, %
600	170,000	19	158,000	17
800	110,000	21	90,000	23
900	78,000	30	52,000	40

Elongation values determined in the present research for 600°F were somewhat lower than the values reported by Armco.

No evidence of notch embrittlement was discovered for specimens with $K_t = 3.1$ in test times that extended to nearly 1000 hours. Data for 800°F indicate possible notch sensitivity at that temperature for times beyond several thousand hours. However, apparent convergence of the smooth-specimen and notched-specimen curves at 800°F is at variance with the observed divergence at 600° and 900°F for increasing test duration.

At all three test temperatures 17-7PH in the TH 1050 condition displayed extensive early creep. At least 1% and usually nearer to 2% of creep strain occurred before 10% of the rupture life of smooth specimens had passed, suggesting that this alloy should rapidly redistribute concentrated stresses such as are to be found near notches or other stress raisers. The period of primary creep is rather short, with the curve for the initial period fairing into a curve of relatively-high minimum creep rate during the first few per cent of the test duration.

Even at the minimum rate, creep is substantial. A stress of 125,000 psi at 600°F should correspond to an estimated rupture life of over 100,000 hours according to the rupture curve of Figure 7, but for this extended-life test condition the minimum creep rate still exceeds 0.001%/hour, or one per cent creep strain in less than ten per cent of the expected life. Long-time tests at 800° and 900°F indicated one per cent creep at the minimum rate should require a time equal to but five or six per cent of the respective rupture lives. Under such conditions of opportunity for rapid stress redistribution by creep a high stress concentration can hardly be expected to be retained at a notch root even if the notch were introduced after prior creep exposure had eliminated the higher rates of primary creep. A few spot tests have been run to confirm this expectation for 17-7PH sheet specimens.

Special Tests with 17-7PH Specimens.

For each test temperature a single smooth specimen was allowed to creep for 100 hours at a stress chosen so that the minimum creep rate would be attained or approached in the 100 hours. The specimens were cooled under load to minimize recovery from creep, and then notches were machined into the edges of the pre-crept gauge section. The notched specimens were returned to the test stands and brought to temperature under partial load chosen to place the fibers at the notch root at approximately the same stress as was used for the initial smooth-specimen creep. When the test temperature was reached, the entire load was put onto the specimen and the test was run the same as for any other notched rupture specimen. In all three experiments of this type the life of the specimen notched after prior creep equalled or exceeded that of notched specimens prepared from blanks just as heat treated. The results are included in Table 2 along with the data from normal tests.

To learn whether possible detrimental effects of the creep might have been offset by general strengthening from continued aging during the 100 hours at temperature, companion specimens were held at temperature for 100 hours under zero load before notching. Results with these specimens were inconclusive for

600°F, where one specimen broke during loading and a duplicate lasted considerably longer than either of the similar specimens with and without prior creep. Results at 800° and 900°F suggest that for the notch geometry and stress levels studied, exposure to creep conditions prior to the introduction of a notch produced no radical departure from rupture characteristics determined on 17-7PH specimens notched before any exposure to creep temperature or stress.

Two additional tests were performed, one at 800° and the other at 900°F, in which the load on a notched specimen was alternated between 8-hour periods at a stress corresponding to 50 or 100 hours rupture life and 16-hours periods at a low stress which would result in many thousands of hours of life if maintained steady. The cumulative time at the higher stress when rupture occurred was at least equal to that obtained for other notched specimens under high steady load and may actually have been longer. (See Table 2 for results of these special tests).

A similar previously unreported test was conducted in the past with S-816 alloy at 1350°F, using round notched specimens with $K_t = 5.7$. Under a steady 50,000 psi stress the measured life was 116.6 hours. In a second test the stress was alternated between 50,000 psi and 8,670 psi every five hours for the first 100 hours, and then permitted to run to rupture at the higher stress. Total time at 50,000 psi when fracture took place was now 151.5 hours. Both the 17-7PH and S-816 were strengthened by notches in steady-load tests. Indications from such materials might not apply to notch brittle alloys. Tests under alternating stresses would seem desirable using materials exhibiting marked notch weakening.

Findings presented earlier for A-286 suggest that momentary overloadings of smooth specimens at test temperature to produce plastic prestrain may afford insight into reasons for observed notch behavior. Table 2 lists three such tests for 17-7PH. The first specimen tested at 900°F yielded less than 0.1% on loading to 98,500 psi at the start of the test. Its subsequent life at 65,080 psi agrees closely with the average rupture curve in Figure 7. A second test at 900° with 0.22% plastic prestrain and one at 800°F with 0.45% prestrain showed rupture lives lower than the average curves, but still probably within the maximum scatter band for rupture times without prestrain. It might be noted that the stress levels required to produce the reported prestrains (112,500 psi at 900° and 144,100 psi at 800°F) correspond to rupture lives somewhat less than 0.1 hour so that even the brief period required for the initial overloading step could have used up a measureable portion of the total rupture life of the specimens and thus account for the possible small loss in life obtained.

Creep curves for all specimens bore a similarity in shape; that is, all exhibited roughly the same total creep at corresponding percentages of life expired. The prestrained specimen tested at 800°F crept 1.7% during the first tenth of its rupture life at 100, 450 psi. Two non-prestrained specimens at 100,000 psi crept 1.5% and 1.8% during the similar portions of their respective tests. The specimen at 900°F with higher prestrain showed 2.2% creep during the first 10% of the test and that with 0.09% prestrain, 2.0% creep. Specimens tested under 60,000 and 70,000 psi stress at 900°F averaged 1.7% creep strain for the first tenth of their lives, with individual values ranging from 1.5 to 1.9%. Final elongation at rupture for prestrained specimens showed no particular trend of divergence from results of other tests.

Prestrain may possibly have increased the creep rate slightly in early stages and may have slightly lowered rupture life, but these effects should tend to counteract each other insofar as they affect notch behavior. The three tests to date suggest little significant change in creep-rupture properties of 17-7PH from plastic strains up to a quarter or a half of one per cent.

Considered as a whole, these several types of special tests indicate that notch-rupture behavior of 17-7PH sheet in the TH1050 condition is rather insensitive to many variations of a nature similar to those of service. However, since this investigation has been very meager and random, these results cannot and must not be taken as general for 17-7PH with other treatments or at other temperatures, or particularly for other types of alloys.

Test Results for Waspaloy:

Small amounts of Waspaloy from two heats were supplied by Allegheny-Ludlum Steel Corporation for the continuing study into reported variable notch response of this material according to the heat treatment employed. Compositions of the two lots were as follows:

	Heat 63,559	Heat 63,561
C	0.06	0.03
Mn	0.74	0.64
Si	0.49	0.56
Cr	19.13	20.12
Ni	Bal	Bal
Co	13.29	14.10
Mo	2.89	3.06
Ti	2.30	2.21
Al	1.50	1.34
Fe	0.97	0.96
S	0.014	0.019
P	0.016	0.015
Cu	0.15	0.16

The Heat 63,559 material was hot rolled bar with 1-3/4 inch diameter.

Specimens were prepared from wedges obtained by splitting the stock lengthwise into six equal segments. Specimens from Heat 63,561 were machined directly from suitable lengths of the 7/8 inch diameter bar supplied. In each case test samples were given the appropriate heat treatment before machining took place.

For each heat of the alloy, some specimen blanks received the following conventional heat treatment:

1975°F, 4 hours, air cool +
1550°F, 4 hours, air cool +
1400°F, 16 hours, air cool.

Another group of specimens had the same treatment less the intermediate age at 1550°F.

Fifteen tests have been completed for Heat 63,559 and sixteen tests for Heat 63,561. Results are listed in Tables 3 and 4 and are shown graphically on Figures 8 and 9.

Past studies on Waspaloy Heat 63,613 disclosed no detectable difference in the usual rupture properties between smooth bars with the complete conventional heat treatment and those treated without an intermediate 1550°F age. (See Figures 23 and 24 of Ref. 1). In contrast, both of the heats of alloy under present consideration had measurably lower rupture strength for specimens without the 1550°F age.

For all three heats tested, material with the two different treatments appeared to exhibit a difference in yield strength, as determined from loading curves obtained at the start of prestrain tests. Approximate average values of the yield strengths found were as follows:

	0.2% Offset Yield Strength, 1000 psi	
Heat No.	Conventional H. T.	1550°F Age Omitted
63,613	90	87
63,559	91	85.5
63,561	87.5	86

No significance is placed on the differing absolute values for the several lots of alloy, but the conventional heat treatment does seem to correspond to the higher relative yield strength for each set of data.

In every example studied, for all three heats of alloy and for both of the heat treatments, plastic prestrain of from 0.5 to 2% resulted in a subsequent rupture life of from half to less than two per cent of the normal rupture life for the test stress used after prestraining. Data from the prestrain tests are plotted in Figure 10 to show the percentage of the normal rupture life retained versus the percentage of prestrain. Allowing for some data scatter, the percentage loss of life from prestrain seems to be independent of which heat treatment was used for a particular lot of alloy.

For a given initial overload stress in the prestrain tests on smooth specimens, specimens without the intermediate aging step suffered the greatest loss in subsequent life. Figure 10 can be interpreted to say this was a consequence of the lower yield strength and therefore larger plastic strains obtained in the material without the 1550°F age. If this is correct, by proper choice of the overload stress to produce equal prestrain for both heat treatments, the same degree of lowering of the normal life should result. The truth of this expectation can be tested by conducting further tests on material with conventional heat treatment and prestrained in the range between 1 and 2% which has been covered to date only for specimens without the intermediate age.

