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SEVENTH 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

Previous reports prepared under Contract AF 18(600)-62 have shown a qualitative relationship between notched-bar rupture properties and relaxation characteristics for three heat-resistant alloys with conventional heat treatments. The present report shows similar agreement in the case of two of the same alloys but with non-standard heat treatments.

Future efforts are to be directed toward obtaining a quantitative correlation of data now on hand. Some experimental work remains, chiefly to evaluate effects of residual stresses and metallurgical changes in notched bars as a result of machining practices and of localized straining during loading.

INTRODUCTION

This report covers work performed in the second quarter of 1954 under Contract AF 18(600)-62. A study of creep and relaxation and of certain metallurgical variables for heat-resistant alloys is called for, in an effort to determine how these factors affect notch sensitivity of such alloys at elevated temperatures.

Past reports have established a qualitative relationship between notch strengthening or weakening and creep-relaxation properties of three alloys with conventional heat treatments. At temperatures where initial stress concentrations could relax quickly without using up a large portion of the total rupture life, notched bars had a longer rupture life than did smooth bars with the same nominal stress. When relaxation was slow so that a stress concentration was retained for a major portion of the test period, the life of notched bars was found to be less than for smooth specimens.

The present report extends coverage of notch properties to two of the alloys after non-standard heat treatments for which relaxation data have already been submitted.

CURRENT STATUS OF THE INVESTIGATION

Investigation of the Significance of Creep and Relaxation in Notch Behavior

All tests originally planned for S-816, Waspaloy and Inconel X-550 at 1350°F, and for Waspaloy at 1500°F with conventional heat treatments have been completed and reported upon. Three other tests now in progress or scheduled should finish planned work on relaxation characteristics and notch characteristics at 1500°F for both S-816 and Waspaloy with extraneous cold working introduced into the heat treatment. No comparable tests on metallurgical variables have been initiated for the Inconel X-550.

During the course of the overall study, the desirability of additional types of tests became evident. Results on two such investigations are expected to be completed by about the end of September:

1. Evaluation of effects of notch-preparation methods upon notched-bar rupture life.
2. Effects of periodic stressing on rupture life of notched bars.

Some preliminary calculations have been performed to estimate the notched-bar rupture life for one case, starting from experimental data obtained with smooth bars alone. Further refinements are indicated before the calculated life and that found experimentally can be brought into agreement. Major efforts for the next quarter are to be directed toward finding a more quantitative correlation method.

Investigation of Some Metallurgical Variables and Their Effects on Notch Behavior

Planned experimental work on metallurgical variables was limited to effects of cold working on properties of S-816 and Waspaloy at 1500°F, for which temperature both of these materials are strengthened by most notches. It is expected that any further tests on metallurgical variables for the original heats of alloys studied will be limited to the investigations mentioned above on effects of machining methods and on notch-bar behavior under periodic stressing at creep conditions.

To date, no other heats of the alloys studied have been obtained with notch properties different from those of the particular heats used in this program. If such other heats can be obtained in time, it is hoped to determine what differences exist in relaxation or in other metallurgical characteristics which might explain the variable response to notches between heats.

STRESS - RUPTURE TIME PROPERTIES AT 1500°F FOR NOTCHED AND SMOOTH BARS OF S-816 WITH VARIOUS UNCONVENTIONAL HEAT TREATMENTS

Incomplete results previously reported (See page 39, Ref. 1) showed a 10,000 to 20,000 psi rise in smooth-bar rupture strengths at 1350° and 1500°F when S-816 was cold rolled after solution treatments. Elongation and reduction of area for these tests were much lower than for conventional treatment. Ductilities were especially low for two tests at 1500°F for bars which had been solution treated at 2325°F, 1 hour, water quench and then reduced 13.5 percent at 1200°F before final aging for 12 hours at 1400°F, air cool. (Elongations were about 1 percent, compared with values of from 35 to 50 percent normal for this alloy.)

Table I, below, and Figure 1 present rupture properties at 1500°F for smooth and notched bars of S-816 with the above non-standard trestment. Notched were made by turning with a formed lathe tool to give the following nominal dimensions in inches:

Shank diameter, D	0.500
Diameter at notch root, d	0.360
Notch root radius, r	0.004
Notch angle	60°

The notch strengths lie some 5,000 to 10,000 psi below those for smooth bars with this same treatment, but are nearly equal to those for smooth bars with conventional heat treatment.

