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ELEVENTH PROGRESS REPORT
TO
MATERIALS LABORATORY
WRIGHT AIR DEVELOPMENT CENTER
ON
NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

by

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SUMMARY

Task No. 73605 under Contract AF 18(600)-62 calls for continuation of a study into factors affecting notch sensitivity of alloys at elevated temperatures. Past work has shown that rupture properties of a notched bar in tension depends chiefly on the portion of life consumed in lowering initial stress concentrations near the notch root. These past studies employed round smooth and notched specimens of three heat-resistant blade alloys.

The current contract calls for extension to an aluminum alloy and a low-alloy steel, and to flat specimens with edge notches. Additional studies were also specified to clarify effects of factors other than creep-relaxation properties on notch sensitivity and to attempt measurement of strain patterns in flat notched bars.

Substantially all experimental work to meet these contract commitments has been completed except for a few tests now in progress to investigate variable notch behavior of one lot of Waspaloy and to measure strain patterns during creep.

Tests for the past quarter centered around the effect on notch behavior of plastic strains which occur in fibers near the notch root during loading. Smooth specimens of S-816 and Inconel X-550 were pre-strained by momentary overloading at 1350°F to give plastic strains of the magnitude to be expected in a notched bar.

For the S-816, plastic pre-strain accelerated relaxation in early stages but resulted in slower rates of relaxation at longer times. Neither initial plastic deformation nor a prolonged relaxation period following it had much effect on subsequent life to rupture. In contrast, increasing initial plastic strains up to 2.6% markedly lowered relaxation strength of Inconel X-550 and left the material with but a fraction of its initial rupture life.

Fragmentary tests on one particular heat of Waspaloy indicate that a similar lowering of rupture strength by plastic pre-straining may explain the severe

weakening reported previously for the material when the 1550°F intermediate age was omitted from the conventional heat treatment.

New data for 2024-T4 aluminum alloy at 400°F and for "17-22-A"S low-alloy steel at 1100°F suggest that caution must be used in applying the rule previously proposed for adding life fractions in creep-rupture under variable stress.

A mathematical analysis was proposed in previous reports to correlate notch behavior with smooth-bar creep and rupture properties. The original analysis has been modified by adoption of a more rational division of the cross section and by direct application of the effective stress and effective creep rate to the calculations instead of dealing with individual principal components. Calculations are to continue until other alloys and conditions tested have been considered.

NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURES

INTRODUCTION

This report covers experimental work performed between July 1 and October 15, 1955 on Task No. 73605 under Air Force Contract No. AF 18(600)-62, which calls for study of factors affecting notch sensitivity of alloys at elevated temperatures.

The influence of a notch on the creep-rupture performance of an alloy is dependent on the way the stress concentration near the root of the notch is redistributed by creep. A notch not only causes a stress concentration but introduces complex stresses. Creep redistributes the stress, with the fastest reduction of the stress in the direction of the highest (axial) stress component. Reduction of this peak stress component can produce an effective stress below the nominal.

Notch weakening or notch strengthening is dependent on the portion of total rupture life consumed during relaxation of initial high stresses. If the effective stress can relax to a low enough value without excessive life being consumed, rupture life is prolonged. If, however, the material is highly creep resistant, the rupture life may be used up so rapidly at the high stresses that life is shortened even though a low effective stress may eventually be reached.

In past reports, a mathematical analysis was developed which enabled the calculation from tension creep data of the stress redistribution by creep. Combined with calculations of the rate at which rupture life is used up, this enabled prediction of the rupture life of notched bars. The analysis has been applied to structurally stable alloys for which experimental observations have shown that fractions of rupture life under varying stress are additive. Stepwise calculations determine the stress changes and the rupture life used during succeeding time intervals for several representative areas in the notched specimen. The calculations are continued until rupture of the critical fiber for the particular specimen is established. The whole specimen is considered to fail very rapidly thereafter.

The phenomenological approach adopted considers that, under variable stress, the rate of life expenditure in any period of the specimen history depends only on the current stress and a current strength, conveniently expressed by stress-rupture life data. This current strength is a composite result of initial heat treatments and the entire stress-strain-time history to date.

Anything which alters either the inherent strength or the stress distribution between fibers of a notched specimen may be expected to affect rupture life of the specimen. The simple rule proposed for adding life fractions might be seriously in error when material properties change during the life of a specimen, whether the change is brought about by gradual microstructural alterations or by plastic strains such as usually occur near the notch root during stressing of a notched specimen. The present report includes results of a few preliminary tests performed to determine the magnitude of differences in notch effects to be expected from such initial plastic strains.

CURRENT STATUS OF THE INVESTIGATION

Initial studies under this extended program compared creep-relaxation properties of smooth specimens and rupture properties of round bars with a circumferential notch. Three heat-resistant blade alloys were investigated. Task No. 73605 involves extension to:

1. Materials of other types (an aluminum alloy and a Cr-Mo-V low-alloy steel)
2. Flat specimens with edge notches. If possible, distribution of creep strains is to be measured on some of these sheet specimens.

Further studies were also specified to investigate the role of factors other than the creep-relaxation properties on notch sensitivity, including unfinished studies on effects of residual machining stresses. In particular, the cause of reputed variability in notch behavior of some lots of Waspaloy was to be investigated.

Finally, mathematical correlation of creep-relaxation and notched-bar rupture tests was to be completed on the basis of addibility of life fractions.

Considerable progress has been made on all these phases of the investigation except the measurement of strain patterns of notched flat specimens following creep.