Relative notched-bar strength may be determined largely by whether or not yielding takes place under the stress concentration near the notch root. With $K_t = 2.4$, the multiaxial stress near the notch results in an effective stress (shear stress invariant) about 2.1 times the nominal stress under elastic conditions. Localized yielding in Waspaloy at 1350°F should thus become significant at a nominal stress equal to the yield strength divided by 2.1, or slightly over 40,000 psi nominal stress. The meager data available to construct the curves of Figure 8 (Heat 63,559) lend rather good support to this expectation, with transition from severe notch weakening to notch strengthening indicated to occur as nominal stresses drop below 40,000 psi. The curves of Figure 9 are less conclusive, but confirm the anticipated trends. For this group of specimens (Heat 63,561) transition to notch strengthening for the conventional heat treatment is indicated to take place above 50,000 psi and that for the other heat treatment somewhat below 40,000 psi. This disparity may result from lack of sufficient data to define the exact curves, but may also indicate secondary effects of the prestrain in addition to the direct effect on rupture strength.

According to the analysis put forth in Reference 1, the importance of creep to notch behavior should in large measure depend on the initial stages of the creep. Two alloys with the same rupture strengths and the same elongation at fracture might still differ widely in the relative proportions of creep early and late in the test. High primary creep strain would be most effective since it would exert a major influence on stress redistribution in the critical time of high initial stress concentration near the notch root. More appropriately, the relationship between the amount of creep and the portion of life expended in the process should be the critical criterion and not the creep rate as such. Table 5 lists the creep strains during time periods equal to 10, 25 and 50% of the respective rupture lives for the tests on Waspaloy Heats 63,559 and 63,561.

Consider the data of Figure 8 for two notch tests at 45,000 psi. This 45,000 psi nominal stress would require a maximum theoretical effective stress of about 94,500 psi at the notch root if elastic properties were to be retained to that level, wherefore plastic yielding will ensue for this load on the notched bars tested. The most applicable data from Table 5 for the tests on Heat 63,559 are therefore the results of prestrain tests. Prestrain from momentary overloading to the same 95,000 psi stress produced smooth-bar rupture lives for the two heat treatments in the ratio 26.9 hr./1.5 hr. = 18. The slightly more drastic ratio of 16.9 hr./0.45 hr. = 37.5 obtained at 45,000 psi for the notched specimens with the different treatments might reflect simple data scatter but can also be explained in terms of the consistently greater proportion of the available life used up to obtain a given degree of creep strain (stress relaxation) when the 1550°F age is omitted from the conventional heat treatment.

Plastic prestrain should not be present at all for the notched bars tested at 35,000 psi nominal stress and should be negligible for 40,000 psi. Appropriate smooth-bar data for evaluation of properties near the notch are now those from tests without prestrain. Material with the conventional heat treatment should still have the combined advantages of slightly higher inherent life and slightly more rapid creep, but relative differences in notched-bar strength for the two heat treatments should become smaller when the nominal stress is 40,000 psi or below.

One point on Figure 8 (the 35,000 psi notch test with conventional heat treatment) appears to be out of line. Notch tests at 45,000 and 40,000 psi provide excellent agreement with anticipated results.

Adequate explanation of the pronounced difference between the two curves for notched specimens shown in Figure 9 for Heat 63,561 is difficult using data of Table 5. Differences in smooth-bar rupture life for the two heat treatments, with or without prestrain, are not nearly as great as are the experimental differences in notched-bar life. Moreover, absolute creep rates are actually higher for specimens without the intermediate age, and even when properties are based on equal portions of the respective lives the creep of specimens without the intermediate age is about equal to that for specimens with the complete conventional heat treatment. Though the data for this group of tests are meager, they do appear to have internal consistency insofar as can be judged from corresponding shapes of the separate curves.

The sparse data for the separate lots of Waspaloy permit only qualitative comparisons between heats. However, Heat 63,559 did seem to suffer greater loss of strength from prestrain than did Heat 63,561 according to the curves of Figure 10. In agreement, the Heat 63,559 material exhibits the greater relative notch embrittlement for like nominal stress. At 45,000 psi the notch strength ratios from Figure 8 for Heat 63,559 are approximately 0.45 hr./100 hr. = 0.0045 for material without the 1550°F age and 16.9 hr./300 hr. = 0.056 with the conventional heat treatment. Corresponding results for the same stress, estimated for Heat 63,561 from the curves of Figure 9, are 1.5 hr./50 hr. = 0.03 and >1, respectively.

REVIEW OF AVAILABLE DATA FOR GENERAL RELATIONSHIPS BETWEEN NOTCH SENSITIVITY AND RESPONSE OF SMOOTH BARS TO PRIOR STRAIN

Results reported here indicate that reduction of an alloy's inherent strength by prior plastic deformation may be a prominent factor in notch sensitivity of the material. To date this explanation seems to best fit the observed behavior for several lots of Waspaloy tested at 1350°F, but correlations have been neither universal nor exclusive of other explanations. Negative support has been provided by the apparent lack of serious detrimental effects of prior strain on A-286 and 17-7PH and concurrent lack of notch weakening for most conditions studied.

The technical literature and results of past research for WADC have been reviewed to learn whether this apparent correlation between notch-rupture characteristics and response of smooth bars to prior strain is or is not general.

Several examples have been found where notch strengthening was associated with increased smooth-bar life after plastic prestraining. Additional cases were also found in which notch weakening accompanied loss of smooth-bar life from prior plastic strains. In no case now known to the authors has notch weakening occurred without concurrent loss in rupture strength from prestrain. Conversely, no instance of proven notch weakening is known for conditions that lead to marked increase of rupture strength upon plastic deformation of an alloy.

Stress-rupture time properties at 1200°F have been released (Ref. 4) for 16-25-6 alloy tested (1.) as solution treated, (2.) after 25% cold work at 1350°F, and (3.) after 30% cold work at 1300°F. Effect of the cold work was to increase the rupture strength of smooth specimens. Corresponding to the strengthening effect of plastic strains, the as-received material was strongly notch strengthened. (See Figures 7 and 8 of Reference 1, Part I).

In tests at 600°C on an 18 Cr, 10 Ni, 1.4 W, 0.55 Ti, 0.06 C, 0.06 Al alloy, Siegfried found that 10% of plastic work in tension or 10-20% cold work by torsion increased smooth-bar life over that of as-received specimens at times to 2000 hours. Notched bars tested in the as-received condition exhibited higher strengths than did corresponding smooth specimens (See Ref. 5).

Materials investigated under Contract AF18(600)-62 involved two alloys which were strengthened by a variety of notch acuities and test stresses -- S-816 at 1350°F and 2024-T4 at 400°F. At these test temperatures, both alloys respond to plastic strains by an increase in rupture strength and an acceleration of early-stage creep.

Borderline ratios of notched-bar life to smooth-bar life prevailed for tests on 17-22A(S) at 1100°F where plastic prestrain produced a slight loss of subsequent smooth-bar strength. Inconel X-550 at 1350°F is characterized by a pronounced lowering of smooth-bar life following plastic prestrain. In common with Waspaloy, notched specimens believed to be free from residual machining stresses were decidedly weakened at intermediate nominal stresses where plastic straining occurred at the notch root. For nominal stresses below the level where localized straining takes place upon load application, indications are that notched specimens should last longer than smooth specimens. At very high nominal stresses, where both smooth and notched specimens are subject to plastic strains on loading, the stress-rupture life curves for the two types of specimens appear to approach one another.

Prestrain effects alone may not be able to explain all notch behavior, but response of the material to plastic strains appears to be a necessary part of any complete analysis of notch effects.

If no effect on creep characteristics results from prestrain, the loss of life from strain damage should determine the occurrence of notch weakening. A major uncertainty about strain-damaged materials is the relative importance to notch sensitivity of altered strength versus altered ability to relax stresses by creep.

DISCUSSION

When the experimental materials were selected for the investigation, they were believed to provide suitable test materials to check the indicated variables controlling reduced rupture life in notched specimens. The A-286 alloy in particular was chosen with the expectation that a range in notch sensitivity could be developed by increasing the temperature of solution treatment. Furthermore, the theoretical stress-concentration factors for the notches used in the investigation had been specified at approximately 1.5 - 2.0 and 3.0 - 3.5. Neither of the two materials met the rather exacting requirements of the investigation. The A-286 material showed notch strengthening at a K_t of 3.0 even when solution-treated at high temperature where smooth bar ductility in the rupture tests was very low. Even the use of a much sharper notch ($K_t = 4.1$) similar to those commonly used in industry to check the notch sensitivity of A-286 showed at most borderline sensitivity under the conditions examined.

The lack of notch sensitivity in the A-286 when smooth bar ductilities were very low is probably the outstanding feature of the results. The general pattern of the relative strengths for notched and smooth specimens followed the changes in smooth-bar ductility, as would be expected from published data. The development of at most mild notch sensitivity with such large changes in smooth bar ductility and with such low values as 1-percent elongation was unexpected.

Because the A-286 did not develop the desired notch sensitivity, most of the critical experiments planned were not undertaken. Considerable time elapsed while a heat treatment was sought which would give the expected characteristics. The intention was to investigate the relative effects of the major factors which to date seemed to control notch sensitivity. This would have involved consideration of stress redistribution in notched specimens during loading through yielding, the effect of such yielding on subsequent creep and rupture behavior, the rate of exhaustion of creep-rupture life in relation to the rate of stress redistribution, and the role of ductility.

The loss in creep-rupture life of A-286 alloy from prior plastic strain was very small at the borderline notch sensitivity conditions in comparison to previously observed losses in highly notch sensitive materials. The lack of notch sensitivity (or the very mild sensitivity) observed could be due to this alone. The insensitivity of the 17-7PH to notches was accompanied by no positive loss in strength due to prestrain. The very few tests conducted on the additional heats of Waspaloy did not strengthen the prestrain hypothesis as much as expected. The inconclusive results could have been influenced, however, by insufficient information on the yield characteristics of the base material and consequent improper selection of test conditions for the prestrain tests. The general conclusion still seems to be that prestrain damage can be a major factor and in some cases may be the controlling factor in notched-bar rupture life.

