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INVESTIGATION ON NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURE

(RUPTURE STRENGTH OF NOTCHED BARS AT HIGH TEMPERATURES)

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FOREWORD

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ABSTRACT

Stress-rupture tests were conducted on notched and unnotched or plain bars of S-816, Inconel "X" Type 550, and Waspaloy alloys at test temperatures ranging from 1200°F to 1600°F. The notched specimens had 50 per cent, 60-degree, V-notches with the root radii ranging from 0.005 inch to 0.100 inch. In some tests, as many as three notches of different root radii were used.

The test results indicated that S-816 alloy was notch strengthened by all of the notches used, in the temperature range from 1350°F to 1600°F. Inconel "X" Type 550 was always notch strengthened by all of the notches only at the test temperature of 1600°F. Waspaloy was always notch strengthened by all notches only at the temperature of 1500°F. Both Inconel "X" Type 550 and Waspaloy could be notch strengthened for some test conditions (notch sharpness and time) at temperatures below 1600°F and 1500°F, respectively.

Factors considered to have an influence on stress-rupture behavior have been studied and the results are included. The factors investigated are notch geometry, notched and unnotched ductility, the modes of deformation and fracture, metallurgical changes, and surface condition. The influence of some of these factors can vary considerably from alloy to alloy. It does not appear possible, therefore, to evaluate the notch and unnotched stress-rupture behavior of a given alloy completely by any simple method. Rather, an evaluation should be based upon the combined consideration of those factors that are influential in each individual case.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

TABLE OF CONTENTS

APPENDIX

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INVESTIGATION ON NOTCH SENSITIVITY OF HEAT-RESISTANT ALLOYS AT ELEVATED TEMPERATURE (RUPTURE STRENGTH OF NOTCHED BARS AT HIGH TEMPERATURES)

INTRODUCTION

In recent years the use of metal parts at high operating temperatures has increased the number of problems confronting the designer. If he is to achieve efficient design, he must have a method of interpreting available data in such a fashion as to guide his design. The data which he will usually have consist of stress-rupture tests on unnotched and, perhaps, notched bars. Although these tests reflect the creep behavior of the respective metals, and in some instances their susceptibility to metallurgical change, their relation to the information that the designer wants is not immediately obvious.

In this program, three heat-resisting alloys were studied — S-816, Inconel "X" Type 550, and Waspaloy — and the objective was to learn under what conditions the materials could be used in a notched form without difficulty. That is, it would be desirable to have a ratio of notched strength to unnotched strength of greater than one.

To accomplish this objective, stress-rupture tests were conducted on both notched and unnotched bars. In order to study the influence of notch sharpness, three notches of the same depth, but of different radii were made in each notched-bar specimen. This made it possible to locate the notch sharpness of lowest strength with only one test bar. Since the sharpness of the notch in which rupture occurs is intimately related to the ductility of an alloy, ductility measurements were obtained on both the notched and the unnotched bars.

The results of this program are described in detail in later sections of this report. For the sake of organization and convenience, the most significant points are given in the list below:

(1) The unnotched-rupture ductility, although a rough index of available ductility, cannot be used as an efficient guide for indicating notch sensitivity. Notch strengthening has been associated with unnotched-rupture ductilities as low as 10 per cent (Waspaloy at 1500°F). Notch sensitivity has been detected with unnotched-rupture ductilities as high as 60 per cent [Haynes 88 at 1350°F (4)*]. It should be noted that these data were both obtained on notches of high notch sharpness.

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* References will be found in the bibliography at end of report.

(2) Notch-rupture ductility appears to be the simplest gage of notch sensitivity. As indicated by Brown, et al.(4), notch sensitivity seems to be associated with notch-rupture ductilities of less than 3 per cent.

(3) The most desirable condition for design purposes is for the alloy to be notch strengthened for a wide range of notch sharpness. S-816 fulfills this condition for all of the test temperatures used, whereas Inconel "X" Type 550 and Waspaloy satisfy it only at 1600°F and 1500°F, respectively.

(4) It is probable that an alloy that is notch sensitive for high notch sharpnesses can be used safely if it can be notch strengthened for lower notch-sharpness values. This could be achieved primarily by avoiding the use of sharp notches in design. Since there is no direct relation between notched test bars and service parts, however, special care would be necessary. It would also be desirable to have more detailed data than for alloys satisfying the condition in Item 3 above. Waspaloy and Inconel "X" Type 550 represent such alloys, because more data are desirable for them than for S-816.

(5) A review of the data obtained and that available in the literature appears to indicate that there may be a maximum possible notched rupture-to-unnotched rupture value. It appears to approach 1.7. This probably represents the most efficient use of the triaxiality present. As would be expected, values of this order are associated with notched bars of high notch sharpness for alloys with large ductilities.

(6) Metallurgical changes which can cause embrittlement must be considered influential in any interpretation of notched and unnotched stress-rupture tests.

(7) The preferred modes of deformation and the type of fracture characteristic of a given alloy are factors of importance. They are likely responsible for the wide variation in ductility requirements for notch strengthening for different alloys.

(8) Surface condition as determined by surface preparation probably has an influence on stress-rupture results. It is possible that surface condition is quite important in service parts where the special procedures used to prepare test bars are not observed. This could result not only in lower strengths, but also greater variation in strengths because control would be less rigid.

GENERAL CONSIDERATIONS

The usual interpretation of notched-bar behavior is based on a consideration of the stress distribution resulting from the notch geometry and the available ductility of the bar material. If a notched bar of a given material ruptures at an average stress that is greater than the stress necessary to cause rupture in an unnotched bar of the same material, the material is said to be notch strengthened.

For notch strengthening to occur, it is necessary that sufficient ductility must be available to relieve the longitudinal stress concentration at the base of the notch. Strengthening can then result from the triaxial tensile stress state retained. Theoretically, a hydrostatic tension would always result in a brittle fracture for an ideal, isotropic material, since no shear stress would be present to cause flow. In the case of notched bars, a hydrostatic tension is only approached. How closely it is approached in a given specimen depends on the notch geometry. Figure 1 (Figure 11 in Reference 1) illustrates the variation of triaxiality at the center of infinitely deep notches with various notch sharpnesses. In the graph, the maximum and minimum normal stresses are designated as σ_1, and σ_3, respectively. The ratio σ_3/σ_1 is, therefore, an index of how closely a hydrostatic tension is approached; i.e., for a hydrostatic tension, $\sigma_3/\sigma_1 = 1$.

Although Neuber's equations, used to obtain the graph of Figure 1, are not exactly applicable to the notches used in this investigation, they should describe the existing trends. For this reason, the notch-sharpness ratios for three of the notch radii used have been indicated. As can be seen, the triaxial ratio σ_3/σ_1 changes markedly with changing a/r only for $a/r < 15$.

If the material has adequate ductility, then the sharper the notch, the greater the strengthening. A material with inadequate ductility would fail under a lower average stress than an unnotched test bar; therefore, the sharper the notch, the lower the rupture stress.

It should be noted that the above explanation of notch strengthening has been modified by Orowan and his coworkers(2) to include size effect. In essence, it is maintained that the stress necessary for flow in a very small region can be considerably larger than in a large region. This interpretation follows from the fact that the smaller the stressed region is, the less chance there is for favorable paths for glide to exist.

To illustrate how this effect would apply to notched bars, a graph of the variation of the ratio of the maximum shear stress, τ_m, to the average stress, σ_a with the distance from the axis of the specimen in the plane of the notch has been prepared. In Figure 2 plots for two notch radii, and a plot of the variation for an unnotched bar, have been made for purposes of comparison. As can be seen, the area upon which τ_m/σ_a for the notched bars exceeds that of the unnotched bar is relatively small. This is particularly true of the notch with r = 0.005 inch. If, then, a size effect is operative, the demand for available ductility for notch strengthening in sharply notched bars can be somewhat relaxed.

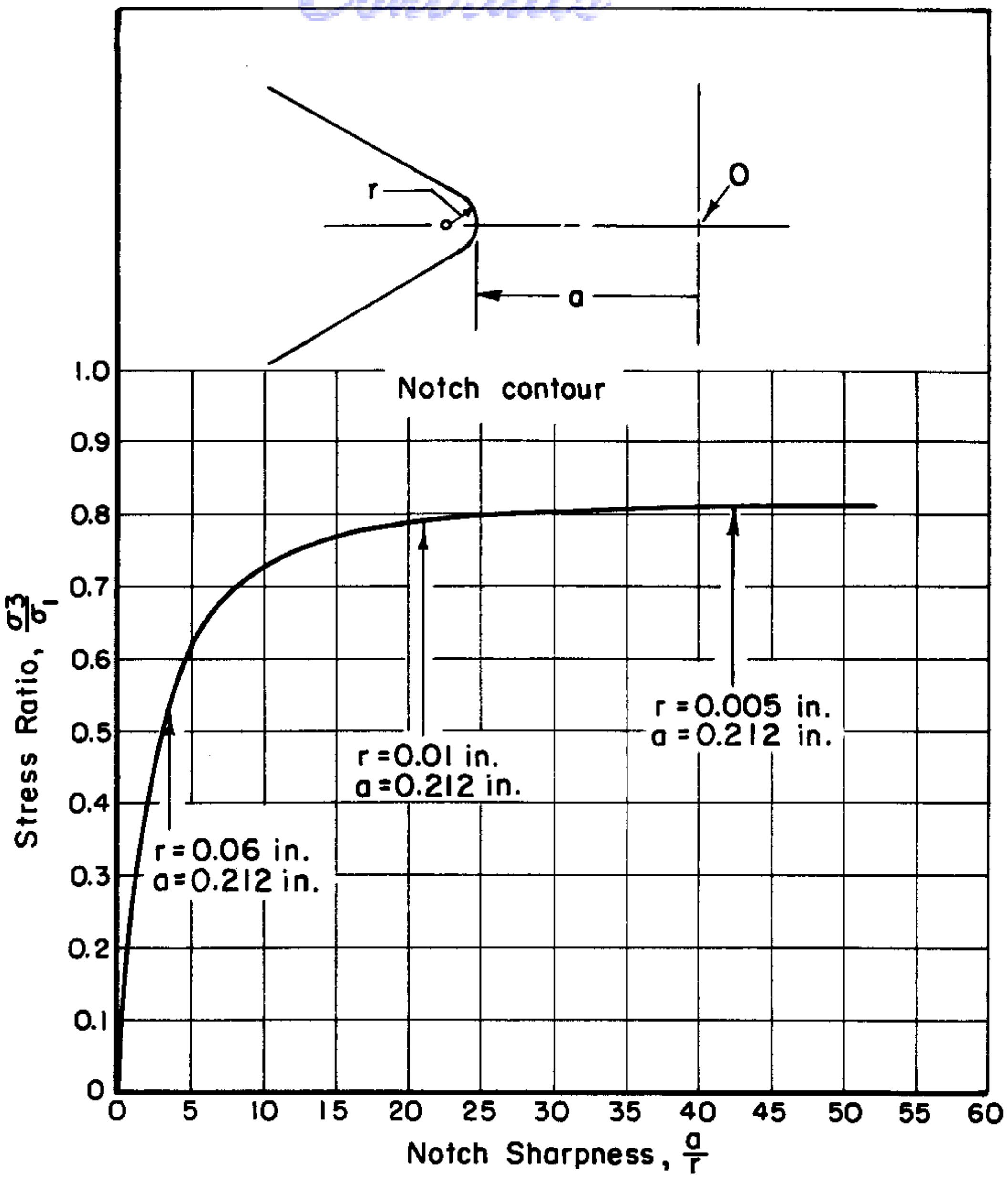

FIGURE I. EFFECT OF NOTCH SHARPNESS ON TRIAXIALITY AT CENTER (POINT O)

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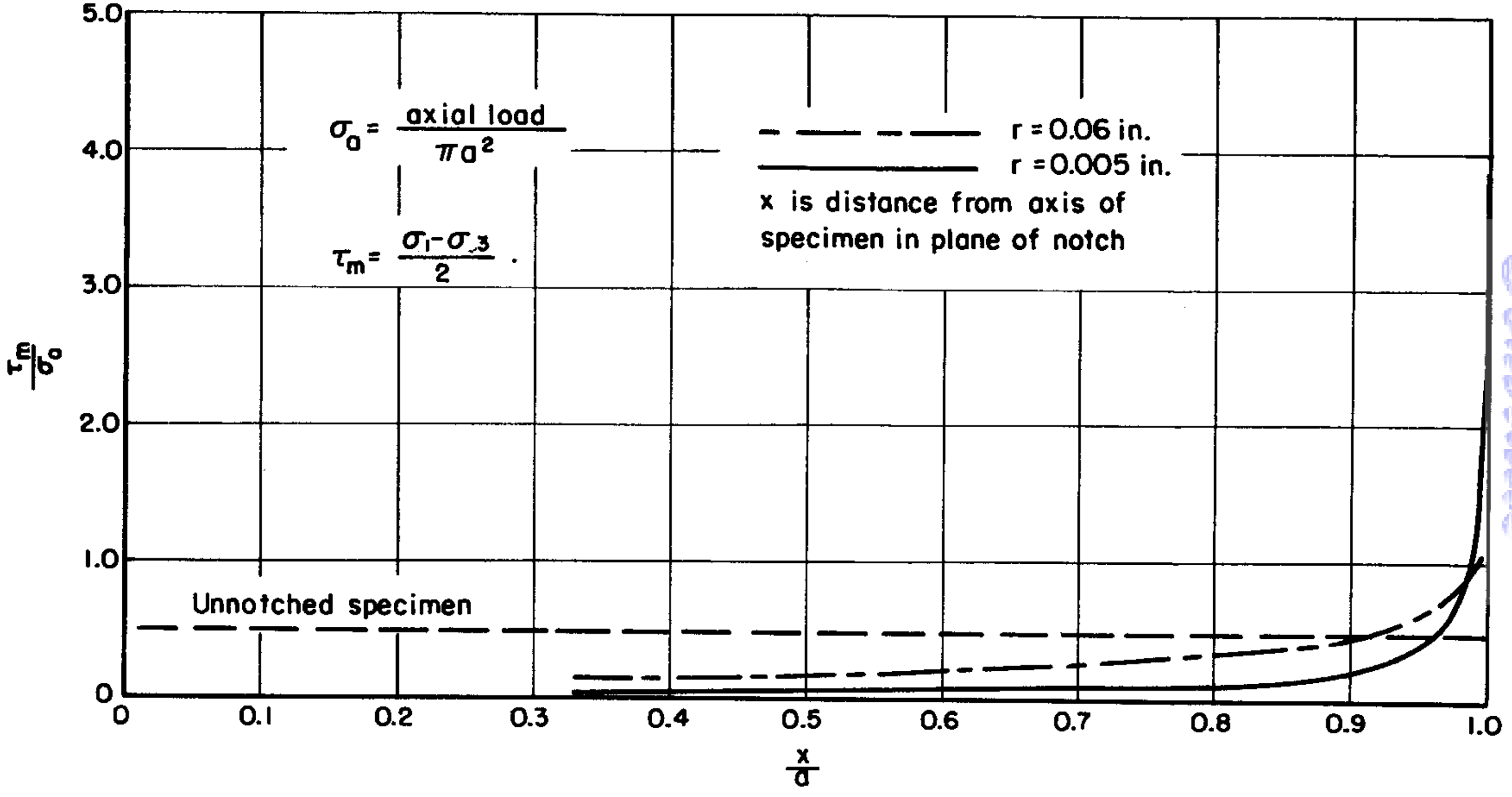

FIGURE 2. VARIATIONS OF MAXIMUM SHEAR STRESS FOR TWO NOTCH RADII

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The above discussion did not include a consideration of the effects of creep. Insofar as creep is a time-dependent, permanent deformation, it can be expected to help relieve local stress concentrations. In essence, the stress at the base of the notch can be expected to undergo relaxation. The maximum shear stress at each point in the neck of the notched bar will undergo readjustment. In order for each element of material to remain compatible or to "fit", it must be expected that the higher shear stresses will be decreased or relaxed (the external load remains constant), and the lower shear stresses will have a tendency to increase. The general tendency will be for a smoothing or leveling of the shear stresses governing flow. Since it would be expected that some of the initial triaxiality in the core of the notch would be retained, the maximum shear stresses in the core would tend to be less than those in an unnotched bar under the same average stress. This behavior presupposes the ability of the bar material to flow and readjust as described above. In this investigation, the test bars of S-816 alloy were notch strengthened at all test conditions, so it can be presumed that adequate flow was available. The two remaining alloys, Inconel "X" Type 550 and Waspaloy, were notch sensitive for some test conditions and notch strengthened for others. With regard to "available ductility", these alloys might be considered borderline cases. As such, they are strongly influenced by changes in notch geometry and test temperature. In contrast, the S-816 alloy bars were notch strengthened for all test temperatures and there was evidence that the rupture-stress versus failure-time curves for the different notches were close to one another. This is particularly true of the notched bars with $r = 0.06$ inch and 0.01 inch at 1350°F and $r = 0.01$ inch and 0.005 inch at 1500°F and 1600°F.