TABLE I

RUPTURE PROPERTIES AT 1500°F FOR SMOOTH AND NOTCHED BARS OF S-816 SOLUTION TREATED AT 2325°F AND THEN REDUCED 13.5% AT 1200°F BEFORE CONVENTIONAL AGING

Type Specimen	Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
Smooth	40,000	20.9	1	4.5
Smooth	30,000	204.1	1	5
Smooth	25,000	(600+) In progress		
Smooth	20,000	(4725.1+) Discontinued		
Notched	35,000	8.05		
Notched	30,000	8.4		
Notched	25,000	59.7		
Notched	20,000	840.2		

Results are also available now for three notched-bar rupture tests at 1500°F for S-816 with extraneous cold working after solution at 2150°F. The notch geometry and preparation were the same as above.

Heat Treatment	Stress (psi)	Rupture Life (hours)
2150°F, 1 hr, W.Q. + 10% Red. at 75°F + 1400°F 12 hrs, A.C.	25,000	370.9
2150°F, 1 hr, W.Q. + 13.5% Red. at 1200°F + 1400°F 12 hrs, A.C.	25,000	352.1
2150°F, 1 hr, W.Q. + 13.5% Red. at 1200°F + 1400°F 12 hrs, A.C.	20,000	2502.1 (a)

(a) r = 0.0005 inch.

A single smooth bar with the first of these heat treatments ruptured in 318.5 hours at 25,000 psi and 1500°F. Elongation and reduction of area at fracture were 5 and 6 percent respectively.

All four of the above points are included in Figure 1.

COMPLETION OF TESTS ON METALLURGICAL VARIABLES FOR WASPALOY AT 1500°F

Table II lists rupture-test results at 1500°F for smooth and notched bars of Waspaloy after two non-standard heat treatments. The data are presented graphically in Figure 2. Notches for these tests were made with a lathe tool to the following dimensions in inches:

Shank diameter, D	0.500
Diameter at notch root, d	0.375
Notch root radius, r	0.004
Notch angle	60°

Relaxation characteristics for these conditions were shown in Figure 6 of the previous progress report (Ref. 2), but the heat treatments stated in the legend were in error. This figure has been corrected and included as Figure 3 of the present report.

TABLE II

RUPTURE - TEST DATA AT 1500°F FOR WASPALOY WITH EXTRANEOUS COLD WORKING BETWEEN CONVENTIONAL SOLUTION AND AGING TREATMENTS

Type Specimen	Stress (psi)	Rupture Life (hours)	Elongation (%)	Reduction of Area (%)
1975°F, 4 hrs, A.C. + 5% Red. at 75°F + 1550°F, 4 hrs, A.C. + 1400°F, 16 hrs, A.C.				
Smooth	30,000	3.2(±3)	<1	2
Smooth	25,000	89.0	3	2
Notched	25,000	73.9		
Notched	20,000	136.6		
1975°F, 4 hrs, A.C. + 15% Red. at 75°F + 1550°F, 4 hrs, A.C. + 1400°F, 16 hrs, A.C.				
Smooth	30,000	5.8	1	1
Smooth	25,000	26.3	1	2
Notched	25,000	85.3		
Notched	20,000	53.0		

MISCELLANEOUS ADDITIONAL TESTS AT 1350°F FOR S-816 WITH CONVENTIONAL HEAT TREATMENT

1. Effect of Methods of Notch Preparation.

Notched bars used in studies of metallurgical variables were all finished with a formed lathe tool, whereas data cited for notch properties with conventional treatments (Ref. 3) were for specimens finished by grinding. As a partial check for possible effects on notch behavior from methods of notch preparation, four notched bars of S-816 with similar geometry and with 0.004 to 0.005-inch root radius were run to rupture:

Method of Finishing Notch	Root Radius (inches)	Stress (psi)	Rupture Life (hours)
Turned on lathe	0.004	50,000	112.5
Turned on lathe	0.004	40,000	624.6
Grinding	0.005	50,000	116.6
Grinding	0.005	50,000	126.1

The last specimen was heated to 1500°F for 1 hour, air cool, after grinding and before testing at 1350°F. A single smooth bar similarly heated to 1500°F for 1 hour after conventional heat treatment lasted 70.3 (±2) hours at 40,000 psi. Elongation and reduction were 50 and 58 percent respectively.

2. Change in Notch Shape on Loading and during Testing

Three specimens with ground notches (D = 0.600 inches, d = 0.424 inches, r = 0.005 inches) were used in these tests. The first specimen was loaded to 50,000 psi at 1350°F and then unloaded after three minutes and allowed to cool to room temperature. No change in notch root radius could be detected at 50 diameters magnification. Further, any change in specimen diameter at the base of the notch was less than 0.0005 inches, which is about the least change detectable with the equipment used. The specimen was then reheated to 1350°F and loaded to 58,000 psi for three minutes. Later examination showed that even at this higher stress there was no detectable change in either notch root radius or in specimen diameter at the notch base within the accuracy of the measurements.

