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TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

NOTCH SENSITIVITY OF STRUCTURAL ALLOYS

by

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SUMMARY

Experimental results are presented for work conducted under Contract AF 33(616)-3380 through 30 June 1957. In search for basic properties of alloys which determine their response to a stress concentration, tests at 1200°F with vacuum melted A-286 alloy have been extended to cover notched rupture specimens with a theoretical stress concentration factor (K_t) from 1.27 to 5.7. Other tests on unnotched specimens have investigated creep and rupture characteristics with and without prior plastic prestrain at the test temperature. The solution temperature used for heat treatment of the specimens was a major variable in this series of tests. The chief finding was a high peak at rather low K_t in the curve of rupture strength at 60 - 70,000 psi stress plotted as a function of K_t.

Additional experiments were conducted with this and another lot of A-286, with three heats of Waspaloy and with two small heats of a 55 Ni, 20 Cr, 15 Co, 4 Mo, 3 Ti, 3 Al alloy to further investigate effects of test temperature, boron content and plastic prestrain on notch behavior. No one of these factors by itself seemed to be a key determinant of notched-bar rupture characteristic. Apparently, together with melting and rolling practice they exert their effect by helping to determine the inherent yield, creep, rupture and ductility properties of the alloy and by influencing the stability of these properties at test conditions.

Emphasis during the remainder of the contract term is expected to be placed on attempts at quantitative correlation of smooth-bar properties to notch-bar behavior. Detailed study of variables considered to date or of rolling procedure is planned only as needed to provide quantitative data for correlations.

Plans have been made to examine fractured notch specimens for clues into the character of notch behavior under different conditions. Such studies would be particularly useful if combined tension-torsion tests were available to demonstrate what combinations of principal stresses or principal strains determine creep-rupture life under variable complex stresses.

INTRODUCTION

This report presents results of experiments conducted through 30 June 1957 under USAF Contract No. AF 33(616)-3380. The work is part of a continuing study into creep rupture of notched tension specimens of aircraft structural and engine alloys. It has the objective of clarifying the basic properties of such materials which determine their response to the presence of a stress concentration.

One aim of this research is to permit the prediction of notch behavior of an alloy from properties determined with conventional specimens. If a satisfactory quantitative solution can be found for notched specimens under constant axial tension, attempts are to be made to generalize the analysis to include any and all arbitrary patterns of stress distribution with time.

Earlier experiments surveyed notch-rupture behavior of seven different materials ranging from an age-hardening aluminum alloy to heat-resistant turbine alloys. A variety of heat treatments was used with two of the materials, with five separate heats of the alloy having been studied in the case of Waspaloy at 1350°F.

For each condition tested, properties of conventional unnotched (smooth) specimens were determined and studied for factors influencing creep-rupture response to a notch. All experimental trends appeared capable of qualitative explanation in terms of three general factors:

(1.) The initial stress pattern around the notch, taking into account any yielding when the load is applied.

(2.) The rate of creep relaxation of the remaining stress concentration, compared to the rate at which rupture life is used up.

(3.) Alteration of basic creep and rupture properties as a result of the plastic strain at loading or of time-dependent metallurgical changes during the subsequent period of variable-stress creep.

A step-wise calculation method to predict notched-bar rupture life was developed (Ref. 1), based on the assumptions that rupture under creep conditions is controlled by an effective stress derived from the shear stress invariant theory and that fractions of rupture life are quantitatively additive for creep under variable effective stress. Predicted notched-bar rupture life agreed reasonably well with experimental determinations for materials tested under conditions where they are metallurgically stable. In some cases where agreement was less favorable, observed deviations could be explained with the aid of fragmentary data on changes in creep-rupture properties of smooth specimens subjected to a history of variable stress designed to simulate conditions in typical fibers of a notched bar. However, for none of the original alloys studied was sufficient stock available to permit complete evaluation of the material's smooth-bar behavior under all types of stress history to be found in notched rupture specimens investigated.

The present phase of the investigation seeks to overcome this deficiency by permitting extensive work on a single alloy. For this particular research, A-286 alloy was chosen in the belief that both notch strengthening and notch weakening should be obtainable with the same heat of material by merely altering the solution temperature. Concurrent tests on this or other alloys were aimed at delineation of the role of smooth-bar rupture ductility in notch response under creep conditions and at clarification of the part played by minor amounts of boron, zirconium or other elements in the reputed variable notch behavior of specimens from different heats of alloy with a common nominal composition.

EXPERIMENTAL RESULTS

Test data for A-286 in the temperature range from 1100° to 1300°F and for Waspaloy at 1350°F have been obtained to supplement results reported the first year of the current contract (See Ref. 2). New test materials include a lot of A-286 believed to be more prone to notch effects than the original stock, as well as two small melts of a 55 Ni - 20 Cr - 15 Co - 4 Mo - 3 Ti - 3 Al alloy prepared at the University of Michigan with different levels of boron content. The A-286 and Waspaloy were donated by the Allegheny-Ludlum Steel Corporation.

The producer supplied the chemical analyses, in weight percent, for the major elements. Analysis for the low boron contents is difficult and imperfectly standardized. Where indicated in the following tabulation, independent check analyses were made without charge by the Universal-Cyclops Steel Corporation:

Alloy:	A-286		Waspaloy			55 Ni - 20 Cr - 15 Co - 4 Mo - 3 Ti - 3 Al	
Heat No.:	21,030	43,297	63,559	63,561	63,613	1148	1150
C	0.06	0.025	0.06	0.03	0.04	0.08	0.07
Mn	1.35	1.21	0.74	0.64	0.73	0.13	0.12
Si	0.47	0.86	0.49	0.56	0.66	0.17	0.16
P	0.018	0.016	0.016	0.015	0.014	0.006	0.008
S	0.014	0.017	0.014	0.019	0.014		
Cr	14.58	15.12	19.13	20.12	20.16	19.7	19.4
Ni	25.30	26.16	Bal	Bal	Bal	Bal	Bal
Mo	1.38	1.32	2.89	3.06	3.15	3.90	3.75
Co			13.29	14.10	14.25	15.0	16.5
Fe	Bal	Bal	0.97	0.96	1.33	<0.30	<0.30
Al	0.17	0.40	1.50	1.34	1.00	3.35	3.26
Ti	2.00	1.94	2.30	2.21	2.54	3.08	3.02
V	0.21	0.23					
Cu			0.15	0.16	0.06	<0.01	<0.01
Mg						<0.01	<0.01
N		0.010					
Zr						<0.01	<0.01
B	0.004	0.002				0.0002	0.009
a)B	0.0019	0.0008					
b)B		0.0005					

a) Check analysis by Universal-Cyclops Steel Corp.; determined by wet chemistry.
b) Check analysis by Universal-Cyclops Steel Corp.; determined spectrographically.

Specimen blanks were given the complete heat treatment prior to machining. Unnotched specimens were prepared by turning between centers on a lathe and then polishing by hand. Notch roots were finished by the lapping process described in Reference 1.

All testing was carried out in University of Michigan creep-rupture frames employing dead-weight loading through a beam and using a modified Martens-type optical extensometer system to measure creep of unnotched specimens.

Test results for each lot of material will be considered separately in the subsections to follow.

A-286 Heat 21,030

This material was melted by the vacuum consumable-electrode process. The 20-inch diameter ingot was processed by the producer 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 so rolled was neither straightened nor annealed before use. Specimen blanks were heat treated by a one-hour solution at a selected temperature, oil quenched, and then aged at 1325°F for 16 hours, air cooled.

Solution temperatures covering the range from 1650° to 2300°F were employed in tests reported previously (Ref. 2) for smooth specimens and for notched specimens with theoretical stress concentration factors of 1.8, 3.0 and 4.1. At nominal stresses of 60,000, 65,000 and 70,000 psi the rupture life at 1200°F for all four types of specimen increased with solution temperature, reached a maximum at solution temperatures of 2000 - 2100°F, and then fell off again for still higher solution temperature. Rupture elongation of smooth specimens dropped steadily from about 9% for 1650°F solution temperature to near 1% for solution temperatures near 2200°F and then rose again for solution temperatures to 2300°F.

From these preliminary findings, solution temperatures of 1800°F and 2200°F were chosen for investigation over wider ranges of applied stress and notch acuity. To date, notched-bar rupture tests have been run for theoretical stress concentration factors of 1.27, 1.54 and 5.7 in addition to the geometries studied previously. For convenient reference, all the rupture-test results at 1200°F, both new and old, are assembled in Table 1 and are plotted separately in Figure 1 for each solution temperature used.