It is of interest to note that the notch-strengthening index, as reflected by the notched rupture stress-to-unnotched rupture stress ratio, probably has an upper limit which would be approached for high notch sharpness in metals with enough available ductility (both time-independent and time-dependent ductility) to take advantage of triaxiality. A review of the data obtained and that available in the literature(4, 5) appears to indicate an upper limit in the vicinity of 1.7. In terms of stress redistribution and retention of triaxiality, a value of this order probably represents a limiting efficiency.

The use of the designations "notch sensitive" and "notch strengthened" should be made with caution. So long as stress-rupture-test results are properly interpreted, they can be useful gages of material behavior. It should be noted, however, that a rupture in a notched bar is a rupture under very special conditions. By virtue of the constraint imposed on the notch by the sections above and below the notch, flow within the notch is restricted. This is reflected in the reduction in area values for notched bars, as compared to unnotched bars (see Tables 2, 3, and 4).

It is of interest to note also that, in some instances, a ratio of the notched-rupture strength to the unnotched-rupture strength can be somewhat misleading. Consider, for example, two tests on S-816 alloy at 1350°F. In one test an unnotched bar failed in 44 hours under a load that gave an initial stress of 45,000 psi. Since the reduction in area was 52.8 per cent, the average stress at rupture was 95,300 psi. In another test on a notched bar, failure occurred in 32.1 hours under a load that gave an initial stress of 58,000 psi. Here the reduction in area was 35.4 per cent, so the average stress at failure was 89,800 psi. It is apparent, therefore, that a strength ratio based on initial stresses does not give, in itself, a completely accurate evaluation of material strength.

In discussing notched-bar stress-rupture results, it is pertinent to consider still another effect that may be of basic importance as far as understanding fracture initiation. Although the effect is undoubtedly present in notched-bar tests, its presence or influence is more obscure there than in unnotched-bar tests. The behavior consists of a decrease in ductility with decreasing average stress or increasing time. It should be noted that this general tendency has been observed frequently in the past. In the results of this investigation (see Tables 2, 3, and 4) the tendency appears to be most pronounced in what are considered the two least ductile of the three test materials — Inconel "X" Type 550, and Waspaloy. It can be observed also that the amount of decrease for each material becomes larger with increasing test temperature. Although this tendency toward "embrittlement" might be attributed to a metallurgical change, this may only be a partial explanation. A discussion of metallurgical changes in the alloys studied is given in the section of the report on Microstructure Studies.

Zener(3) has suggested an explanation for this behavior which is based on possible differences in the modes in which deformation can occur. He maintains that during creep at elevated temperatures, shear stresses along grain boundaries are relaxed by slip along the boundaries. Because relative slip with respect to corners at which three grains meet is not possible, there is a tendency for the relaxed load to shift to these sites. According to Zener, high hydrostatic tensions can be developed, and these can be responsible for the initiation of cracks. He then goes on to state that at low-load conditions, for which large plastic deformation within the grains is not possible, the formation of cracks, according to the above mechanism, is responsible for low ductility for low-load creep conditions.

Perhaps the major importance of this explanation is the fact that it focuses attention on the importance of different possible modes of deformation. The role of the grain boundary need not, perhaps, be restricted to the interior as indicated above. It is conceivable, for example, that particular orientations of grain-boundary surfaces intersecting the specimen surface may create conditions favorable for the formation of a crack. Figures 18 and 19 of cracked notched bars suggest this possibility.

It should be noted that Brown, et al.(4), have suggested that a precipitation mechanism is responsible for the reduction in ductility mentioned above. Although this can be a contributing factor (see Microstructure Studies), the evidence supporting it is not complete. It is entirely possible, of course, that both of the above explanations are influencing factors whose relative importance is determined by the material and test conditions.

Using either of the above explanations, it is possible to describe cases in which the notched-to unnotched strength ratio decreases with increasing time as being instances in which the stress concentration at the base of the notch had not been relieved by flow. For a given average stress, the stress concentration in the notched bar makes it more susceptible to the formation of cracks resulting from the reduction in ductility. For materials which are weakened by such a loss of ductility, the notched-rupture test appears to be, for this reason, a more sensitive indicator than the unnotched-rupture test. In a later section of this report, ductility data for the test results of this investigation are discussed further.

During the course of this investigation, it became apparent that the condition of the surface layer of material at the base of the notch might be an important factor in notched-bar behavior. Since multiple-notch specimens were used, it was possible in many instances to inspect cracks which were initiated in the unruptured notches. As all of the cracks inspected initiated at or near the surface, near the base of the notch, it was felt that the condition of the surface could be a factor in notch behavior. An inspection of the notches indicated that for all of the test materials, the cold-worked surface layer was subject to precipitation or recrystallization at some of the test temperatures. As is indicated later in the report, the study made of the surface-layer condition is largely exploratory. There are indications, however, that surface conditions should be considered an influencing factor in rupture behavior studies of this type. It should also be noted that further knowledge of the effect of surface condition would be of practical value. Such a study might, for example, contribute toward a better understanding of how different surface preparation procedures affect service-part strengths.

This section has been devoted to a discussion of several of the factors which can be expected to have an influence on notched and unnotched stress-rupture behavior. As has been indicated, the behavior is complex and cannot be interpreted completely by the consideration of only one of the factors. The bar geometry, the possible modes of deformation and fracture, metallurgical changes, and the surface condition should all be considered as contributing toward the resultant behavior. Where pertinent, reference will be made to these factors in other sections of this report.

Test Material

The three heat-resistant alloys selected for this investigation were S-816, Waspaloy, and Inconel "X" Type 550. S-816 and Waspaloy alloys were melted and processed by Allegheny Ludlum Steel Corporation, and Inconel "X" Type 550 was melted and processed by The International Nickel Company. The chemical composition of the three alloys is given in Table 1.

Bar stock of the three alloys was processed as follows:

The 9-inch-square ingot of S-816 alloy was hammer cogged to 2-7/8-inch-square billets in six heatings from 2150° to 2200°F, rolled to 2-1/8 inch round in one heating from 2200°F, rolled to 1-5/8 inch round in one heating from 2150°F, rolled to 1-1/4 inch round in one heating from 2100°F, centerless ground to 1-3/16 inch round, rolled to 51/64 inch in one heating from 2100°F, annealed at 1800°F (1 hour) and air cooled, and centerless ground to 3/4 inch round.

The Waspaloy bar stock was cogged from 9-inch-square ingots to 4-1/2 by 5-1/2-inch billets in two operations from 2200°F, recogged by rolling to 2-1/8-inch-round billets in two operations from 2150°F, recogged by rolling to 1-5/8-inch-round billets from 2050°F, rolled to 1-1/4 inch round from 2050°F, annealed at 1950°F (1 hour) and oil quenched, centerless ground to 1-3/16 inch round, rolled to 7/8 inch round, annealed at 1800 F (1 hour) and oil quenched, and straightened.

The 18 by 18 by 40-inch ingot of Inconel "X" Type 550 was planed to overhaul, then forged to an 8 by 8-inch bloom and spot ground. It was then rolled to 3 by 3-inch billets and ground all over, cogged to 2 by 2-inch billets and spot ground. Finally, it was rolled to 7/8-inch diameter, straightened, ends inspected for pipe, centerless ground to 13/16-inch diameter, and inspected.

Specimen blanks of the S-816 bar stock were heat treated by heating at 2150°F for 1 hour and quenching in water, followed by aging at 1400°F for 12 hours and air cooling.

The specimen blanks of Waspaloy were heat treated using the same heat treatment that Pratt and Whitney Aircraft was using for Waspaloy blade forgings. This treatment is as follows: solution treat 4 hours at 1975°F, air cool; stabilize 4 hours at 1550°F, air cool; age 16 hours at 1400°F, air cool. Quenching from the solution temperature has been found to aggravate notch sensitivity; therefore, air cooling instead of oil quenching was used. Also, a stabilizing treatment at 1550° to 1600°F, after solution treatment but before aging, was found to eliminate notch sensitivity from all heats of Waspaloy. Some Pratt and Whitney data showing the effect of the stabilizing treatment on Waspaloy are given on page 11.

TABLE 1. CHEMICAL COMPOSITIONS OF ALLOYS TESTED

Element	Chemical Composition, per cent S-816 (Heat 63730)	Waspaloy (Heat 44036)	Inconel "X" Type 550 (Heat Y-7180-X)
C	0.38	0.08	0.05
Mn	1.22	0.80	0.73
Si	0.49	0.61	0.28
P	0.012	0.017	--
S	0.018	0.017	0.007
Cr	20.04	18.72	14.97
Ni	19.43	Bal	Bal
Mo	3.98	2.93	--
W	3.93	--	--
Cb	2.89	--	1.03(a)
Co	43.32	13.44	--
Fe	3.44	1.17	6.59
Al	--	1.29	1.16
Ta	0.85	--	--
Ti	--	2.29	2.5
Cu	--	0.10	0.03

(a) Cb + Ta.

Heat Treatment	Hours to Failure at 1350 F and 52,000 psi	
	Smooth Bar	Notched Bar
Solution treat 4 hours at 1975°F, air cool, age 16 hours at 1400°F, air cool	76	1.5
Solution treat 4 hours at 1975°F, air cool, stabilize 4 hours at 1550°F, air cool, age 16 hours at 1400°F, air cool	82.8	150 — No failure; discontinued
Solution treat 4 hours at 1975°F, air cool, stabilize 4 hours at 1600°F, air cool, age 16 hours at 1400°F, air cool	87.4	150 — No failure; discontinued
Solution treat 4 hours at 1975°F, air cool, stabilize 1 hour at 1800°F, air cool, age 16 hours at 1400°F, air cool	1.9	46.6

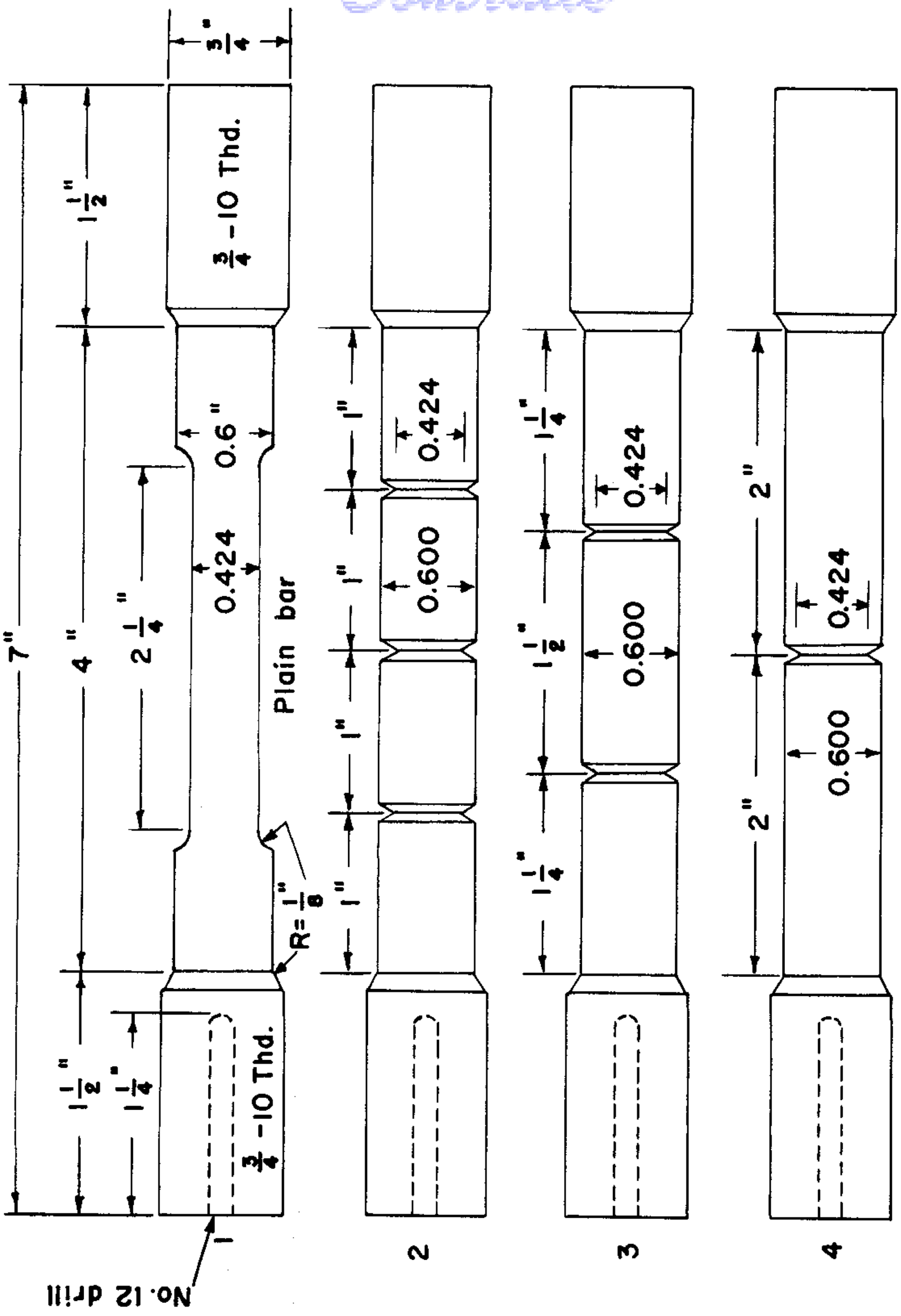
Specimen blanks of Inconel "X" Type 550 bar stock were heat treated by heating at 2150°F for 1 hour and air cooling, followed by 4 hours at 1600°F and 4 hours at 1350°F.

Rupture Specimens and Test Procedure

Conventional creep-rupture tests were made on plain and notched bars to obtain data out to approximately 1000 hours' rupture life. The types of test specimens used are shown in Figure 3. The multiple-notch specimens were used to get a maximum of information from one test. All specimens had a constant shank diameter of 0.600 inch and a notch-root diameter of 0.424 inch ($d/D = 0.707$), giving a 50 per cent reduction of area. The plain specimen had a diameter of 0.424 inch, the same as the notch-root diameter of the notched bars, and a 2-inch gage length.

The various notches in the test specimens were ground by the John Stulen Company of Pittsburgh, Pennsylvania. The notches were turned to 0.020-inch oversize on the diameter. They were then rough ground to 0.003-inch oversize on the diameter, and finish ground to size.

The notch radii used were selected on the basis of the nominal plain-bar ductility of the alloys to be tested. The root radii and the ratio of root radius to root diameter were as follows:



Notches 60°, root radius as indicated in text

Note: Area at base of notch is 50 % of unnotched area

FIGURE 3. PLAIN AND NOTCHED TEST SPECIMENS

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Alloy	Root Radius, in.	r/d
S-816	0.005*	0.0118
	0.010*	0.0236
	0.060*	0.041
Waspaloy	0.005*	0.0118
	0.020	0.0471
	0.040*	0.0944
	0.100*	0.236
Inconel "X" Type 550	0.005*	0.0118
	0.020	0.0471
	0.045*	0.106
	0.100*	0.236

The root radii marked with an asterisk in the above tabulation were used in the three-notch specimens. The two-notch specimens of Waspaloy and Inconel "X" Type 550 had the two coarser notches, and the 0.020-inch radius was only used in single-notch specimens. A few single-notch specimens were also made with the 0.005- and 0.100-inch-radius notches.

The test specimens were not all heat treated and machined at one time, because it was not known at the beginning of the program what heat treatments or notches would be desired before the program was completed. However, the specimens were quite uniform with the exception of the last lot of Inconel "X" Type 550. These specimens, numbers 48 through 82, in general, showed more scatter and lower notch rupture strengths (at the shorter times) than specimens 1 through 47. Hardness measurements indicated that the second lot of specimens had a somewhat higher hardness than the first lot (108.1 and 101.2 Rockwell B). Since the machining procedure was the same for all specimens and the notches were all ground by the same man, it is probable that the difference between the two lots was the result of some minor and undetected variation in the heat treatment.

The procedure followed in carrying out the rupture evaluation program was to first obtain plain-bar rupture data for times out to approximately

1000 hours as a basis for comparison. A series of notched-bar rupture tests was then made on all three alloys using the triple-notch specimen. The alloys that exhibited notch sensitivity in these tests were then tested at the temperatures where notch sensitivity was observed using the double-notch specimen with its coarser notches. These tests were followed by tests using a single-notch specimen having the coarsest notch of 0.100-inch radius. Tests were also made wherever needed using single-notch specimens of either 0.005- or 0.020-inch radius to complete the data.

Test Results

S-816 Alloy

Creep-rupture tests were made on plain and notched specimens of S-816 alloy at 1350°, 1500°, and 1600°F, and the detailed test data are given in Table 2. Since rupture could occur in any one of the three notches, a note in Table 2 indicates which notch failed and any notches which showed cracking during the test.

Figure 4 shows the curves of stress versus rupture time for both the plain and notched bars of S-816 alloy. Different symbols have been used in Figure 4 to indicate which notch failed, and, since S-816 alloy was relatively insensitive to the various notches, the rupture curves were drawn through the points of rupture, regardless of which notch ruptured. Thus the curves might be considered as minimum rupture curves for the notches tested. S-816 alloy was notch strengthened at all temperatures and most failures occurred in the less severe notches.