The following measurements were obtained in two interrupted tests at 50,000 psi stress and 1350°F:

Specimen No.	Total Time at Stress (hours)	Notch Root Radius (inches)	Diameter at Notch Base (inches)	Decrease in Notched Cross Section (%)
N-B-S49	0	0.005	0.426	0
	25.2	0.009	0.418	5.1
	49.2	0.014	0.401	12.6
N-B-S50	0	0.005	0.426	0
	12.0	0.006	0.425	3.1
	36.0	0.009	0.417	5.5

These data are shown in Figure 4.

3. Effect of Periodic Stressing on Notched-Bar Rupture Life.

A notched bar (D = 0.600 inches, d = 0.424 inches, r = 0.010 inches) of S-816 with conventional heat treatment was subjected to 50,000 psi and 8,670 psi at 1350°F for alternate 5-hour periods for 100 hours of testing and then permitted to run to rupture at the higher stress. At fracture the specimen had withstood 50,000 psi stress for a total of 151.5 hours, plus 49.9 hours at 8,670 psi. When a smooth bar was similarly cycled between 40,000 psi stress periods of 5 hours each and 8,710 psi periods of 7 hours each, the total time at 40,000 psi was 72.5 (±4) hours, plus 61.0 hours at the lower stress. Elongation and reduction of area at rupture were each 58 percent.

DISCUSSION

Notch Properties at 1500°F of S-816 and Waspaloy with Extraneous Cold Work during Heat Treatment

Comparison of Figures 1 and 2 gives one more proof that notch weakening or strengthening is not a direct function of one particular minimum value of ductility in the smooth-bar rupture test. Here elongations are about 1 percent for both S-816 and Waspaloy with cold working between solution and aging steps. The reduction of area of the S-816 is double that of the Waspaloy and yet the S-816 shows definite notch embrittlement while smooth and notched bars of Waspaloy with this treatment have essentially equal rupture strengths.

The low notch strength of cold-worked S-816 at 1500°F was anticipated in view of the relatively slow rate of relaxation previously reported (Ref. 2) at stresses giving short smooth-bar lives. The data of Figure 3 for Waspaloy with extraneous cold working are rather skimpy, but they do indicate relaxation rates only slightly below those for conventional heat treatment. Therefore, the lack of marked notch strengthening or weakening appears quite reasonable, even though the cold working has lowered rupture levels of smooth and notched bars alike.

Further work on S-816 cold rolled after solution at 2150°F appears unnecessary if a suitable correlation can be worked out for the extreme cases of notch weakening and notch strengthening for this alloy in different conditions.

Effect of Methods of Notch Preparation

For S-816 at 1350°F both turned and ground notches prepared at the University of Michigan had rupture lives very close to those of Carlson and Simmons (Ref. 4) for ground notches. Stress relief of a ground notch for 1 hour at 1500°F may have raised the notched-bar rupture strength slightly, even though the same treatment seems to have slightly lowered the life of a smooth bar.

These results could well be expected for a material at conditions where relaxation is rapid. Any residual stresses from machining should quickly be erased with little consumption of rupture life. The higher-temperature stress relief should reduce residual stress concentrations with even less loss of life than occurs at the 1350°F test temperature.

At the temperatures studied, the other alloys may behave somewhat differently. The technical literature (Refs. 5, 6, 7) reports tests on residual stresses left after machining and after grinding of flat steel plates. Residual stresses may be either tensile or compressive, depending upon the materials and on methods employed and may reach values near the tensile strength of the steel in the direction of machining.

In grinding tests with mild steel (Ref. 6) residual stresses extended to depths of about 0.012 inches to 0.018 inches for grinding cuts ranging from 0.0003 inches to 0.003 inches. (It might be noted that for the 0.005 inch radius notch used in the present program, initial effective stresses are greater than the nominal stress only for the outer 5 percent of the notch cross section, or to a depth of about 0.008 inch.) Both the maximum stress, found at the surface, and the thickness of the stressed layer increased with depth of the grind. Lapping of a manganese oil-hardened tool steel was found to leave nearly uniform residual compressive stress for a depth of only 0.0002 or 0.0003 inches in one set of tests. (See Ref. 7.)

Residual stresses in notched bars of comparable magnitude and depth to those for flat plates might have significant effect on notch rupture life due to any or all of three factors:

1. The machining operation may actually alter the metallurgical character of fibers near the notch root.

2. If residual stresses remain at the time of loading, the amount of local yielding and the relaxation-time pattern should both be affected.