It had been hoped to run critical tests which would better delineate the role of ductility. The very mild notch sensitivity of the A-286 with very low ductility seems to furnish additional evidence that smooth bar ductility at rupture is a relatively minor factor, provided there is a sufficient though small amount of ductility to allow stress redistribution. The data are not clear proof of this, however. Perhaps a series of critical experiments could have been conducted which would have interrelated stress redistribution on loading, prestrain damage, and smooth bar ductility to have obtained a definite answer. The notch effects were, however, so small that the experiments were not undertaken because a clear cut answer would probably not have been obtained.

Considering the various effects measured for A-286 and 17-7PH along with the prior data, another approach to the ductility problem might be fruitful. The calculation in Reference 1 demonstrated that major stress redistribution usually takes place long before third-stage creep. Consequently, the ductility which is most effective in stress redistribution must be that of any plastic yielding on loading and of primary creep. As previously discussed, it is believed that re-evaluation of ductility from the viewpoint of deformation from yielding and from primary creep would go far towards clearing up the role of ductility in notch sensitivity.

The tests on 17-7PH mainly show the freedom of this material from loss in life from stress concentrations. The few tests with notched specimens under varying loads and with specimens notched after prior creep confirm the resistance of this material to stress-concentration sensitivity, even when plastic straining or opportunity for structural changes may be present.

Differences in notch sensitivity between heats of nickel-base heat-resistant alloys hardened by Ti + Al strongly indicate that some unidentified compositional factor is involved. Recent experience in research on melting-practice variables, being conducted at the University of Michigan for the National Advisory Committee for Aeronautics, has shown pronounced effect on creep-rupture properties from small amounts of such elements as B, Zr and Mg. Probable additional effects are attributable to nitrogen and oxygen. The observed variability of notch sensitivity probably lies in the effect of these trace elements on the damage produced by prior strain and in variation in yield characteristics with the amount of these elements present. This subject seems to warrant thorough investigation if the basic factors behind stress-concentration sensitivity are to be understood.

Explanations Advanced to Explain Notch Behavior:

So far only two rather broad explanations for notch behavior have been found: (1) alteration of the rupture strength of material near a notch under the action of the localized plastic strain there during load application, and (2) interaction of stresses according to the shear stress invariant theory to permit effective stresses less than the nominal when extensive creep can occur before the initial period of high stress uses up all the available life.

The first of these factors can obviously apply only for sharp enough notches or high enough stresses to produce some plastic strain and would not constitute an explanation when stresses at the notch never exceed the elastic range. A cursory review of tests performed to date in this program reveals that the preponderance of data have been obtained for conditions where local yielding took place near the notch.

The present lot of A-286 appears to offer an excellent test material for notch strengthening in the absence of any plastic strains. The highest notch strength ratios were obtained for $K_t = 1.8$. Lowering this theoretical stress concentration factor to 1.4 or less would not only extend the range of available data but would permit specimens solution treated at 1800°F to be run at the 60,000 psi nominal stress with no measureable prior plastic deformation. For design guidance, data with K_t greater than 4.1 should also be valuable and might provide some additional clue regarding the fundamentals of notch behavior.

The alternate explanation for notch behavior stated above rests heavily on expected benefits from the triaxial state of stress in a notched specimen. The very foundation of this explanation is questioned by the latest information available on creep rupture behavior under complex stresses. Careful work by A. E. Johnson and his associates seems to lead to the conclusion that rupture life is controlled by the single largest tension stress acting (See Ref. 6). If this finding is true and of general applicability, no analysis presently known to the writers could adequately account for notch strengthening in the absence of property changes brought about by the stress state at the notch.

The tests reported in Reference 6 involve subjecting thin-walled tubes of 0.5 Mo steel or of copper to different combinations of axial tension and torsion until failure occurs. Interpretation is handicapped by the varying anisotropy developed in the different specimens. Furthermore, the results might still not apply to a notched specimen, even though they may apply strictly for steady-state stresses of complex pattern.

In the case examined by Johnson and co-workers, the combined stress present was substantially uniform and constant over the cross section of the specimen as well as along its length. Conditions for a notched tension bar are quite in contrast--stresses are initially localized near the notch, stress gradients produce non-uniform creep strains from point to point, and the stress level at any given location alters with time as creep relaxation progresses. Of these factors, variation in stress with time seems to be most critical. An important need should be filled by conducting tests in which creep proceeds under one condition of steady combined stresses for part of the test and then continues to rupture under another steady stress combination.

Unless the critical combination of stresses or strains governing fracture after creep is completely identified, any general design method based on usual smooth-bar data is questionable. Until a suitable failure criterion is determined, the relationship between simple tension properties and the rupture life of a part subjected to complex-stress creep must probably be established experimentally.

Stress gradients in a notched specimen may introduce some unanticipated factor, but until evidence of such an effect is produced, the rupture life corresponding to a given history of effective stress and strain should be expected to be the same whether the material under study is part of a notched tension specimen or part of a thin cylinder under tension and torsion. A more plausible explanation for possible discrepancies between Johnson's data for thin cylinders and the present results for notched specimens involves probable different metallurgical response of the test materials to the conditions studied by the two groups of investigators.

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TABLE 1

RESULTS OF PRELIMINARY TESTS AT 1200°F FOR A-286 SPECIMENS WITH DIFFERENT SOLUTION TEMPERATURES

Heat Treatment: 1 hr solution, Oil Quenched + age at 1325°F, 16 hr, AC.

Smooth Bars

Solution Temperature (°F)	Stress (psi)	Rupture Life (hr)	Elongation at Rupture (%)	Reduction of Area (%)
1650	70,000	15.7	9.5	10.
1650	65,000	23.8	13.	18.
1650	65,000	19.9	8.5	11.5
1650	60,000	45.4	8.5	10.5
1800	70,000	14.9	9.5	13.5
1800	70,000	20.3	6.5	8.5
1800	65,000	62.4	5.5	10.5
1800	60,000	99.1	7.	8.5
1800	60,000	79.9	5.	10.
1900	70,000	47.4	6.	9.
1900	65,000	112.2	5.	6.5
1900	60,000	302.9	3.5	5.5
1950	65,000	103.0	5.	7.
2000	70,000	62.3	5.	8.
2000	65,000	198.9	4.	7.5
2000	60,000	493.9	5.	5.5
2050	70,000	48.8	6.5	9.5
2050	65,000	128.4	4.5	6.
2100	70,000	25.3	3.5	5.5
2100	65,000	118.2	4.	7.
2100	60,000	350.9	3.	7.5
2150	70,000	33.8	1.5	6.5
2150	65,000	291.6	1.5	4.
2150	65,000	203.4	2.	4.
2200	70,000	7.2	1.5	7.
2200	60,000	308.7	1.	2.5
2225	70,000	15.1	1.5	5.
2225	70,000	4.8	2.	7.
2225	65,000	117.3	1.5	3.
2225	60,000	316.1	1.	2.5
2300	70,000	3.8	4.	15.
2300	65,000	15.2	4.	12.5
2300	60,000	50.8	1.5	6.5

(Prestrained by momentary overloading at test temperature)

Solution Temp. (°F)	Overload Stress, psi	Plastic Prestrain (%)	Stress (psi)	Rupture Life (hr)	Creep Strain at Rupture	Reduction of Area (%)
1800	100,000 +	0.80	70,560	17.9	7.	9.5
1800	108,240	0.90	60,540	59.8	5.5	11.
1950	98,000	0.72	70,525	31.3	7.5	9.5
1950	100,000	1.33	65,870	90.0	5.5	9.
2050	100,000	2.03	61,220	183.3	4.	9.5
2200	84,070	1.31	60,790	99.8	1.	4.5
2300	83,740	1.56	60,940	17.6	2.	8.5

Notched Bars

Solution Temperature (°F)	Stress (psi)	Rupture Life (hr)	
* Nominal Notch Geometry: D = 0.600, d = 0.424, r = 0.081, $K_t = 1.8$			
1650	70,000	106.3	
1650	65,000	245.6	
1800	70,000	239.6	
1800	65,000	366.2	
1950	70,000	716.1	
1950	65,000	814.3	
2050	70,000	563.7	
2050	65,000	688.9 +	Discontinued (Controller Failure)
2150	70,000	565.8	
2150	65,000	660.1	
2225	70,000	143.3	
2225	65,000	602.9	
2300	70,000	41.2	
2300	65,000	62.8	
* Nominal Notch Geometry: D = 0.460, d = 0.325, r = 0.017, $K_t = 3.0$			
1650	70,000	76.9	
1800	70,000	167.5	
1950	70,000	320.7	
2050	70,000	296.4	
2150	70,000	127.6	
2225	70,000	26.3	
2225	65,000	44.9	
2300	70,000	22.3	
2300	65,000	23.8	
* Nominal Notch Geometry: D = 0.500, d = 0.350, r = 0.009, $K_t = 4.1$			
1800	70,000	112.8	
1800	65,000	168.1	
1800	60,000	227.6	
2200	70,000	14.2	
2200	65,000	43.5	
2200	60,000	288.8	

* D = Diameter of Shank   d = Minimum diameter, at base of notch
r = Notch root radius K_t = Theoretical Stress Concentration Factor

TABLE 2

RUPTURE PROPERTIES AT 600°, 800° AND 900°F FOR SMOOTH AND NOTCHED STRIP SPECIMENS OF 17-7PH (TH 1050)

Smooth Specimens

Temperature (°F)	Stress (psi)	Rupture Life (hours)	Elongation (%/2 in.)
600	180,000	Broke during loading	
600	180,000	0.1	4.
600	175,000	15.1	10.
600	170,000	11.9	7.
600	170,000	42.6	9.
600	165,000	98.8	12.
600	160,000	661.2	16.5
600	150,000	2515.2 +	(Discontinued)
600	125,000	1893.3 +	(Discontinued)
800	105,000	37.3	22.
800	100,000	60.9	43.5
800	100,000	107. (±5)	32.
800	95,000	179.1	26.
800	90,000	555.6	37.5
800	70,000	1936.7 +	(Discontinued)
900	75,000	19.8	31.
900	70,000	24.6	30.
900	70,000	28.4	32.
900	70,000	29.1	28.
900	70,000	56.7	38.5
900	60,000	152.2	33.
900	55,000	323.6	43.
900	50,000	694.1	40.