Results are included on the figures for some smooth specimens subjected to prior plastic strains by momentary overloading at the test temperature before the creep-rupture test. Numbers adjacent to data points for these specimens give the percent of plastic prestrain introduced by the overload application. For the limited conditions studied, little change in subsequent rupture life was found for plastic prestrains below about 1%. Larger prestrains (up to 2%) resulted in rupture lives at 60,000 psi stress which were as low as one-third the value for specimens not prestrained before the start of the test.

Separate symbols were used in Figure 1 to distinguish the several notch acuities (K_t's) tested. Results for the two solution temperatures tested most extensively (1800° and 2200°F) indicate that notched-bar life rose to a maximum with increasing stress concentration factor and then fell again for still sharper notches. These trends are more readily visualized when the data are replotted as in Figure 2. The curves of the latter figure are still inaccurately determined over part of the range of test variables, but one striking characteristic is the rapid rise and fall-off of rupture life for the 2200-2225°F solution temperature as the theoretical stress concentration factor is increased from $K_t = 1.0$ (smooth specimen) to $K_t = 2$. The peak strength with the 1800°F solution temperature appears from the available data to occur at somewhat higher stress concentrations.

Since the notch geometry giving peak rupture strength differed for the two solution temperatures considered in Figure 2, the observed variation in notch properties cannot depend solely on the geometry and nominal stress. The type of notch response exhibited for a given alloy and test temperature must therefore be associated with the material's basic properties at the temperature. Comparison of the curves of Figure 1 for 1800° and 2200°F solution temperatures indicates a much flatter curve of stress versus rupture time for the material with the higher solution temperature. Major differences in yield and creep characteristics are also exhibited by specimens with these two different solution temperatures. (See Figures 3 and 4).

The stress-strain properties shown in Figure 3 are average plots of curves obtained during loading of four creep-rupture specimens solution treated at 1800°F and of five specimens tested with the 2200°F solution temperature.

Creep data have been determined over too narrow a range of stress level to warrant preparation of plots showing creep rate as a function of stress. However, a qualitative picture of the pertinent creep behavior may be developed from a plot of the accumulated creep strain during a fixed fraction of the rupture time at each stress level. Figure 4 compares the creep during the first 5% of the rupture life of specimens solution treated at 1800° and at 2200° - 2225°F. With the 1800°F treatment, the extent of creep in the first five percent of the test time appears to be rather insensitive to the stress level between 60,000 and 90,000 psi. A much greater variation with stress level was found for the 2200° - 2225°F solution temperature. The lower of the two solution temperatures may also have produced a greater increase in early creep strain after about 1 percent prior plastic strain at the test temperature from momentary overloading at the start of the test. This tentative conclusion may not stand after more-complete data are available.

Experiments at 1100° and 1300°F with A-286 have been restricted to specimens solution treated at 1800°F or at 2200°F, with all notched specimens having a theoretical stress concentration factor $K_t = 3$. (See Fig. 5). Mild notch strengthening occurred at 1100°F for both solution temperatures studied, while the notch strength considerably exceeded the smooth-bar rupture strength at 1300°F. Meager survey tests suggest that plastic prestrains of 1 - 2 percent may produce a several-fold loss in subsequent smooth-bar rupture life at 1100°F. The single prestrain experiment at 1300°F suggests a relatively minor decline in smooth-bar life by prestrain at that temperature.

A-286 Heat 43,297

Only a small quantity of 7/8-inch diameter round was available from this lot of alloy. The final hot rolling was from 2050°F, with a finishing temperature in the neighborhood of 1650°F. Heat treatment consisted of a one-hour solution at 1650°, 1800° or 1985°F, oil quench, followed by a 16-hour age at 1325°F, air cool.

Survey tests listed in Table 3 and shown graphically in Figure 6 studied relative rupture strength at 1200°F of smooth bars and notched specimens with $K_t = 3.0$. A single unnotched specimen was allotted for each solution temperature to investigate the magnitude of change in smooth-bar life after prior plastic strain of about 1 percent at the 1200°F test temperature. Decided notch strengthening, mild notch strengthening and mild-to-moderate notch weakening characterized specimens solution treated at 1650°, 1800° and 1985°F, respectively. All three solution temperatures produced about the same decrease in smooth-bar life from plastic prestrain.

55 Ni, 20 Cr, 15 Co, 4 Mo, 3 Al, 3 Ti Alloy at 1600°F

Two ten-pound heats of this alloy were melted in a small vacuum induction furnace at the University of Michigan, using care to follow the same procedures for both melts except for deliberate boron addition to only one (Heat 1150). The 2-1/2-inch diameter round ingot was rolled to 7/8-inch square bar in 22 passes from 2150°F, with a ten-minute reheat in a 2150°F gas furnace after each roll. The reduction of cross section per pass was about 7 - 8 percent. Specimen blanks were sampled from the hot-rolled stock without further thermal treatment.

Experimental results are presented in Table 4 and Figure 7. The presence of 0.009% boron resulted in a substantial strength increase above that of the boron-free (0.0002% B) material. The higher boron content produced definite notch strengthening at stresses where notch behavior seems to be borderline without boron. Presence of small amounts of boron may also have reduced the tendency for plastic prestrain to lower smooth-bar strength at the conditions studied.

Three Heats of Waspaloy

Reference 2 included data for specimen from three heats of Waspaloy used in a study of the effect of plastic prestrain on subsequent rupture life at 1350°F. In those tests, after a momentary overload at test temperature had imparted an initial plastic strain of 0.4 - 2.2 percent the stress was immediately reduced to 50 - 70,000 and then the test was continued to rupture under constant load. In the more recent tests the stress after prestrain has been set at 42,000 or 45,000 psi to extend the range of variables and to learn whether a given amount of prestrain might cause a greater relative reduction of rupture time for tests run at the lower stresses.

All the data, both old and new, are assembled in Tables 5, 6 and 7 for the three lots of alloy investigated. These tabulated results are separated according to whether or not the intermediate 1550°F aging step was included in the following conventional heat treatment:

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

For the prestrain tests the tables list the momentary overload stress and the measured plastic strain produced by it, the subsequent test stress and rupture life. The elongation and reduction of area tabulated are designated as "total" since they report the total plastic strain produced by both the initial overload and the subsequent creep period at lower stress.

For graphical treatment of the data (See Fig. 8), the tests for all three heats of alloy were combined for each of the two heat treatments. Separation was made into rough groups of specimens with zero and about 0.5%, 1% and 1.5% prestrain. Scatter was pronounced, for material without the 1550°F age but at least the results as plotted appear to rule out any significant effect of test stress on the relative reduction of life produced by a given magnitude of plastic prestrain. Better correlation would probably result if more complete testing could have been carried out, permitting separate curves for each lot of alloy, but even with results for all three heats plotted together the influence of amount of prior strain and of which heat treatment was used seems to outweigh uncertainties introduced by heat-to-heat variations.

DISCUSSION AND FUTURE WORK

Experimental results gathered during the past six months are incomplete in many respects and leave unanswered many pertinent questions. But they do provide the outline of notch behavior over a more extended range of variables than hitherto assembled in this program.

The rupture data for A-286 Heat 21,030 at low K_t's should be especially useful to test the ideas and analyses developed in earlier reports. Any theory of notch behavior which fails to predict the sharp peak in rupture strengths at $K_t = 1.2 - 1.5$ for the 2200°F solution treatment and the milder peak at somewhat higher notch acuity for the 1800°F treatment cannot be considered of general applicability.

A notched bar under tension has a concentrated complex stress localized near the notch root. Failure to relieve this high stress may be presumed to result in shorter creep-rupture life in a notched specimen than for a smooth specimen under like nominal stress. So far in this program only two plausible explanations have been conceived for the frequent case where notched-bar rupture life exceeds that of corresponding smooth bars:

1.) Interaction of the principal components of stress produces an effective stress which determines creep and which is lower in magnitude than the axial component used as a comparison with the simple-tension test. The same or some similar combination of the principal stresses may be hypothesized to control rupture behavior of ductile alloys. If extensive creep can relax the initial stress concentration before the bulk of the total rupture life is used up, notch strengthening should be possible.