3. Even if residual stresses relax during the period at temperature prior to loading, part of the rupture life of affected fibers will be used up before the actual notched-bar test has begun.

These effects might be expected to be greatest for conditions of high yield strength and low relaxation rates. Of the conditions studied in this program, this would probably mean Inconel X-550 at 1350°F. For this reason, further tests at this condition are planned with sharp (0.005-inch root radius) notches prepared in different ways and with machining performed at different stages of the heat treatment.

Changes in Notch Shape on Loading and During Testing

The finding of no change in gross geometry of a notch loaded to conditions studied in the present program has been confirmed in a private communication from Mr. Ward Simmons of Battelle Memorial Institute. He reported no change in notch contours after three minutes at stress for the following conditions, even when a comparator accurate to about 0.0002 inches was used to examine the notches after testing:

Alloy	Temperature (°F)	Stress (psi)	Notch Root Radius (inches)
S-816	1350	40,000	0.010
Waspaloy	1500	35,000	0.040
Inconel X-550	1350	60,000	0.005
Inconel X-550	1350	30,000	0.005

The magnitude of local strains on loading of a notched tensile specimen may be roughly estimated from elastic stress concentration factors and the short-time tensile properties. Consider a ring adjacent to the notch root and with a cross section equal to one-fortieth that of the specimen at the base of the notch. The centroid of this outer ring has an effective stress 3.16 times the nominal stress for a 0.005-inch root radius under elastic loading. The energy associated with elastic straining, equal to the area under the stress-strain curve, represents a nearly reversible condition with negligible losses. Above the proportional limit, some energy leaves as heat and some goes into irreversible change of specimen shape. An upper limit to the attainable plastic strain would appear to be approximated by the method illustrated in Figure 5. The elastic strain energy which would be expended if elastic conditions prevailed throughout loading is determined. The actual strain is then read from the tensile curve for the same total energy input. Applying this method to the stress-strain properties reported for S-816 in Reference 1, the maximum strain of the outer ring considered at a nominal stress of 58,000 psi would be about 0.015 inches per inch at the plane of the notch and would fall off at points further removed from this plane. Such a small amount of localized strain is too small to be detected readily by observations of change in notch root radius.

In view of possible strains of several percent for sharp notches on loading, it appears desirable to extend the relaxation tests for Inconel X-550 to higher values of prior strain at test temperature than have been investigated to date.

The data of Figure 4 show the change of notch root radius to be nearly linear with test time, while the decrease in cross section has the typical shape of a creep curve, but with all strains lower than for a smooth bar under the same nominal stress. Extensive tests of this type appear unnecessary since no anomalies have arisen so far.

Effect of Periodic Stressing on Notched-Bar Rupture Life

This type of test was prompted by two considerations:

1. Conclusions drawn from notch tests under steady load might not be valid when extended to applications where the stress level varies with time. A material with moderate relaxation strength might suffer from alternate slow cycling between high and low stresses. Substantial amounts of rupture life would be used up during relaxation from the higher stresses, but if the load were then removed a reverse elastic stress would remain. Additional life would then be expended during relaxation of these reverse stresses, provided the temperature was not reduced below the creep range.

The finding that S-816 had at least the same total life at the high stress portions of the cyclic test as under a steady high stress seems reasonable when one considers the very small fraction of its life used in relaxing under stress concentrations at 1350°F.

2. If a suitable correlation can be found to explain notch behavior in terms of relaxation and rupture properties of smooth bars, the same analysis must be able to explain notch behavior under periodic stresses at constant temperature, if it is to be of general applicability.

FUTURE WORK

As mentioned earlier, maximum efforts are to be devoted toward finding a quantitative correlation between notch behavior and smooth-bar properties.

Experimental work is to concentrate on evaluation of effects of residual stresses and metallurgical changes in notched bars as a result of machining practices and of localized straining during loading.

Once the best method of notch preparation has been determined, notched-bar life under periodic loading will be determined for Waspaloy and Inconel X-550.