S-816 alloy had more than enough ductility at all three temperatures to allow the high-stress concentration at the base of the sharper notch to be reduced by local yielding. This allowed the higher triaxiality associated with the sharper notch to assume importance, and the result was notch strengthening. Thus, the specimens ruptured in one of the less severe notches which had lower triaxiality, and, consequently, less strengthening.

Since S-816 alloy exhibited notch strengthening in all three notches at all test temperatures, only the triple-notch specimen was used, and detailed data for each notch were not determined.

Hardness measurements were made on several of the tested specimens after exposure to the test temperature for times up to approximately 1000 hours. The hardness readings were taken on flats ground on the 0.600-inch-diameter surface of the notched specimens near the center of the specimen. Therefore, the stress in the specimens at the point where the hardness measurements were made was one-half the nominal stress under the notch. The hardness determinations on the plain bars were made on the shoulders at the ends of the gage length. The hardness data obtained, and

TABLE 2. PLAIN- AND NOTCHED-BAR RUPTURE DATA FOR S-816 ALLOY

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction of Area, per cent	Hardness(a), Rockwell B	Remarks
				Plain Bar			
S-1	1350	45,000	44.0	52.8	53.8	102.5	
S-6	1350	40,000	96.0	56.7	51.2		
S-9	1350	34,000	260.1	49.5	57.1		
S-12	1350	28,000	958.7	50.7	53.0	102.5	
				Notched Bar			
S-23	1350	58,000	32.1		35.4		Failed in 0.060-inch-radius notch; 0.005-inch- and 0.010-inch-radius notches cracked
S-17	1350	50,000	89.1(b)		--		Cracked in 0.005-inch- and 0.010-inch-radius notches
S-22	1350	40,000	740.8		15.4		Failed in 0.010-inch-radius notch; 0.005-inch- and 0.060-inch-radius notches cracked
				Plain Bar			
S-2	1500	30,000	20.4	47.2	51.8	101.0	
S-4	1500	25,000	63.8	44.8	58.5		
S-7	1500	20,000	342.8	45.3	55.7		
S-11	1500	17,000	1019.4	38.9	45.4	101.9	
				Notched Bar			
S-28	1500	30,000	88.7		13.7		Failed in 0.010-inch-radius notch; 0.005-inch-radius notch cracked
S-27	1500	30,000	79.8		9.3		Failed in 0.005-inch-radius notch; 0.010-inch-radius notch cracked

TABLE 2. (Continued)

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction of Area, per cent	Hardness[a], Rockwell B	Remarks
				Plain Bar			
S-5	1600	20,000	17.0	47.3	52.1	99.8	
S-8	1600	15,000	171.6	40.4	33.8		
S-10	1600	12,500	751.0	22.7	32.8	101.3	
				Notched Bar			
S-20	1600	27,000	14.6		9.2		Failed in 0.010-inch-radius notch; 0.005-inch-radius notch cracked
S-19	1600	20,000	77.1		6.2		Failed in 0.005-inch-radius notch; 0.010-inch-radius notch cracked
S-21	1600	16,000	301.2		4.3		Failed in 0.010-inch-radius notch; 0.005-inch-radius notch cracked

---

(a) Original Hardness 99.8, Rockwell B.

(b) Not ruptured, discontinued because of furnace failure.

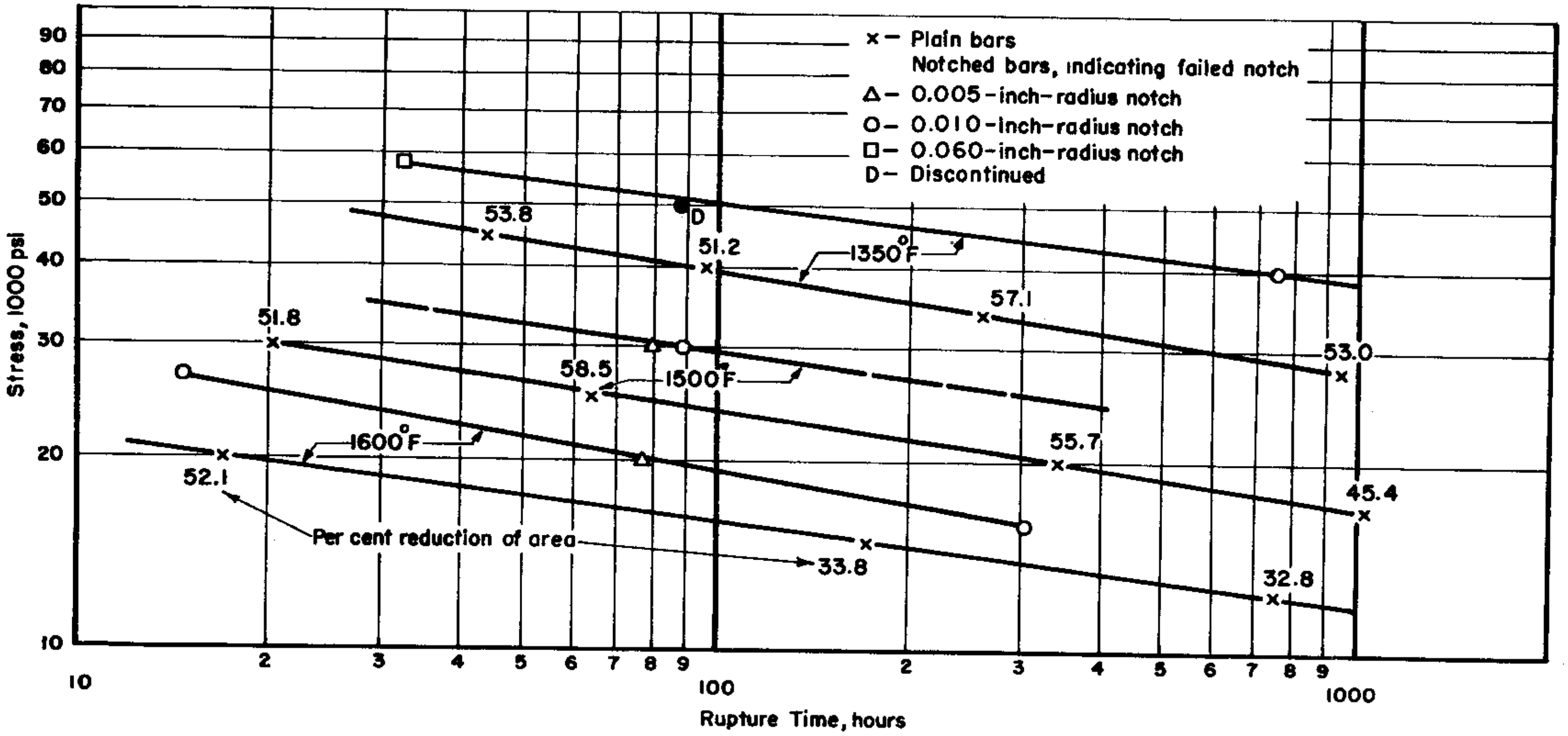

FIGURE 4. STRESS VERSUS RUPTURE-TIME CURVES FOR PLAIN AND NOTCHED BARS OF S-816 ALLOY

C-10772

shown in Table 2, are the averages of four or five determinations. The original hardness of S-816 after heat treatment was 99.8 Rockwell B, and there was only a slight increase in hardness after testing at 1350°, 1500°, or 1600°F. The hardness after testing for 44 and 960 hours at 1350°F was 102.5 R_B. At 1500° and 1600°, the increase in hardness during testing was less.

Inconel "X" Type 550

Creep-rupture tests were made at 1350°, 1500°, and 1600°F on plain and notched specimens of Inconel "X" Type 550 alloy. The detailed creep-rupture and hardness data are given in Table 3, and the rupture data are plotted in Figures 5, 6, and 7.

The hardness data shown in Table 3 indicate a difference in the original hardness of the two lots of this alloy heat treated at different times. The second lot with its higher hardness, Rockwell B, 108.1, as compared with 101.2 for the first lot, showed more scatter of properties and a greater degree of notch sensitivity, particularly at the shorter times. The room-temperature hardness of tested specimens indicated that metallurgical changes affecting the hardness occurred during the testing. The hardness of the first lot of specimens, (original hardness of 101.2 R_B) increased to 106-107 R_B during testing at 1350°F; they showed an increase to 103-104 R_B after short times at 1500°F, but, after longer times at 1500°F, they were back to 101 R_B. After testing at 1600°F, the hardness was 101-102 R_B.

The second lot of specimens, with an original hardness of 108.1 R_B, showed a slight decrease in hardness to 107 R_B after testing at 1350°F. A short testing time at 1500°F gave a hardness of 106 R_B while a longer time gave 103 R_B. Testing at 1600°F reduced the hardness to 102.6 R_B after 29 hours, and to 100.4 R_B after 472 hours. The hardness variations of Inconel "X" Type 550 are plotted in Figure 8.

Figure 5 shows the plain- and notched-bar rupture data for Inconel "X" Type 550 at 1350°F. The plain-bar data and the 0.005- and 0.045-inch-radii notched-bar data were obtained on the first lot of specimens with an initial hardness of 101.2 R_B. Both of these notches produced strengthening at the shorter times at this hardness level where the plain-bar ductility was the highest. The data for the 0.005-inch-radius notches became notch sensitive after about 40 hours and the data for the 0.045-inch-radius notch became notch sensitive after 100 hours. The slopes of the curves for both notches began to decrease at about 40,000 psi, and the greater change in slope was shown by the sharper notch, causing the curves to cross at about 370 hours. Metallurgical changes, such as precipitation (aging) during the test were probably partly responsible for the observed behavior, but it is thought that the difference in behavior between the 0.005- and the 0.045-inch-radii notches was more likely the result of physical effects of notch severity.

TABLE 3. PLAIN- AND NOTCHED-BAR RUPTURE DATA FOR INCONEL "X" TYPE 550

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction, of Area, per cent	Hardness(a), Rockwell B	Remarks
					Plain Bars		
I-1	1350	55,000	46.0	0.9	3.4	--	--
I-8	1350	45,000	302.0	0.5	0.7	--	--
I-11	1350	40,000	456.0	1.3	1.8	--	--
I-42	1350	37,000	762	[illegible]	2.2	--	--
--	1350	35,000	1646.9	0.4	0.5	--	University of Michigan data
			Bars With Three Notches — 0.005-, 0.045-, and 0.100-Inch Radii				
I-13	1350	60,000	30.1	--	Nil	105.8	Failed in 0.005-inch-radius notch; none cracked
I-16	1350	50,000	62.8	--	1.8	106.0	Failed in 0.005-inch-radius notch; none cracked
I-19	1350	40,000	109.4	--	0.5	--	Failed in 0.005-inch-radius notch; none cracked
I-22	1350	35,000	197.4	--	0.4	107.5	Failed in 0.005-inch-radius notch; none cracked
I-40	1350	32,000	697.6	--	Nil	105.9	This bar had only one notch at 0.005-inch radius
I-37	1350	30,000	1208.1(b)	--	--	--	No failure, this bar had only one notch of 0.005-inch radius
			Bars With Two Notches — 0.045- and 0.100-Inch Radii				
I-25	1350	65,000	42.4	--	1.5	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-30	1350	50,000	100.3	--	0.1	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-27	1350	40,000	157.1	--	0.1	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-31	1350	30,000	641.6	--	2.3	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-36	1350	27,500	992.5	--	0.8	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
			Bars With One Notch — 0.020-Inch Radius				
I-55	1350	60,000	11.5	--	1.4	107.2	--
I-62	1350	50,000	14.3	--	0.7	--	--
I-56	1350	50,000	36.9	--	0.9	--	--
I-57	1350	40,000	138.5	--	Nil	--	--
I-58	1350	33,000	466.9	--	--	--	--

TABLE 3. (Continued)

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction of Area, per cent	Hardness(a), Rockwell B	Remarks
			Bars With One Notch -- 0.100-Inch Radius				
I-70	1350	65,000	59.2	--	1.6	--	--
I-73	1350	55,000	56.1	--	0.8	--	--
I-74	1350	50,000	154.7	--	2.1	--	--
I-76	1350	35,000	307.4	--	2.0	107.1	--
I-78	1350	30,000	577(b)	--	--	--	Not failed or cracked
			Plain Bars				
I-4	1500	45,000	9.3	3.2	7.5	--	--
I-2	1500	35 000	37.9	2.6	5.3	--	--
I-6	1500	25,000	291.1	2.7	6.5	--	--
I-9	1500	20,000	1068.6	2.2	3.4	--	--
			Bars With Three Notches -- 0.005-, 0.045-, and 0.100-Inch Radii				
I-21	1500	40,000	27.3	--	0.7	103.1	Failed in 0.005-inch-radius notch; none cracked
I-15	1500	35,000	36.4	--	0.9	103.6	Failed in 0.005-inch-radius notch; none cracked
I-17	1500	30,000	31.9	--	0.7	103.9	Failed in 0.005-inch-radius notch; none cracked
I-20	1500	25,000	109.7	--	1.4	--	Failed in 0.045-inch-radius notch; none cracked
I-41	1500	25,000	288.6	--	0.7	101.5	This bar had only one notch of 0.005-inch-radius
I-24	1500	20,000	655.0	--	0.9	101.0	Failed in 0.005-inch-radius notch; none cracked
			Bars With Two Notches -- 0.045- and 0.100-Inch Radii				
I-29	1500	50,000	7.9	--	1.2	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-26	1500	40,000	38.9	--	2.3	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-28	1500	30,000	138.4	--	1.8	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-32	1500	25,000	365.8	--	2.1	--	Failed in 0.045-inch-radius notch; 0.100 notch sound
I-33	1500	21,000	1133.7(b)	--	--	--	Not failed or cracked

TABLE 3. (Continued)

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction of Area, per cent	Hardness[a], Rockwell B	Remarks
Bars With One Notch -- 0.020-Inch Radius							
I-59	1500	35,000	22.1	--	Nil	--	--
I-60	1500	25,000	80.7	--	Nil	--	--
I-61	1500	20,000	578[b]	--	--	--	Not failed or cracked
Bars With One Notch -- 0.100-Inch Radius							
I-79	1500	45,000	25.4	--	1.8	--	--
I-71	1500	45,000	13.9	--	1.5	106.3	--
I-72	1500	35,000	44.9	--	1.9	--	--
I-77	1500	35,000	69.5	--	1.7	--	--
I-75	1500	30,000	268.2	--	1.7	102.8	--
Plain Bars							
I-5	1600	30,000	1.9	7.7	18.1	--	--
I-3	1600	22,000	60.3	6.3	15.1	--	--
I-7	1600	17,000	113.9	2.2	5.8	--	--
I-10	1600	13,000	428.2	3.5	5.2	--	--
I-12	1600	11,000	509.5	4.4	4.0	--	--
Bars With Three Notches -- 0.005-, 0.045-, and 0.100-Inch Radii							
I-14	1600	25,000	12.9	--	0.5	102.0	Failed in 0.045-inch-radius notch; none cracked
I-18	1600	18,000	358.7	--	3.6	101.3	Failed in 0.100-inch-radius notch; none cracked
I-23	1600	16,000	628.0	--	1.8	--	Failed in 0.100-inch-radius notch; none cracked
Bar With Two Notches -- 0.045- and 0.100-Inch Radii							
I-34	1600	25,000	64.6	--	3.3	--	Failed in 0.100-inch-radius notch; 0.045-inch notch sound
Bars With One Notch -- 0.005-Inch Radius							
I-51	1600	25,000	72.7	--	2.2	--	--
I-49	1600	25,000	29.3	--	1.8	102.6	--
I-50	1600	15,000	472.2	--	1.7	100.4	--

(a) Original hardness of Specimens I-1 through I-47, 101.2 Rockwell B; original hardness of Specimens I-48 through I-82, 108.1 Rockwell B.

(b) Discontinued.

