ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR, MICH.

SIXTH PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

NOTCH SENSITIVITY OF AIRCRAFT STRUCTURAL AND ENGINE ALLOYS

by

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Project 2475

Air Force Contract AF 33(616)-3380
Task No. 73605

January 31, 1958

SUMMARY

Recent experimental work under Contract No. AF 33(616)-3380 has centered around three phases of a research into notched-bar rupture behavior of A-286 alloy at 1200°F:

(1). More-complete evaluation of Heat 21,030 to define the test times and notch geometries for which notch weakening may be encountered.

(2). Survey of other available lots of A-286 alloy to determine whether one of these might be more prone to notch sensitivity.

(3). Evaluation of creep-rupture behavior of Heat 21,030 under variable simple tension, to provide necessary data for proposed correlation attempts to predict notched-bar rupture behavior from smooth-bar properties.

Contrary to original expectations, notch weakening in reasonable test periods was found for some test conditions with material solution treated at 1800°F, but not for specimens with a 2200°F solution temperature, at least for $K_t < 4.1$.

Survey tests with three new heats of A-286 alloy brought to light one which may permit study of A-286 with pronounced notch weakening in short time periods. The difference of this from other heats of the alloy seems to be largely a matter of the time beyond which notch weakening may be found for a given heat treatment and notch geometry.

Tests in which the stress level on Heat 21,030 specimens was lowered in discrete steps for succeeding time periods were evaluated in terms of addibility of rupture life fractions. For the 1800°F solution temperature, the computed sum of rupture life portions fell far short of 100%, while specimens with 2200°F solution temperature gave computed total lives well in excess of 100%. Reasons for this disparate behavior with the two treatments are not understood.

Priority during the rest of the contract term will be placed on obtaining a quantitative treatment of creep and rupture behavior of A-286 Heat 21,030 under variable simple tension.

INTRODUCTION

This research under Contract AF 33(616)-3380 seeks to extend and verify findings from earlier studies into factors which influence the rupture life of notched specimens tested at elevated temperature under steady tension. Specifically, attempts were to be made to find a material which could be made to produce both notch weakening and notch strengthening with different heat treatments and/or test conditions. Efforts were to be directored toward quantitative explanation of the results, following methods developed in earlier studies to correlate notched-bar behavior in terms of stress redistribution under the influence of different creep rates from point to point in the specimen. Sufficient tests were to be conducted on one particular lot of alloy to clarify possible effects of such variables as smooth-bar ductility and strain damage from localized plastic strains during load application.

A-286 alloy was selected for the experimental material with the expectation that the notch-rupture response would alter appreciably when different solution temperatures were used in its heat treatment. Previous progress reports (Refs. 1 and 2) include experimental results at 1200°F from the A-286, Heat 21,030, donated for this study by the Allegheny-Ludlum Steel Corporation. Preliminary survey tests covered solution temperatures from as low as 1650°F to as high as 2300°F. More intensive investigation has been made for solution temperatures of 1800° and 2200°F, which give roughly comparable smooth-specimen rupture lives but widely-different rupture ductilities. The higher solution temperature resulted in a coarse grain size but was selected to give elongation at fracture of 1% or less in unnotched specimens.

Early results for notched bars with theoretical stress concentration factors ranging from $K_t = 1.27$ to $K_t = 10$ showed notch strengthening at 55,000 to 70,000 psi nominal stress for all but the sharpest notches. However, extrapolation of the trends found with specimens given the 1800°F solution temperature suggested that possible notch weakening might result for long-time tests at lower test stresses. A major portion of the subsequent testing time has been devoted to investigation of this lower-stress region.

Simultaneous tests were made to evaluate smooth-bar creep-rupture properties of this lot of alloy when the load is increased or decreased during the test, to obtain basic properties for use in calculation of expected life for notched specimens.

When the probability still appeared to be remote for finding decided notch weakening in A-286 Heat 21,030 at reasonable test times, material was sought from other lots of the alloy which might be more prone to notch weakening. Experimental results were obtained with specimens representing several commercial and research heats of A-286 alloy.

Available data and current status of tests in progress for these several phases of the experimentation are the principal content of this report.

EXPERIMENTAL RESULTS

Original plans under the current contract called for extensive tests with A-286, Heat 21,030, to establish and analyze conditions for notch strengthening and notch weakening. When initial tests all showed notch strengthening for stress levels and specimen geometries permitting reasonable estimate of initial stress patterns, the study was broadened to include material from other lots of the alloy for which limited tests by others suggested that these lots might be more prone to notch sensitivity than was Heat 21,030.

Rupture Properties at 1200°F for Notched and Smooth Specimens of A-286

Available chemical analyses and processing conditions for the lots of A-286 investigated are summarized in Table 1. The rupture data obtained are listed in Tables 2 through 5 and plotted on Figures 1 through 5. All test results are given for the new lots of material added to the program, but in the case of the original Heat 21,030 only the data for 1800° and 2200°F solution temperatures have been repeated in this report.

Heat 21,030

Specimen blanks were sampled from the 3/4-inch round stock supplied from a commercial heat prepared by the vacuum consumable-electrode process. Prior to machining, the blanks were solution treated for one hour and oil quenched; aging was at 1325°F for 16 hours with an air cool. Gauge section of unnotched specimens were hand polished after turning. Notches were finished by form lapping after preliminary rough turning and grinding operations. Details of the notching operation have been published in WADC reports (see Reference 3).

Data available at the time the last prior progress report was issued suggested weakening from dull or moderate-acuity notches would occur for this heat of alloy only at times in excess of about 1000 hours. The more-complete results of Table 2 demonstrate transition to notch weakening at 300-400 hours for theoretical stress concentration factors of K_t = 5.7 and 4.1 with specimens solution treated at 1800°F. If the curves of Figure 1 correctly represent the data for the material with 1800°F solution temperature, the dullest notch studied (K_t = 1.27) should also show notch embrittlement at a nominal stress of 30,000 psi or below.

Test results for material solution treated at 2200°F exhibited considerable scatter, particularly in the case of specimens with the dullest notch (K_t = 1.27). However, no evidence at all was obtained which would suggest transition to notch weakening in reasonable test periods for specimens with theoretical stress concentrations between K_t = 1.27 and 3.0. This is true despite smooth-bar elongation of 1% or less for stresses of 60,000 psi and below. Use of specimens with any sharper notch than K_t = 4.1 has not been considered for the alloy in the coarse-grained condition left by the high solution temperature.

Figure 1 indicates a difference in the notch geometry giving maximum strengthening in samples with the two different solution temperatures. To make the difference more evident, the stress for rupture in 200, 500 and 1000 hours for each specimen geometry was taken from the approximate average curves of Figure 1 and replotted as a function of the theoretical stress concentration factor (see Figure 6). For the 1800°F solution temperature, rupture strength rises with notch acuity at least to K_t of 1.8 and probably to about K_t = 2.2. The peak strength for the 2200°F solution temperature appears to occur for K_t below 1.5.