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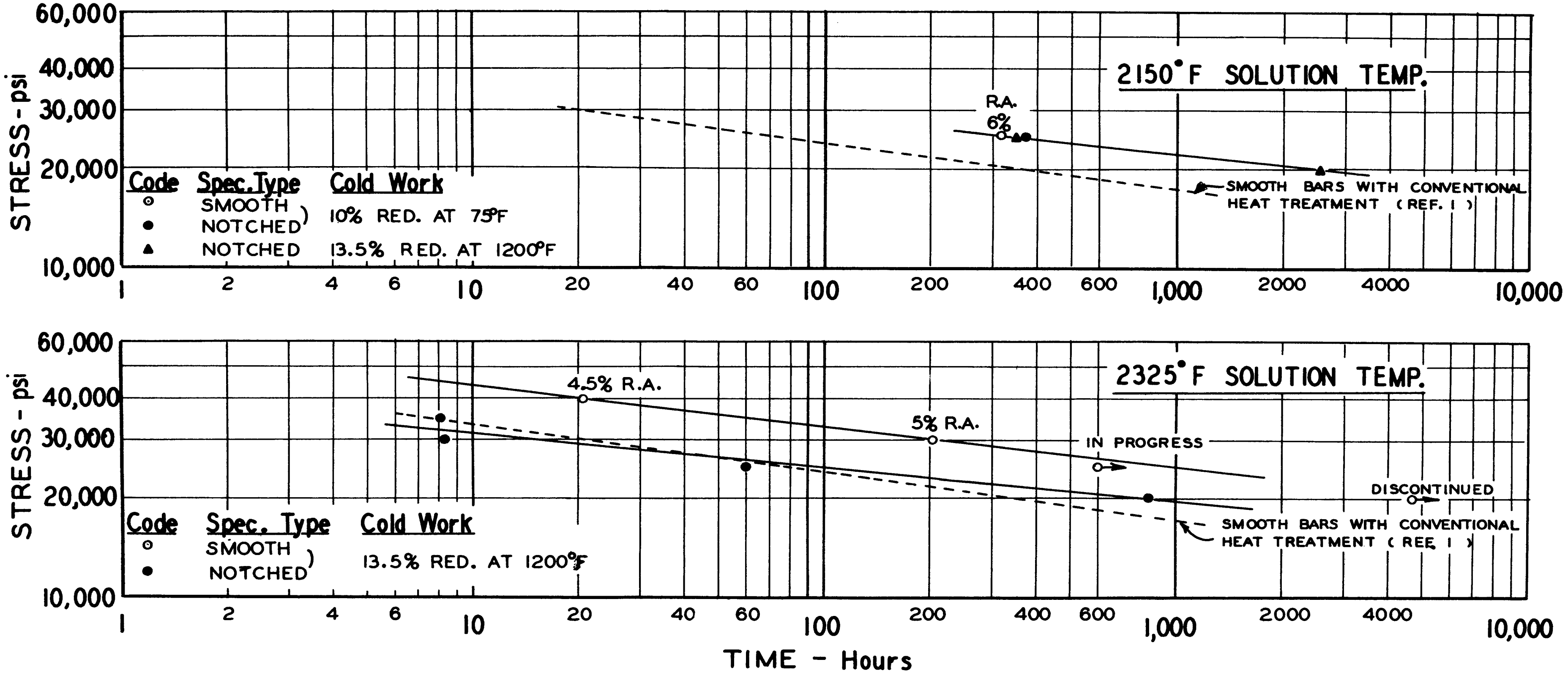

FIG. 1 - STRESS VERSUS RUPTURE TIME AT 1500°F FOR SMOOTH AND NOTCHED BARS OF S-816 COLD ROLLED BETWEEN SOLUTION AND AGING TREATMENTS.