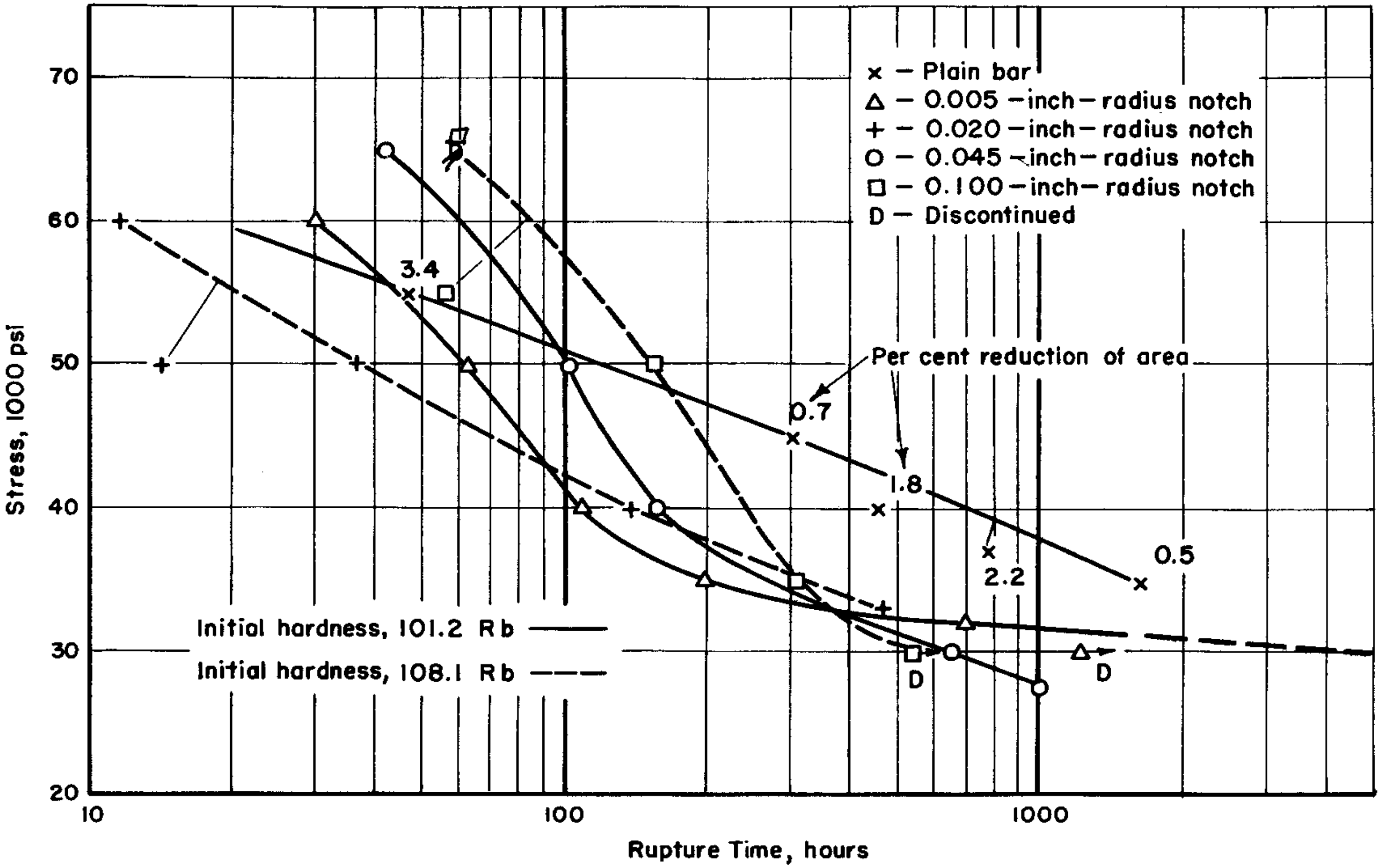

FIGURE 5. STRESS VERSUS RUPTURE TIME FOR INCONEL "X" TYPE 550 ALLOY AT 1350°F

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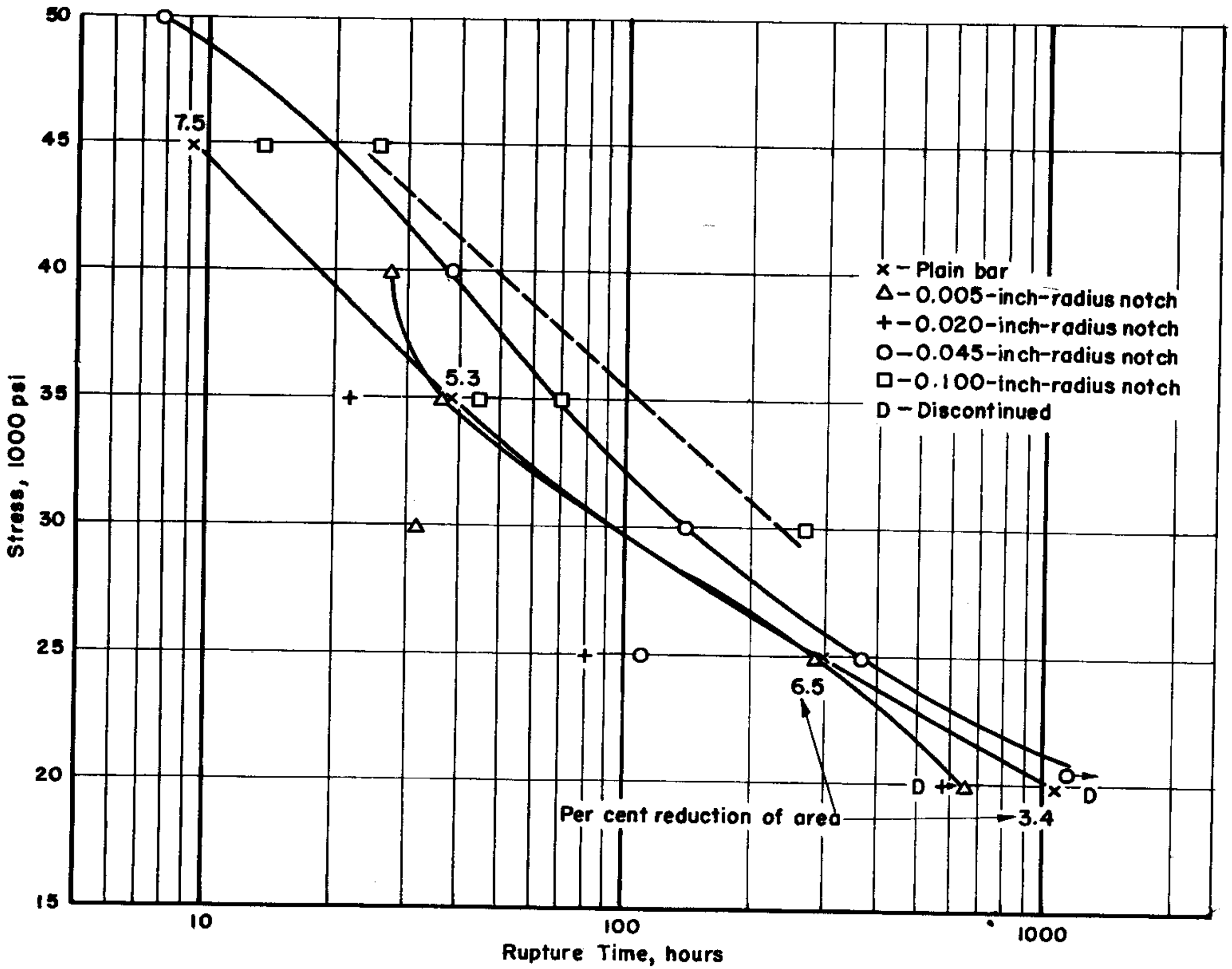

FIGURE 6. STRESS VERSUS RUPTURE TIME FOR INCONEL "X" TYPE 550 ALLOY AT 1500° F

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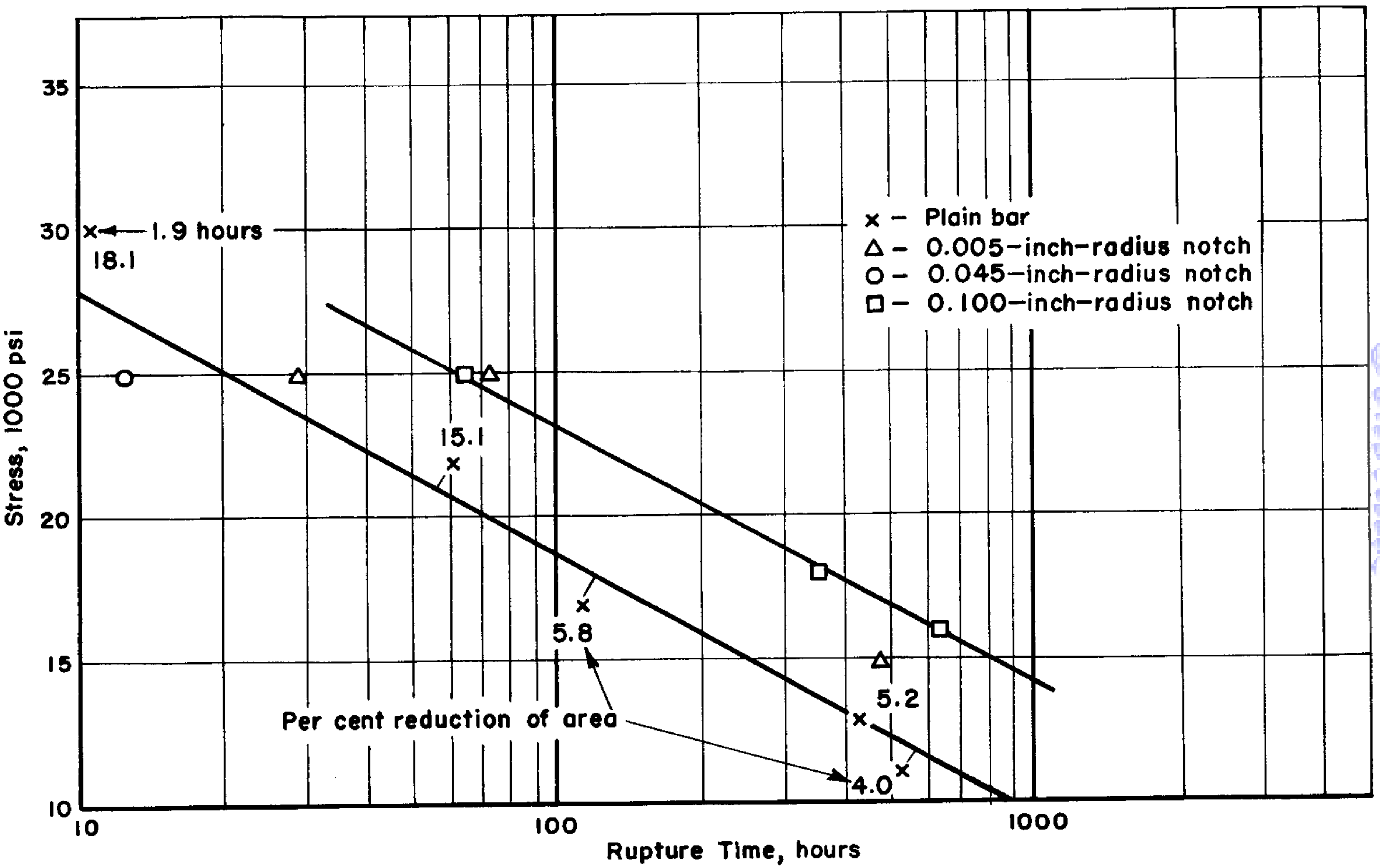

FIGURE 7. STRESS VERSUS RUPTURE TIME FOR INCONEL "X" TYPE 550 ALLOY AT 1600°F

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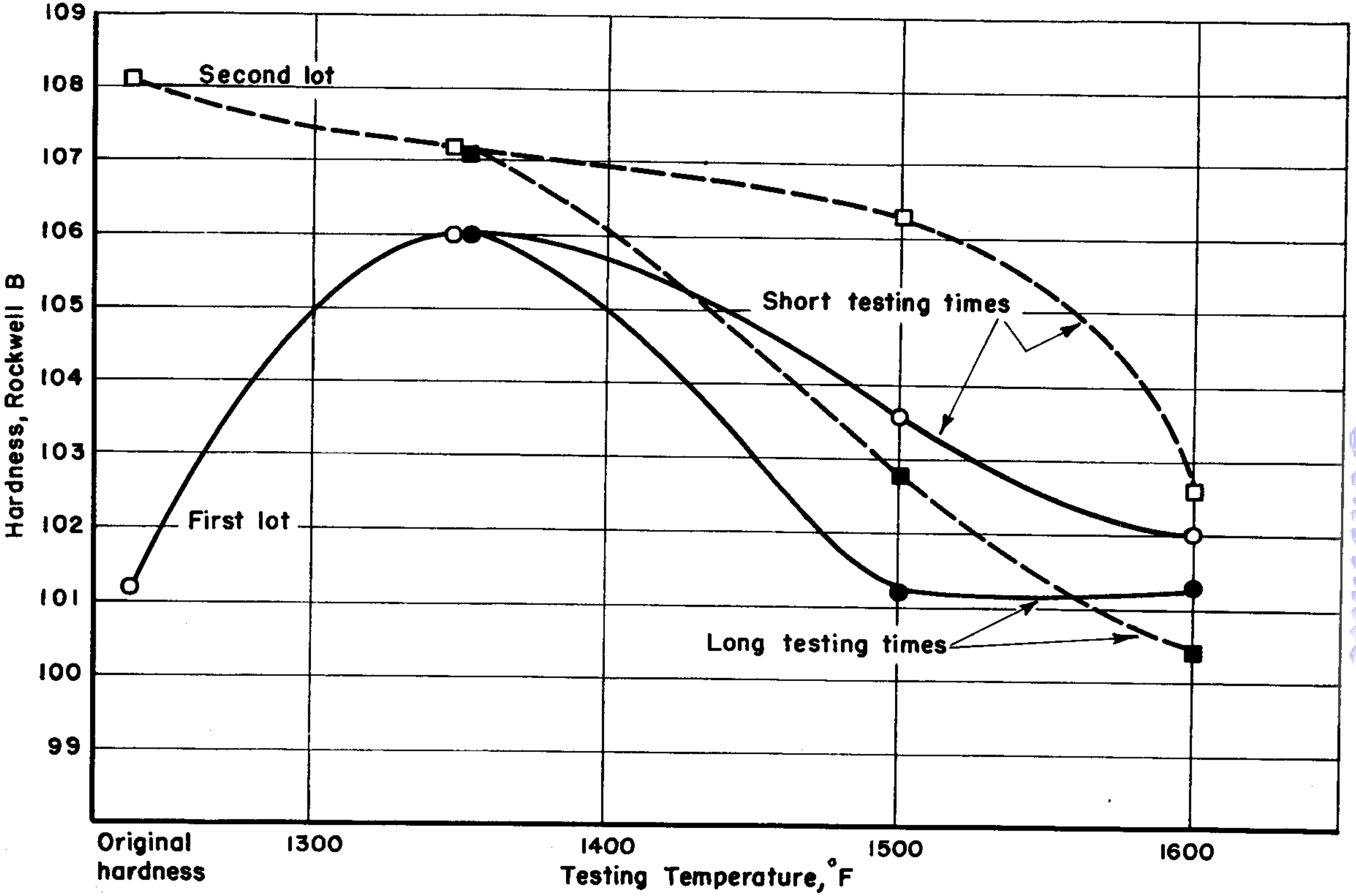


FIGURE 8. ROOM-TEMPERATURE HARDNESS VARIATIONS OF INCONEL "X" TYPE 550 ALLOY AFTER RUPTURE TESTING

A-10776

One explanation of this behavior is as follows: The stress concentration and triaxiality are both higher for the 0.005-inch-radius notch (see Figure 1). Thus, if sufficient time and ductility are available before rupture (low stresses), the stress concentration of the 0.005-inch-radius notch is relieved, permitting the strengthening effect of the higher triaxiality associated with the sharper notch to become effective.

Ductility and time are both important. At sufficiently long times, however, notch strengthening effects may be observed at relatively low ductility. This is indicated by the shape of the plain- and 0.005-inch-radius notch-bar curves in Figure 5.

The rupture curves for the 0.020- and 0.100-inch-radius notch bars were obtained from the second lot of specimens with an initial hardness of 108.1 R_B. The curve for the 0.20-inch-radius notch bars was lower than expected for times less than 100 hours, and at longer times it was not accurately determined. The curve for the 0.100-inch-radius notch has the same shape as the 0.045-inch-radius notch-bar curve, and is located about where it should be if it had been determined on specimens from the first lot. In other words, the increased hardness does not appear to have affected markedly the shape or location of this curve.

Figure 6 shows the stress versus rupture time curves for Inconel "X" Type 550 at 1500°F. The plain-bar curves and the curves for the 0.005- and 0.045-inch-radius notch bars were obtained from the first lot of specimens. The curve for the 0.005-inch-radius notch bars is essentially the same as for the plain bars, while the 0.045-inch-radius notch produced a slight but consistent strengthening. Two specimens of the first lot broke at shorter times than would be expected from normal scatter of the data. Specimen I-17 broke in 31.9 hours at 1500°F and 30,000 psi, and Specimen I-20 broke in 109.7 hours at 1500°F and 25,000 psi. No microscopic cracks or flaws were observed in these specimens. The microstructure of both tested and untested specimens will be discussed in another section of this report.

The 0.20- and 0.100-inch-radius notch specimens tested at 1500°F also came from the second lot of specimens with 108.1 R_B original hardness. These specimens gave shorter rupture times than expected at times under 100 hours. At longer times, Specimen I-75 ruptured about as expected and Specimen I-61 was discontinued (because of the end of the project) as it was approaching the data from the first lot of specimens.

The data at 1600°F on plain and notched bars of Inconel "X" Type 550 are shown in Figure 7. The tests with the triple-notch specimen indicated that this alloy was notch strengthened at 1600°F, and rupture occurred in the 0.100-inch-radius notch, with the exception of Specimen I-14 which failed in the 0.045-inch-radius notch at an excessively short time. Two of three tests on 0.005-inch-radius notch specimens from the second lot broke at times shorter than for specimens from the first lot even though the hardness after test was equal or lower than for specimens from the first lot. This is an indication that hardness values after testing, although they may be helpful, particularly at the lower temperatures, do not tell the whole story of the effect of structural changes during testing. As a rule, it was the shorter time tests, under 100 hours duration, which showed increased notch sensitivity for the second lot of Inconel "X" Type 550, indicating that after additional aging had reduced the initial difference in hardness, the properties were more nearly equal. This is evidence of structural changes affecting the notch sensitivity.