Smooth Specimens

(Prestrained by momentary overloading at test temperature)

Test Temp. (°F)	Overload Stress, psi	Plastic Prestrain (%)	Stress (psi)	Rupture Life (hours)	Creep Strain at Rupture (%)
800	144,100	0.45	100,450	44.5	20.5
900	98,540	0.09	65,080	82. (±5)	53.
900	112,500	0.22	65,140	65.4	47.

[a] Notched Specimens

Temperature (°F)	Stress (psi)	Rupture Life (hours)	Remarks
600	178,000	1.5	
600	174,000	31.5	
600	174,000	Broke on loading	Notched specimen was held 100 hours at test temperature before load was applied.
600	174,000	504.5	
600	174,000	118.0	Notch introduced after smooth strip had crept 0.174% in 100 hours at 130,000 psi.
600	170,000	709.5	
800	120,000	18.9	
800	110,000	79.4	
800	110,000	67.8	Notched specimen was held 100 hours at test temperature before load was applied.
800	110,000	78.9	Notch introduced after smooth strip had crept 3.15% in 100 hours at 85,000 psi.
800	110,000 9,330	110.6 208.0	Alternate 8.0 hours at 110,000 psi and 16.0 hours at 9,330 psi.
800	100,000	215.8	
800	95,000	429.1	
900	80,000	9.1	
900	75,000	41.2	
900	75,000	48.8	Notched specimen was held 100 hours at test temperature before load was applied.
900	75,000	51.9	Notch introduced after smooth strip had crept 1.63% in 100 hours at 45,000 psi.
900	75,000 9,360	54.5 96.0	Alternate 8.0 hours at 75,000 psi and 16.0 hours at 9,360 psi.
900	70,000	59.5	
900	65,000	183.9	
900	60,000	360.4	

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a) Nominal Notch Geometry:
Width of Shank, W = 0.600 inch
Minimum width, at base of notch, w = 0.300 inch
Notch root radius, r = 0.024 inch
Theoretical Stress Concentration Factor, $K_t = 4.1$

TABLE 3

RUPTURE TESTS AT 1350°F FOR SMOOTH AND NOTCHED SPECIMENS OF WASPALOY HEAT 63559

Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)	Remarks
Smooth Specimens, Conventional H. T.				
70,000	4.55	1	5	
50,000	90.9	1.5	3.5	
40,000	832.8	1.5	3.5	
50,360	14.4	1.5	4	0.725% Plastic Prestrain at Test Temp.
50,250	26.9	1.5	3.5	0.515% Plastic Prestrain at Test Temp.
Notched Specimens, Conventional H. T.				
45,000	16.9	--	--	$K_t = 2.4$
40,000	792.1	--	--	$K_t = 2.4$
35,000	115.5	--	--	$K_t = 2.4$
Smooth Specimens, 1550°F Age Omitted				
70,000	0.95	1	5.5	
50,000	19.2	2	2.5	
40,000	308.1 +	(Discontinued due to controller failure)		
50,650	1.5	2	3.5	1.23% Plastic Prestrain at Test Temp.
50,370	3.6	2.5	3	0.74% Plastic Prestrain at Test Temp.
Notched Specimens, 1550°F Age Omitted				
45,000	0.45	--	--	$K_t = 2.4$
40,000	663.4	--	--	$K_t = 2.4$
35,000	2283.2	--	--	$K_t = 2.4$

TABLE 4

RUPTURE TESTS AT 1350°F FOR SMOOTH AND NOTCHED SPECIMENS OF WASPALOY HEAT 63,561

Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)	Remarks
		Smooth Specimens, Conventional H. T.		
70,000	5.7	3.	5.	
55,000	43.3	1.5	5.	
42,000	1007.3	1.5	4.5	
50,300	53.2	2.	3.	0.59% Plastic Prestrain at Test Temp.
50,210	34.7	1.5	4.5	0.42% Plastic Prestrain at Test Temp.
		Notched Specimens, Conventional H. T.		
65,000	7.2	--	--	$K_t = 2.4$
60,000	11.0	--	--	$K_t = 2.4$
50,000	816.6	--	--	$K_t = 2.4$
		Smooth Specimens, 1550°F Age Omitted		
70,000	4.9	--	6.5	
55,000	19.0	1.5	6.	
42,000	614.3	3.	4.5	
50,390	7.4	3.	4.	0.78% Plastic Prestrain at Test Temp.
50,250	20.8	2.	4.	0.51% Plastic Prestrain at Test Temp.
		Notched Specimens, 1550°F Age Omitted		
65,000	0.5	--	--	$K_t = 2.4$
50,000	1.5	--	--	$K_t = 2.4$
40,000	12.6	--	--	$K_t = 2.4$

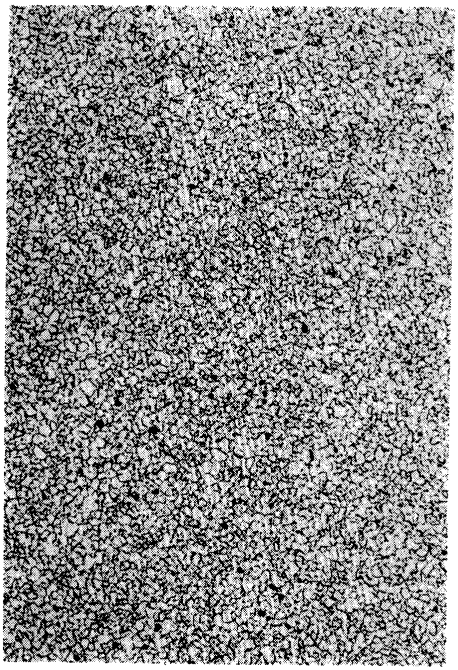
TABLE 5

CREEP STRAINS CORRESPONDING TO 10, 25 AND 50% OF THE RUPTURE LIFE FOR WASPALOY SPECIMENS TESTED AT 1350°F

Stress (psi)	Plastic Prestrain, %	Rupture Life (hours)	Cumulative Creep Strain, %		
			10% of life	25% of life	50% of life
		Heat 63,559 - Conventional H. T.			
70,000	---	4.55	0.044	0.094	---
50,000	---	90.9	0.044	---	---
40,000	---	832.8	0.077	0.118	0.185
50,360[a]	0.72	14.4	0.074	0.097	0.126
50,250[b]	0.52	26.9	0.068	0.123	0.186
		Heat 63,559 - 1550°F Age Omitted			
70,000	---	0.95	0.013	0.027	0.046
50,000	---	19.2	0.02	0.031	0.045
50,650[b]	1.23	1.5	0.016	---	---
50,370[c]	0.74	3.6	0.008	0.019	0.031
		Heat 63,561 - Conventional H. T.			
70,000	---	5.7	0.049	0.125	0.265
55,000	---	43.3	0.105	0.18	0.31
42,000	---	1007.3	0.19	0.30	0.88
50,390[b]	0.78	34.7	0.052	0.115	0.211
50,300[b]	0.59	53.2	0.085	0.175	0.030
		Heat 63,561 - 1550°F Age Omitted			
70,000	---	4.9	0.048	0.088	0.15
55,000	---	19.0	0.020	0.036	0.064
42,000	---	614.3	0.19	0.29	0.51
50,720[a]	1.44	7.4	0.041	0.078	---
50,250[c]	0.51	20.8	0.055	0.095	0.142

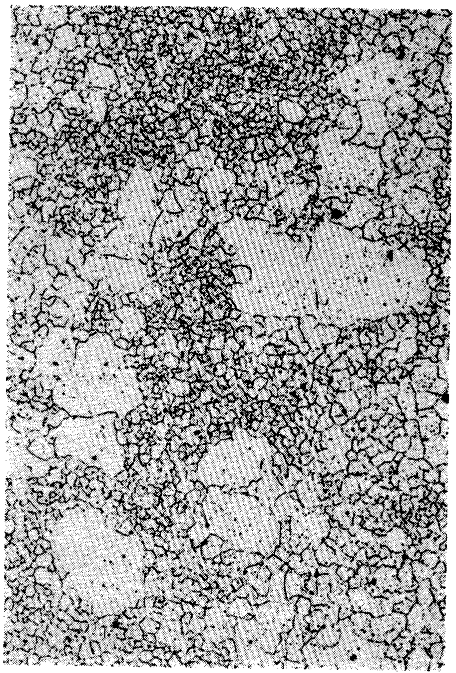
---

a) Overload stress 98,000 psi.
b) Overload stress 95,000 psi.
c) Overload stress 92,000 psi.