Notch Geometry (Inches): D = 0.500 d = 0.360 r = 0.004 Notch Angle = 60°

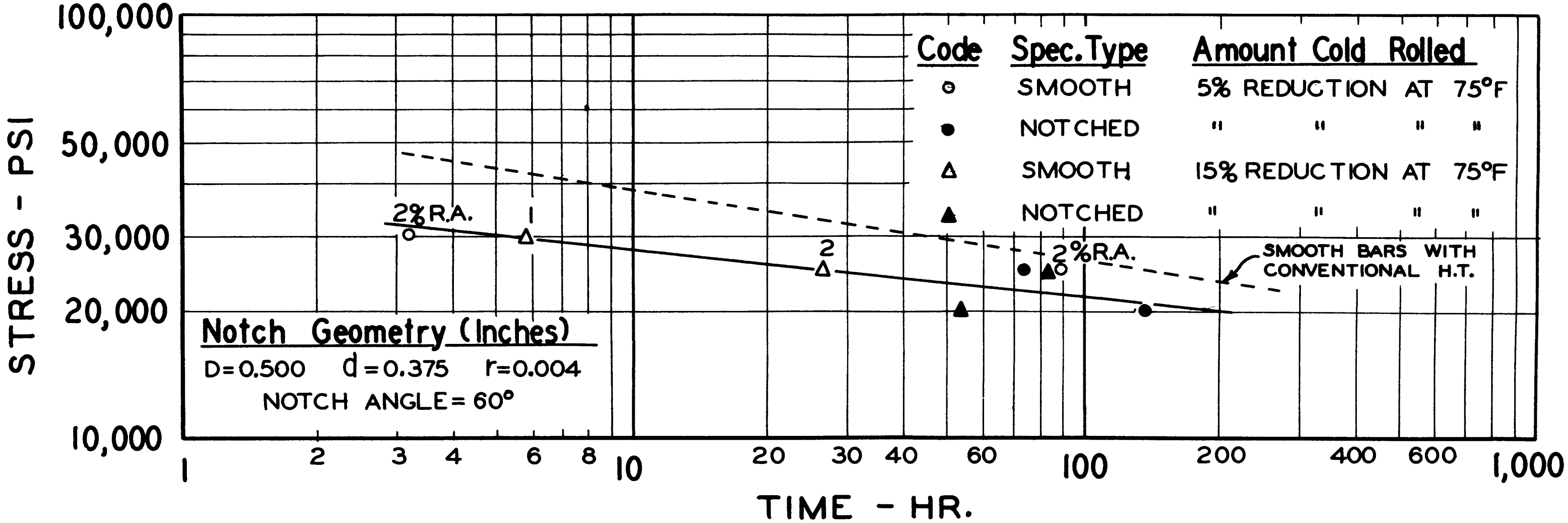

FIG. 2 - STRESS VERSUS RUPTURE TIME AT 1500°F FOR SMOOTH AND NOTCHED BARS OF WASPALOY COLD ROLLED BETWEEN CONVENTIONAL SOLUTION AND AGING TREATMENTS.