Waspaloy

Creep-rupture tests were made on plain and notched specimens of Waspaloy at 1200°, 1350°, and 1500°F, and the detailed creep-rupture and hardness data are given in Table 4. The data are plotted in Figures 9, 10, and 11.

The hardness of Waspaloy as heat treated was 106.8 Rockwell B, and there was no change in hardness after rupture testing at 1200°and 1350°F. The hardness dropped to 105 R_B after short times in test at 1500°F, and to 103 R_B after 484 and 1180 hours.

The plain- and notched-bar rupture data for Waspaloy at 1200°F are shown in Figure 9. The 0.005-inch-radius notch specimens were very notch sensitive. The 0.020-inch-radius notch specimens were considerably less notch sensitive, and the 0.040-inch-radius notch specimens gave rupture data essentially the same as the plain bars. The specimens with the 0.100-inch-radius notch were notch strengthened. It should be noted that as the time increased the notch sensitivity of the 0.005-inch-radius notch specimens, with their higher triaxiality, became less, indicating that time is a factor in the notch behavior of Waspaloy just as it was for Inconel "X" Type 550 at 1350°F.

Figure 10 shows the stress versus rupture time curves for Waspaloy at 1350°F. At this temperature the 0.005-inch-radius notch was still producing notch-sensitive rupture results, but only slightly so, and the rupture data for the 0.020-inch-radius notch specimens were about the same as for the plain bars. The data for the 0.040- and 0.100-inch-radius notch specimens mens showed notch strengthening.

The data for Waspaloy at 1500°F shown in Figure 11 indicate that all three notches produced about the same amount of notch strengthening at this temperature. This is an indication that Waspaloy is insensitive to notch severity, at 1500°F, at least for the notches studied.

It is apparent from the data obtained on Inconel "X" Type 550 and Waspaloy that notch sensitivity is a function of notch severity, temperature, and time.

TABLE 4. PLAIN- AND NOTCHED-BAR RUPTURE DATA FOR WASPALOY

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction of Area, per cent	Hardness(a), Rockwell B	Remarks
			Plain Bars				
W-4	1200	90, 000	28. 4	2. 2	9. 4	--	--
W-1	1200	80, 000	127. 5	2. 7	6. 1	--	--
W-5	1200	75, 000	287. 2	2. 6	5. 6	--	--
W-15	1200	70, 000	440. 6	1. 8	7. 5	--	--
W-18	1200	60, 000	1055. 7(b)	--	--	--	--
			Bars With Three Notches -- 0. 005-, 0. 040-, and 0. 100-Inch Radii				
W-11	1200	90, 000	0. 1	--	2. 2	106. 9	Failed in 0. 005-inch-radius notch; none cracked
W-21	1200	75, 000	2. 3	--	0. 9	107. 6	Failed in 0. 005-inch-radius notch; none cracked
W-23	1200	60, 000	41. 8	--	1. 3	--	Failed in 0. 005-inch-radius notch; none cracked
W-24	1200	50, 000	1006. 0(b)	--	--	106. 3	Not failed or cracked
			Bars With Two Notches -- 0. 040- and 0. 100-Inch Radii				
W-30	1200	90, 000	45. 3	--	3. 2	--	Failed in 0. 040-inch-radius notch; 0. 100-inch notch sound
W-28	1200	75, 000	219. 9	--	2. 7	--	Failed in 0. 040-inch-radius notch; 0. 100-inch notch sound
W-32	1200	70, 000	617. 8	--	2. 8	--	Failed in 0. 040-inch-radius notch; 0. 100-inch notch sound
			Bars With One Notch -- 0. 020-Inch Radius				
W-46	1200	80, 000	24. 6	--	3. 9	--	--
W-49	1200	70, 000	125. 8	--	2. 5	--	--

TABLE 4. (Continued)

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction of Area, per cent	Hardness[(a)], Rockwell B	Remarks
				Bars With One Notch — 0.100-Inch Radius			
W-50	1200	90,000	113.0	--	4.6	--	--
W-53	1200	80,000	498.7	--	4.5	--	--
				Plain Bars			
W-7	1350	60,000	10.6	2.6	5.3	--	--
W-2	1350	55,000	56.6	3.0	5.8	--	--
W-3	1350	50,000	161.4	5.2	6.7	--	--
W-14	1350	45,000	265.1	5.3	6.9	--	--
W-17	1350	35,000	1201.6[(b)]	--	--	--	--
				Bars With Three Notches — 0.005-, 0.040-, and 0.100-Inch Radii			
W-9	1350	60,000	4.0	--	0.7	105.9	Failed in 0.005-inch-radius notch; none cracked
W-12	1350	50,000	0.6	--	3.7	107.0	Failed in 0.005-inch-radius notch; none cracked
W-25	1350	45,000	130.7	--	1.9	--	Failed in 0.005-inch-radius notch; none cracked
W-22	1350	40,000	977.0[(b)]	--	--	107.0	Not failed; 0.005-inch-radius notch cracked
				Bars With Two Notches — 0.040- and 0.100-Inch Radii			
W-39	1350	85,000	9.1	--	4.6	--	Failed in 0.040-inch-radius notch; 0.100 notch sound
W-31	1350	70,000	29.8	--	3.7	--	Failed in 0.040-inch-radius notch; 0.100 notch sound
W-29	1350	60,000	112.9	--	2.2	--	Failed in 0.040-inch-radius notch; 0.100 notch sound
W-33	1350	50,000	400.1	--	3.1	--	Failed in 0.040-inch-radius notch; 0.100 notch sound
W-37	1350	45,000	1006.8[(b)]	--	--	--	Not failed or cracked

TABLE 4. (Continued)

Specimen	Temperature, °F	Stress, psi	Rupture Time, hours	Elongation, per cent	Reduction of Area, per cent	Hardness(a), Rockwell B	Remarks
			Bars With One Notch — 0.020-Inch Radius				
W-48	1350	70,000	9.9	--	0.7	--	--
W-44	1350	60,000	17.5	--	1.2	--	--
W-45	1350	55,000	75.6	--	2.6	--	--
W-47	1350	50,000	104.7	--	0.2	--	--
			Bars With One Notch — 0.100-Inch Radius				
W-54	1350	70,000	57.2	--	4.5	--	--
W-52	1350	60,000	172.4	--	4.0	--	--
			Plain Bars				
	1500	50,000	2.4	--	11.5	--	University of Michigan data
W-6	1500	35,000	17.2	10.5	15.7	--	--
W-8	1500	25,000	184.3	9.8	12.2	--	--
	1500	23,000	292.1	--	12.0	--	University of Michigan data
W-13	1500	20,000	307.6	7.9	9.8	--	--
W-16	1500	13,000	1180.8(b)	--	--	102.9	--
			Bars With Three Notches — 0.005-, 0.040-, and 0.100-Inch Radii				
W-26	1500	45,000	13.7	--	3.3	104.7	Failed in 0.005-inch-radius notch; none cracked
W-10	1500	35,000	72.5	--	2.3	--	Failed in 0.040-inch-radius notch; 0.005-inch-radius notch cracked
W-20	1500	25,000	484.3	--	4.9	102.7	Failed in 0.100-inch-radius notch; 0.005-inch- and 0.040-inch-radius notches cracked
			Bars With Two Notches — 0.040- and 0.100-Inch Radii				
W-36	1500	45,000	14.5	--	2.2	--	Failed in 0.040-inch-radius notch; 0.100 notch sound
W-38	1500	35,000	97.6	--	3.1	--	Failed in 0.040-inch-radius notch; 0.100 notch sound

(a) Original hardness 106.8 Rockwell B

(b) Discontinued.