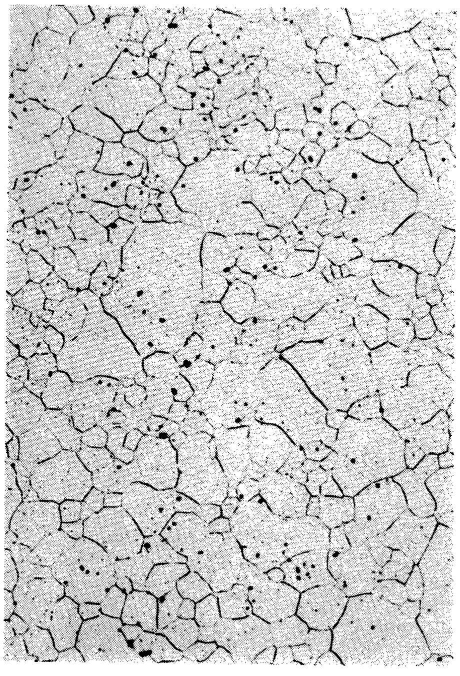
57-349

1650°F



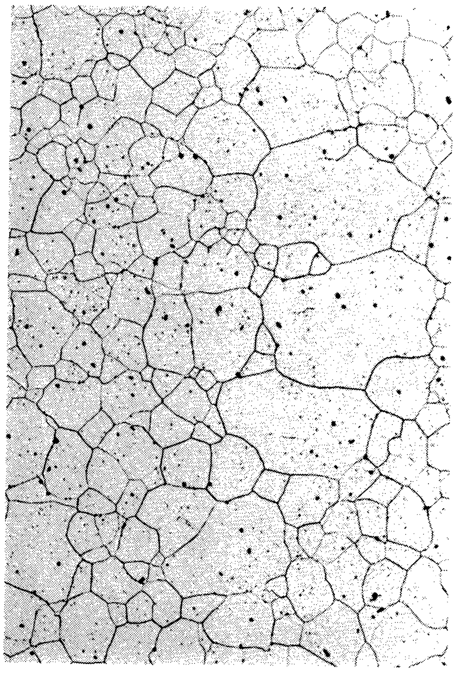
57-350

1800°F



57-351

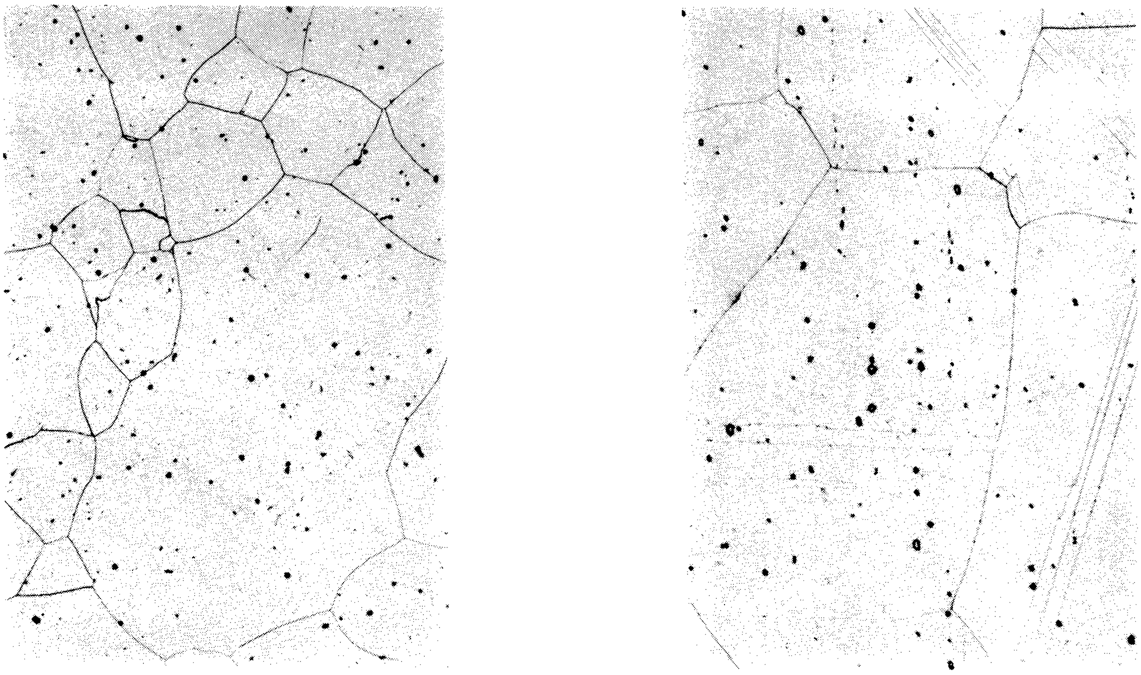
1900°F



57-352

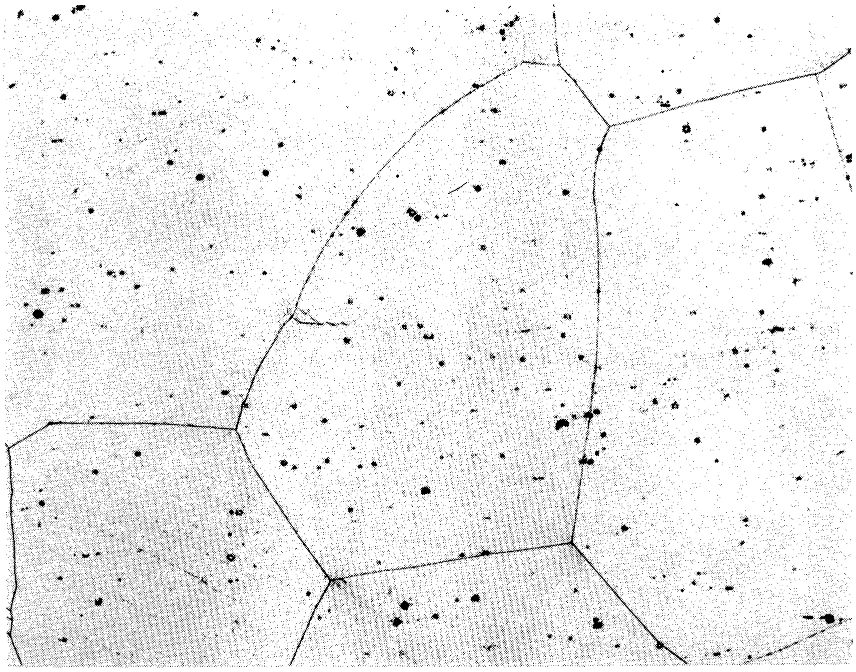
2000°F

Fig. 1 - Representative Photomicrographs of A-286 Alloy, Showing Variation in Grain Size with Solution Temperature. (X100D).



2100°F 57- 353

2225°F 57-354



Solution Temperature: 2300°F

57- 355

Fig. 1 - (con'd.)

Representative Photomicrographs of A-286 Alloy, Showing Variation in Grain Size with Solution Temperature. (X100D).

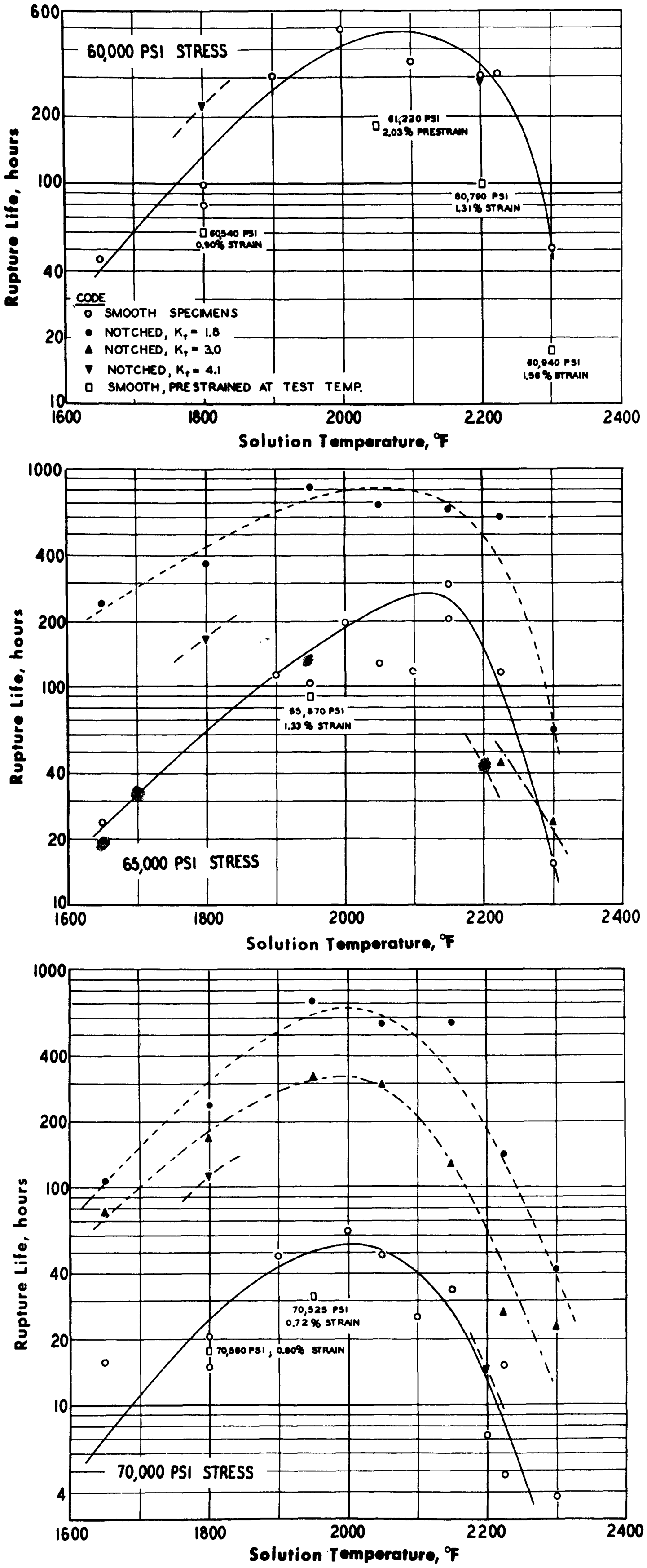


FIG. 2 - VARIATION WITH SOLUTION TEMPERATURE OF THE RUPTURE LIFE AT 1200°F FOR SMOOTH AND NOTCHED SPECIMENS OF A-286 TESTED AT THREE STRESS LEVELS.