The curves of Figure 6 are tentative and approximate, but for each heat-treatment condition a minimum seems to be present in the 1000-hour curve for a theoretical stress concentration about 1.5-2.0 times that giving maximum strength. If this indication is confirmed by the tests now in progress, an excellent test of any calculation method is whether it will predict such a minimum.

The indicated inflections of Figure 6 stem in large measure from the data for K_t = 4.1, in particular the sharp downward break of the stress-rupture life plot for this theoretical stress concentration in specimens solution treated at 1800°F. When the test in progress at 35,000 psi stress is completed the curve for the 1800°F treatment at K_t = 4.1 should be well established, but at least one more test (say at 52,500 psi) seems desirable for the 2200°F solution temperature in order that the indicated shallow slope for $K_t = 4.1$ may be confirmed, or else the presence of a "break" in the curve established.

Theoretical considerations by others of notched-bar tension tests have indicated a maximum possible strengthening of 1.4 to 1.5 based on nominal stress. Present results suggest a strength ratio of 1.6 is attainable with the 2200°F solution temperature. Further testing to confirm the curve of Figure 6 would have limited service application but should be of considerable interest from the standpoint of fundamentals.

Figure 6 suggests future studies for two additional stress concentration factors. Results for $K_t = 2.4$ would better define the peak strengthening with the 1800°F solution temperature. Determination of the stress concentration factor to give maximum strength for the 2200°F solution temperature would be aided by tests at $K_t = 1.4$.

These suggested tests could not be completed during the current contract period, but are appropriate and desirable extensions of the research on A-286 Heat 21,030.

Heat 43,297

Only a small amount of 7/8-inch diameter bar stock was available from this air-melted heat, one of several used by the Allegheny-Ludlum Steel Corporation in a research study of the alloy. Limited test results plotted in Figure 2 show a transition from pronounced notch strengthening, to mild notch strengthening and then to notch weakening with $K_t = 3.0$ as the solution temperature is increased from 1650° to 1800° to 1985°F.

The probable greater tendency toward notch sensitivity of Heat 43,297 compared to Heat 21,030 may be associated with its corresponding greater susceptibility to weakening from strain damage evidenced by the few prestrain tests conducted on these materials. (See Tables 2 and 3). At the start of these prestrain tests a momentary overload was applied to produce the desired amount of plastic yielding, the excess weight was immediately removed and the creep measurements started. Extensometer readings taken during the load application and during its reduction permitted calculation of the plastic strain at the start of the test and of the correct nominal stress present when creep determinations were begun, assuming the plastic strain was uniform along the gauge section of the specimens.

Material remaining from this lot of alloy would conveniently serve to make only from 8 to 12 test specimens, wherefore extensive studies are not possible. The stock on hand has been placed in reserve for possible future use in checks of correlations obtained with other heats of A-286.

Heat 52, 853

Originally this lot of alloy was one of four materials in a research into effects of processing variables on fracture of notched disks at elevated temperatures. That research by the General Electric Company under Contract No. AF 33(616)-2778 included tests at 1100°F with notched and unnotched specimens of A-286 in two conditions of heat treatment. At the 1100°F test temperature, borderline notch properties were obtained after the following treatment: 2150°F, 2 hr, O.Q. + 1650°F, 2 hr, O.Q. + 1300°F, 16 hr + 1200°F, 16 hrs. Specimen blanks were cut from disks forged from 2000°F.

Portions of the 4-1/2-inch diameter billet transferred from General Electric were re-rolled to 1/2-inch square bars at The University of Michigan prior to sampling and heat treating. Three different rolling temperatures (2100°, 1950° and 1800°F) were surveyed for specimens solution treated at 1800°F. Limited data indicated mild notch weakening at 20-60 hours for a K_t = 4.1 with specimens rolled from 1950°F (See Figure 3). Material rolled at the more conventional temperature of 2100°F produced test results quite comparable to those found with Heat 21,030. Solution temperatures of 1800°, 2000° and 2200°F all failed to produce notch weakening at 1200°F in fragmentary studies on Heat 52,853 material rolled from 2100°F. From these preliminary tests, no evidence has been found favoring Heat 52,853 in the search for conditions of notch sensitivity in A-286.

Heat K-65-X:

In the course of an investigation relating melting variables to properties of certain alloys, research personnel at Firth Sterling, Inc. procured an experimental heat of A-286 produced by the vacuum consumable-electrode method. This material, designated by them as "K-65-X", gave indications of notch embrittlement at 1200°F and 65,000 psi stress for bars samples from an 8.5-inch square billet and then solution treated at 1800°F, oil quenched, aged at 1300°F for 16 hours and air cooled to room temperature.

Knowing of the attempts to locate notch-sensitive A-286 for the present program, Firth Sterling representatives arranged to supply enough of the experimental billet to permit comparison against Heat 21,030.

Property scatter in notched specimens sampled directly from the billet was very wide. Re-rolling from 2100°F before sampling appeared to eliminate this scatter (See Figure 5). For both conditions, specimens with the 1800°F solution treatment and subsequent 1325°F aging for 16 hours developed mild-to-moderate notch weakening in test times of a few hundred hours. Corresponding specimens from other heats studied to date in this program produced notch strengthening. Heat K-65-X thus seems to offer the best opportunity found so far to study a lot of A-286 with pronounced notch weakening in reasonable test periods.

Comparison of notch behavior for the several lots of A-286 alloy:

Results from this and other research programs at the University of Michigan point out the important changes in creep-rupture properties that can be brought about by small variations in trace-element content and by different working conditions prior to the final heat treatment. Accurate delineation of the influence from one of these variables demands the others be held fixed, but this desirable aim is difficult to fulfill. Quantities of boron, oxygen and nitrogen known to have measurable effect on rupture life of heat-resistant alloys are near the limits of present quantitative analysis for these elements. What other trace elements might produce helpful or harmful effects of like magnitude and how these different elements interact in effect remains largely unknown.

Similarly, the ways in which prior processing conditions carry through to influence later mechanical properties are little understood. Even for the same nominal rolling conditions, the actual local history of temperature and strain for different portions of the final rolled stock is subject to wide uncontrollable variation.

Despite these complications, the four heats of A-286 studied can profitably be compared for the common conditions of rolling from 2050°-2100°F and subsequent 1800°F solution temperature. At rupture times of the order of 100 hours, Heats 21,030, 43,297 and 52,853 all exhibited notched-specimen rupture strengths 10-20% above the smooth-bar values for K_t's of 2 to 4. Heat K-65-X, on the other hand, showed mild notch weakening under roughly comparable conditions. The most plausible explanation lies in the boron contents for the four lots of material. The single analysis available for boron in Heat K-65-X was below the average boron content indicated by the pairs of analyses obtained for the other three heats. Unfortunately, the analysis for boron in the low amounts present is difficult and agreement between laboratories was unsatisfactory for a successful correlation attempt. Re-evaluation of these four heats would be desirable on the basis of boron contents all determined by the same laboratory with the same set of standards.