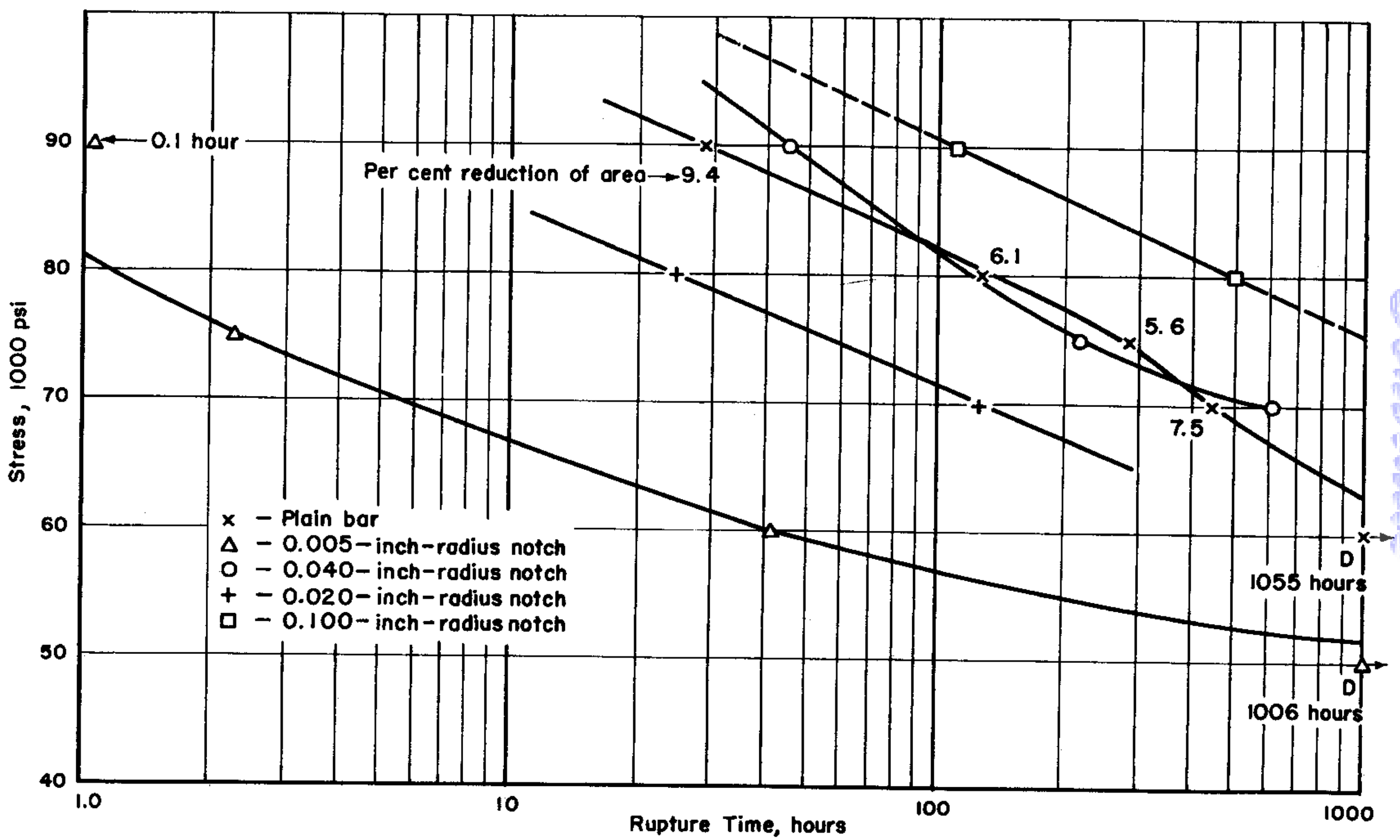


FIGURE 9. STRESS VERSUS RUPTURE TIME FOR WASPALOY AT 1200° F

C-10777

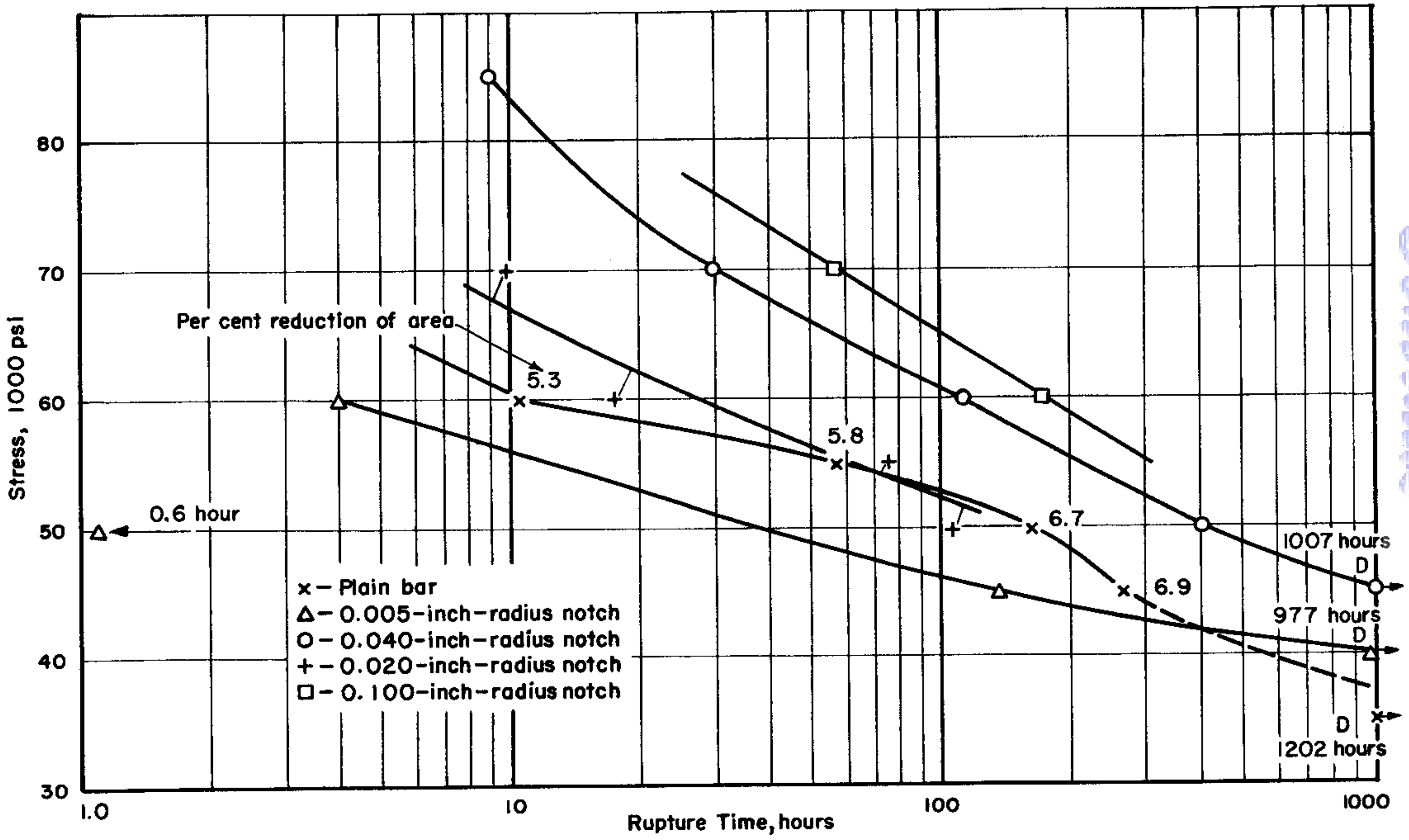


FIGURE 10. STRESS VERSUS RUPTURE TIME FOR WASPALOY AT 1350°F

C-10778

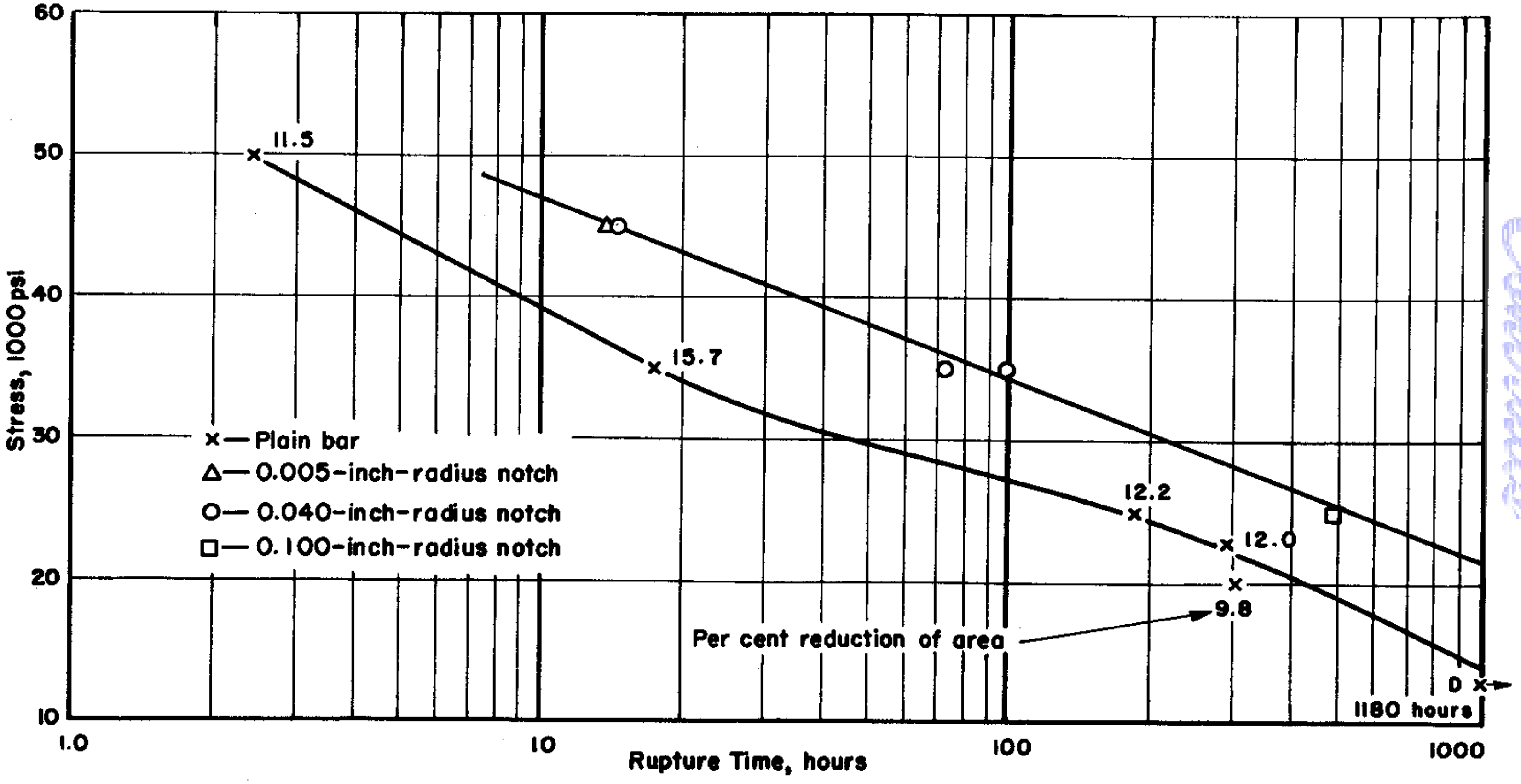


FIGURE 11. STRESS VERSUS RUPTURE TIME FOR WASPALOY AT 1500° F

A-10779

DUCTILITY CONSIDERATIONS

As has been indicated in previous sections of this report, the available ductility that a material possesses plays an important role in determining whether the material is "notch strengthened" or "notch sensitive". It is natural, then, that the question of how much ductility is enough to insure "notch strengthening" be asked. This has been answered, tentatively, at least, by Brown, et al.(4) They suggest that the best index is given by the notched-bar ductility. For the alloys which were studied as a part of their investigation, it was observed that notch-rupture sensitivity was associated with notch-rupture ductilities of less than 3 per cent. This value refers to the sharp notch utilized, and would not necessarily be expected to be valid for markedly different notches. Since, however, the sharp notch ductility requirements are much greater than those of significantly less sharp notches, the use of sharp notch can be considered as a severe screening test.

For design interests, it should be noted, however, that some value is to be derived from the use of notches of more than one sharpness. As has been indicated by Davis and Manjoine(5), the designation of an alloy as "notch sensitive" is arbitrary when judged on the basis of results for only one notch sharpness. They observed that, for a given time, an alloy is strengthened (the notched- to unnotched-rupture strength ratio increases) with decreasing sharpness up to a maximum value. If this ratio can become greater than unity, it ultimately decreases to unity, since a bar of zero notch sharpness is an unnotched bar.

In this investigation, it has been found that all of the alloys tested had the ability to be notch strengthened for some of the test temperatures and notch sharpness values used. It is also of interest to note that (see Tables 2 and 3) at some of the test temperatures, notch strengthening was observed for the entire time range (approximately 1000 hours) in spite of the fact that the reduction in area of the notched bar was only slightly above one per cent at times. The reduction in area of the unnotched bars for these temperatures was as low as five per cent. It thus appears that ductility requirements for notch strengthening can vary considerably. It should be emphasized, nevertheless, that the rule of associating notch sensitivity with notch-rupture ductilities of less than 3 per cent is both useful and safe.

To obtain additional information about the deformation characteristics, of notched bars, contour measurements of the notched bars were made before and after testing. The results of some of the measurements made are given in the Appendix. The aim of this phase of the study was to determine if it was possible to analyze the deformation by making certain simplifying assumptions. After a few preliminary computations, however, work was suspended because the inconclusiveness of the data suggested the probability that the assumptions made oversimplified the problem.

It should be noted also that a study of the reduction in area of the unruptured notches failed to reveal any conclusive trends.

As has been noted previously in this report, the problem under study is complex, and it is probable that simple rules that apply always, without reservation, can be established only if one is satisfied with a rule which very likely will be excessively conservative in some instances.

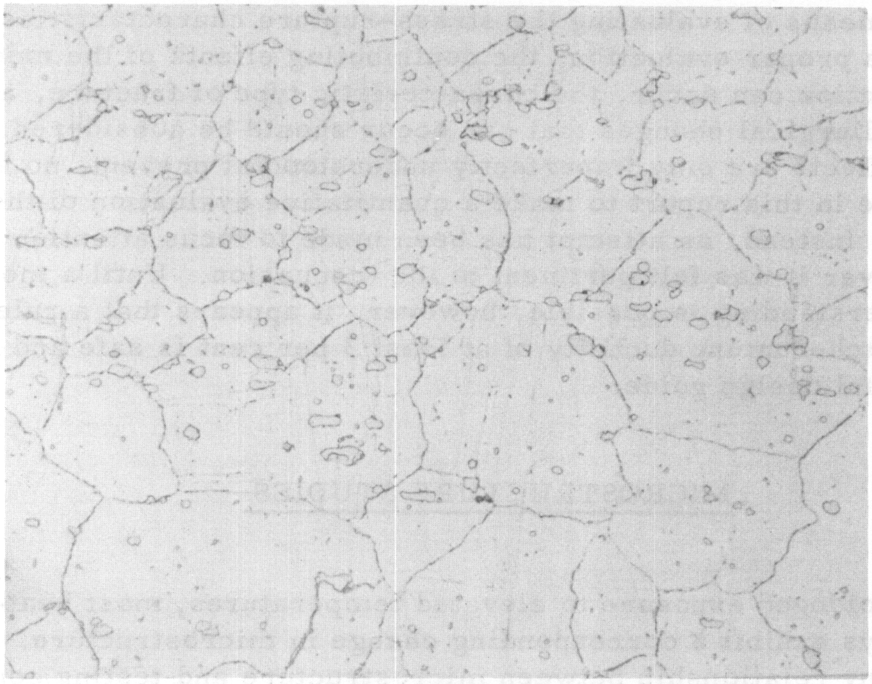
An example of this is the use of a design rule that indicates that an alloy should be suspected of being notch sensitive if the unnotched reduction in area is less than 30 per cent. If one considers S-816 and Waspaloy at 1500°F, however, this is seen to be a very rough gage of notch sensitivity. At 1500°F, both of these alloys are notch strengthened by a factor of approximately 1.2, and they appear to be relatively insensitive to differences in notch sharpness. From these facts one would be inclined to expect an unnotched ductility in excess of 30 per cent. For S-816, this is true, since the value is of the order of 50 per cent. The Waspaloy, however, ranges in value from 10 to 16 per cent. It is apparent that the internal response to loading must be different (see Examination of Cracks and Fractures).

It is apparent, then, that gross ductility, as such, is not a completely satisfactory means of evaluating the stress-rupture characteristics of alloys. For a proper evaluation, the contributing effects of the modes in which deformation can occur, the characteristic type of fracture, and the types of metallurgical changes that can occur should be considered. Since these effects are only imperfectly understood at present, no attempt has been made in this report to make a quantitative evaluation of their contribution. Instead, an attempt has been made to focus attention on these effects whenever it was felt pertinent to the discussion. Until a more complete understanding is possible, however, it appears that a rule which requires a notch-rupture ductility of at least 3 per cent is safe and can be used as a useful design guide.

MICROSTRUCTURE STUDIES

With prolonged exposure to elevated temperatures, most heat-resistant alloys exhibit a corresponding change in microstructure. In order to establish any relationship between microstructure and testing conditions with respect to the alloys used in this investigation, metallographic analyses were made of rupture-bar specimens representing the range of temperatures studied. Characteristic microstructures were obtained by longitudinally sectioning the stress-rupture bar through the center of the notched region. Sectioning was done with a water-cooled cutoff wheel with special care taken to avoid altering the existing microstructure by excessive cutting temperatures. Standard metallographic procedures were used for preparing the alloys for microscopic inspection.

With respect to the S-816 alloy, no observable change in microstructure was evident with rupture bars exposed for various periods of time at either the 1350°F or 1500°F test temperatures. In general, the microstructure was typical of quenched and aged S-816 material (a carbide phase dispersed in a solid-solution alloyed cobalt matrix with carbides present along the austenitic grain boundaries). It has been observed by some investigators that continued exposure to temperatures above 1600°F will produce an observable change in the characteristic aged microstructure. In general, high-temperature exposure initiates a solutioning process by which the grain-boundary carbide phase gradually enters into solid solution. The rate of such a process is both temperature and time dependent. A photomicrograph characteristic of the beginning of grain-boundary solutioning is presented in Figure 12. This represents the microstructure of a notched-rupture bar (Specimen S-21) exposed to a temperature of 1600°F for 301 hours. It can be observed that the grain boundaries appear somewhat intermittent or "spotty", indicative of the first stage of solutioning. At higher test temperatures, the grain boundaries gradually become exhausted of carbides and apparently lose their original aged strength.



500X Etchant: 5 Parts HCl N14559
1 Part HNO_3

FIGURE 12. EFFECT OF EXPOSURE TO HIGH TEMPERATURE FOR S-816 ALLOY

Intermittent grain boundaries indicate initiation of solutioning

Inconel "X" Type 550 is characterized by a precipitation hardening. Under the normal aging at 1600°F and 4 hours at 1350°F) matrix precipita standard microscopic techniques. With longer ex peratures of 1500°F or 1600°F, matrix precipitati ample, Specimen I-20 (1500°F — 110 hours) revea matrix precipitation, whereas Specimen I-23 (160 cated extremely heavy precipitation.

With the exception of the addition of cobalt, Waspaloy resembles to some degree that of Incon test temperatures of 1200°F and 1350°F, no visib structure was apparent. At the higher test tempe some matrix precipitation similar to that reporte 550 was evident.

Essentially, this microscopic study has sho resistant alloys used in this investigation exhibit microstructures at either 1500°F or 1600°F. The structural variations in the three different alloys posures to elevated temperatures are intended to the factors influencing the behavior of notched-ru presented to emphasize that metallurgical change and temperature, and must be taken into account temperature behavior.

The physical condition of the surface at the ceivably has considerable influence with respect in notched-rupture bars. If structural damage do preparation, i.e., grinding, it is probable that th vary from notch to notch because of the unreprod mechanism. This fact by itself might account fo testing data. Realizing that such a surface condi affect notch-rupture data, an investigation was in the surface condition of machined rupture bars.

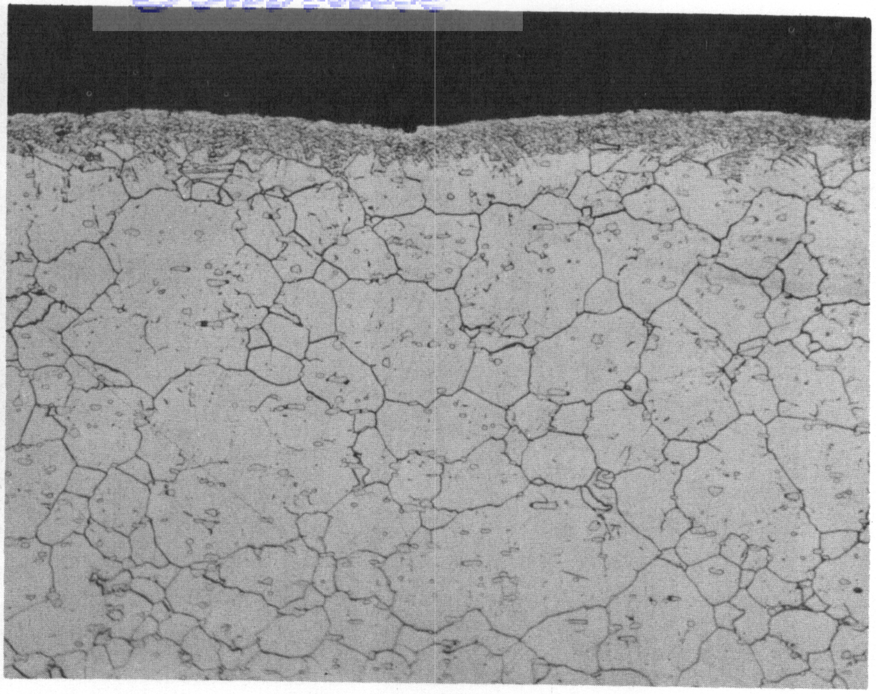
The procedure for this phase of the investi longitudinally sectioning an untested notched-rupt alloy through the notch diameter. These notch c metallographically examined for any surface crac of the notch) which might have been introduced by After completion of this examination, the notch c at a temperature of 1500°F for a period of 24 hou then re-examined microscopically.

No evidence of surface cracking or grain d machining was noted in either of the three notche rupture bars. After aging, however, each alloy in surface microstructure, seemingly brought ab

deformation. In the S-816 alloy, both the gage-length s
notch-contour surface revealed indications of massive c
tion. This surface condition can be seen by examining t
graphs presented in Figures 13 and 14. Figure 13 show
tion of somewhat uniform thickness (0.001 inch) on the g
specimen, while Figure 14 shows deformation at the roo
inch-radius notch. It is interesting to note the uneven d
precipitation at the notch root, indicative that the grindi
not applied evenly. On the left side of the notch, the de
almost 0.002 inch in thickness. It is apparent that the
temperature was not sufficient to promote recrystalliza
formed surface layer, although capable of allowing carb
In stressed bars of S-816 alloy, the effects of surface d
were present. At 1600°F the deformed surface areas we
recrystallized. At very close inspection and by slightly
microstructure, a mass of small grains could be observ
regions.

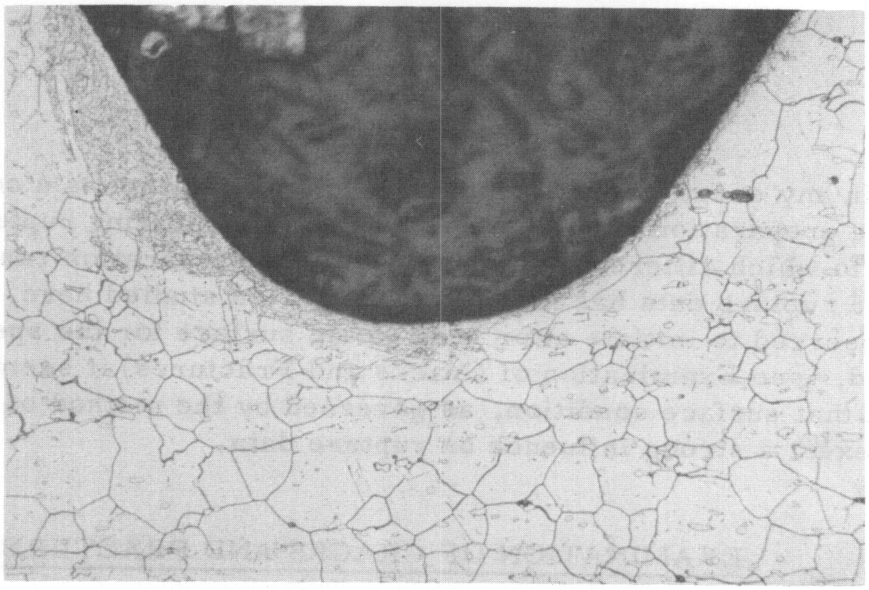
This recrystallization layer also was observed at
surface and notch-contour surface with the unstressed m
both Inconel "X" Type 550 and Waspalloy. In these speci
temperature was adequate to allow recrystallization to o
stressed rupture bars, a similar condition was present.
was noted that intergranular oxidation had occurred alon
of the newly formed surface grains. As would be expect
oxidation increased with time and temperature. The pho
Figure 15 clearly shows the surface region of recrystall
notched-rupture bar of Inconel "X" Type 550 stressed at
of 628 hours. The lighter etching surface area represen
recrystallization. Evidence of intergranular oxidation o
the surface also can be seen. The matrix precipitation
above discussion also is evident.

Microexamination, therefore, has indicated that th
erations required to prepare a notched-rupture specimen
duce various surface conditions which might exert consid
rupture properties of notched bars. A surface layer of
precipitation, as found in the S-816 alloy at the lower tes
is conceivably less ductile with reference to the unaffect
material. Such a condition at the root of a notch would b
for crack initiation. Once the propagation of a crack rea
ductile interior, the original geometry of the notch chang
creating further complications. When the test temperatu
ranges of recrystallization for the particular alloys cons
formed surface layers contain many small recrystallized
face layer of this nature offers a multitude of locations fo
rupture to begin, especially when exposure to elevated te
intergranular oxidation to occur.