2.) Yielding occurs near the notch root for most materials for the test conditions and notch geometries used in the common acceptance tests. Such yielding limits the magnitude of the peak stresses obtained. If the resultant plastic strain raises the rupture strength of the material near the notch root, prolongation of life beyond that of the normal smooth specimen could be expected. Should the initial plastic strain damage the material near the notch root, notch weakening should follow.

The partially-completed series of experiments with A-286 at K_t = 1.27 and 1.54 should furnish a good test of whether notch strengthening requires short-time plastic redistribution of stresses to lower the peak stresses or whether the creep process alone can suffice. Allowing for the demonstrated influence of stress interaction on yield characteristics, the peak effective stress under elastic loads at K_t = 1.27 is just under 1.2 times the nominal value, and for K_t = 1.54 about 1.45 times the nominal stress. This means that for a 60,000 psi nominal stress studied to date the maximum amount of local yielding at the notch root does not exceed a few hundredths of a percent when the load is added to a specimen with K_t = 1.27. With K_t = 1.54 considerable initial yielding would take place in the specimens with 2200°F solution, but very little for the material with 1800°F treatment. Reduction of the nominal stress to 50,000 psi should eliminate all perceptible yielding in a notch with K_t = 1.27 for either treatment, assuming reasonable freedom from any residual stresses imparted by the notching operation.

Results available so far with the A-286 from Heat 21,030 suggest that different heat treatments result not so much in different kinds of notch behavior as in shifting of the conditions at which a given degree of notch strengthening or weakening will occur. For example, the trends of the data in Figure 1 for K_t = 1.8 and K_t = 3.0 suggest that for any solution temperatures between 1800° and 2300°F longer-time tests (i.e., at lower nominal stresses) might be expected to show a transition to notch weakening. This matter deserves experimental verification.

Another trend in common for the entire range of solution temperatures is the initial gain in rupture life at 60 - 70,000 psi stress as the notch acuity is increased, followed by a fall to near the smooth-bar strength when theoretical stress concentration factors become greater than 3 - 4. One might inquire whether the latter fall-off is due to the initial local deformation, which may reach several percent at the very root of a notch with K_t of 5 or 6 at 70,000 psi stress. A preliminary step in this direction is planned in the form of short-time tensile tests at 1200°F using smooth specimens with the 1800°F and the 2200°F solution temperature. Suitable follow-up tests would include experiments on unnotched specimens in which a momentary prestrain stress was followed by successive periods at lower and lower applied stress, approximating the type of stress pattern anticipated to occur near a notch during a constant-load test with a notched specimen.

Such "notch simulation" tests should provide useful indications of expected behavior around a notch root, but they are completely lacking in the element of complex stress pattern present in the notched tension bar. A firm demonstration of the general role of ductility and/or time at stress in creep-rupture behavior under the variable stress pattern of a notch must include provision for simultaneous multi-axial loading of a suitable test specimen. Introduction into the program of equipment to investigate creep-rupture of tubular specimens under variable combined tension and torsion would appear desirable.

With a compound-stress test unit one should be able to clarify questions which must be answered before a general procedure for design under variable concentrated stresses can be set up; namely, what combinations of principal stresses or principal strains determine creep-rupture under conditions of interest. The answer may not be simple. Indeed the largest principal stress, the effective stress and some measure of strain may all be controlling for the same material exposed to different situations or when conditioned differently by variations in trace-element content, rolling practice or heat treatment.

Another area of study yet to be exploited is detailed examination on both a macro and a micro scale of fractured notch specimens to determine whether the type of notch response is associated with transgranular versus intergranular type of fracture. Such studies alone may provide valuable clues into the character of notch behavior under different conditions, but would be especially useful if combined with tests of the type suggested in the preceding paragraph.

Experimental results presented earlier show notch properties to be significantly altered by changes in trace-element chemistry, heat treatment, test temperature and prestrain effects. These factors are probably all interrelated, as well as related to melting and rolling practice. By itself no one factor seems a key determinant of notch rupture characteristics, but rather plays a part by helping to determine the inherent yield, creep, rupture and ductility properties of the material, and by influencing the stability of these properties at test conditions. At the present stage of progress in this research, detailed study of any one of the above influences seems undesirable except as needed to provide data for use in attempted quantitative correlations between smooth-bar properties and notched-bar behavior. Emphasis is expected to be placed for the remainder of the current contract period on efforts at such correlations for the A-286 Heat 21,030.

The supply of material from the three heats of Waspaloy and the two lots of 55 Ni, 20 Cr, 15 Co, 4 Mo, 3 Al, 3 Ti alloy has been completely exhausted. Enough stock is left from A-286 Heat 43,297 for at most 10 further tests; this remaining material will be reserved for critical tests which may be developed at a later time.

Material from A-286 Heat 21,030 should be adequate for any further tests which are now foreseen, but it does not lend itself to convenient investigation of rolling-practice variables, nor does it exhibit notch weakening under usual conditions of commercial testing. Both these limitations appears to be overcome by a new lot of air melted A-286 recently transferred to this project from a completed study of forged rotor disks performed by the General Electric Company for the Materials Laboratory, WADC under Contract AF 33(616)-2778. A total of 142 pounds of material was supplied as rough-turned round stock with 4-1/2-inch diameter. An initial portion has been planned for rolling under a schedule comparable to that used by Allegheny-Ludlum for the Heat 21,030 stock. Any later modifications of the rolling procedure can best be selected when results for A-286 Heat 21,030 become available under another project at the University of Michigan. (This work under contract AF 33(616)-3239 includes a study of the influence of working conditions on creep-rupture properties.) The amount of A-286 in the new lot should be ample for detailed study under a wide range of prior history and test conditions, if this seems desirable as the program progresses.

BIBLIOGRAPHY

1. Voorhees, H. R. and Freeman, J. W. Notch Sensitivity of Heat-Resistant Alloys at Elevated Temperatures. Wright Air Development Center, Technical Report 54-175, Part 3, Final Data and Correlations, September, 1956.

2. Voorhees, Howard R. and Freeman, James W.; Notch Sensitivity of Aircraft Structural and Engine Alloys. Wright Air Development Center, Technical Report 57-58, Part I, Preliminary Studies with A-286 and 17-7PH (TH 1050) Alloys, May 1957.

TABLE 1

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

(Heat No. 21,030)

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	90,000	1.45	8.	9.
1800	80,000	4.25	8.	8.5
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	75,000	3.8	2.5	5.5
2200	70,000	7.2	1.5	7.
2200	60,000	308.7	1.	2.5

TABLE 1 (con'd.)

Solution Temperature (°F)	Stress (psi)	Rupture Life (hr)	Elongation at Rupture (%)	Reduction of Area (%)
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)	Total Elongation at Rupture (%)	Total Reduction of Area in Rupture (%)
1800	100,000 +	0.80	70,560	17.9	8.	9.5
1800	108,240	0.90	60,540	59.8	6.5	11.
1950	98,000	0.72	70,525	31.3	8.	9.5
1950	100,000	1.33	65,870	90.0	7.	9.
2050	100,000	2.03	61,220	183.3	6.	9.5
2200	84,070	1.31	60,790	99.8	2.5	4.5
**2200	100,000	0.97	60,000	226.6 +	--	--
**2200	82,000	0.37	59,920	328	--	--
2200	81,000	0.90	60,240	307.0	1.5	4.
2300	83,740	1.56	60,940	17.6	3.5	8.5

** Overheated -- discontinued

TABLE 1 (con'd.)

Notched Bars

Solution Temperature (°F)	Stress (psi)	Rupture Life (hr)	
* Nominal Notch Geometry: D = 0.462, d = 0.326, r = 0.237, K_t = 1.27			
1800	70,000	22.6	
1800	60,000	319.3	
2200	70,000	451.3	
* Nominal Notch Geometry: D = 0.462, d = 0.327, r = 0.108, K_t = 1.54			
1800	70,000	215.3	
1800	65,000	292.3	
2200	70,000	657.5	
* 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	
2200	70,000	206.3	
2200	65,000	257.7	
2225	70,000	143.3	
2225	65,000	602.9	
2300	70,000	41.2	
2300	65,000	62.8	

TABLE 1 (con'd.)