Although the amount of boron or other trace elements in the alloy seems to affect notch sensitivity, the effect is probably not one of either permitting or eliminating notch sensitivity, but rather one of shifting the test time at which notch weakening begins for a given notch geometry. For short test times, the bulk of the test data suggest notched-bar rupture plots have the same slope as do those for unnotched specimens. The rupture-test results for Heat 21,030 with the 1800°F solution temperature produced three good examples of a definite and abrupt change in slope for notched-specimen curves at times beyond 150-250 hours. More extensive testing would probably verify this finding for other notch geometries, treatment conditions or lots of the alloy.

Creep-Rupture of A-286 Heat 21,030 Under Variable-Stress Loading

The analysis developed to compute rupture life of notched specimens from smooth-specimen data requires knowledge of creep and rupture behavior when the stress level on a metal fiber increases or decreases during the test (See Ref. 3). The research under the current contract included a number of tests devised to obtain the required data for A-286 Heat 21,030 at a test temperature of 1200°F.

These particular tests differed from usual constant-load tests only in that the applied stress was changed from one discrete level to another one or more times during the test.

Experimental conditions and test results are summarized in Table 6 for both the 1800° and 2200°F solution temperatures. The table lists first the plastic deformation on loading as percent plastic strain. Continuing across the page, for each period of constant stress is listed the stress level, the length of time the stress acted, the ratio of this time to the rupture life in a conventional rupture tests at the stress and the increment of creep (inches/inch) which occurred during the period. Finally the ductilities (percent elongation and percent reduction of area) at fracture are listed, together with the sum of the rupture-life portions for all creep periods.

In the first experiments performed for each solution temperature, the test started and ended at the same nominal stress, with the stress level either raised or lowered during a mid-portion of the test. Stresses used were all below the yield range and the change in stress was moderate. Under these conditions the sum of the rupture-life portions was substantially equal to 100%, in agreement with past results for other alloys tested under conditions of good metallurgical stability.

The bulk of the results reported in Table 6 involve step-down tests in which the starting stress produced measurable initial plastic strain, and in which the stress level was lowered for each succeeding portion of the test period. For all specimens with 0.1% or greater plastic strain on loading, the computed sum of rupture-life portions for the material treated at 1800°F fell far short of 100%, while specimens with 2200°F solution temperature gave calculated total lives well in excess of 100%.

Reasons for the apparent disparate behavior under variable stress for the two heat treatments are not understood. The observed results must be clarified because a major objective for the remainder of the contract period will be quantitative evaluation of notched-bar rupture behavior. This evaluation requires firm knowledge of how to compute rupture life under varying stress.

FUTURE WORK

During the balance of the current contract term priority will be placed on obtaining a quantitative method for treating creep and rupture behavior under variable stress at 1200°F for A-286 Heat 21,030. Once this information is satisfactorily in hand, calculations may proceed to determine how well rupture lives of notched specimens of this material can be predicted by the analysis developed in past research.

Any future continuation of the program should include metallographic and allied studies to seek the reasons for the observed behavior under variable simple tension. A logical extension would include determination of the general creep-rupture performance under variable multi-axial stresses.

The influences of trace elements, particularly boron content, has not been adequately covered in the research to date. Extensive testing with A-286 Heat K-65-X and with experimental melts to be prepared at the University with minimum boron content should be most valuable if adequate precision in the boron determinations can be obtained. Results from Heat 52,853 listed in this report suggest the greatest tendency toward notch weakening will probably be found for material rolled from 1800°-2000°F and subsequently given an 1800°F solution before aging at 1325°F.

BIBLIOGRAPHY

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3. Howard R. Voorhees and James W. Freeman, "Notch Sensitivity of Heat-Resistant Alloys at Elevated Temperatures," WADC Technical Report TR 54-175, Part 3. (ASTIA Document No. AD 97253), September 1956.

4. Richard Sakamoto, "Effects of Processing Variables on Fractured and Disk-Bursting Characteristics of Four High Temperature Materials," WADC TR 57-154, May 1957.

TABLE 1

CHEMICAL ANALYSES AND PROCESSING CONDITIONS FOR THE VARIOUS LOTS OF A-286 ALLOY INVESTIGATED

Heat No.	Type of Melt	C	Mn	Si	Cr	Ni	Mo	Ti	V	Al	S	P	Fe	B
		Chemical Composition, percent by weight												
21,030	Vacuum consumable electrode	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) (0.0019)
43297	Two-ton air	0.025	1.21	0.86	15.12	26.16	1.32	1.94	0.23	0.40	0.017	0.016	Bal	*(0.002) (0.0008)
52853	Not Stated	*(0.06 (0.064	1.21 1.37	0.66 0.62	15.12 15.55	26.06 26.50	1.38 1.27	2.12 2.12	0.16 0.10	0.20 0.10	0.012 0.010	0.022 0.023	Bal) Bal)	*(0.0016) (<0.001)
K-65X	Vacuum consumable electrode	0.053	1.32	0.54	14.75	26.60	1.38	2.00	0.25	0.146	0.012	0.025	Bal	0.0007

Other:	W	Co	Cu	Pb	O	H	N
	0.13	0.11	0.06	0.0009	0.08	0.0008	0.04

Heat No.	Processing Procedure Prior to Receipt at the University of Michigan
21,030	20" round ingot pressed and cogged to 4-1/4" square from 2150°F. Recogged to 2-7/8" square from 2100°F; Rolled to 3/4" diameter from 2100°F. Bars neither straightened nor annealed before shipping.
43297	Hot rolled from 2050°F; As-rolled hardness BHN 163-179. (Finishing temperature approximately 1650°F). Supplied as 7/8" diameter rounds.
52853	5-1/2" round-corner square billets ground all over; soaked at 2025-2050°F; rolled as a hand round 4-3/4" diameter billet with finishing temperature approximately 1850°F, air cooled. Rough turned to 4-1/2" diameter.
K-65X	19" diameter ingot reduced to 8.5" square from 2075-2100°F.

* Check analyses by different Laboratories.

TABLE 2

RUPTURE-TEST RESULTS AT 1200°F FOR A-286 HEAT 21,030

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

UNNOTCHED SPECIMENS

Stress (psi)	Rupture Life (hours)	Elongation at Rupture (%)	Reduction of Area (%)
	1800°F Solution Temperature		
112,000	(Short-time tensile strength)	18.	19.
100,000	0.26	17.	18.
90,000	1.45	8.	9.
80,000	4.25	8.	8.5
a) 70,560	17.9	8.	9.5
70,000	14.9	9.5	13.5
70,000	20.3	6.5	8.5
65,000	62.4	5.5	10.5
b) 60,540	59.8	6.5	11.
60,000	79.9	5.	10.
60,000	99.1	7.	8.5
50,000	384.6	6.	8.
45,000	615.5	4.	8.
45,000	771.3	3.	4.5
40,000	In progress 1140 hours	--	--
	2200°F Solution Temperature		
101,500	(Short-time tensile strength)	10.5	12.5
80,000	0.87	4.	7.
75,000	3.8	2.5	5.5
70,000	7.2	1.5	7.
c) 60,790	99.8	2.5	4.5
d) 60,240	307.0	1.5	4.
60,000	308.7	1.	2.5
55,000	587.9	1.	2.
50,000	2068.3	<0.5	1.

a) 0.80% plastic prestrain from momentary initial overload to >100,000 psi.
b) 0.90% plastic prestrain from momentary initial overload to 108,240 psi.
c) 1.31% plastic prestrain from momentary initial overload to 84,070 psi.
d) 0.90% plastic prestrain from momentary initial overload to 81,000 psi.