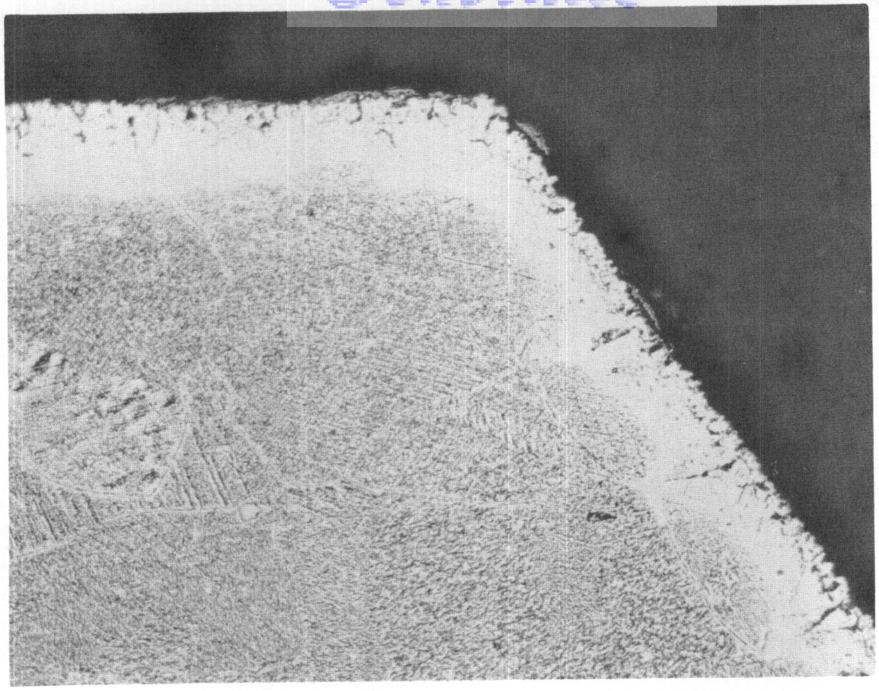
250X Etchant: 5 Parts HCl
1 Part HNO_3 N14000

FIGURE 13. SURFACE DEFORMATION IN S-816 RUPTURE BAR



250X Etchant: 5 Parts HCl
1 Part HNO_3 N14001

FIGURE 14. SURFACE DEFORMATION AT ROOT OF NOTCH (0. 005-INCH RADIUS) IN S-816 RUPTURE BAR



250X Etchant: 5 Parts HCl
1 Part HNO_3 N14558

FIGURE 15. SURFACE CONDITION AT NOTCH-GAGE LENGTH INTERFACE IN INCONEL "X" TYPE 550 RUPTURE BAR STRESSED AT 1600°F FOR 628 HOURS

In any event, the existence of surface condition as a consequence of surface preparation should be considered in evaluating rupture data. The extent to which different methods of surface preparation could be expected to alter rupture data has not, of course, been studied here. Since fracture was observed to initiate at or near to the surface for the specimens inspected, (see Examination of Cracks and Fractures) it seems reasonable to expect that surface condition, as governed by the method of preparation, could exert a strong influence on rupture data.

EXAMINATION OF CRACKS AND FRACTURES

The examination of cracks and fractures was facilitated by the preparation of photomicrographs. Those included in this section of the report were selected as being representative of the specimens tested. The three alloys investigated, S-816, Inconel "X" Type 550, and Waspaloy, will be discussed separately.

The etchant used on the sectioned S-816 bars was a mixture of 5 parts HCl and 1 part HNO_3. The test conditions are described beneath each figure.

The fracture surface in Figure 16 is at the top of the figure and the notch contour is along the left edge. The photomicrograph reveals that severe deformation has occurred, and there is considerable evidence of intergranular cracking. This is typical of the S-816 fractures with the exception that at the higher temperatures — 1500°F and 1600°F — the amount of deformation prior to fracture decreased. This was also evidenced in a decrease in the reduction in area values, and a shifting of fracture occurrence from the milder notches ($r = 0.06$ inch and 0.01 inch) to the sharper notches ($r = 0.01$ inch and 0.005 inch). This, of course, would be expected for a decrease in ductility.

The fracture surface of the specimen of Figure 16 was visually inspected, and from the variation in darkness of the oxide film on the fracture surface, it appears that a circumferential crack formed at or near the root of the notch and progressed inward. The fractured surface has a fibrous appearance in the dark, outer oxide band, and tends toward a granular appearance in the central portion. From these observations, it might be concluded that the circumferential crack was initiated after considerable plastic deformation had occurred. After initiation, the crack propagated slowly until a critical condition was reached. Fracture then occurred abruptly.

Since most of the notched bars tested contained three notches, it was possible to examine the notch contour in the unruptured notches. Figure 17 represents such a notch. Here, the structure at the base of the notch has deteriorated after severe, local deformation.

In a few instances, forked cracks were observed to have been present in unruptured notches. Figure 17 shows some evidence indicating that a forked crack might originate from such a beginning. It should be noted, of course, that the propagation of the individual branches of adjacent cracks probably must proceed together. If they do not, one branch would be likely to cease propagating. This should follow from the fact that the traction or force on the cracked surfaces is zero. If one of the branches falls behind, the axial force exerted across its crack tip would tend to be decreased.

From some of the observations made above, it might be concluded that for the test conditions used, S-816 can tolerate the presence of cracks. This is also confirmed in Table 2, where the frequent occurrence of cracks in the unruptured notches has been noted under the heading of "Remarks".

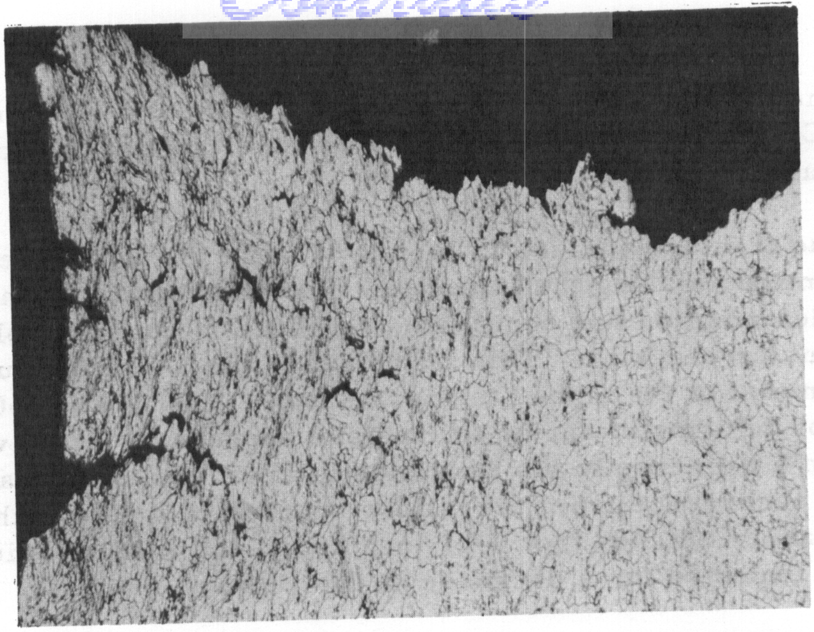


FIGURE 16. FRACTURE OF S-816 (r = 0.06 INCH)

(Fracture occurred in 32.1 hours at 1350°F and 58,000 psi)

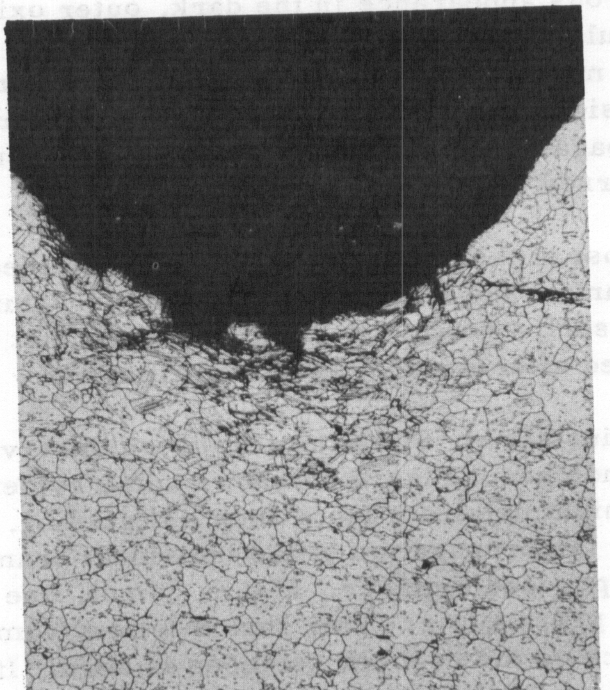


FIGURE 17. CONTOUR IN S-816 (r = 0.01 INCH)

(Test discontinued after 89.1 hours at 1350°F and 50,000 psi)

To try to obtain a relative idea of the rates at which these cracks were propagating, several cracked, but unruptured notches were broken, and the ends were inspected visually. In most instances, the cracks had penetrated to an approximately uniform depth. Furthermore, it was found that the oxide film was very dark and of uniform intensity in the crack band. The transition from the dark, cracked surface to the clean, newly broken surface was very abrupt. This tends to indicate that the cracks had penetrated to a certain depth, and then had either ceased to grow or were growing very slowly.

The possibility of the cracks penetrating to a certain depth, and then stopping is of interest for several reasons. This would indicate that, temporarily at least, an adjustment had occurred which made the crack stable. One possible explanation for such a behavior is that the crack moves through the cold-worked surface layer* and then stops in the more ductile interior. In some instances, the cracks' depths appear to be of the approximate order of the cold-worked layer. A more detailed discussion of the surface layer appears in the section of this report on microstructure.

Cracks of the above type could, of course, ultimately become unstable by several means. Metallurgical change could bring about embrittlement, the grain-boundary mechanism discussed earlier might cause embrittlement, or corrosion of the material at the tip of the crack might occur. One important thing to note, however, is that a cracked bar has an essentially new notch geometry. This adds still another complication to those mentioned earlier, because any description of the fracture process should trace the formation and growth of such cracks.

Inconel "X" Type 550

Fractures of the Inconel "X" Type 550 specimens occurred after relatively small amounts of deformation. Evidence of this is given in Table 3 under the column marked "Reduction in Area" for which the values are small. The fracture surfaces were quite distinctly intergranular with very slight indication of deformation within the grains. It should be noted also that the absence of cracks in the unfractured notches (see Remarks in Table 3) tends to indicate that this alloy is more sensitive to the presence of cracks than S-816. It appears that cracks could be tolerated only a short time after initiation.

To illustrate the initiation of cracking in this alloy, the photomicrograph of Figure 18 has been prepared. This, incidentally, represents an instance in which cracking did occur in one of the unruptured notches, but was not detected visually. The etchant used was a mixture of 5 parts HCl and 1 part HNO_3. The test conditions are described beneath the figure.

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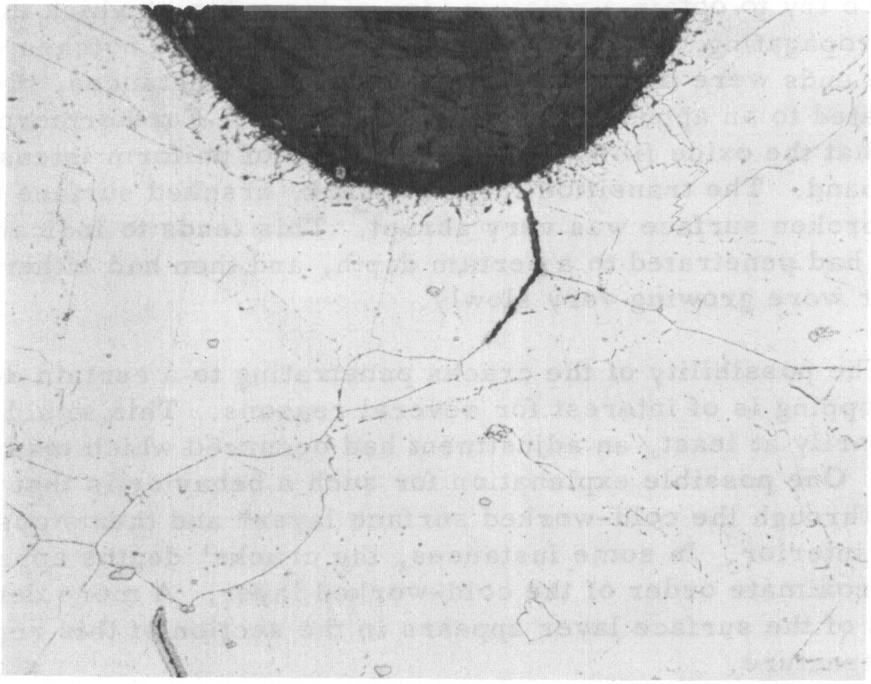
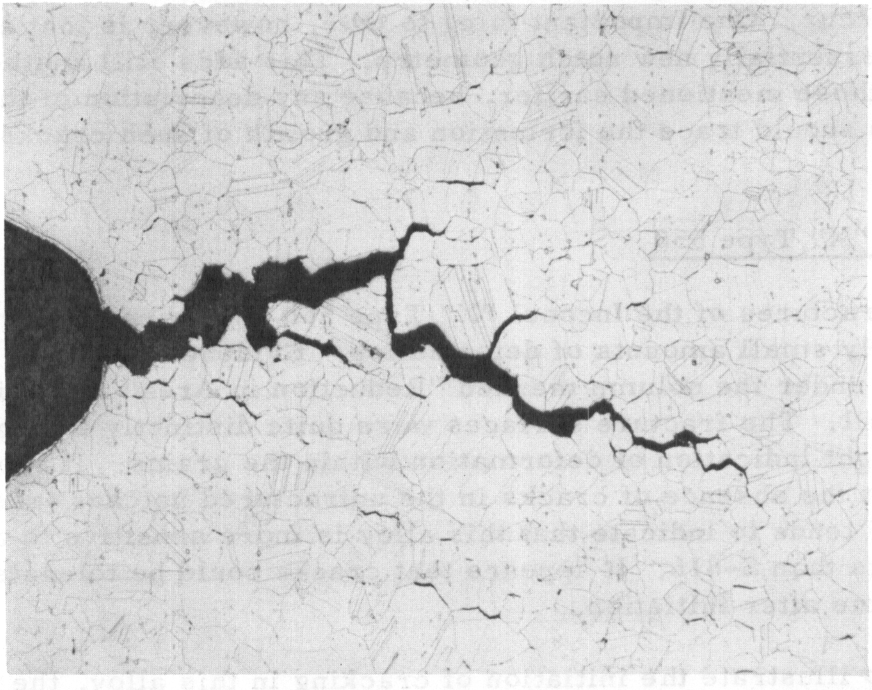
* The layer referred to here is that introduced in the grinding of the notch during the specimen preparation.



250X N14557

FIGURE 18. CONTOUR IN INCONEL "X" TYPE 550 ($r = 0.005$ INCH)

(Fracture occurred in $r = 0.045$-inch notch in 109.7 hours at 1500°F and 25,000 psi)



75X N14560

FIGURE 19. CONTOUR IN WASPALOY ($r = 0.005$ INCH)

(Fracture occurred in $r = 0.040$-inch notch in 72.5 hours at 1500°F and 35,000 psi)

As can be seen, the crack has been initiated with very little deformation in the adjacent grains, and it is quite distinctly intergranular.

Waspaloy

As in the case of Inconel "X" 550, fracture in Waspaloy was not preceded by severe deformation. Also, fracture was intergranular in nature and appeared to initiate at, or near, the surface.

To illustrate the initiation of cracking in this alloy, the photomicrograph of Figure 19 has been prepared. The etchant used was a mixture of 5 parts HCl and 1 part HNO_3. The test conditions are described below the figure.

Although there is evidence of twinning within the grains, the deformation of the grains is very slight. This is evidenced further by the fact that it appears as though the crack surfaces almost could be fitted together again because of the small amount of distortion that has occurred. It is of interest to note also that at 1500°F, Waspaloy was notch strengthened for all of the notches in spite of the fact that the unnotched ductility ranged from only about 10 to 16 per cent. It should be noted further that Figures 17 and 19 both represent deformation and cracking for notch-strengthened test conditions. In spite of the fact that the response to the external load resulted in notch strengthening for both alloys, it is apparent that the modes of deformation and cracking are markedly different.

SUMMARY AND CONCLUSIONS

Stress-rupture tests were made on plain and notched bars of S-816, Inconel "X" Type 550, and Waspaloy alloys. S-816 and Inconel "X" Type 550 alloys were tested at 1350°, 1500°, and 1600°F, and Waspaloy was tested at 1200°, 1350°, and 1500°F. Specimens with 60-degree V-notches of root radii between 0.005 and 0.100 inch, and 50 per cent reduction of area were used.

S-816 alloy was notch strengthened under all conditions of notch severity and test temperatures.