Solution Temperature (°F)	Stress (psi)	Rupture Life (hr)
* 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
2200	65,000	219.3
2200	60,000	414.2
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
* Nominal Notch Geometry: D = 0.600, d = 0.424, r = 0.005, K_t = 5.7		
1800	70,000	27.3
1800	65,000	106.7

* 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 1100° AND 1300°F FOR A-286 HEAT 21,030

Heat Treatment: 1 hr Solution, Oil Quenched + Age at 1325°F, 16 hr, Air Cool.

Solution Temp (°F)	Test Temp (°F)	Stress (psi)	Rupture Life (hr)	Total Elongation at Rupture (%/2 in.)	Total Reduction of Area at Rupture (%)	Remarks
					SMOOTH BARS	
2200	1100	85,000	23.1	4.	6.5	1.65% Plastic strain on loading to test stress
2200	1100	75,000	642.6	1.5	3.5	
2200	1100	85,400	54.7	2.5	8.5	1.43% Plastic prestrain by momentary overload to 95,000 psi
2200	1100	76,000	20.1	4.	7.5	2.23% Plastic prestrain by momentary overload to 96,370 psi
1800	1100	85,000	31.5	4.	8.5	
1800	1100	75,000	176.8	4.	7.5	
1800	1100	75,070	102.4	4.	7.5	1.1% Plastic prestrain by momentary overload to 110,000 psi
2200	1300	45,000	303.3	4.	6.5	
2200	1300	44,970	262.1	5.	10.	1.05% Plastic prestrain by momentary overload to 70,000 psi
1800	1300	45,000	44.6	14.	24.	
					[a] NOTCHED BARS	
2200	1100	85,000	126.4	--	--	
1800	1100	85,000	43.6	--	--	
2200	1300	45,000	740.2	--	--	
1800	1300	45,000	167.2	--	--	

[a] Nominal Notch Geometry: Diameter of Shank, D = 0.460 inch
Min. drain, at base of notch, d = 0.325 inch
Notch root radius, r = 0.017 inch
Theoretical stress conc., $K_t = 3.0$

TABLE 3

RUPTURE PROPERTIES AT 1200°F FOR A-286 HEAT 43,297

Heat Treatment: 1 hr Solution, Oil Quench + 16 hr Age at 1325°F, Air Cool

Solution Temp (°F)	Stress (psi)	Rupture Life (hrs)	Elongation at Rupture (%/2 in.)	Reduction of Area (%)	Remarks
			SMOOTH BARS		
1650	65,000	24.9	10.5	14.5	
1650	60,000	41.9	8.5	12.5	
1650	55,000	75.4	9.	13.	
1650	55,000	30.1	10.5	19.	1.0% plastic prestrain by momentary overload to 108,060 psi
1800	65,000	29.2	4.	6.5	
1800	55,000	121.4	9.	11.5	
1800	59,850	34.4	4.	7.5	0.76% plastic prestrain by momentary overload to 104,520 psi
1985	65,000	73.5	3.	5.5	
1985	55,000	385.5	4.	5.5	
1985	55,020	176.2	1.5	4.5	1.13% plastic prestrain by momentary overload to 98,000 psi
			[a]NOTCHED BARS		
1650	70,000	86.5	--	--	
1650	65,000	126.8	--	--	
1650	60,000	109.2	--	--	
1800	65,000	60.4	--	--	
1800	60,000	124.9	--	--	
1800	55,000	284.1	--	--	
1985	65,000	4.0	--	--	
1985	55,000	270.8	--	--	

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[a] Nominal Geometry: Diameter of Shank, D = 0.460 inch
Min. drain, at base of notch, d = 0.325 inch
Notch root radius, r = 0.017 inch
Theoretical stress conc., K_t = 3.0

TABLE 4

RUPTURE PROPERTIES AT 1600°F FOR TWO HEATS OF A 55 Ni, 20 Cr, 15 Co, 4 Mo, 3 Al, 3 Ti ALLOY MELTED AT THE UNIVERSITY OF MICHIGAN

Heat Treatment: Hot rolled from 2150°F

Momentary Overload Stress (psi)	Measured Plastic Strain from Overload (%)	Test Stress (psi)	Rupture Life (hours)	Total Elongation at Rupture (%)	Total Reduction of Area at Rupture (%)
SMOOTH BARS, HEAT 1148 (0.0002%B)					
-	-	20,000	70.5	10.	4.5
85,000	1.05	20,010	46.8	1.	5.
82,500	0.39	19,980	73.1	4.	4.
[a]NOTCHED BARS, HEAT 1148 (0.0002%B)					
-	-	30,000	14.0	-	-
-	-	25,000	33.8	-	-
-	-	20,000	112.6	-	-
SMOOTH BARS, HEAT 1150 (0.009%B)					
-	-	35,000	67.5	10.	15.
-	-	30,000	120.8	9.	9.5
90,140	1.31	25,075	275.6	9.5	11.
[a]NOTCHED BARS, HEAT 1150 (0.009%B)					
-	-	30,000	330.6	-	-
-	-	25,000	668.0	-	-
-	-	20,000	1349.8	-	-

[a] Nominal Notch Geometry:
Diameter of Shank, D = 0.355 inch
Min. drain. at notch root, d = 0.250 inch
Notch root radius, r = 0.011 inch
Theoretical stress conc. factor, $K_t = 3.2$

TABLE 5

SMOOTH-BAR RUPTURE TESTS AT 1350°F FOR WASPALOY HEAT 63559

Momentary Overload Stress (psi)	Measured Plastic Strain from Overload (%)	Test Stress (psi)	Rupture Life (hours)	Total Elongation at Rupture (%)	Total Reduction of Area at Rupture (%)
		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
98,000	0.725	50,360	14.4	1.5	4.
95,000	0.515	50,250	26.9	1.5	3.5
104,620	1.36	45,200	21.1	2.	2.
		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)	
95,000	1.23	50,650	1.5	2.	3.5
92,000	0.74	50,370	3.6	2.5	3.
90,000	0.51	45,030	17.7	1.	1.

TABLE 6

SMOOTH-BAR RUPTURE TESTS AT 1350°F FOR WASPALOY HEAT 63,561

Momentary Overload Stress (psi)	Measured Plastic Strain from Overload (%)	Test Stress (psi)	Rupture Life (hours)	Total Elongation at Rupture (%)	Total Reduction of Area at Rupture (%)
		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
98,000	1.14	44,800	50.7	2.	3.5
95,000	0.59	50,300	53.2	2.5	3.
95,000	0.78	50,390	34.7	2.	4.5
99,000	1.01	41,800	120.6	2.5	2.5
		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
92,000	0.52	44,930	50.3	1.5	2.
98,000	1.44	50,720	7.4	3.	4.
92,000	0.51	50,250	20.8	2.	4.
95,000	1.25	42,100	17.3	3.	4.

TABLE 7

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)	Total Elongation at Rupture (%)	Total Reduction of Area at Rupture (%)
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.
100,000	1.02	44,850	32.5	1.5	4.
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
95,000	0.45	44,700	42.4	1.5	3.