Experimental Properties of Notched Versus Smooth Specimens

Constant-load creep tests to rupture have been completed for all materials in the program, including a few rupture tests on flat smooth specimens.

Experiments now in progress and expected to be finished by early November should complete the establishment of rupture properties for both round and flat specimens containing notches relatively free from effects of residual machining stresses. These notch characteristics have been obtained for two theoretical stress concentration factors (K_t = 3.1 and 2.0).

For each alloy and temperature investigated, at least one relaxation curve has been determined for initial stresses of a magnitude experienced by fibers near the root of a typical notch. No further such tests are planned under the current contract.

Measurement of Distribution of Creep Strains in Flat Notched Specimens

A ruled grid is currently being scribed on the first of several flat notched specimens for use in studies of creep-strain distribution. Actual measurements are to be attempted in late October.

Studies of Notch Preparation Methods

During the current year routine finishing of notches has been by careful grinding followed by hand lapping. Results from these specimens are being compared with those from bars notched by other methods designed to minimize residual machining stresses.

Three specimens of Inconel X-550 were finished at the University of Minnesota by a refined lapping technique developed there. The specimen blanks were heat-treated and rough machined at the University of Michigan prior to finishing and were returned to Michigan for testing. The test data are included in this report.

Five other specimens of Inconel X-550 have been sent to the Sheffield Corporation of Dayton, Ohio. That company is to attempt notch preparation by experimental techniques under development by them. As yet, none of these specimens has been returned for testing.

Two specimens of the "17-22-A"S low-alloy steel were heat treated in vacuum after notching to insure relief of residual stresses. Results are included in this report.

Variable Notch Behavior of Some Lots of Waspaloy

The tenth progress report on this investigation indicated a definite difference in notch rupture strength for one heat of Waspaloy, depending on whether or not an intermediate aging for 4 hours at 1550°F was included between solution treating and the 1400°F age of the conventional heat treatment. This difference in notch sensitivity could be explained by any of at least three factors:

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

2. Differences in creep-relaxation properties or rupture properties for material with the two treatments.

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

To date, four tests have been run in which creep-rupture properties of smooth specimens were determined after momentary initial overloading to give about 1% plastic pre-straining. Other tests scheduled for late October will use all remaining alloy from this heat.

Effect of Plastic Strains on Creep, Relaxation and Rupture Properties

Initial tests on the above Waspaloy specimens showed a probable large effect of plastic pre-straining on smooth-bar creep and rupture properties. Limited tests were run on other alloys of the program to ascertain the order of magnitude of effects on creep, relaxation and rupture characteristics resulting from initial plastic strains. Tests already finished or in progress should be sufficient to establish the qualitative effect of such plastic strains on notch behavior of the several alloys under study.

Mathematical Correlation of Notch Behavior and Smooth-Bar Properties

The mathematical analysis proposed in previous reports and based on addibility of life fractions has since been modified slightly. It is anticipated that the general validity of the modified analysis for the alloys under study can be adequately examined within the time limits of the present contract.

EXPERIMENTAL RESULTS

Creep and Rupture Tests for Smooth and Notched Specimens

During the past quarter, a number of tests were performed to complete the coverage of stress-rupture time data for both smooth and notched specimens of the two alloys introduced into the program during the present year. These new results are tabulated below.

2024-T4 Aluminum Alloy at 400°F

Specimen No.	Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
		Round Smooth Bars		
S-A612	17,500	476.2	11.5	36.5
S-A651	18,000	Scheduled		
		Flat Smooth Bars		
FS-A647	30,000	13.2		25.5
FS-A648	20,000	401.8		30.5
		Round Notched Bars		K_t
N-A621	40,000	13.2		3.1
N-A620	20,000	1154.8		3.1
N-A632	20,000	616+ (In progress)		1.9
		Flat Notched Bars		
FN-A636	40,000	6.3		3.1
FN-A635	30,000	37.9		3.1
FN-A638	20,000	167+ (In progress)		3.1
FN-A643	35,000	48.9		2.0
FN-A642	30,000	168.45		2.0
FN-A646	25,000	546.25		2.0

Comparison with past results indicates that rupture life for smooth bars appears to be independent of whether round or flat specimens are used.

In the Tenth Progress Report (Ref. 1), rupture-test results for both round and flat notched bars with a theoretical stress concentration factor of 1.9 and for round notched bars with K_t = 3.1 all fell on a common curve about 5000 to 10,000 psi above that for smooth specimens. The new results for flat notched bars with K_t = 3.1 appear to lie about midway between the previous curves for notched and smooth specimens.

"17-22-A"S Low alloy steel at 1100°F

Specimen No.	Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)	K_t
		Round Smooth Bars			
S-L730	73,000	0.47	23	71	
		Flat Smooth Bars			
FS-L744	60,000	8.1			
FS-L745	45,000	50.5			
FS-L743	30,000	183.0			
		Round Notched Bars			
[a] N-L753	40,000	68.6			3.1
[a] N-L755	25,000	368.6			3.1
		Flat Notched Bars			
FN-L742	20,000	764.6			1.9

(a) Notch ground and lapped before conventional heat treatment in vacuum.

Results for the flat smooth specimens of this alloy agree closely with the curve for smooth round bars presented in Fig. 4 of Ref. 1. This agrees with findings reported previously for the other alloys.

From the single pair of tests available to date, heat treatment before or after the notch is finished by grinding and lapping appears to cause no variation in rupture life. (For K_t = 3.1 and a nominal stress of 40,000 psi, rupture lives of 73.5 and 68.6 hours were obtained for the two cases).