TABLE 2 (con'd.)

NOTCHED SPECIMENS

1800°F Solution Temperature Stress (psi)	1800°F Solution Temperature Rupture Life (hours)		2200°F Solution Temperature Stress (psi)	2200°F Solution Temperature Rupture Life (hours)
		K_t = 1.27		
			80,000	127.4
			75,000	264.5
70,000	22.6		70,000	451.3
70,000	97.2		70,000	996.0
65,000	241.6		65,000	416.4
60,000	319.3		60,000	417.5
50,000	840.0		60,000	1242.5
47,500	1043.6		55,000	783.5
		K_t = 1.54		
			80,000	225.0
70,000	215.3		70,000	657.5
65,000	292.3			
60,000	481.3		60,000	568.7
			55,000	(In Progress 2475 hr)
			55,000	(In Progress 2310 hr)
		K_t = 1.82		
80,000	109.5			
70,000	239.6		70,000	206.3
65,000	366.2		65,000	257.7
60,000	543.4		60,000	1151.1
55,000	994.3		55,000	727.4
		K_t = 3.0		
70,000	167.5			
45,000	(In Progress 290 hr)		65,000	219.3
			60,000	414.2
			50,000	(In Progress 1900 hr)
		K_t = 4.1		
80,000	20.9			
70,000	112.8		70,000	14.2
65,000	168.1		65,000	43.5
60,000	227.6		60,000	288.8
50,000	363.0			
45,000	490.3			
40,000	508.8			
35,000	(In Progress 315 hr)			

TABLE 2 (con'd.)

NOTCHED SPECIMENS

1800°F Solution Temperature		2200°F Solution Temperature	
Stress (psi)	Rupture Life (hours)	Stress (psi)	Rupture Life (hours)
K_t = 5.7 - 6.0			
70,000	27.3		
65,000	106.7		
*65,000	43.4		
60,000	119.7		
55,000	257.1		
45,000	464.8		
40,000	(In Progress 985 hr)		
K_t = 8.7 - 10.0			
*70,000	6.5		
*65,000	6.65		
*60,000	11.1		
40,000	451.9		

* Aging step performed after notching operation.

TABLE 3

RESULTS OF SURVEY TESTS AT 1200°F ON 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 initial 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 initial 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 initial 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	--	--	

[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

RESULTS OF SURVEY TESTS AT 1200°F ON A-286 HEAT 52853

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

(Rolled to 1/2-inch squares at the University of Michigan prior to heat treatment)

UNNOTCHED SPECIMENS

Rolling Temp. (°F)	Stress (psi)	Rupture Life (hours)	Elongation at Rupture (%)	Reduction of Area (%)
		1800°F Solution Temperature		
1800	65,000	15.5	8.	11.
1950	65,000	16.4	6.	7.
1950	60,000	60.5	5.	11.
1950	55,000	125.2	5.5	8.5
2100	70,000	8.7	7.5	10.
2100	60,000	27.4	7.	11.
2100	50,000	145.0	8.	9.5
		2000°F Solution Temperature		
2100	70,000	11.7	3.	6.
2100	65,000	114.5	5.	6.5
2100	60,000	281.1	3.5	7.
		2200°F Solution Temperature		
2100	70,000	24.2	2.	3.
2100	60,000	120.4	2.	3.5
2100	55,000	501.4	1.5	2.

TABLE 4 (con'd.)

NOTCHED SPECIMENS

Rolling Temp. (°F)	Stress (psi)	Rupture Life (hours)	Rolling Temp. (°F)	Stress (psi)	Rupture Life (hours)
		1800°F Solution Temperature			
	K_t = 1.27			K_t = 4.1	
1800	65,000	81.1	1800	65,000	21.8
1800	60,000	220.7	1800	60,000	88.9
1950	70,000	55.5	1950	65,000	17.4
1950	65,000	140.5	1950	60,000	45.6
			1950	55,000	63.8
2100	70,000	41.8	2100	70,000	16.0
2100	60,000	115.5	2100	60,000	58.2
		2000°F Solution Temperature			
	K_t = 3.1				
2100	75,000	381.1			
2100	70,000	531.6			
2100	65,000	793.4			
		2200°F Solution Temperature			
	K_t = 1.72				
2100	75,000	73.1			
2100	70,000	171.0			
2100	65,000	389.6			

TABLE 5

RESULTS OF SURVEY TESTS AT 1200°F ON A-286 HEAT K65X

Heat Treatment: 1800°F, 1 hr, Oil Quench + 1325°F, 16 hr, Air Cool

UNNOTCHED SPECIMENS

Stress (psi)	Rupture Life (hours)	Elongation at Rupture (%)	Reduction of Area (%)
Specimens Sampled Lengthwise from the Billet Supplied			
70,000	49.1	2.	3.5
60,000	192.6	2.	2.5
55,000	300.4	1.	1.5
Material Rerolled from 2100°F Before Sampling			
65,000	35.6	3.5	7.
55,000	116.8	4.5	5.5
50,000	209.6	4.	5.

NOTCHED SPECIMENS

Stress (psi)	Rupture Life (hours)	Stress (psi)	Rupture Life (hours)
K_t = 1.72		K_t = 4.1	
Specimens Sampled Lengthwise from the Billet Supplied			
65,000	137.0	70,000	41.8
55,000	232.3	65,000	109.6
		60,000	90.8
		55,000	35.3
		55,000	44.9
		50,000	128.4
Material Rerolled from 2100°F Before Sampling			
		65,000	36.1
		55,000	87.8
		50,000	146.1