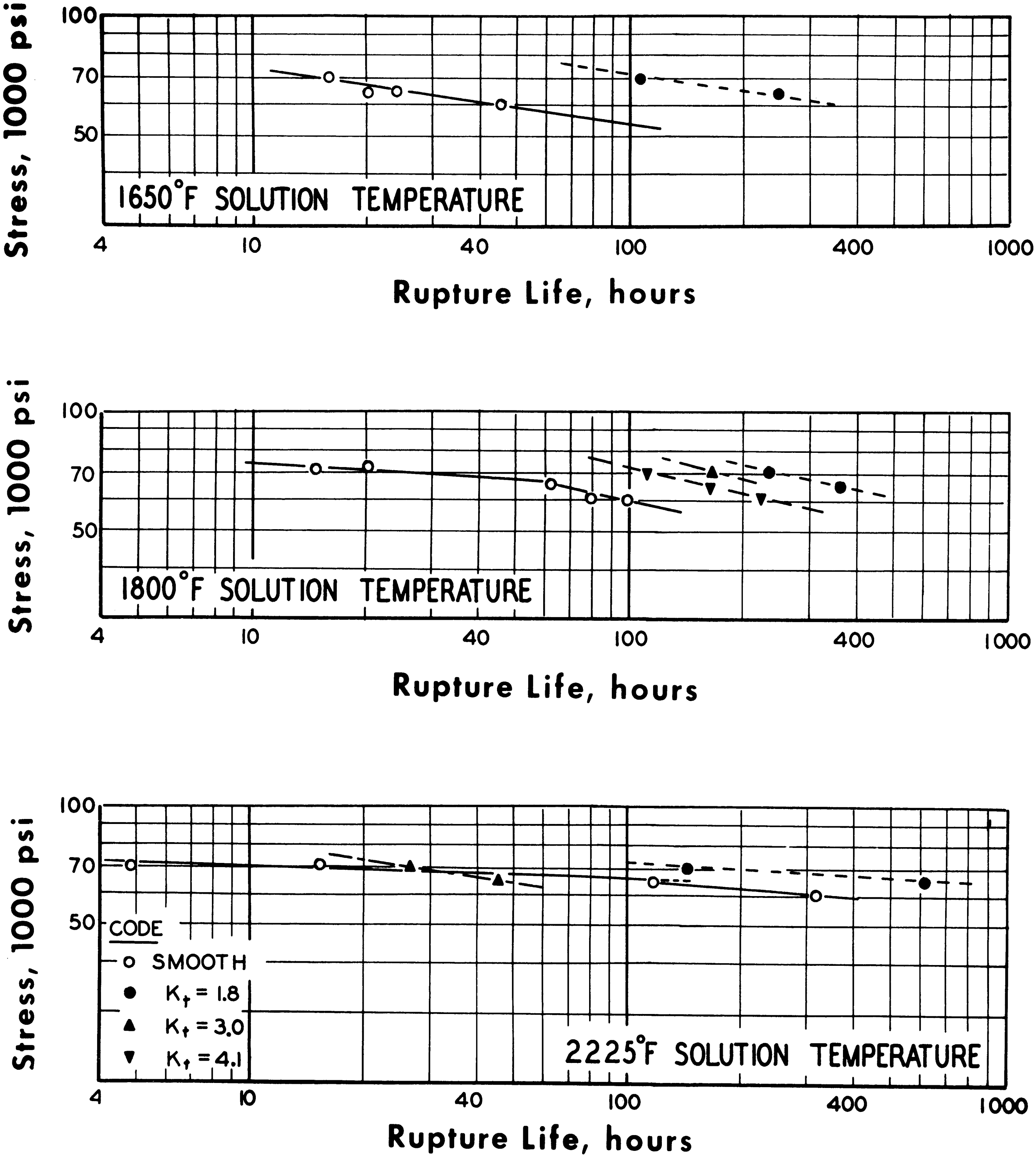


FIG. 3 - STRESS VERSUS RUPTURE LIFE AT 1200°F FOR SMOOTH AND NOTCHED SPECIMENS OF A-286 FOR THREE DIFFERENT SOLUTION TEMPERATURES.

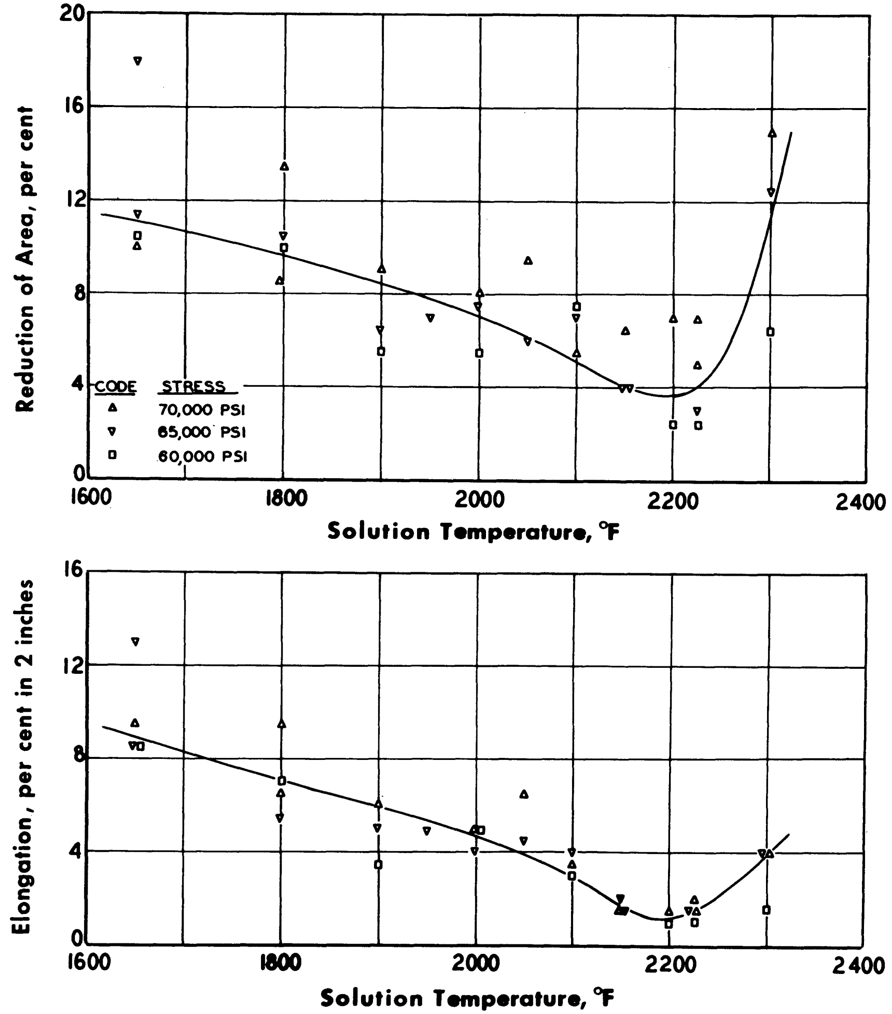


FIG. 4 - EFFECT OF SOLUTION TEMPERATURE ON REDUCTION OF AREA AND ELONGATION OF A-286 AT 1200°F.

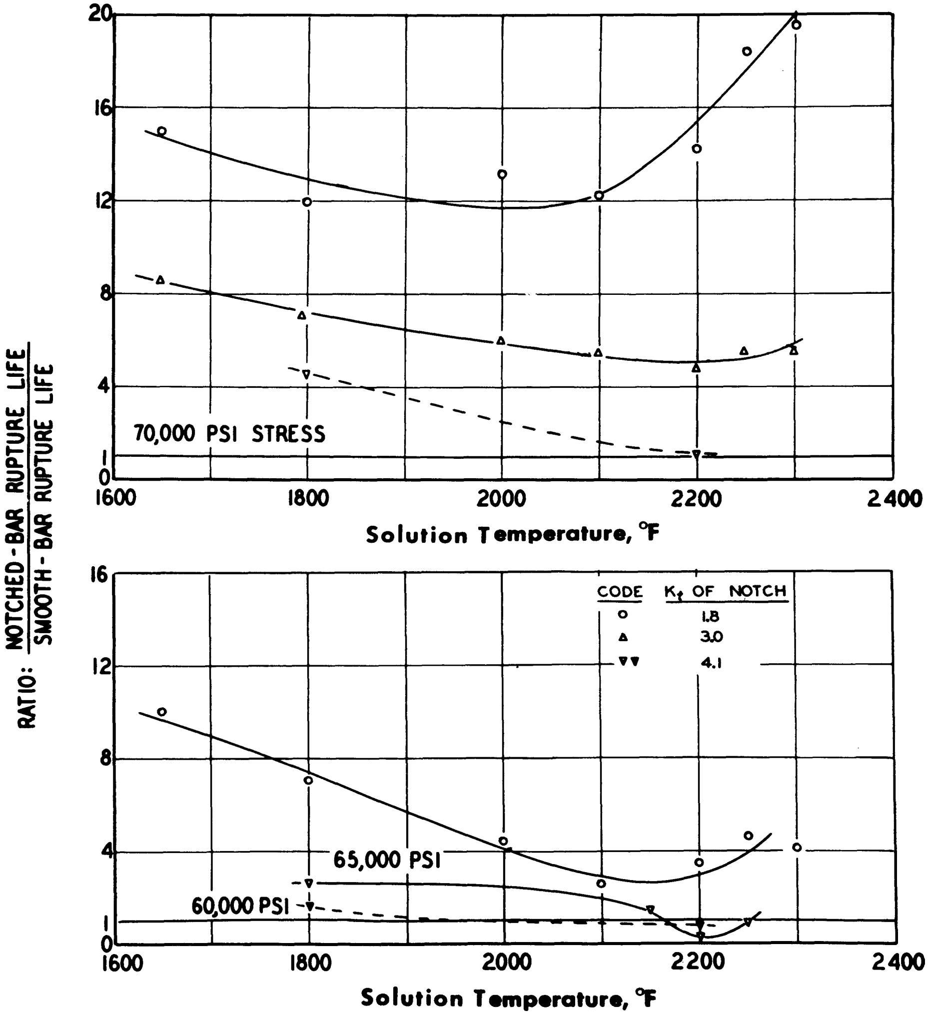


FIG. 5 - VARIATION OF NOTCH STRENGTH RATIO WITH SOLUTION TEMPERATURE FOR A-286 AT 1200°F.