Notch Preparation Studies

In the notch-finishing procedure employed at the University of Michigan, the notch root receives a final lapping with movement of abrasive particles in the circumferential (transverse) direction. At the University of Minnesota Department of Mechanics and Materials a more refined lapping technique employs a rotating wire so that abrasive movement at the root of the notch is in the axial direction.

Comparable specimens with K_t of about 3 were prepared at the two laboratories from the same lot of Inconel X-550, with heat treatments, rough machining and testing all performed at the University of Michigan:

Notched Bars of Inconel X-550 at 1350°F, $K_t = 3$

Spec. No.	Laboratory Where Notch was Finished	Stress (psi)	Rupture Life (hours)
N-X572	Michigan	55,000	31.5
N-X573	Michigan	35,000	523.1
N-X579	Minnesota	50,000	134.8
N-X578	Minnesota	40,000	185.4
N-X577	Minnesota	35,000	568.4

These test findings plotted on Fig. 3 show considerable scatter, but no particular trend is apparent to indicate any consistent effect from the differences in the two lapping techniques.

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

A private communication from Mr. F. Vitovec of the University of Minnesota showed very close agreement between specimens finished at Michigan and at Minnesota for one case each of rupture at 1350°F and 1500°F and fatigue at 75°F and 1350°F under reversed stress. The fifth specimen tested to rupture at 1350°F broke at a much shorter time than comparison specimens machined at the two different laboratories.

Study of Property Differences of Waspaloy Heat 63613 With and Without an Intermediate Aging Step

The previous report included fragmentary data for notched specimens sampled from the 1-3/4 inch diameter stock of Waspaloy Heat 63613 rolled by the supplier. Mild notch strengthening was indicated for specimens given the conventional heat treatment, while similar specimens with the 1550°F age omitted were decidedly weakened by the notch.

This observed contrast in notch behavior must reflect either some inherent difference in smooth-bar properties for the two heat treatments or else some difference in response for the two conditions to plastic strain during loading or to holding at temperature during the test.

Only enough material from this particular lot was available to make a total of eighteen specimen blanks. Four of these were used to obtain the notch data presented in Figure 3 of Reference 1. Those notch tests are to be supplemented by two more now in progress.

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

A more fruitful approach appears to have been made in other tests where a smooth specimen was first overloaded momentarily to cause an initial plastic strain approximating conditions at a notch root. Available data listed below are still too sparse to permit firm conclusions, but plastic pre-straining does appear to shorten rupture life considerably. Omission of the 1550°F aging step seems to accentuate this fall-off in rupture strength from initial strains.

Smooth-Bar Rupture Tests on Waspaloy Heat 63613 at 1350°F

Spec. No.	Momentary Overload Stress (psi)	Test Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area(%)
		Conventional Heat Treatment			
S-W363		75,000	1.6	3.	3.5
S-W365		45,000	587.3		3.5
OS-W361	98,000	70,000	1.1	4.	6.5
OS-W373	98,000	60,000	9.8		4.5
		1550°F Age Omitted			
S-W370		75,000	2.4	2.5	8.5
S-W368		45,000	579.6	5.	3.5
OS-W372	100,000	70,000	0.12	4.	8.
OS-W374	98,000	60,000	3.85	2.5	4.5

Multiple-Stress Rupture and Relaxation Properties for 2024-T4 and "17-22-A"S

Past work with three heat-resistant alloys indicated that when the applied stress is varied the fraction of rupture life consumed during any period of given stress level equals the time at the stress divided by rupture life in a constant stress test at the same stress level. It might be anticipated that for alloys and temperatures where metallurgical structures undergo alteration, with resultant changes in inherent strength, this simple rule may fail. Since the calculation method proposed in earlier reports assumes quantitative addibility of life fraction, multiple-stress experiments to test this premise have been necessary for the two alloys added to the program during 1955:

Results of Multiple-Stress Rupture Tests on Smooth Specimens

Spec. No.	Stress (psi)	Fraction: Time at Stress / Rupture Life at Stress	Sum of Life Fractions	Elongation (%)	Reduction of Area (%)
		2024-T4 at 400°F			
MS-A602	20,000	173/460 = 0.376			
	30,000	0.4/18 = 0.022	0.398	18.7	17.5
MS-A604	10,000	95/(10,000) = 0.01			
	30,000	0.375/18 = 0.02	0.03	13.	51.
MS-A614	30,000	10/18 = 0.556			
	20,000	277.25/460 = 0.603	1.16	8.5	30.
		2024-T4 at 500°F			
MS-A615	15,000	10.5/24.5 = 0.428			
	10,000	168.75/165 = 1.023	1.45		
		"17-22-A"S at 1100°F			
MS-L707	25,000	197/430 = 0.458			
	60,000	0.66/9.8 = 0.067	0.525	8.	30.
MS-L710	60,000	5.5/9.8 = 0.562			
	25,000	238.35/430 = 0.554	1.116	5.	4.
MS-L711	25,000	131.3/430 = 0.305			
	60,000	0.085/9.8 = 0.009	0.314	12.5	47.
MS-L712	60,000	1.1/9.8 = 0.112			
	50,000	3.9/35 = 0.112			
	30,000	40.0/220 = 0.182			
	20,000	114.7/880 = 0.131	0.537	9.	22.
MS-L729	60,000	3.67/9.8 = 0.375			
	25,000	130/430 = 0.305			
	60,000	3.0/9.8 = 0.306	0.986	15.5	32.5

The 2024 aluminum alloy in the T-4 condition (room temperature age) can be expected to over-age during prolonged exposure to a temperature of 400° or 500°F. A period of 100 or 200 hours at 400°F appears to result in a 30 to 50 fold reduction in rupture life at a subsequent stress of 30,000 psi, compared with the original rupture strength at this stress.