TABLE 6

MULTIPLE-STRESS CREEP-RUPTURE TESTS AT 1200°F FOR A-286 HEAT 21,030

Initial Plastic Strain (%)	1st Creep Period				2nd Creep Period				3rd Creep Period				4th Creep Period				Total Plastic Strain at Fracture		Sum of Rupture Life Portions (%)
	Stress (psi)	Duration (hr)	Portion of Rupture Life (%)	Creep Increment (in/in)	Stress (psi)	Duration (hr)	Portion of Rupture Life (%)	Creep Increment (in/in)	Stress (psi)	Duration (hr)	Portion of Rupture Life (%)	Creep Increment (in/in)	Stress (psi)	Duration (hr)	Portion of Rupture Life (%)	Creep Increment (in/in)	% Elong.	% Red. of Area	
									Specimens with 1800°F Solution Temperature										
0	50,000	105.0	31.5	0.00315	65,000	12.0	26.1	0.00792	50,000	146.5	43.4	--					5.	9.	101.0
0	65,000	12.0	26.1	0.00219	50,000	105.0	31.4	0.00104	65,000	2[illegible].9	54.2	(0.01)					7.	9.	111.7
0	50,000	40.0	12.0	0.00070	55,000	27.0	15.8	0.00135	60,000	56.5	62.8	--					6.	8.	90.6
0.135	90,000	0.1	9.8	0.00932	80,110	0.55	12.8	0.0233	70,090	3.25	16.1	0.0506	60,080	0.1	0.1	--	9.5	11.	38.7
0.18	90,000	0.1	9.8	0.01105	80,140	0.9	21.0	0.0415	70,125	2.4	11.9	>0.03					10.	31.5	42.7
0.11	90,000	0.1	9.8	0.00622	60,110	42.8	49.3	(0.063)									~~6.5~~ 6.	10.5	59.1
0.40	100,000	0.0167	5.4	0.00718	60,240	38.5	44.2	~~(0.113)~~	0.109								~~12.~~ 11.5	12.5	49.6
0.505	100,000	0.0167	5.8	0.00952	90,500	0.1	11.0	0.0119	80,400	0.983	23.9	0.0362	70,400	2.35	12.2	~~70.05~~	~~6.~~ 5.5	11.5	52.9
0.295	100,000	0.004	1.2	0.00287	90,270	0.021	2.1	0.00091	80,240	0.1	2.4	0.00116	70,210	0.375	1.9	0.00105			
									5th Creep Period				6th Creep Period						
									60,180	2.5	2.9	0.0013	50,150	187.6	62.6	(0.071)	~~8.~~ 7.5	8.5	73.1
0	50,000	258.1	77.4	0.00602	Short Time Tensile Test at 1200°F: 112,500 psi T.S.; 99,000 psi 0.2% Y.S.; 12% El.; 14% R.A.														
0	none				Short Time Tensile Test at 1200°F: 112,000 psi T.S.; 18% El.; 19% R.A.														
									Specimens with 2200°F Solution Temperature										
0.025	65,000	15.0	10.1	0.000488	55,000	210.0	25.8	0.000423	65,000	73.9	46.9	(0.0042)					2.	3.	82.8
0	55,000	210.0	25.8	--	65,000	15.0	10.1	0.00061	55,000	612.3	75.4	(0.002)					0.5	2.5	111.3
0	50,000	50.0	2.6	0.00005	55,000	52.0	6.3	0.00015	60,000	236.6	63.4	(0.01)					1.	5.	72.3
0	65,000	52.7	33.4	0.00202	60,000	159.1	42.7	(0.005)									1.	3.5	76.1
0.04	70,000	0.5	2.0	0.00185	65,000	5.0	3.2	0.00001	60,000	351.1	94.2	>0.006					1.	3.	99.4
0.41	70,000	1.0	4.0	0.00916	60,250	24.0	6.7	0.00046	50,200	2232.6	121.1						3.	2.	131.8
1.62	80,000	0.004	0.5	--	73,200	0.096	1.2	0.000179	69,100	1.1	3.2	0.000253	65,000	14.0	8.9	0.000663			
													5th Creep Period						
													61,000	353.8	110.0	--	4.	5.5	123.8
0.73	76,000	0.02	0.6	0.00178	72,600	0.05	0.5	0.00152	68,500	3.45	8.1	0.00047	64,500	26.0	13.6	0.00050			
													5th Creep Period						
													60,400	521.7	148.5	>0.0084	3.	4.5	171.3
0	60,000	246.8	66.1	0.000956	Short Time Tensile Test at 1200°F: 98,200 psi T.S.; 85,500 psi 0.2% Y.S.; 6.5% El.; 8% R.A.														
0	none				Short Time Tensile Test at 1200°F: 101,500 psi T.S.; 10.5% El.; 12.5% R.A.														

