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Effect of Notch Geometry and Temperature on the Creep–Rupture Behavior of a Titanium Alloy

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Creep-rupture tests were made on circumferentially notched Ti–8Al–1Mo–1V specimens at temperatures of 600, 800, 1000, and 1200 °F (588, 699, 811, and 921 K) with stresses to produce rupture times ranging from 1 min to several thousand hours. A comprehensive study was made to determine the effects of notch geometry (angle, depth, root radius) on creep, rupture, and ductility characteristics of the alloy. Although a limited first stage and well-defined second and third stages of creep were observed, neither rupture times nor reduction of area values were predictable from extension-time behavior. Rupture time and ductility appeared to be affected more by the initial root radius at the base of the notch than by notch depth. Differences in mechanical behavior between specimens of different notch geometries were less as the temperature was increased or the stress decreased. A limited number of tests indicated that prior strain history had a marked effect on subsequent creep-rupture behavior at 1000 °F.

Relative amounts of alpha and beta constituents, the number of observed internal cracks, and the mode of fracture were affected by notch geometry and test temperatures.

Key words: Creep; elevated temperature; engineering design; notch geometry; stress concentration; stress-rupture; titanium alloy.

1. Introduction

Notch sensitivity of metallic materials is one of the most important factors to be considered in the selection and use of metals in design of engineering components. Notches in metals may, in general, be classified as metallurgical (grain boundaries, precipitates, lattice defects, inclusions, etc.) or geometrical (screw threads, scratches, cracks, dents, etc.). Research at the National Bureau of Standards has been directed towards evaluating the factors influencing the mechanical behavior of metals by using specimens whose notch geometery was known [1, 2, and 3].[1] The majority of the NBS data was obtained from short-time tests at low or elevated temperatures. A number of other researchers have made experiments, designed to evaluate the notch sensitivity of metals in elevated temperature creep-rupture tests, but these have been confined mainly to materials for use in specific products [4]. It is recognized that, at low temperatures, hexagonal close-packed (hcp) metals are less notch sensitive than body-centered cubic (bcc) metals. The phenomenon has been investigated only to a limited extent at elevated temperatures with alloys in which the two structures (hcp and bcc) coexist [4,5]. The purpose of the present research is to study the effects of notch geometry, temperature, and stress on creep behavior, rupture time, ductility, and microstructural changes of a titanium alloy, initially heat-treated to produce an alpha (hcp) and beta (bcc) structure.

[1] Figures in brackets indicate the literature references at the end of this paper.

2. Material, Specimens, and Experimental Procedures

The experimental program consisted of creep-rupture tests at 600, 800, 1000, and 1200 °F (588, 699, 811, and 921 K) on notched cylindrical specimens of a duplex-annealed Ti–8Al–1Mo–1V alloy. This alloy was selected for the research as it is one of the candidate materials for aerospace applications in components used at intermediate temperatures (up to 1000 °F). Furthermore, its short-time tensile notch behavior and long-time creep properties on unnotched cylindrical specimens have been extensively investigated at the National Bureau of Standards [3, 6].

Test specimens were prepared from bars obtained from the same heat of material as that used in the previous investigations. The chemical composition of the alloy is given in table 1.

TABLE 1. *Chemical composition (percentage by weight) of the alloy used* [a]

Titanium	90.4
Aluminum	7.7
Molybdenum	1.0
Vanadium	0.7
Iron	.08
Carbon	.01
Hydrogen	.0094
Oxygen	.0628
Nitrogen	.0022

[a] Analysis made at the National Bureau of Standards.