When a substantial fraction of the rupture life was expended at an initial higher stress and the stress then reduced, the remaining life was somewhat longer than is predicted by the life fraction rule based on constant-stress data. This finding appears to be reasonable.

Results for the "17-22-A"S Cr-Mo-V low alloy steel exhibited similar trends, but much less drastic. They indicate that the simple rule proposed previously for addibility of life fractures of stable alloys should be applied with caution to fibers in a notched bar of this alloy tested at 1100°F.

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

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

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

A single relaxation test each has now been run for 2024-T4 aluminum alloy at 400°F and for "17-22-A"S low alloy steel at 1100°F, with initial stress in each case roughly midway between the proportional limit and the 0.2% offset yield strength. The aluminum alloy required about 13 hours to relax from the 10-hour rupture stress to that corresponding to 1000-hour life. The low alloy steel took roughly twice as long (30 hours) to relax between its 10-hour and 1000-hour rupture stresses.

Both these specimens are currently being allowed to creep to rupture at the residual stress remaining after the relaxation period.

Relaxation and Rupture Properties After Pre-Strain at Test Temperature

Early in this program it was noted that a small amount of plastic strain seemed to promote more rapid creep in S-816 tested at 1350°F. More recent tests mentioned above suggest initial plastic strains may lead to shortened life at later reduced stress levels. These effects have now been studied more critically with the two heat-resistant alloys for which enough stock remained.

Five specimens of S-816 were pre-strained at 1350°F by amounts ranging from zero to 9.2% after they had received a conventional heat treatment. Each was then reloaded to an initial stress of 37,500 psi at 1350°F test temperature and relaxation characteristics obtained, as presented in Figure 1.

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

Relaxation characteristics were obtained to rather low stresses in test times of several hundred hours. In every case, the calculated portion of life consumed in the entire relaxation period was less than one percent. The stress on each specimen was later raised and the test allowed to proceed at this new stress until rupture occurred. Table I lists the time required for relaxation to

TABLE I

Effect of Plastic Pre-Straining on Relaxation and Rupture of S-816 and of Inconel X-550 Tested at 1350°F

S-816

Spec. No.	Plastic Pre-Strain (%)	Relaxation Time 37,500 psi to 15,000 psi (hr)	Life used in Relaxing to 15,000 psi (%)	Subsequent Creep to Rupture: Stress (psi)	Subsequent Creep to Rupture: Fraction: Time at Stress / Rupture Life at Stress		
RS-(B)S14	0	5.25	0.25	40,000	61.9/87	=	0.71
ORS-(B)S17	1.35	5.5	0.17	40,000	70.15/87	=	0.81
ORS-(B)S23	3.15	6.0	0.15	40,000	60.3/87	=	0.69
ORS-(B)S38	6	14.9	0.33	37,500	190.75/135	=	1.41
ORS-(B)S48	9.2	61.8	0.58	40,000	90.9/87	=	1.05

Inconel X-550

Spec. No.	Plastic Pre-Strain (%)	Relaxation Time 60,000 to 40,000 psi (hour)	Life used in Relaxing to 40,000 psi (%)	History of Stress and Life Consumed: Stress (psi)	History of Stress and Life Consumed: % of Total Life Consumed
RR-X501	0	100	34.6	Relax 60,000 to 22,360 psi Relax 60,000 to 38,060 psi (Ruptured at 38,060)	77.2 3.1 80.3%
ORS-X555	0.25	93.9	42.2	Relax 60,000 to 14,600 psi 35,000 psi to Rupture	70.0 1.3 71.3%
ORS-X556	0.85	32.3	14.1	Relax 60,000 to 11,690 psi 35,000 psi to rupture	34.0 4.0 39.0%
ORS-X557	1.4	21.6	9.5	Relax 60,000 to 40,000 psi 40,000 psi to rupture	9.5 24.4 33.9%
ORS-X558	2.6	5.7	2.4	Relax 60,000 to 40,000 psi 40,000 psi to rupture	2.4 19.5 21.9%

15,000 psi and life expenditure during that initial period of relaxation, along with rupture life during the subsequent higher-stress period.

Plastic pre-straining of more than a few percent delays relaxation at the lower stresses. This results in little increase in rupture life used up while the stress is being redistributed. When life fractions were calculated from rupture properties of unstrained material, specimens with 6 to 9 percent initial plastic strain were found not to be weakened by the plastic deformation or by a prolonged relaxation period following it, and an increase in total rupture life may actually be experienced.

Corresponding tests on Inconel X-550 with initial plastic strains up to 2.6% exhibit quite different behavior. Increasing amounts of pre-strain shorten relaxation times (See Figure 2) but when the specimen is then held at constant stress following the relaxation, specimens with initial strains of about 1% or more had but a fraction of the life to be expected from calculations based on properties of unstrained material (See Table I).