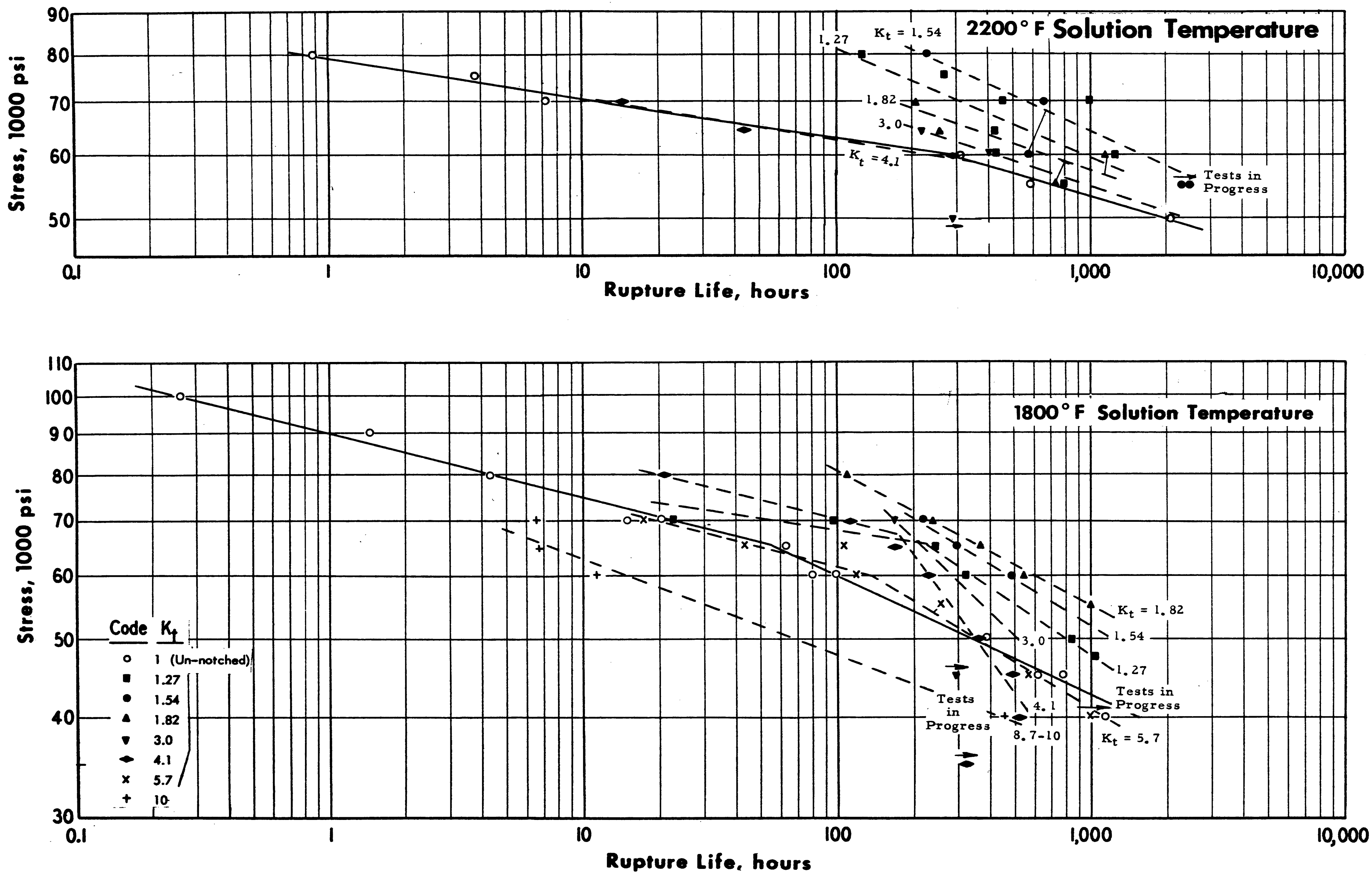

Fig. 1 - Rupture Properties at 1200 °F for Smooth and Notched Specimens of A-286 Heat 21,030.

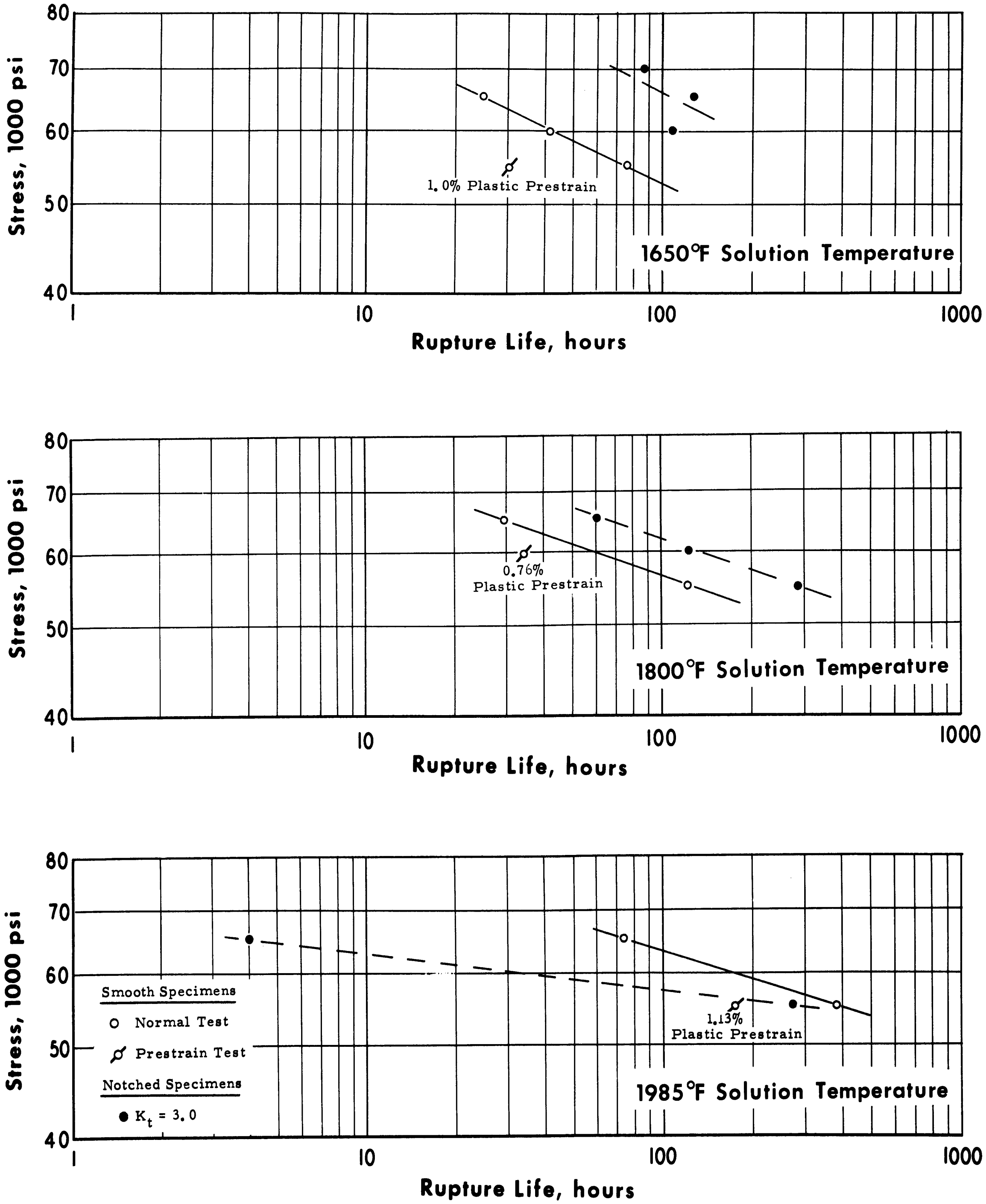

Fig. 2 - Rupture-Test Results at 1200 °F for A-286 Heat 43,297.