Inconel "X" Type 550 was notch strengthened at short times 1350°F, but at longer times was notch sensitive. An extrapolation indicates that at times approaching 10,000 hours the 0.005-inch-radius notch might again produce notch strengthening for Inconel "X" Type 550 at 1350°F. At 1200°F, Waspaloy was very notch sensitive in the 0.005-inch-radius notch. The 0.020-inch-radius notch specimens were considerably less notch sensitive, and the 0.040-inch-radius notch specimens gave rupture data essentially the same as the plain bars. The specimens with the 0.100-inch-radius notch were notch strengthened.

At the highest temperatures, 1600°F for Inconel "X" Type 550, and 1500°F for Waspaloy, both of these alloys were notch strengthened.

The data indicate that the effect of notches on the rupture strength was dependent on the notch severity, temperature, and time. It appears that even an alloy of relatively low ductility may be notch strengthened if stresses are low and rupture does not occur until very long times. It is apparent that no single value of smooth-bar ductility can be selected below which notch sensitivity will be observed and above which notch strengthening is assured.

It is concluded that several factors can be expected to have an influence on notched and unnotched stress-rupture behavior. For this reason, these behaviors are complex and can only be interpreted completely by a combined consideration of the governing factors. These factors include not only the notch geometry and available ductility, but also the possible modes of deformation and fracture, metallurgical changes, and the surface condition. Since the influence of these latter factors can vary considerably from alloy to alloy, it does not appear possible, at this time, to give simple design rules which can be used efficiently for all alloys under all of the various conditions likely to be used.

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(2) Strength and Testing of Materials, Part I, published by Her Majesty's Stationery Office (1952), "Notch Brittleness and Ductile Fracture in Metals" (E. Orowan, J. F. Nye, and W. J. Cairns), pp 127-175.

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(4) Brown, W. F., Jr., Jones, M. H., Newman, D. P., "Influence of Sharp Notches on the Stress-Rupture Characteristics of Several Heat-Resisting Alloys", Symposium on Strength and Ductility of Metals at Elevated Temperatures, American Society for Testing Materials, Special Technical Publication No. 128, pp 25-45 (1952).

(5) Davis, E. A., Manjoine, M. J., "Effect of Notch Geometry on Rupture Strength at Elevated Temperatures", Symposium on Strength and Ductility of Metals at Elevated Temperatures, American Society for Testing Materials, Special Technical Publication No. 128, pp 67-87 (1952).

APPENDIX

NOTCH-CONTOUR MEASUREMENTS

The most commonly used measure of strain in notch-rupture testing is the reduction of area at the root of the notch. For the information that has been derived up to the present, this type of measurement has been proved adequate. As a consequence, notch-contour deformation that occurs during testing has been largely ignored. Since it was felt that measurements describing the contour change might prove of interest, it was decided that "before" and "after" measurements of a few selected notch contours should be made.

Notch measurements were obtained by using a Jones and Lamson pedestal-type comparator with a magnification of 50X. After centering the notch to be measured on this instrument, the following measurements were obtained.

(1) Diameter at root of notch
(2) Depth of notch
(3) The distance across the notch at the top of the notch, and 0.040, 0.010, 0.005 inch from the root of the notch

After these measurements were obtained for one orientation, the specimen was rotated 180° about its axis, and a second set of readings was obtained. The values used to plot notch contours were averages of the two readings obtained.

"Before" and "after" plots of three notch contours are given in Figures 20, 21, and 22. These notches were on the same specimen. The test conditions were as follows.

Material — S-816
Average stress — 50,000 psi
Test temperature — 1350°F
Test time — 89.1 hours (no rupture — test discontinued because of furnace failure)

The value of measuring the change in notch contour is limited if the displacement of each point of measurement on the notch contour is not known. A plot of the contours alone does not reveal this displacement, because the length of the contour curve is changed by nonuniform deformation. Methods available for analyzing plastic and creep deformation cannot trace the complex displacements which occur. However, these displacements can be determined approximately if some simplifying assumptions are made:

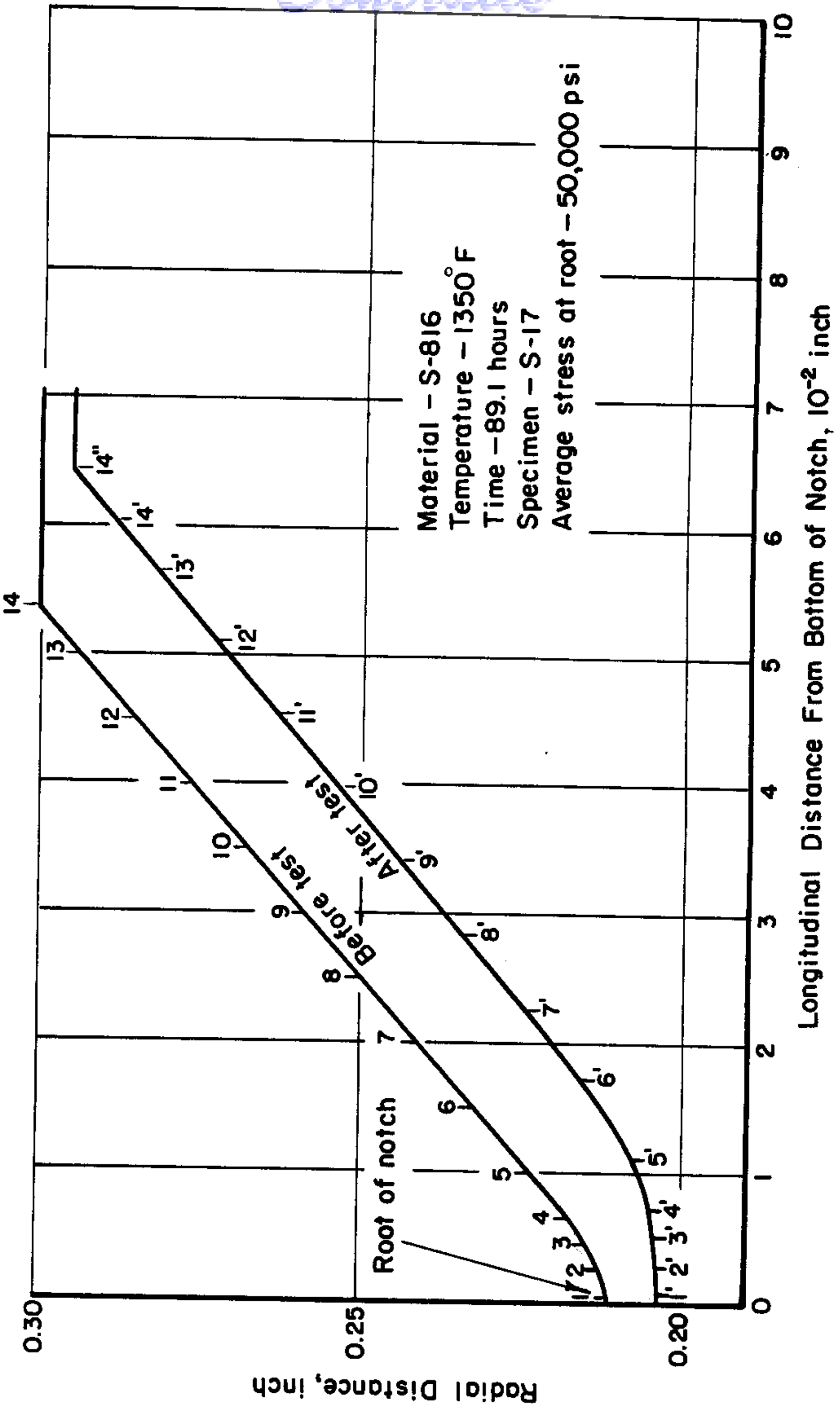

FIGURE 20. UNDEFORMED AND DEFORMED NOTCH CONTOURS FOR 0.005-INCH-RADIUS NOTCH

A-8404

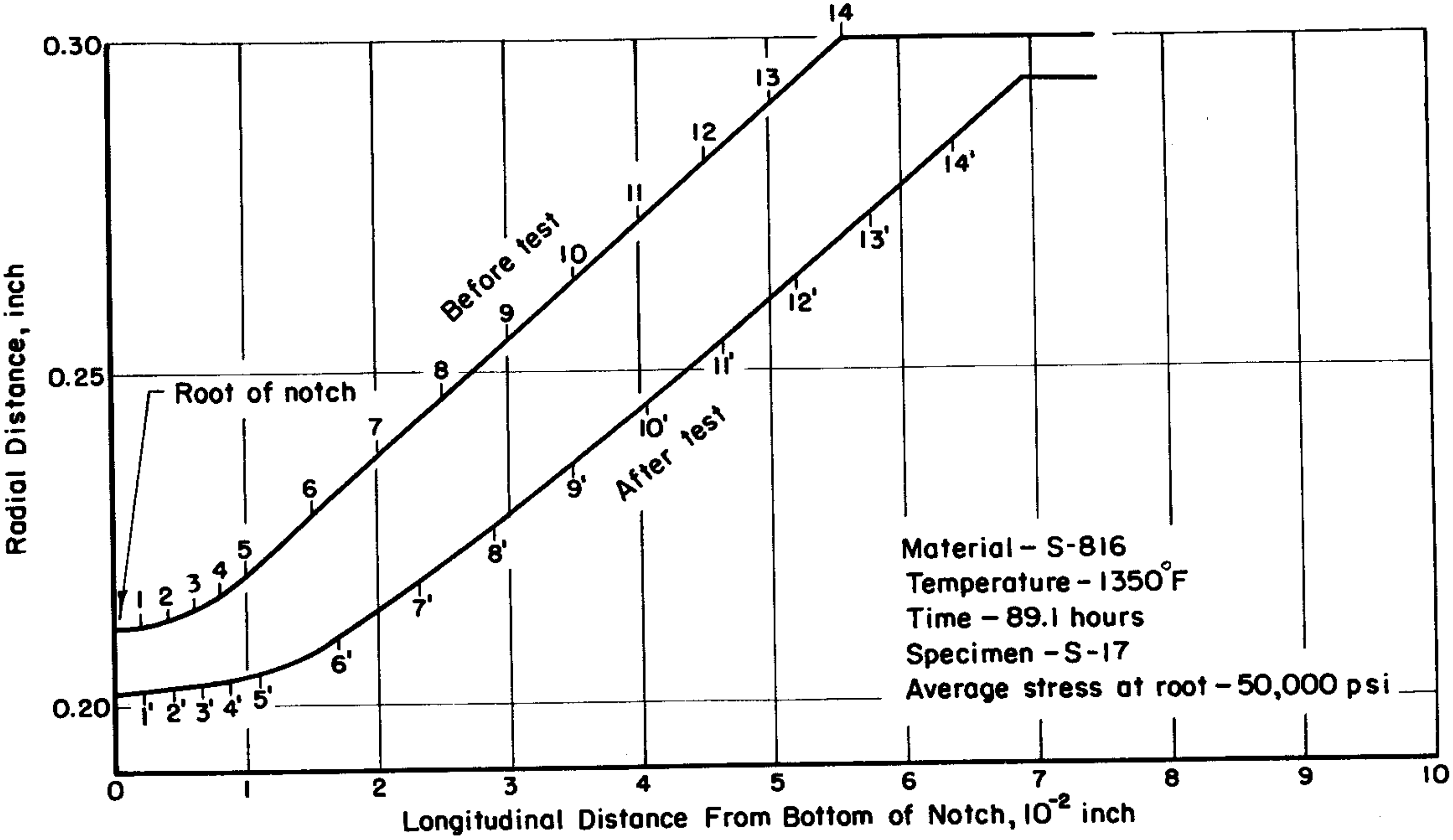

FIGURE 21. UNDEFORMED AND DEFORMED NOTCH CONTOURS FOR 0.010-INCH RADIUS NOTCH

A-8404

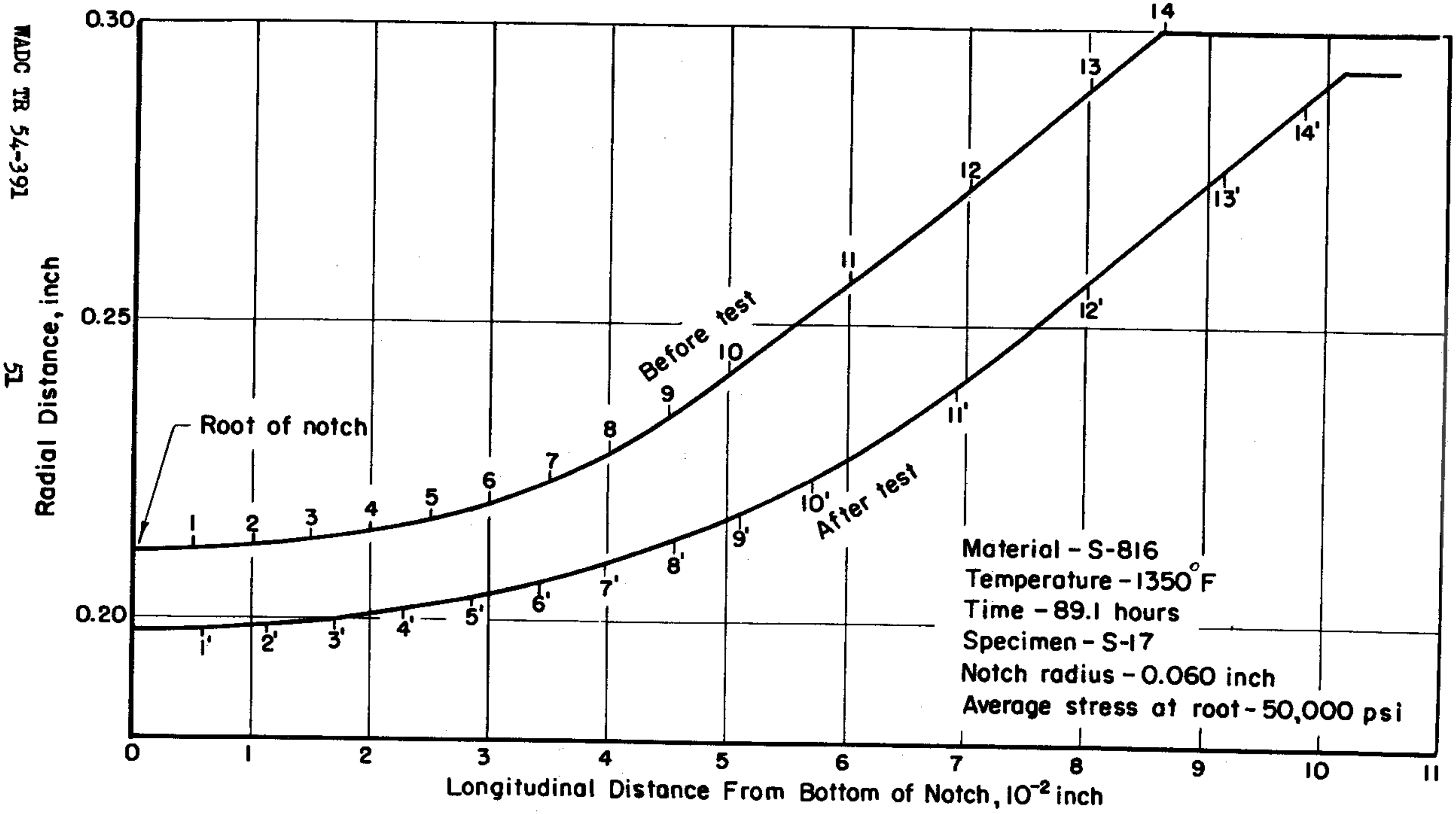

FIGURE 22. UNDEFORMED AND DEFORMED NOTCH CONTOURS FOR 0.060-INCH-RADIUS NOTCH

A-8406

(1) Sections plane and normal to the specimen axis before deformation remain plane and normal.

(2) The volume remains constant.

Although the notch stresses are not uniform, most of the variation that does occur is close to the notch surface. The stress state at interior points in a plane normal to the specimen axis is relatively uniform. It is possible, then, that the first assumption is a fair approximation.

The assumption of constant volume is a good approximation when the elastic strains are small compared with the permanent strains (although an external load does not exist after testing, elastic strains can be retained due to residual stresses). For a relatively ductile material having a large flow capacity, constant volume could be a good assumption. Such an assumption would be better, for example, for a notch-strengthened material than for a notch-sensitive material. The contour measurements included in this report are for S-816, which is notch strengthened for the test condition used.

By using the above assumptions, the locations of Points 1, 2, . . . , n of the undeformed contours of Figures 20, 21, and 22 have been determined for the deformed contour. The notation used indicates that Point 1 has moved to Point 1', Point 2 to Point 2', and so forth.

Inspection of the notches in Figures 20, 21, and 22 reveals that, in each case, there appears to have been a volume increase. It will be remembered that the computation procedure was based on the assumption of constancy of volume (see (1) and (2) above). The computed volumes under the surface contours are equal, for example, up to the points 14 and 14' in Figure 20. It will be noted, however, that whereas point 14 is on a corner, 14' is located down along the contour. Since it would be expected that a "corner" would remain a "corner" during deformation, the point 14' should be at 14" if the volume remained constant. It follows then, that the volume under the surface from 14' to 14" represents a volume increase. In Figure 20, the volume increase is given by the rotation of the arc 14' - 14" about the specimen axis.