"17-22-A"S at 1100°F

A single pair of creep tests is available for this low alloy steel, with one specimen pre-strained only about 0.11% by momentary overloading to 74,000 psi:

Spec. No.	Plastic Pre-strain (%)	Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
S-L704	0.	40,000	87.2	4.5	6.5
OS-L728	0.11	40,000	81.4	4.	4.5

The two specimens appeared to have the same rupture life and ductility properties but for at least the first twenty hours the specimen with pre-strain had a creep rate about 20% lower than that for the bar not pre-strained.

Another test with a larger initial plastic strain is planned to verify this pattern of response.

2024-T4 at 400°F

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

A second smooth specimen of this alloy was similarly pre-strained about 1% at temperature and then run to rupture at a 35,000 psi stress. A life of 7.3 hours was obtained compared to about 6 hours shown by the smoothed curve for specimens not pre-strained (Fig. 6 of Ref. 1). For both conditions, measured reduction of area after rupture was 37%.

These fragmentary data indicate a possible slight increase in rupture strength at 400°F by pre-straining 2024-T4, with no observable effect on ductility.

Multiple-Stress Notch Rupture Tests

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

The first of these tests was listed in Table 2 of Reference 2. There, Inconel X-550 specimen X-531 was reported to have been run 1343.7 hours at 1350°F and 24,500 psi. It was then raised to 35,000 psi stress. At this new level another 270.9 hours elapsed until rupture, even though other notched specimens failed in 197.4 and 31.2 hours when subjected to 35,000 psi stress throughout their tests at this temperature.

The second test was with a notched specimen prepared from the 1/2-inch square stock rolled at the University of Michigan from Waspaloy Heat 3-260 and given a conventional heat treatment less the 1550°F age. After 2280.8 hours at 40,000 psi and a temperature of 1350°F the stress was raised to 55,000 psi, at which stress a smooth-bar life of 400 hours is indicated by Fig. 3 of reference 3. When the specimen had lasted another 1029 hours at this stress, the level was again raised, this time to 60,000 psi where the smooth-bar life is about 170 hours. Rupture occurred after 584.6 hours at the high stress. Other tests with a similar notch, but with 50,000 or 60,000 psi stress from the beginning, gave rupture lives of only a few hours.

From these unexpected results, it appeared that a long time exposure of a notched bar to a low initial stress might allow later high stress with greatly extended rupture life compared with notch strengths obtained under conditions of constant high nominal stress throughout the test.

In another instance, a specimen of this same material with a root radius of 0.018 inches ($K_t = 3.3$) was given a conventional heat treatment. The notch root for this specimen was finished by grinding and lapping, while other tests were with notches turned on a lathe and then heat treated.

A stress of 50,000 psi was chosen. At this level, the rupture life for the notched bars with $K_t = 6.8$ shown in Ref. 3 was about 10 hours and for the smooth bars about 800 hours. The present specimen had still not failed at 3179.1 hours, wherefore, the stress was increased to 70,000 psi. At this latter level, an additional 64.3 hours was obtained; this is approximately equal to the smooth-bar rupture life at 70,000 psi.

In this last example several factors differ from the data used for a comparison, but once more a possible extension of notch rupture life by an initial low-stress period is indicated. To check this possibility, two additional experiments were conducted:

Comparison of Multi-Stress and Constant-Stress Notch Rupture Tests
$(K_t = 3.1)$

Spec. No.	Stress (psi)	Fraction of Smooth-Bar Life for Same Stress		
		Inconel X-550 at 1350°F		
MN-X574	35,000	103.25/1280	=	0.081
	45,000	22.3/310	=	0.072
	55,000	12.7/100	=	0.127
				0.28
N-X 573	35,000	523.1/1280	=	0.41
N-X 572	55,000	31.5/100	=	0.315
		"17-22-A"S at 1100°F		
MN-L747	20,000	216.5/888	=	0.244
	40,000	32.0/87	=	0.368
				0.61
N-L717	20,000	699.6/888	=	0.79
N-715	40,000	73.5/87	=	0.83

Under the conditions examined here, a moderate time period at lower stress did not increase life at later higher stresses and may even have reduced the total life for the entire test.

DISCUSSION OF RESULTS

All evidence gathered to date in this entire program seems to verify the general soundness of the basic premise that rupture life under conditions of initial stress concentration can be explained in terms of the changing stress pattern and the rupture strengths at existing stresses. It still appears that the only major factors involved are the variable creep (or relaxation) rates which permit reduction of stress gradients and the stress-rupture time properties existing in different fibers at each stage of stress-strain-time history.

For specimens with relatively dull notches, or loaded to rather low nominal stresses, and made of alloys with reasonably stable structure,the methods proposed in earlier reports can be expected to predict approximate notch sensitivity rather closely. Under such conditions the rule found for addibility of life fractions should be valid and differences in relaxation properties have been shown to correlate with notch sensitivities of different alloys. For the "17-22-A"S low-alloy steel at 1100°F and the 2024-T4 aluminum alloy at 400°F these relationships should still hold at least qualitatively despite shortcomings of the life fraction rule for these conditions.

For the aluminum alloy, the fibers near the notch root experience falling stress level during the test. The single multiple-stress rupture test performed for such a stress change indicates that these fibers may be expected to have a life at least as long as the simple life fraction rule predicts, and perhaps longer. If overaging occurs, fibers nearer the axis, with a steady rise in stress, can be expected to retain a smaller portion of residual life than simple addibility of life fractions predicts and may well be the site of the first fracture.