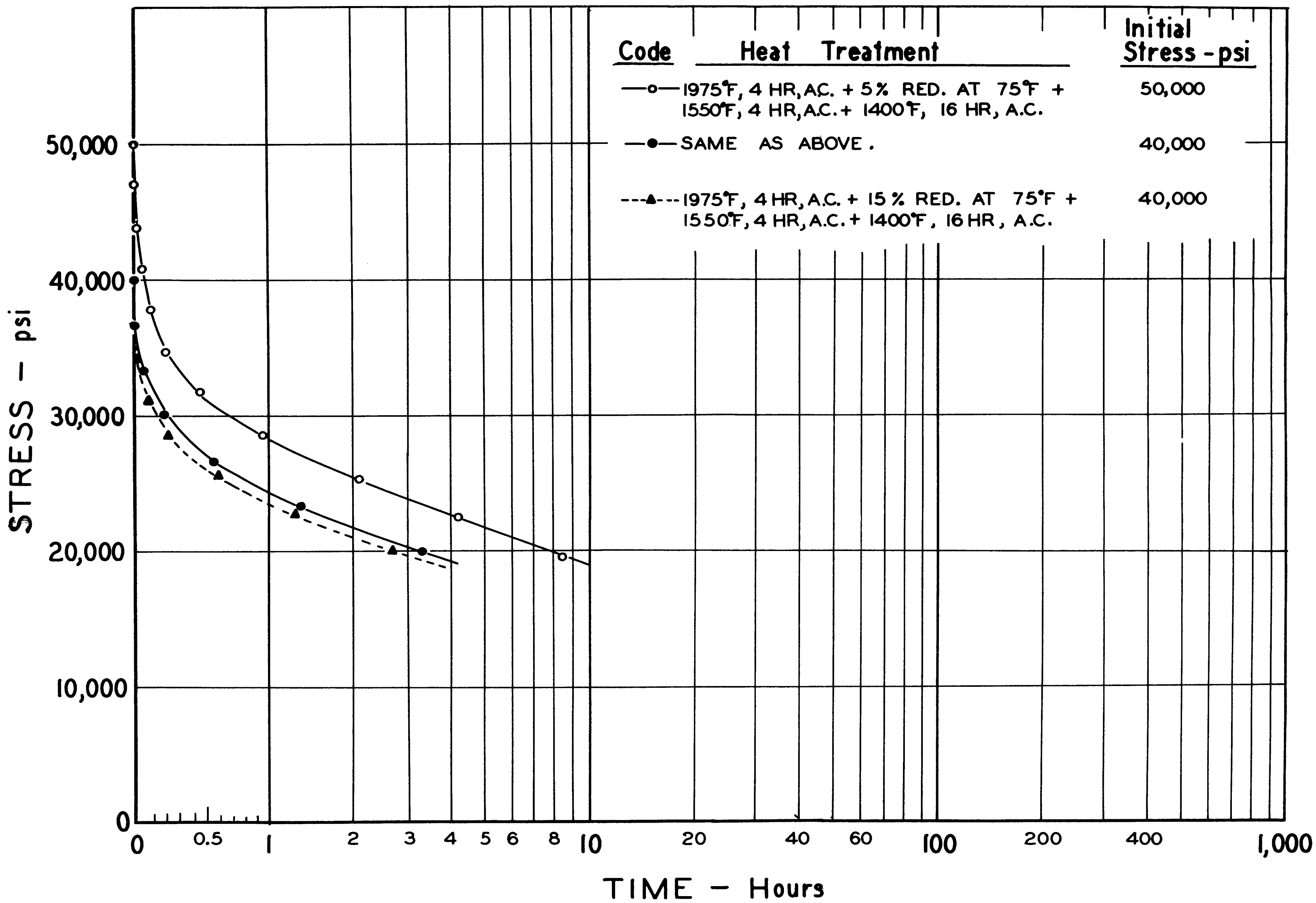

FIG. 3 - RELAXATION CHARACTERISTICS AT 1500°F OF WASPALOY COLD ROLLED BETWEEN CONVENTIONAL SOLUTION AND AGING TREATMENTS.

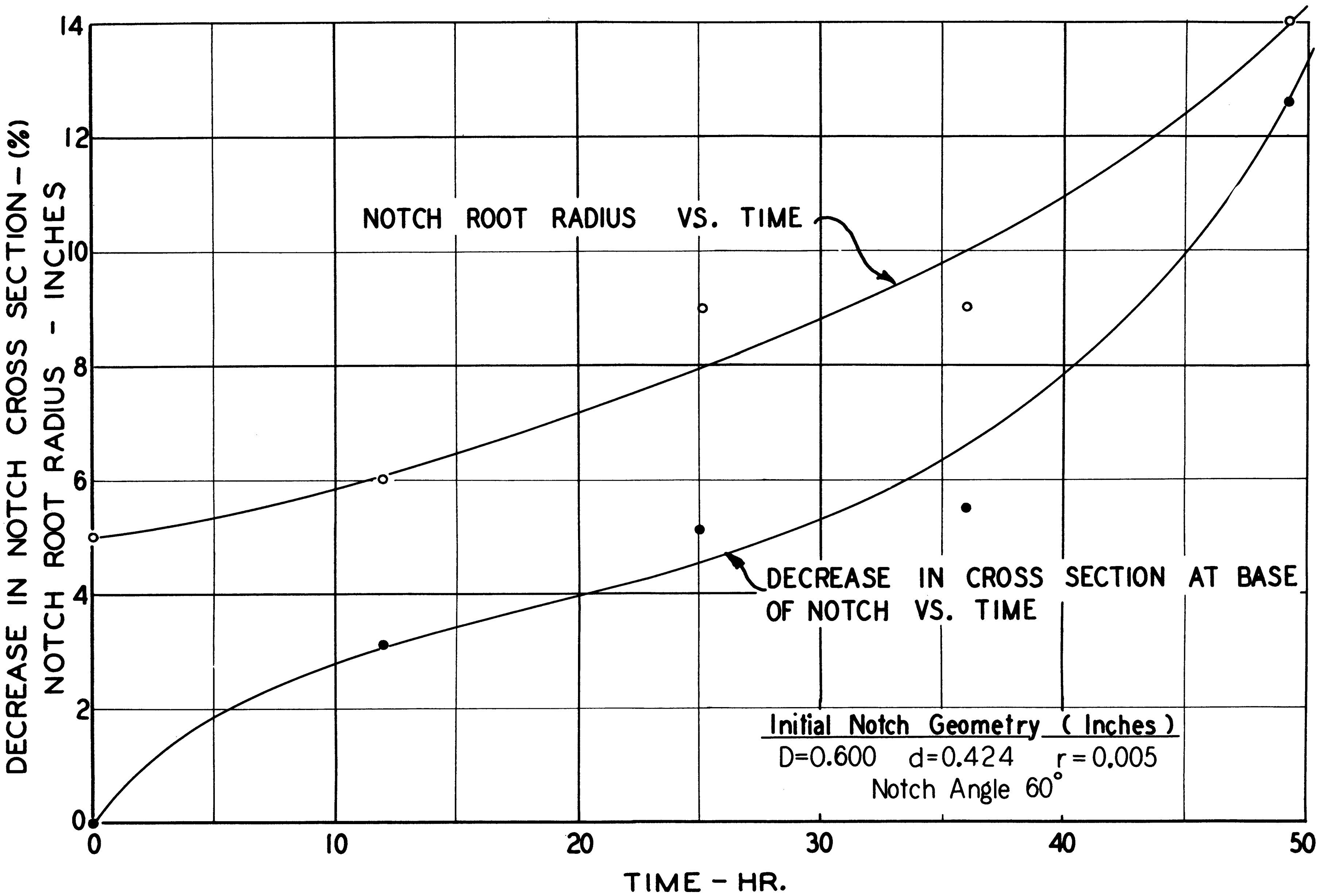

FIG. 4 - CHANGE OF NOTCH GEOMETRY DURING TEST OF S-816 AT 1350°F AND 50,000 PSI STRESS.