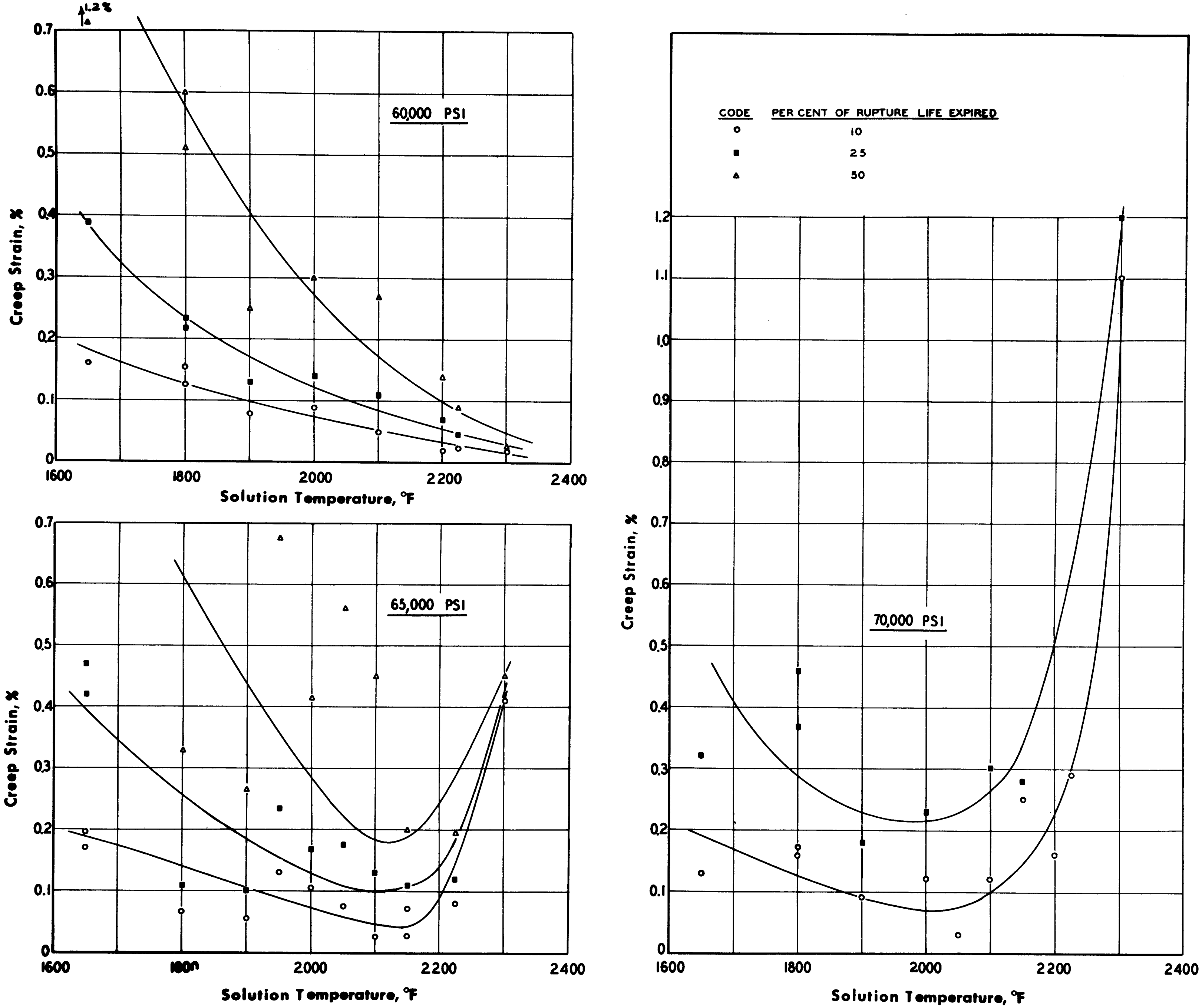


FIG. 6 - CUMULATIVE CREEP STRAIN VERSUS SOLUTION TEMPERATURE FOR SPECIFIED STRESSES AND PERCENTAGES OF RUPTURE LIFE EXPIRED IN A-286 TESTED AT 1200°F.

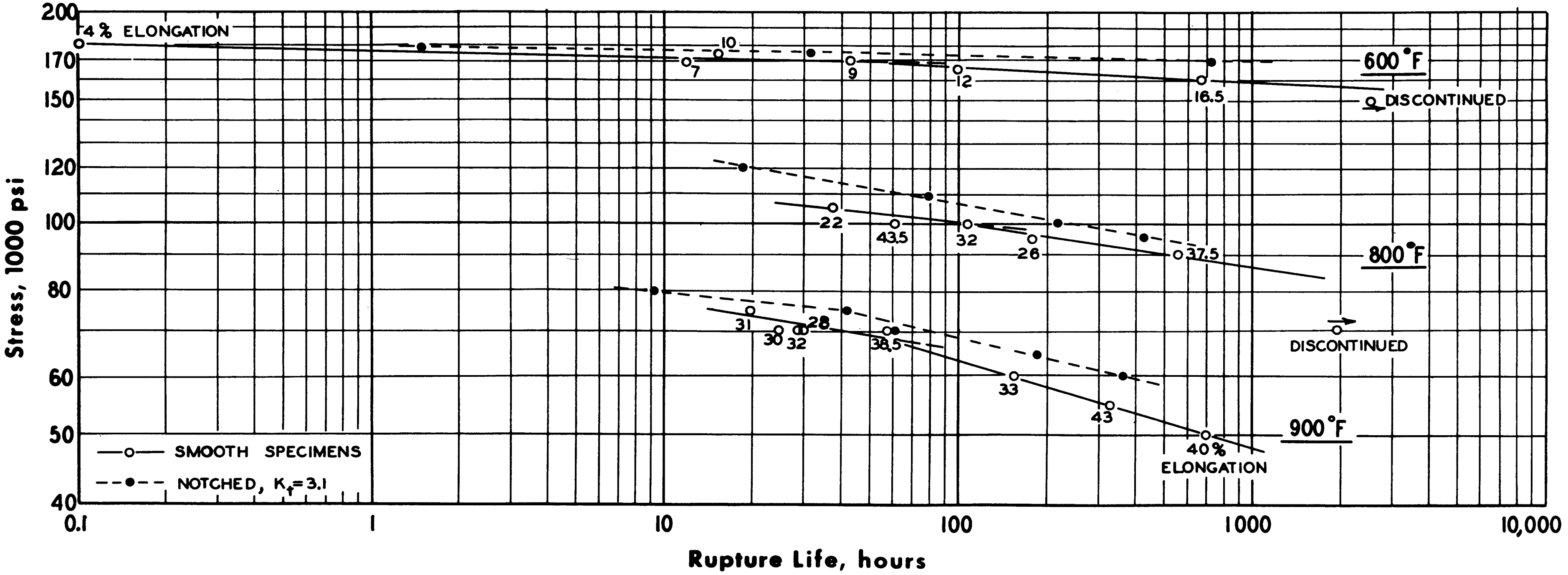


FIG. 7 - STRESS VERSUS RUPTURE LIFE AT 600°, 800° AND 900°F FOR SMOOTH AND NOTCHED SHEET SPECIMENS OF 17-7PH IN THE TH-1050 CONDITION.