Probable Effects of Creep Prior to Introduction of a Notch

Should a part be subjected to creep conditions for an extended time before a notch is introduced, as by impact from a foreign object, sensitivity to the stress concentration thus produced may be presumed to depend on the creep and rupture properties of the alloy at the time the notch appears. Relaxation strength and consequent ability to relieve the high localized stress may be either more or less favorable than in the material as originally placed into service. Thus, alloys with prolonged primary creep and little third-stage creep should behave quite differently from an alloy which exhibits a continual increase in creep rate after very early times.

Lowered creep strength resulting from metallurgical alterations during creep service would favor more rapid stress redistribution, but this may be more than offset by a corresponding drop in rupture strength. This could well be the case for a specimen of 2024-T4 alloy in which a stress raiser appears after long service at 400° or 500°F, where overaging is to be expected. Verification of this point would appear worthwhile not only for the better insight it would provide into the fundamentals of notch-rupture behavior but also to provide information of seeming immediate application.

Effects of Plastic Strain at Notch Root

Rupture results for notched specimens loaded to high stresses probably reflect effects of initial plastic strains at the notch root more than any other one variable. The peak stresses present at the start of the test are determined by the stress-strain properties and ability of the alloy to deform plastically. Plastic strain, even of small magnitude, appears to cause significant changes in creep rate and rupture strength. For the cases of S-816 and Inconel X-550 studied at 1350°F properties alter so as to have opposing effects on rupture life of highly-stressed fibers near the notch root. If conditions were such that plastic strain were to both slow down the rate of stress relaxation and lower subsequent rupture strength, the combined effect could lead to drastic lowering of notch bar rupture life when applied stresses were raised above some critical level or when a very sharp notch was used. The extreme notch embrittlement reported in Ref. 3 for

Waspaloy Heat 3-260 with a notch root radius of 0.004 inches may perhaps be explained in this manner. The test for this same material but with a notch root radius of 0.018 mentioned in the present report indicates notch strengthening for the less severe notch. Presumably, in this latter instance, no corresponding large loss in strength properties was caused.

PROPOSED MODIFICATIONS IN MATHEMATICAL CORRELATION PROCEDURE

In the original calculation method proposed in Reference 2, the cross section in the plane of the notch was divided into nine concentric rings chosen arbitrarily to give four small bands of equal area near the notch. The next four rings toward the axis each had an area four times that of the outermost rings. A central ring covered half the total cross section.

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

More recent calculations have employed only six concentric rings, with each half the area of the next ring toward the axis. For such a pattern, elastic stress changes at any interface are always distributed in the ratio 2/1 between the two rings involved. Under the new distribution the outermost ring is 1/63 of the total area, so that the stress at its centroid is very near the value at the surface of the specimen near the notch root.

When the notch problem was first analyzed, attention was focused on changes in the separate component stresses and relaxation was assumed to proceed independently for the three principal deviator stress components, following usual rules of plastic behavior. Further recent consideration indicates that such an approach may not be completely valid since any elastic change in one stress component will result in accompanying elastic strains in other directions. In any case, it appears unnecessary to deal with stress components if the current shear stress invariant (effective stress) controls the effective creep rate and the rate of life expenditure.

Calculations have now been repeated for the conditions of the first example cited under the Sample Calculation in Reference 2. (Waspaloy at 1500°F under a nominal stress of 25,000 psi with a notch root radius of 0.100 inch). The effective creep rate was found corresponding to the initial effective stress at the centroid of each ring. The differential creep rate between rings was multiplied by a time interval and the shear modulus to get the stress interaction at each interface.

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

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

Both of the modifications considered here have the virtue of reducing the tedium of the calculations. In the modified form, the analytical method developed could perhaps even be considered as a basis for a general design method, provided further work shows the findings for notched tension specimens to be equally applicable to structures with other patterns of stress concentration.

FUTURE WORK

Experimental work for the remainder of the current contract is to center on: (1) completion of tests with Waspaloy Heat 63613 to determine whether initial plastic strain at the notch root can adequately explain the observed notch behavior in two conditions of heat treatment; (2) attempts to measure distribution of plastic strains near the notch root, using flat notch specimens loaded to a high nominal stress. If possible, creep strains near the notch root will be measured and compared with values predicted by the calculation methods developed in this program.

All test results obtained are to be re-examined for useful empirical correlations.

Calculations are planned to cover all of the alloys, temperatures and heat treatments investigated experimentally.