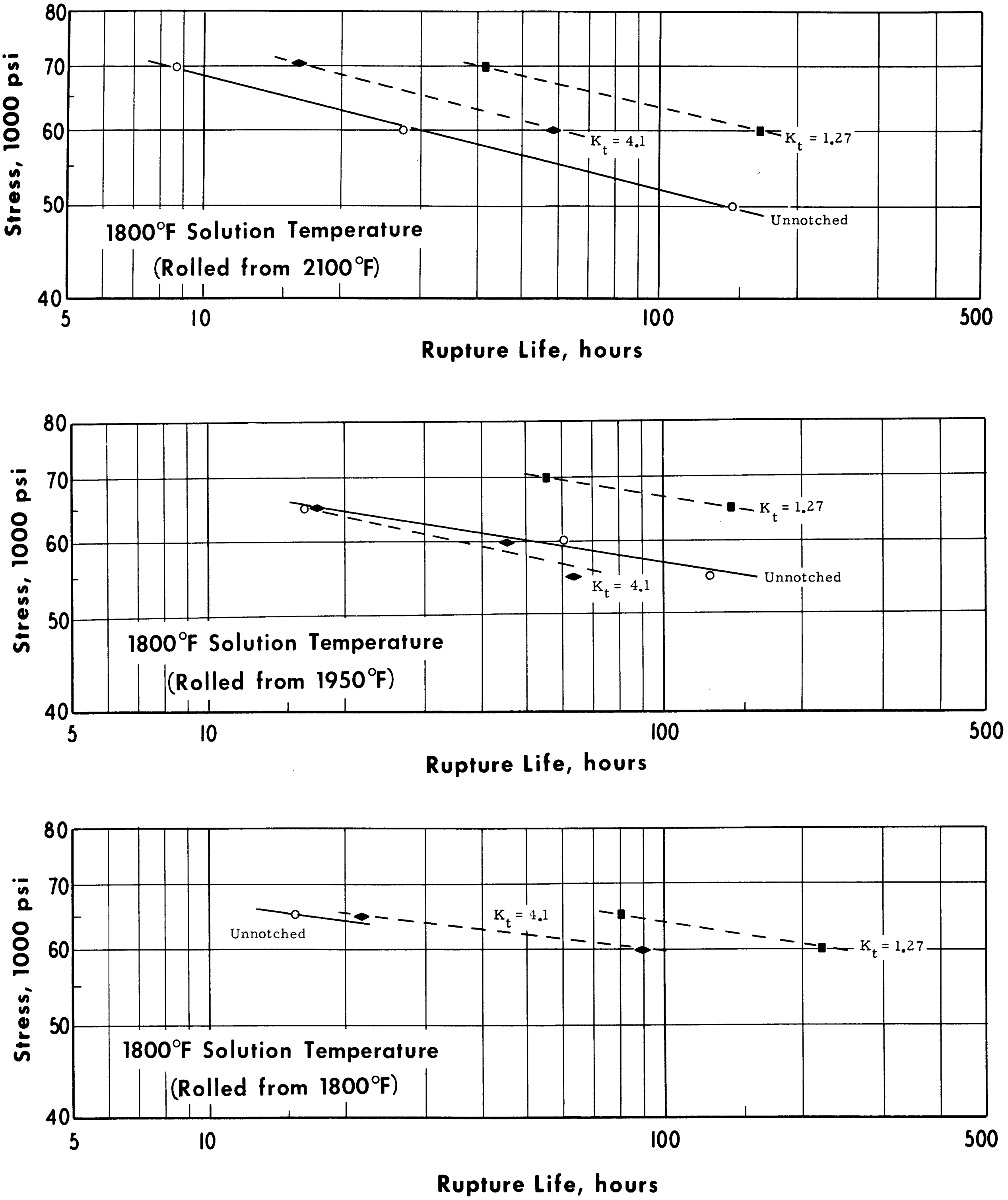

Fig. 3 - Results of Survey Tests on A-286 Heat 52,853 for 1800°F Solution Temperature.

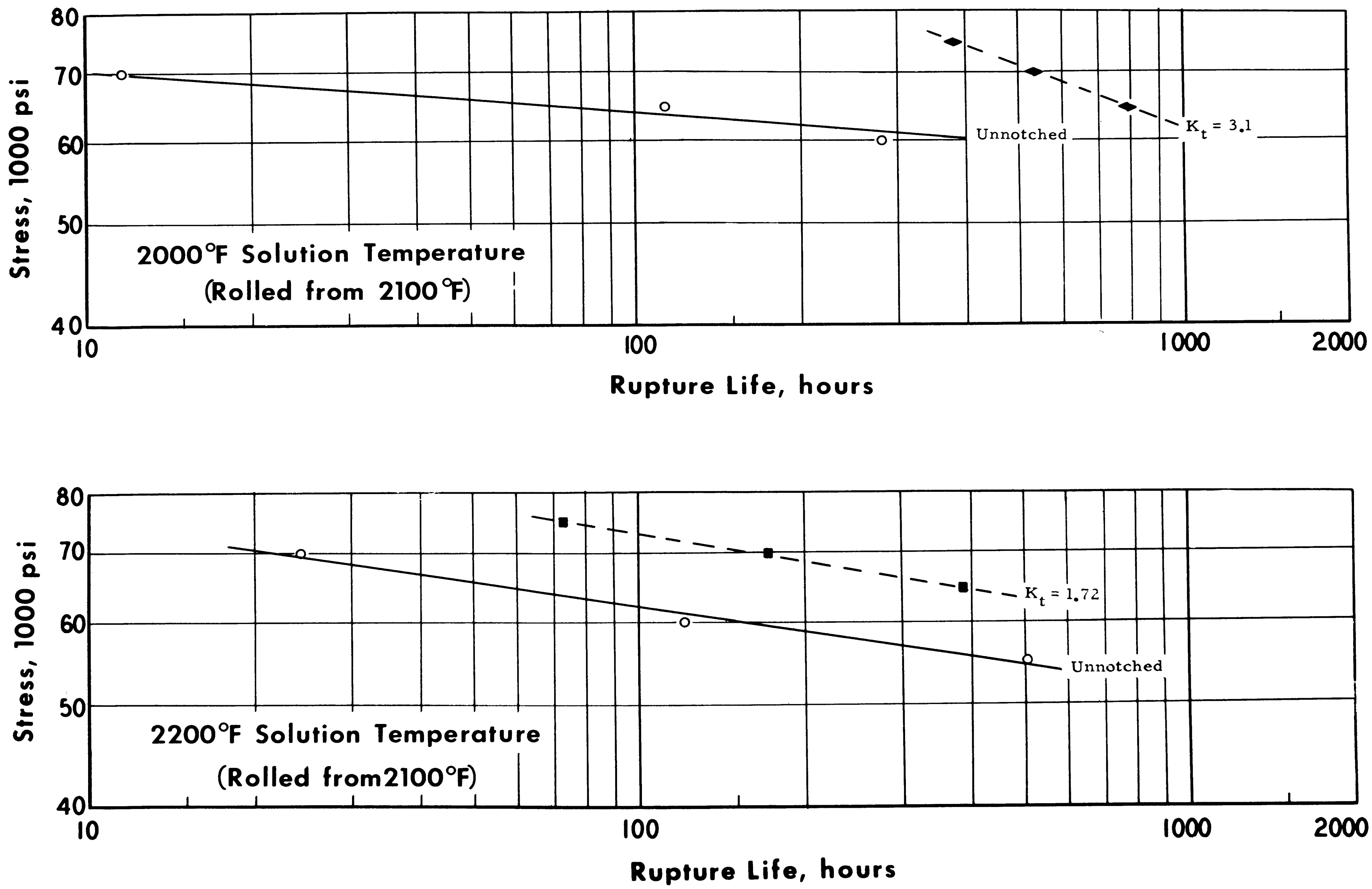

Fig. 4 - Results of Survey Tests on A-286 Heat 52,853 for 2000°and 2200°F Solution Temperatures.