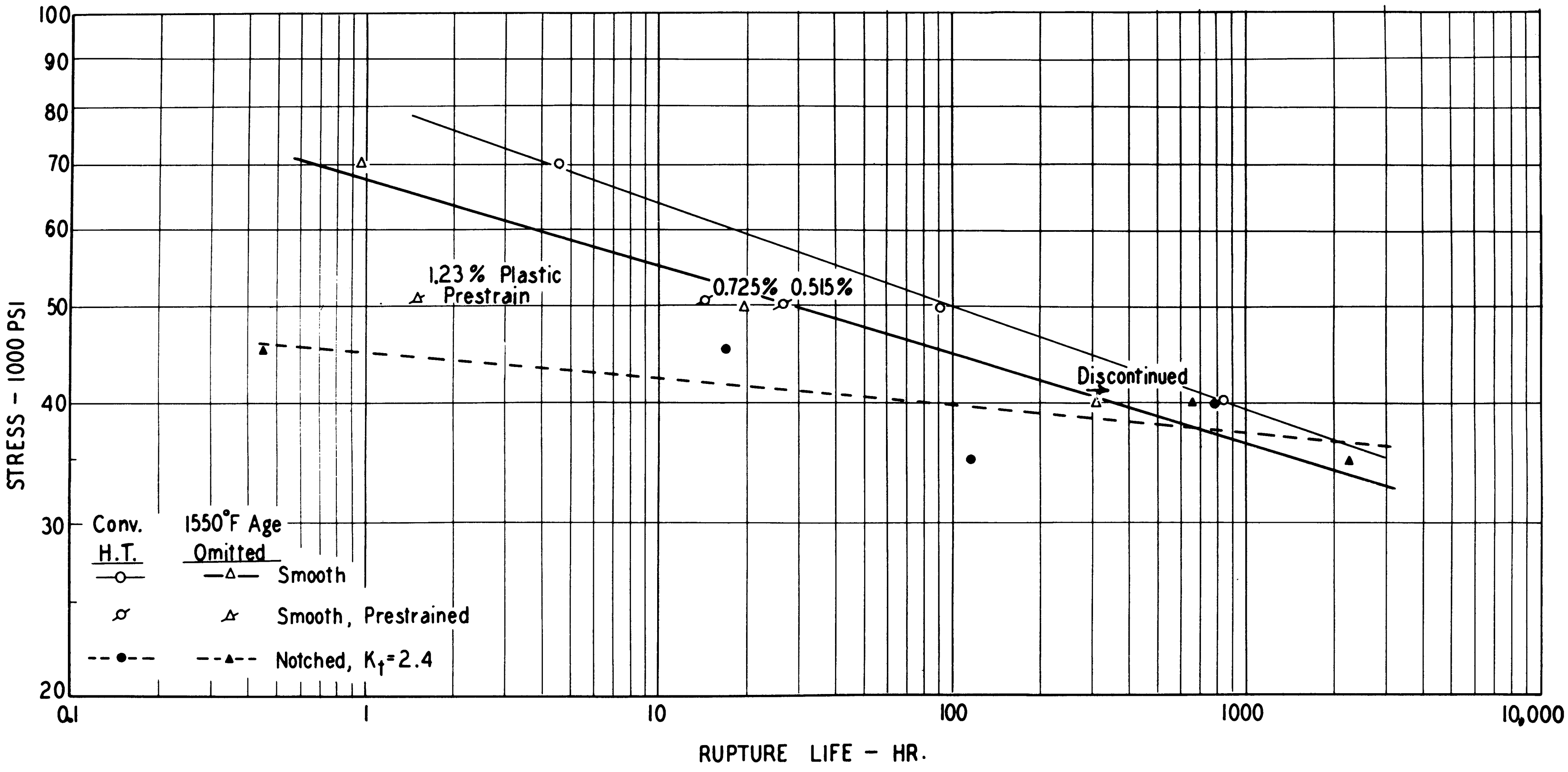


FIG. 8 — RUPTURE PROPERTIES AT 1350°F FOR WASPALOY HEAT 63,559.

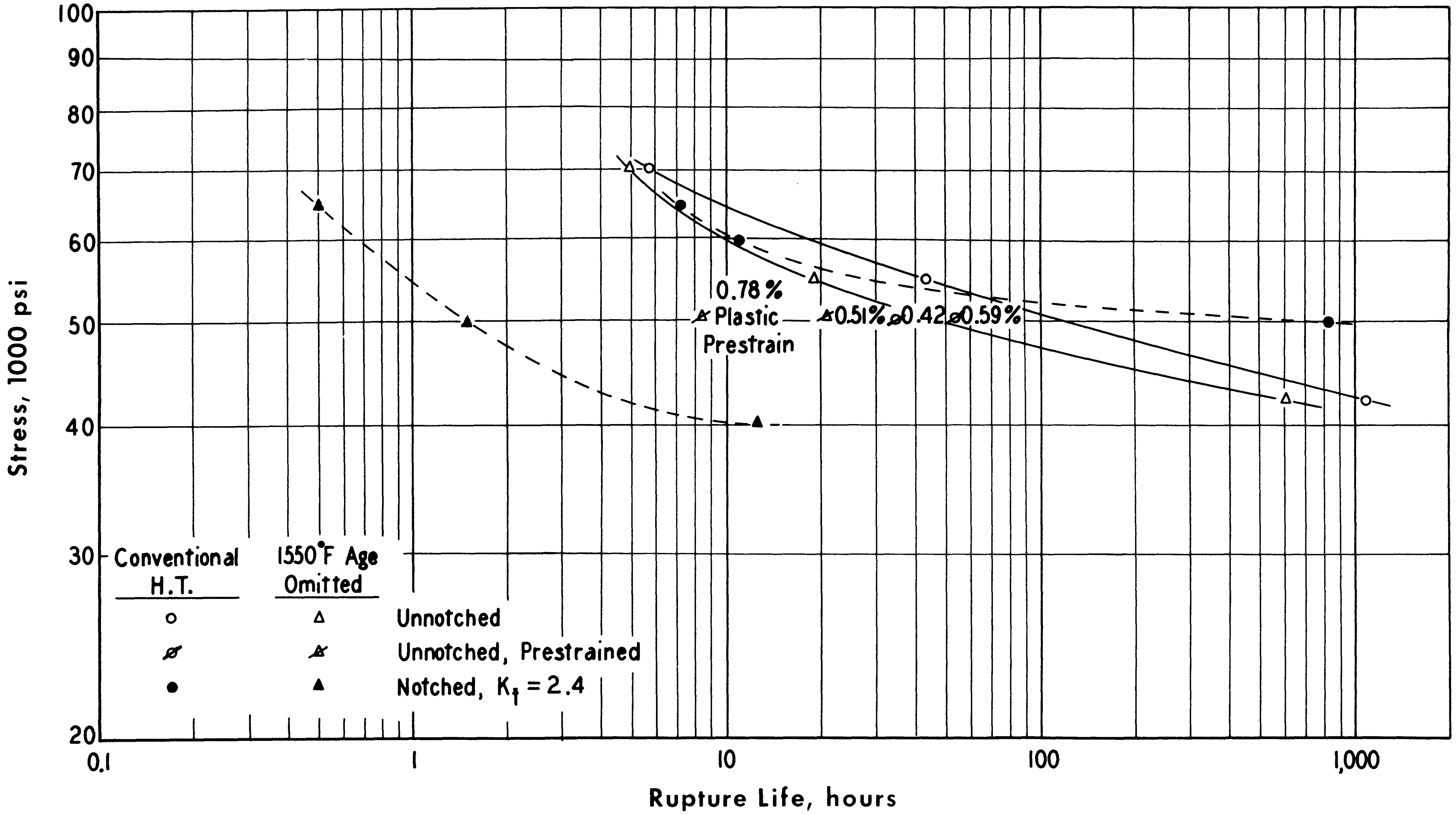


FIG. 9 - RUPTURE PROPERTIES AT 1350°F FOR WASPALOY HEAT 63,561.

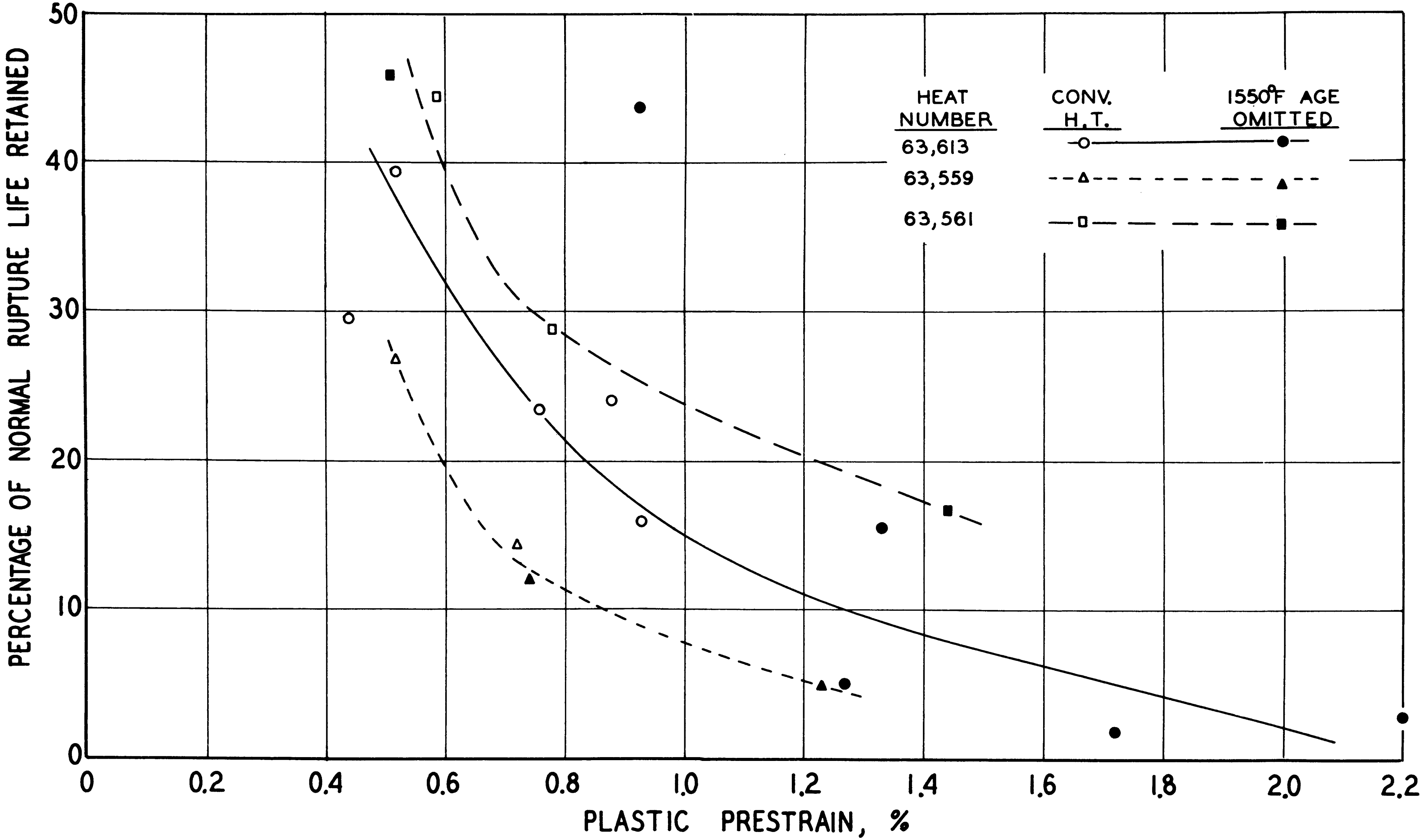


FIG. 10 - EFFECT OF PLASTIC PRESTRAIN ON SUBSEQUENT RUPTURE LIFE OF WASPALOY AT 1350°F.