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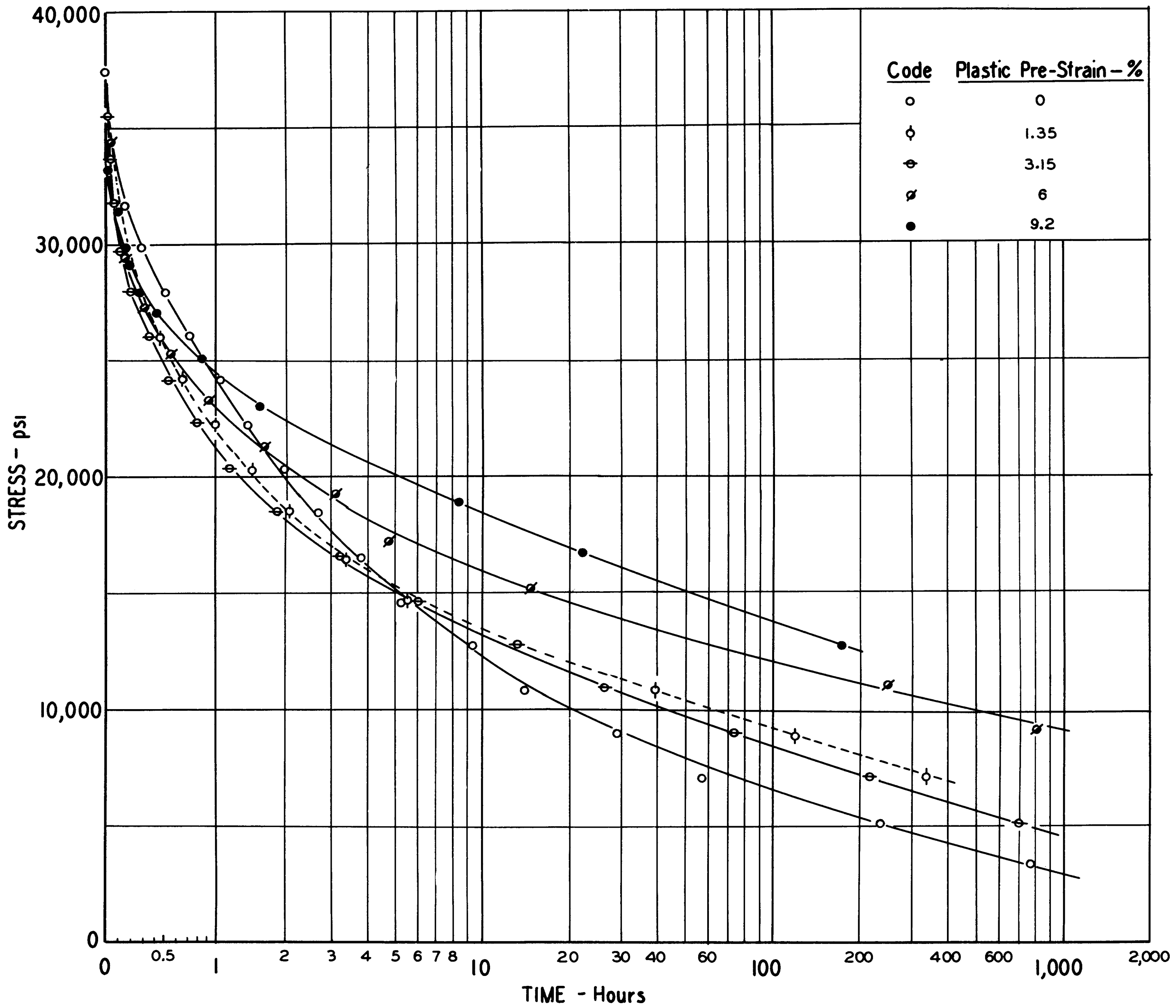

FIG. I - EFFECT OF PLASTIC PRE-STRAIN AT TEMPERATURE ON RELAXATION OF S-816 AT 1350 °F.