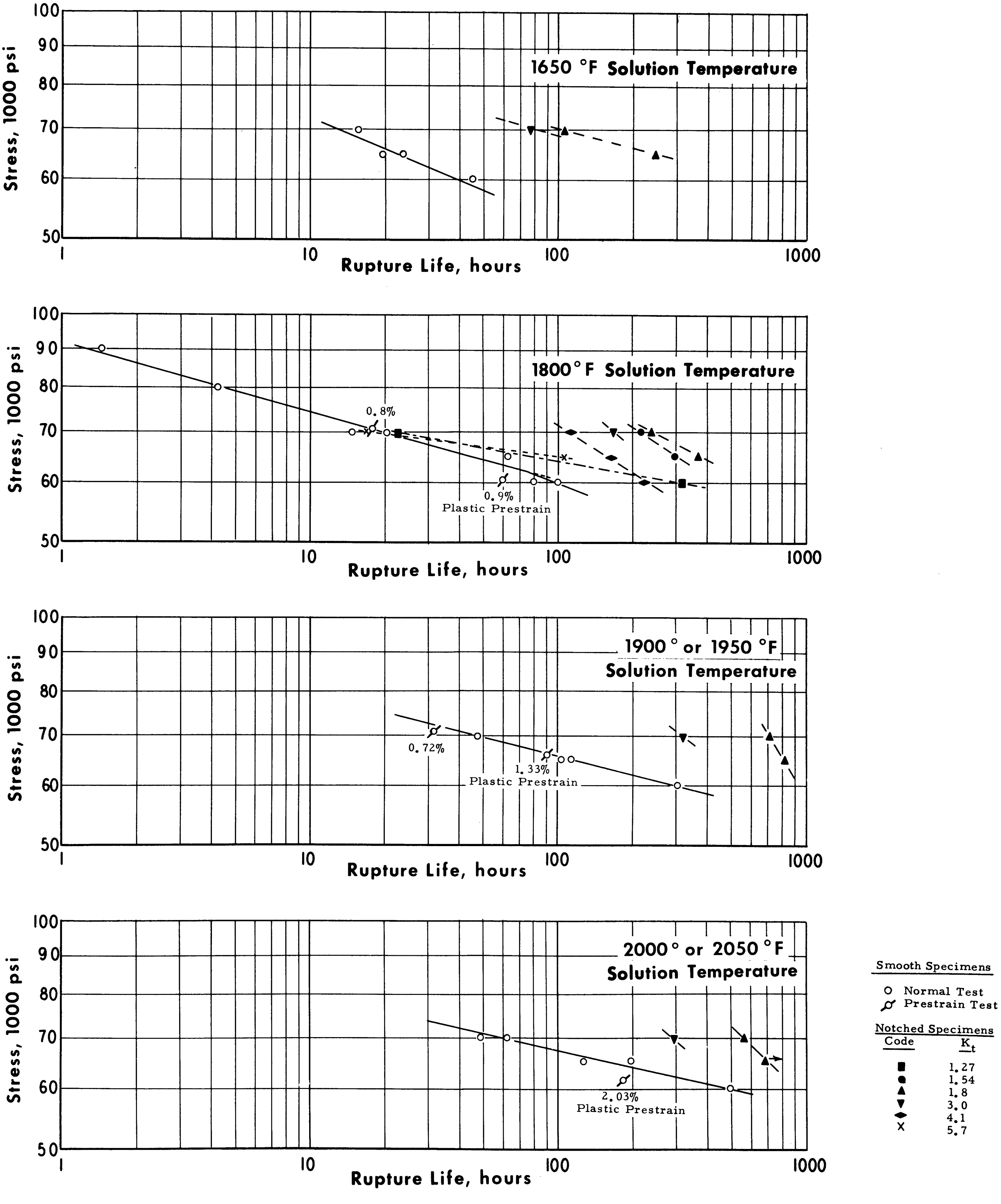

Fig. 1 - Rupture Properties at 1200 °F for Smooth and Notched Specimens of A-286 Heat 21,030 with Different Solution Temperatures.