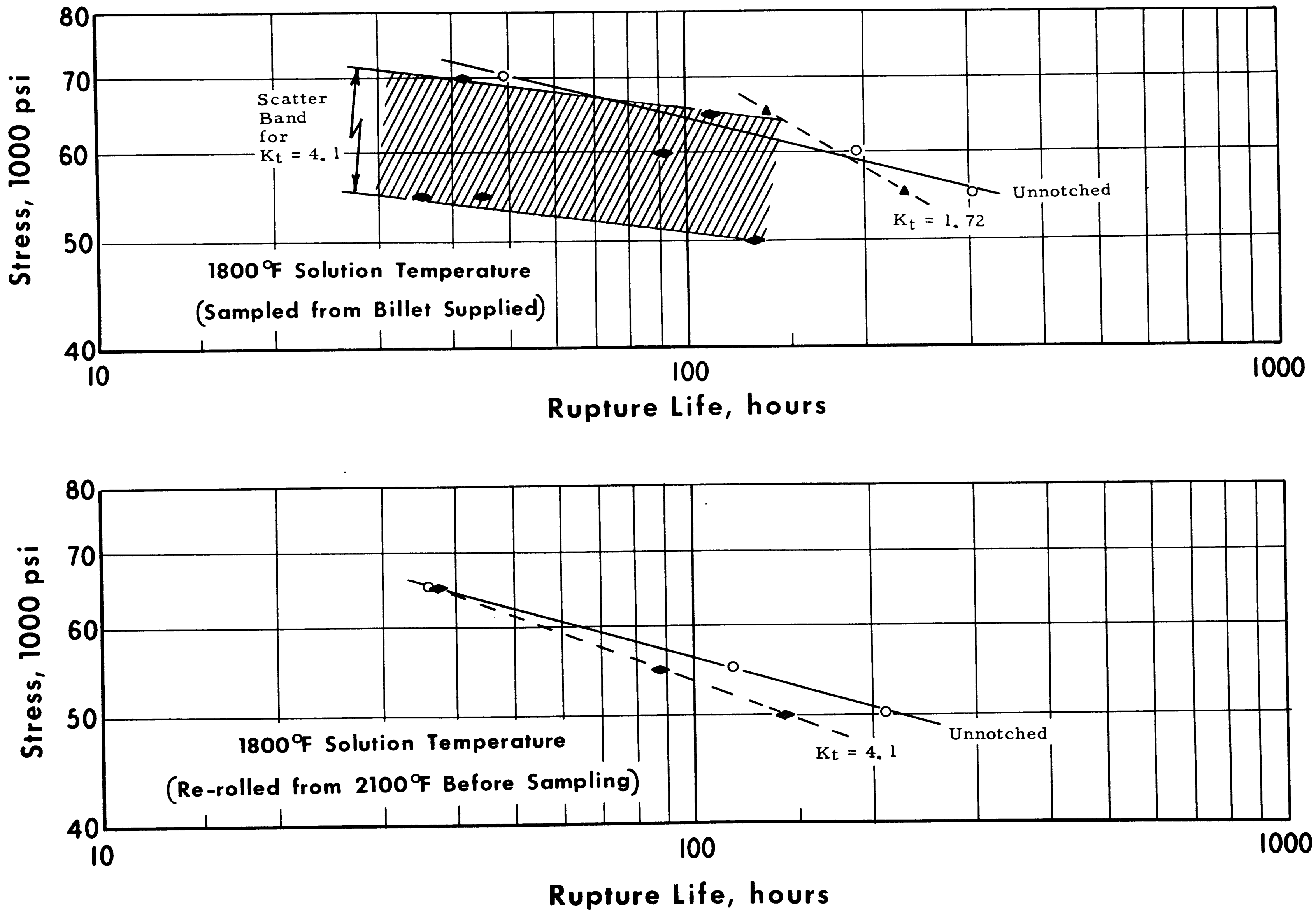

Fig. 5 - Results of Survey Tests on A-286 Heat K-65-X.

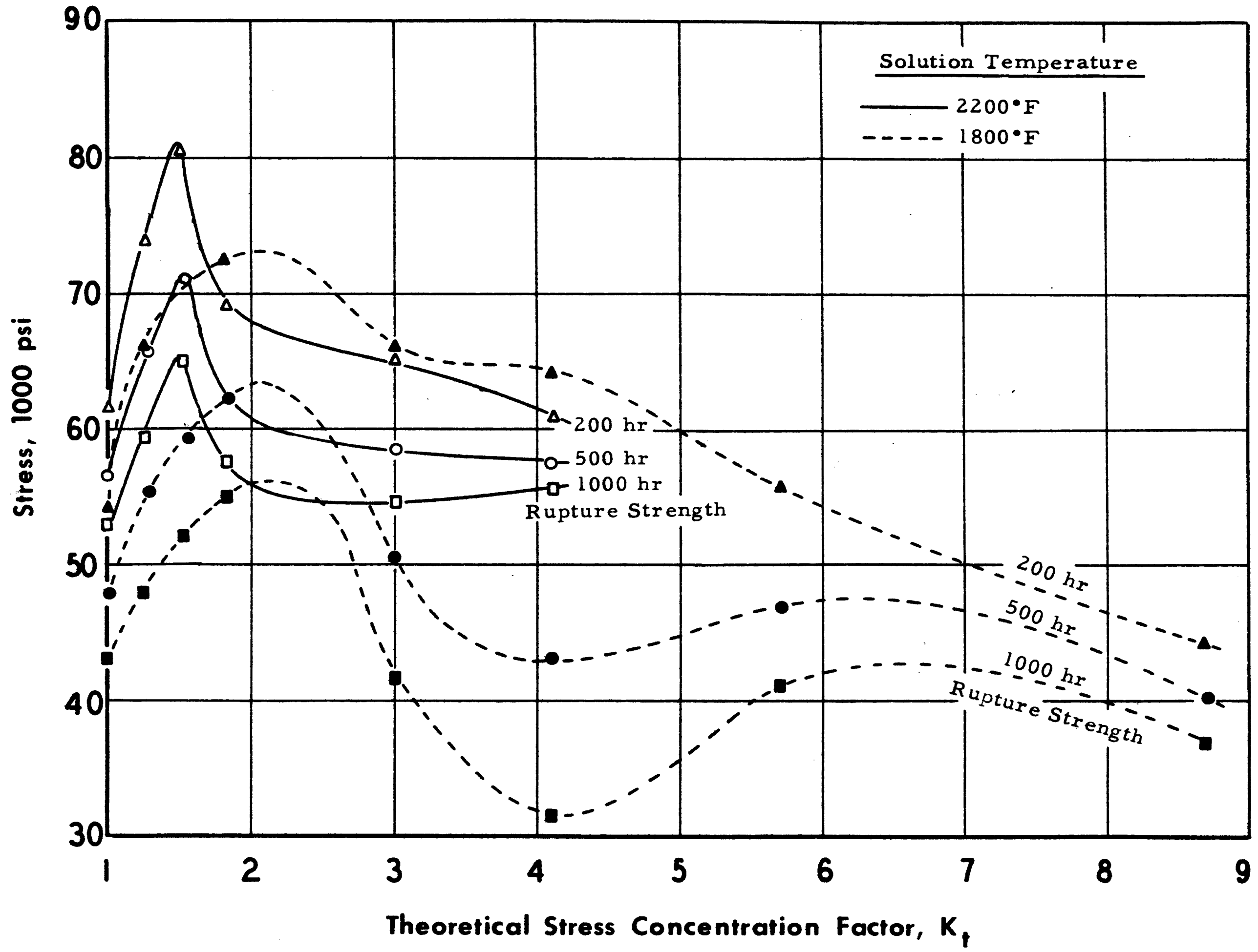

Fig. 6 - Effect of Notch Acuity on Rupture Strength at 1200°F for A-286 Heat 21,030.