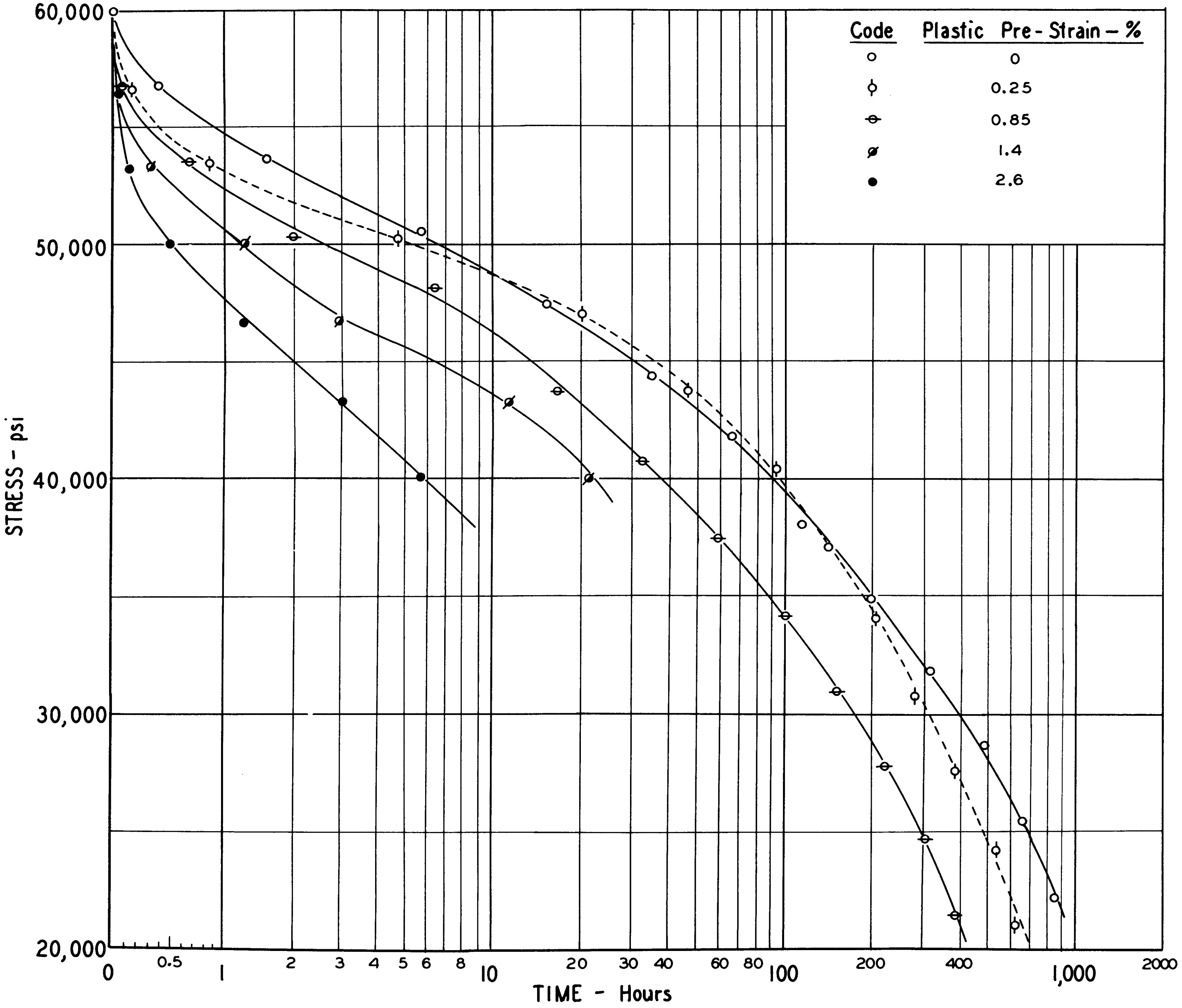

FIG. 2 - EFFECT OF PLASTIC PRE-STRAIN AT TEMPERATURE ON RELAXATION OF INCONEL X-550 AT 1350°F.

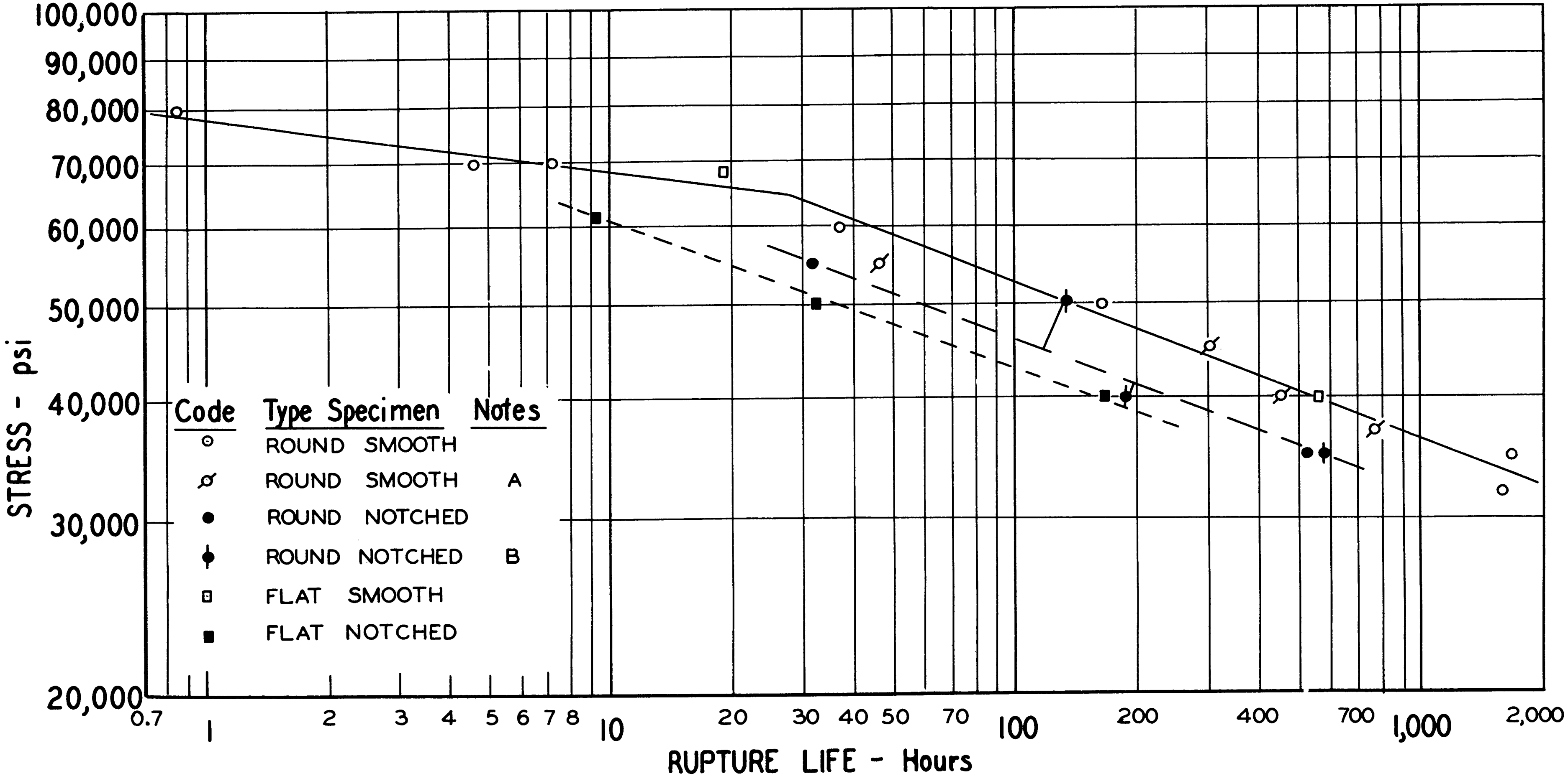

FIG. 3 - STRESS VERSUS RUPTURE LIFE AT 1350 F FOR SMOOTH AND NOTCHED BARS OF INCONEL X-550

NOTES: All notches ground & lapped; $K_t = 3.1$

A: Data of Carlson, et.al.

B: Notch lapped at Univ. of Minnesota