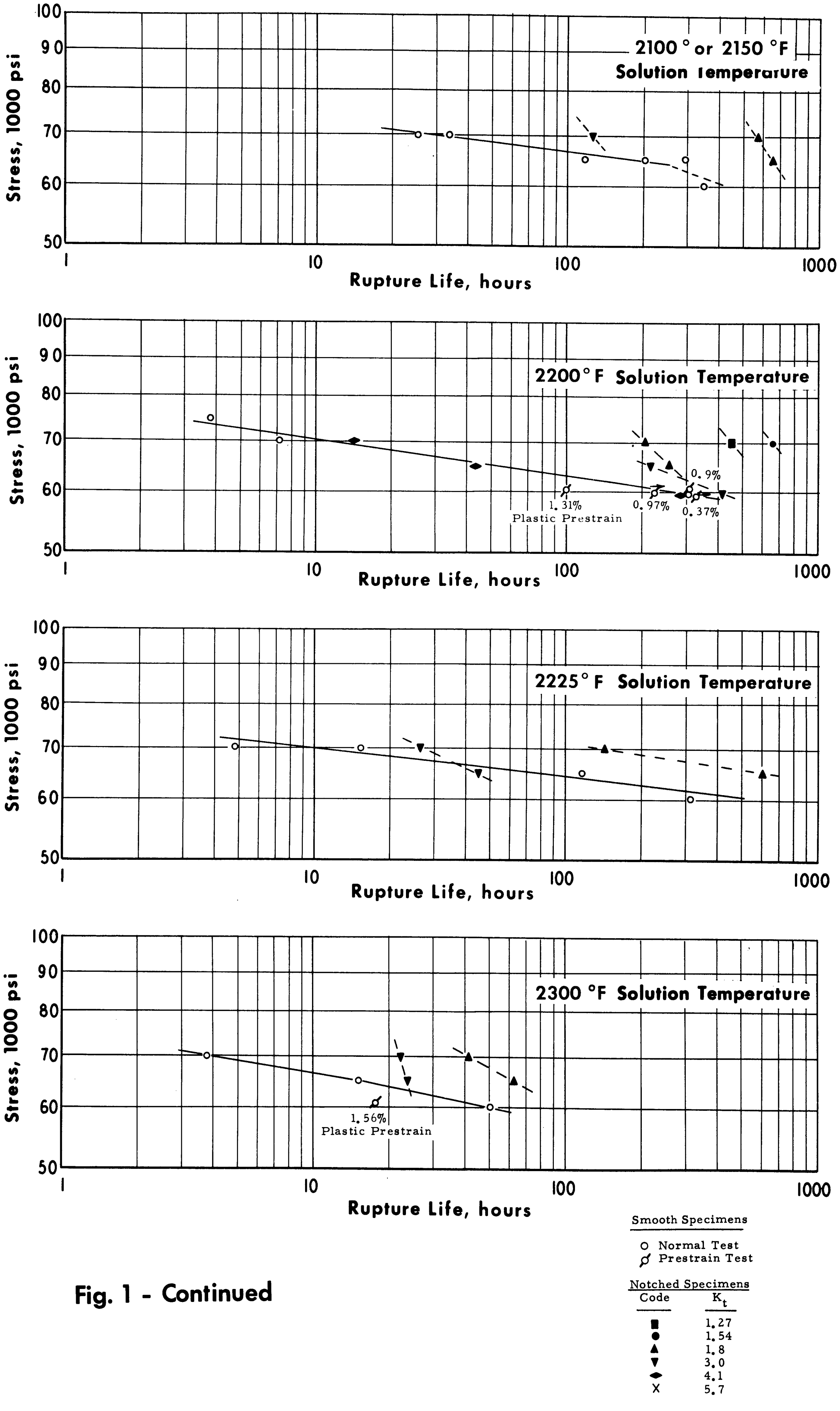

Fig. 1 - Continued

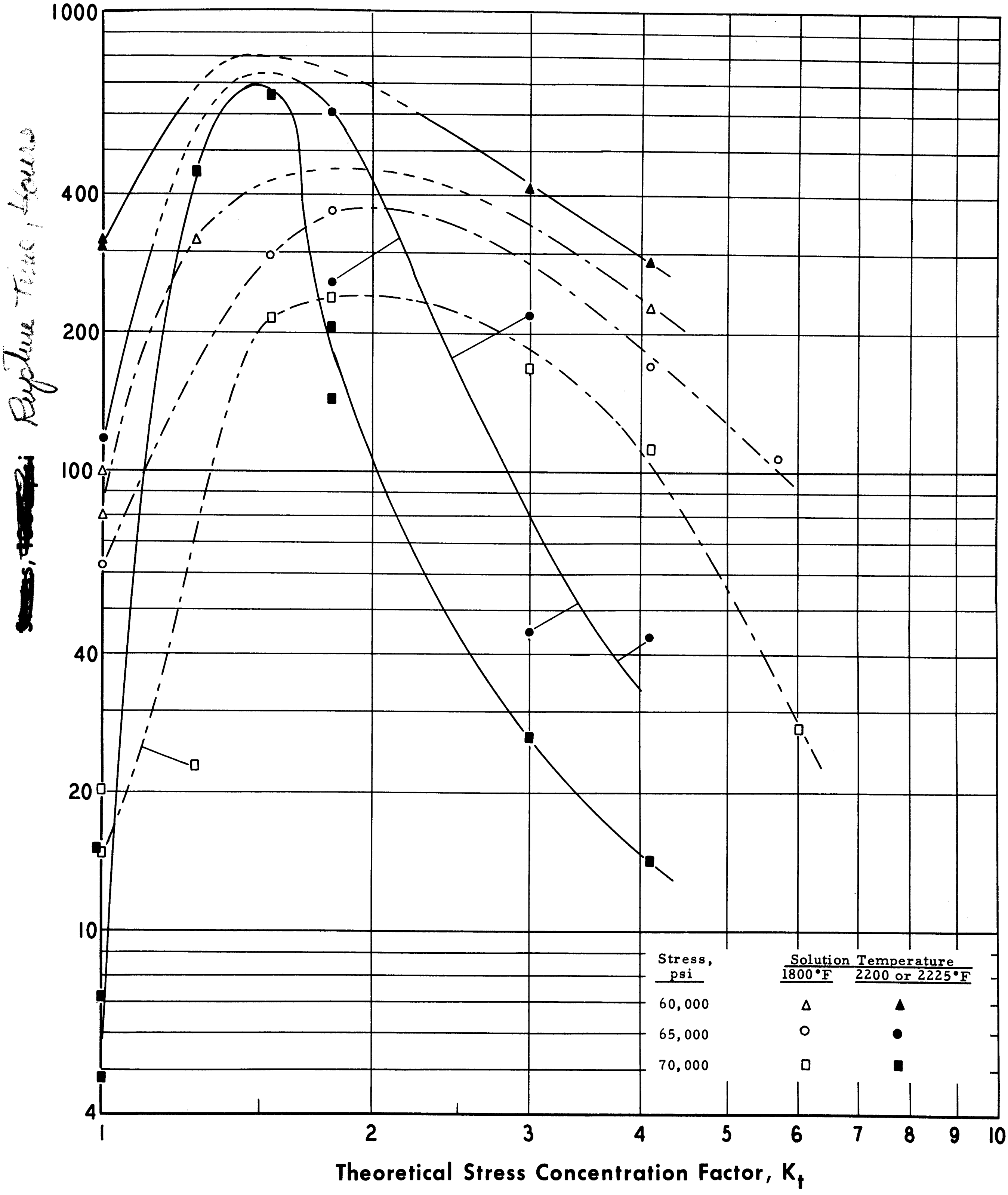

Fig. 2 - Effect of Notch Acuity on Rupture Life at 1200 °F for A-286 Heat 21,030 with 1800° and 2200-2225 °F Solution Temperatures.

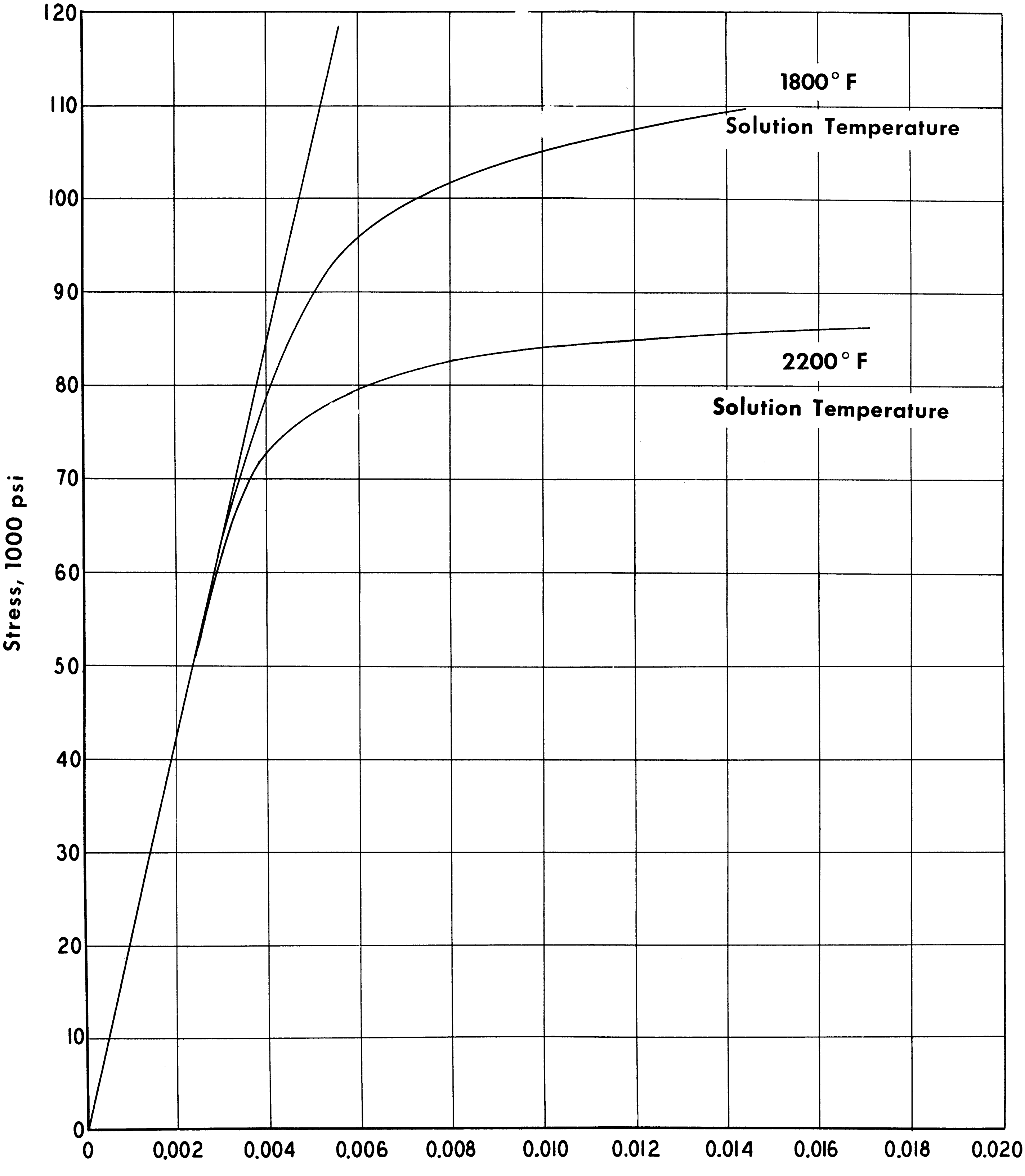

Fig. 3 - Stress-Strain Properties at 1200 °F for A-286 Heat 21,030 with 1800 ° and 2200 °F Solution Temperatures.