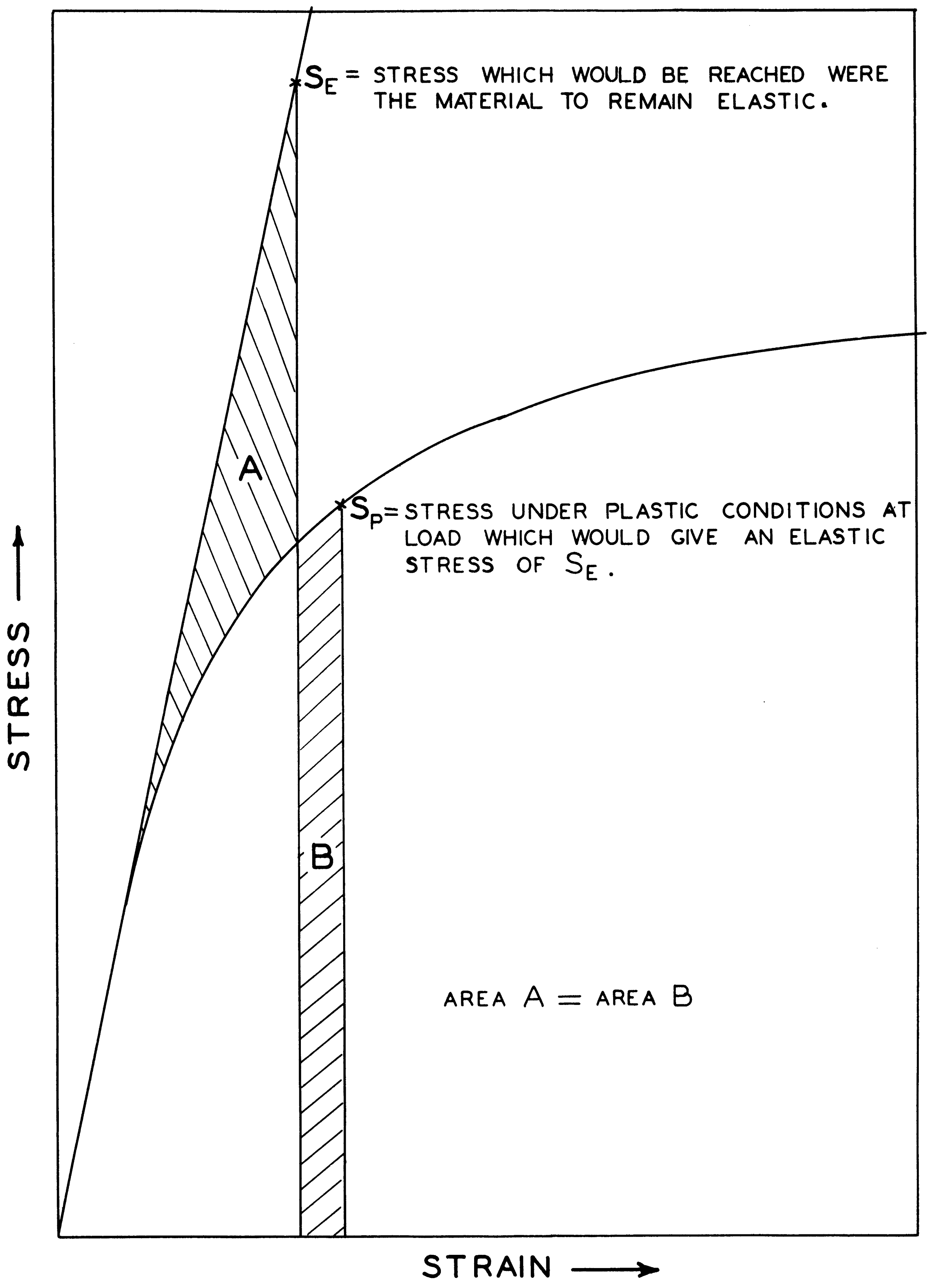

FIG. 5 - ESTIMATION OF STRESS UNDER PLASTIC CONDITIONS WHEN THE ELASTIC STRESS CONCENTRATION FACTOR IS KNOWN.