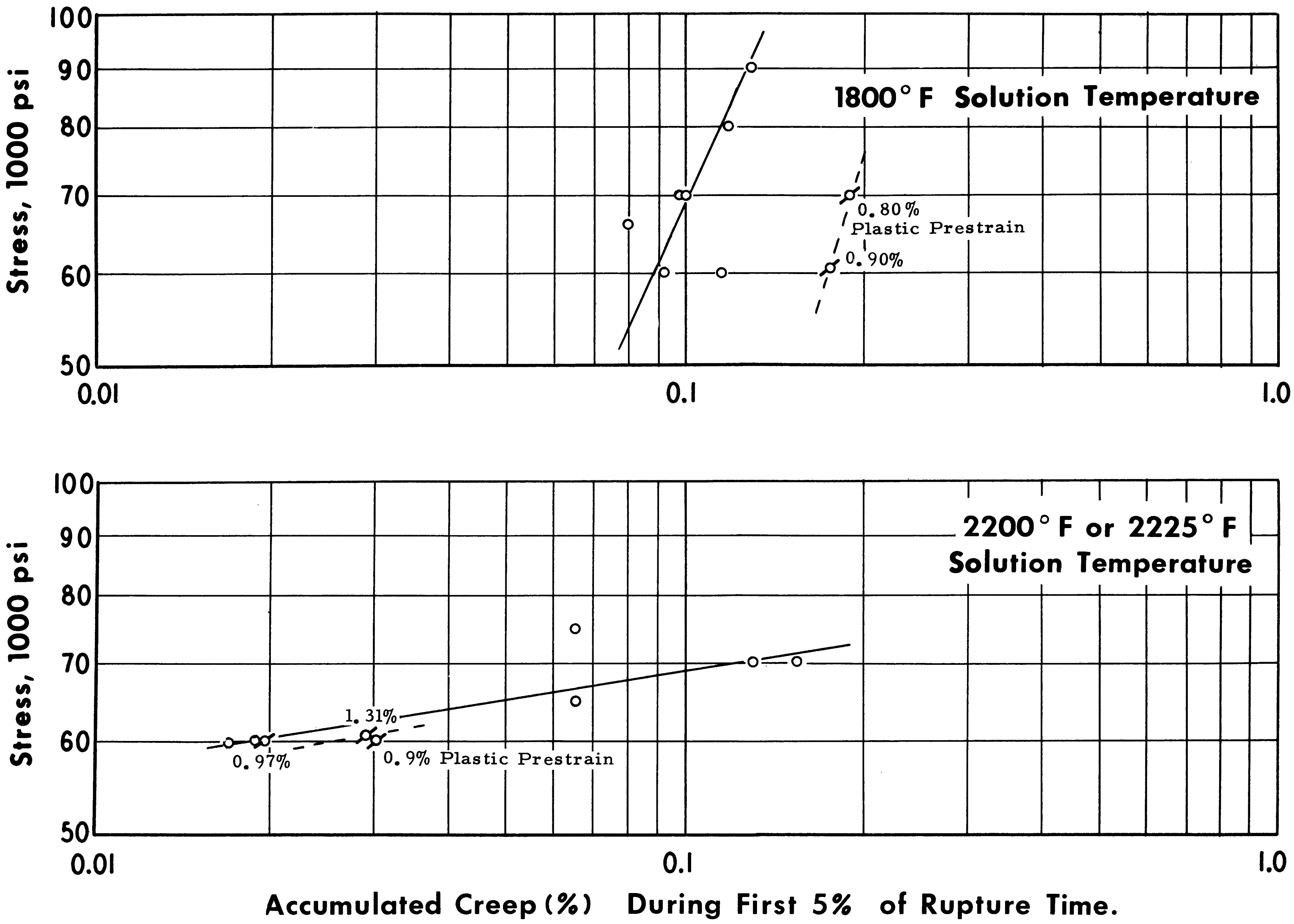

Fig. 4 - Early-Time Creep Strain at 1200 °F for A-286 Heat 21,030 Solution Treated at 1800 °F and at 2200-2225 °F.

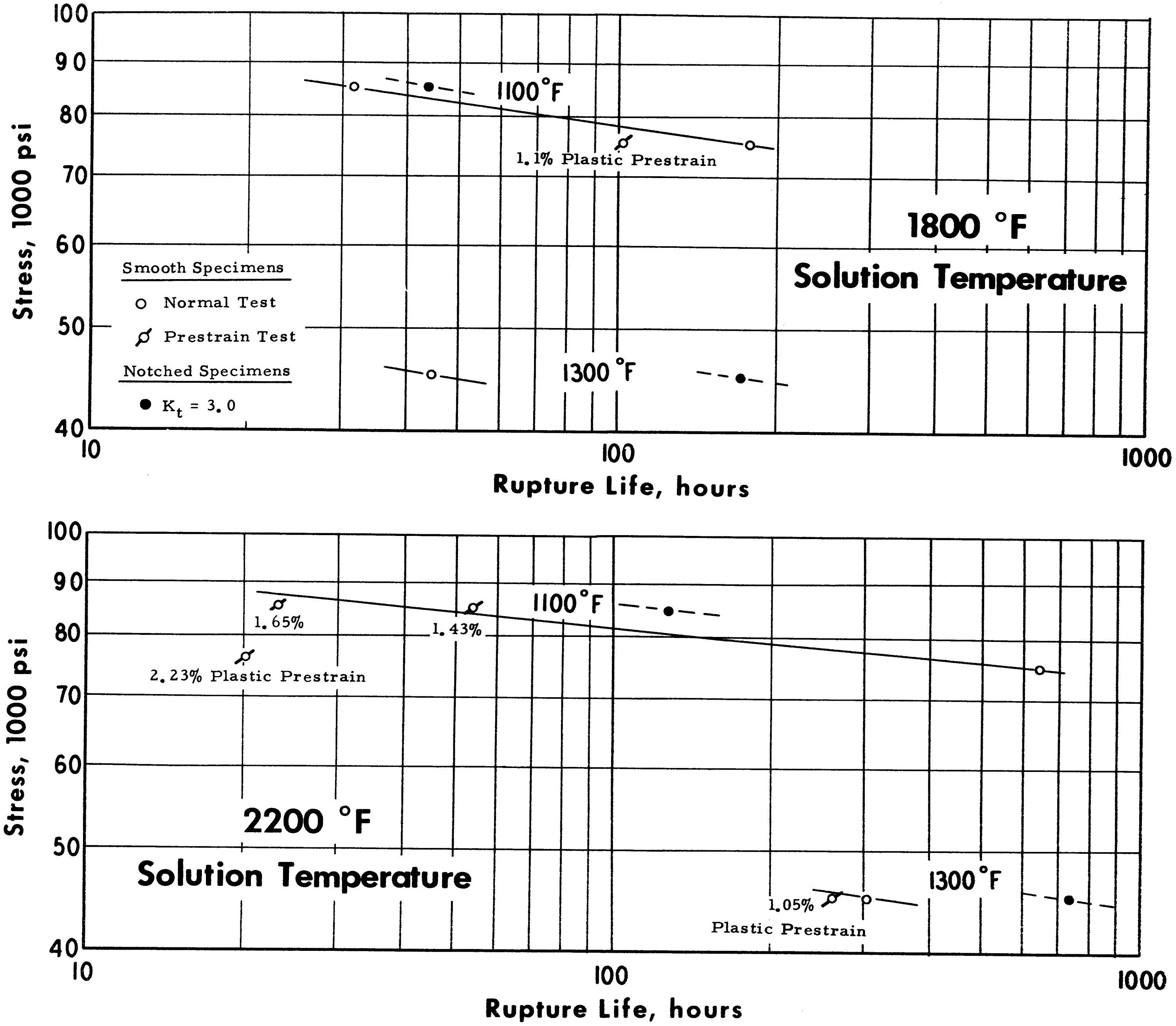

Fig. 5 - Rupture-Test Results at 1100 °F and 1300 °F for A-286 Heat 21,030

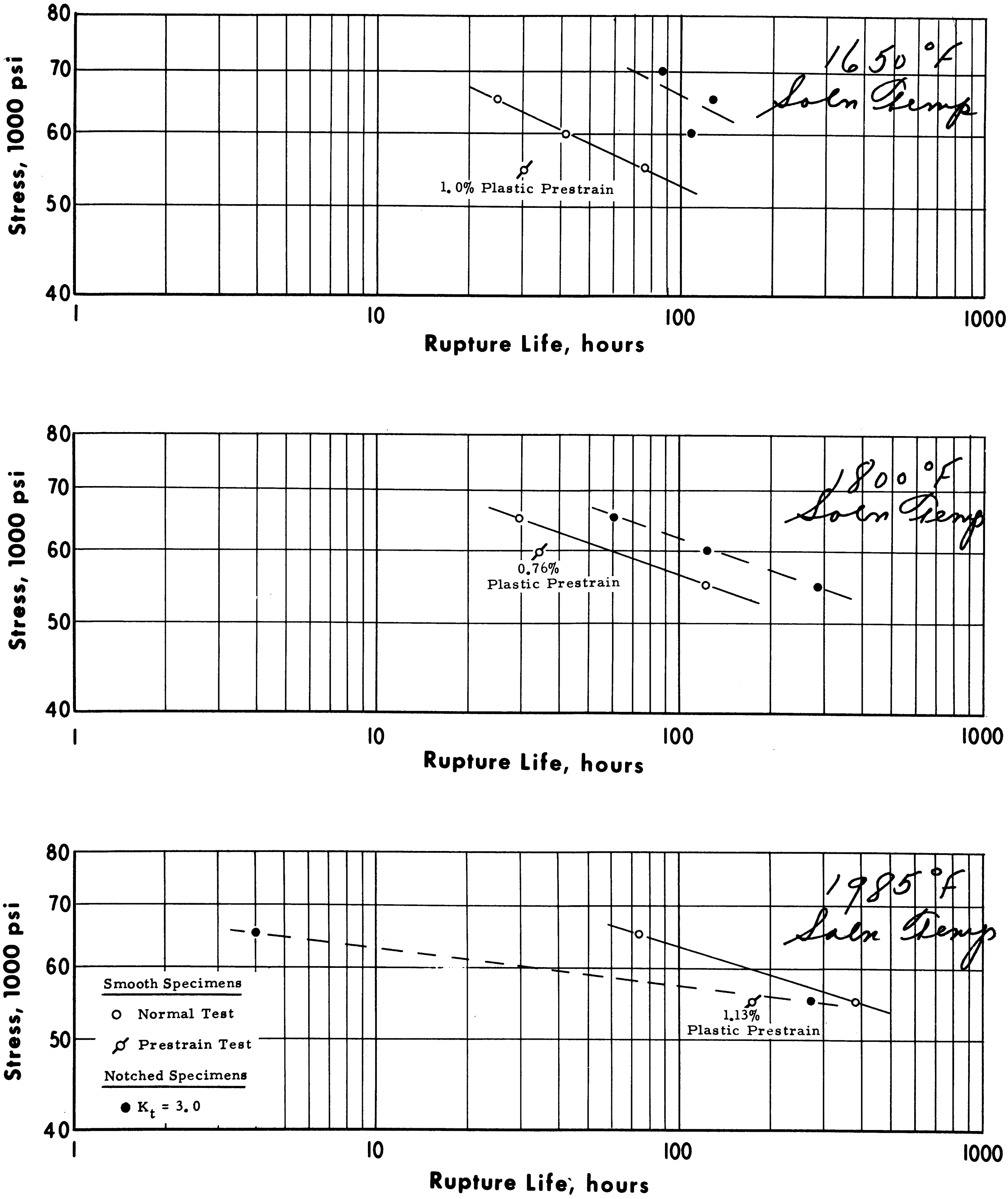

Fig. 6 - Rupture-Test Results at 1200 °F for A-286 Heat 43,297.

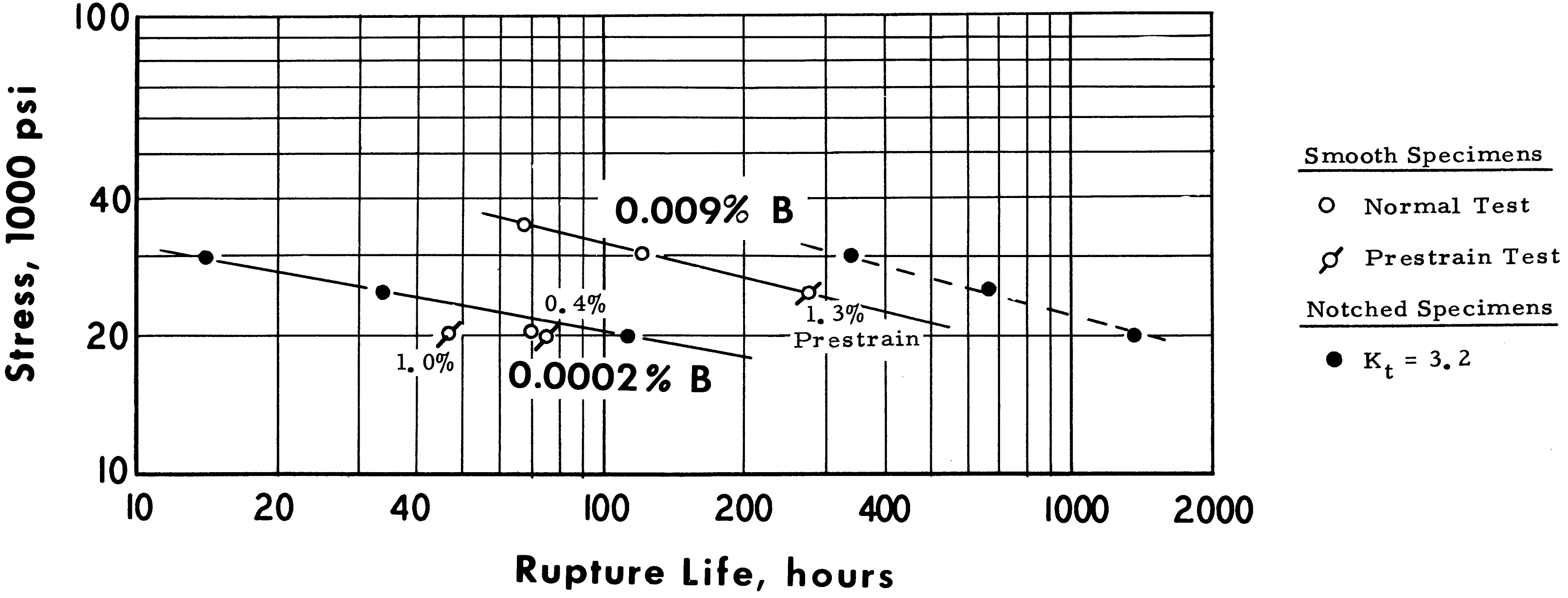

Fig. 7 - Rupture-Test Results at 1600 °F for a 55Ni, 20Cr, 15Co, 4Mo, 3Al, 3Ti Alloy with Two Levels of Boron Content.

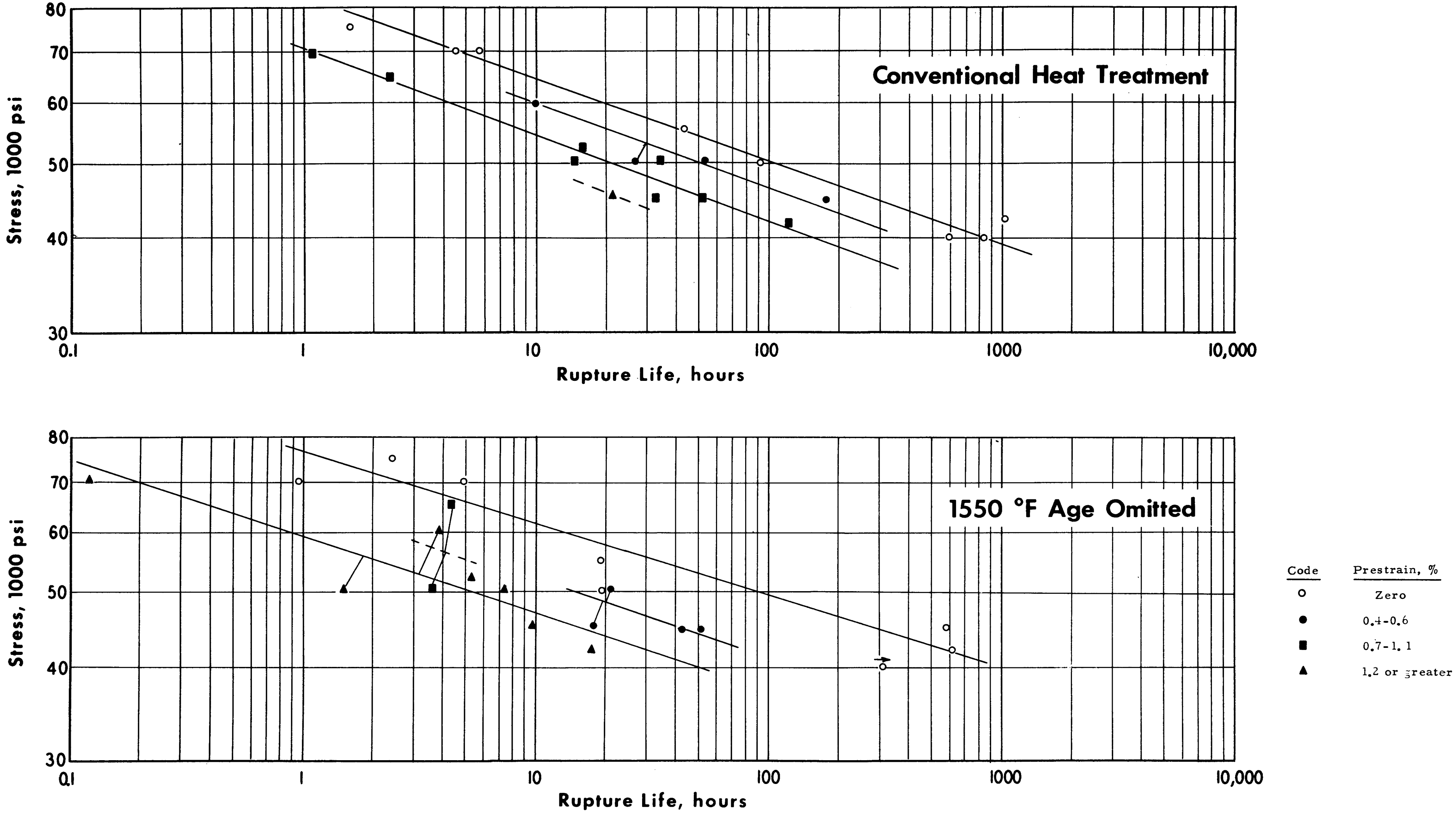

Fig. 8 - Effect of Plastic Prestrain at Test Temperature on Subsequent Rupture Life at 1350 °F for Three Heats of Waspaloy.