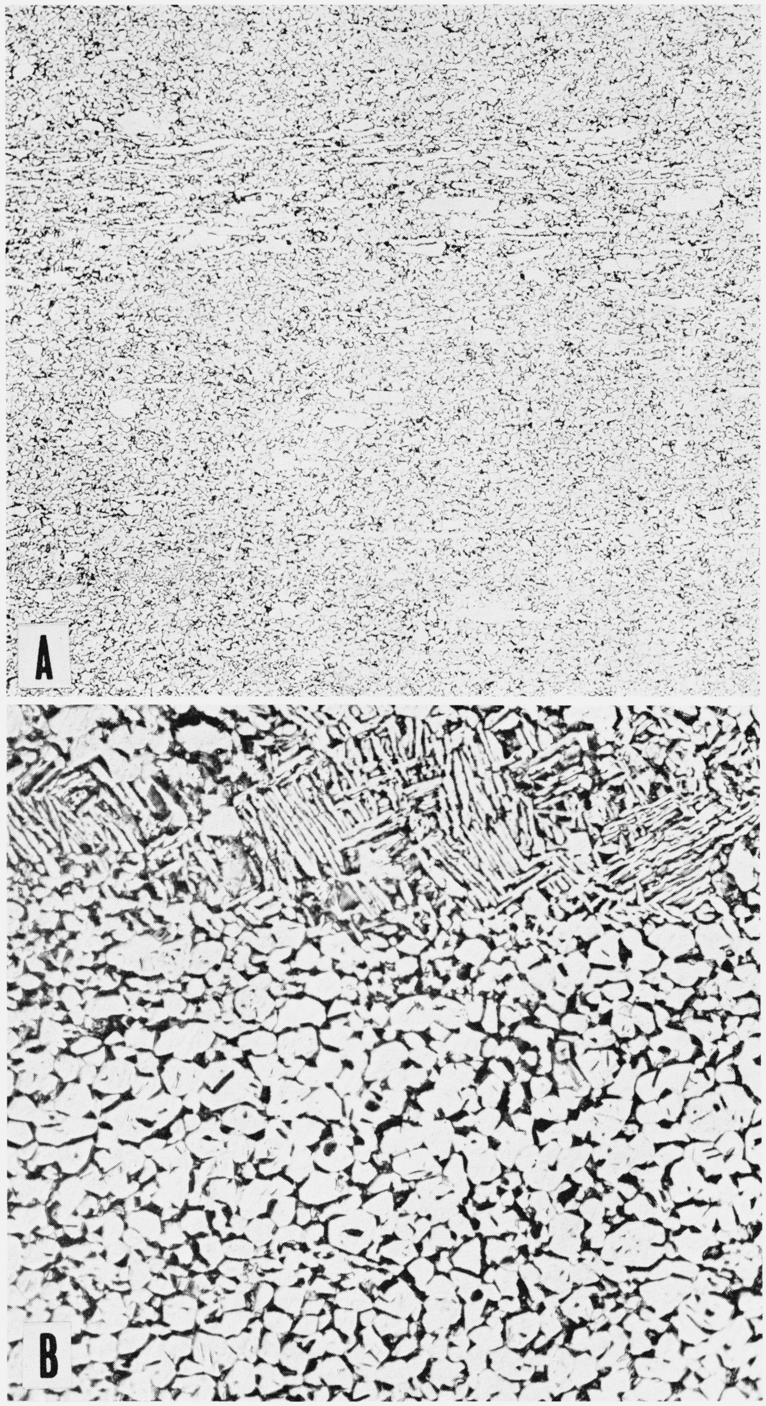


FIGURE 1. *Microstructure of the* Ti–8Al–1Mo–1V *alloy after duplex-annealing.*
Longitudinal sections. Etched in a solution containing 3 ml HF, 6 ml HNO_3, and 100 ml H_2O. A, ×100. B, × 500.

Bars were received in the hot-rolled and annealed condition and were cut into 6.5-in lengths before subsequent annealing at 1750 °F (1226 K) for 1 hr, and air cooling. This was followed by a stabilizing anneal at 1050 °F (838 K) for 8 hr. This heat-treatment was used to cause the coexistence of alpha (hcp) and beta (bcc) structures in the alloy as shown in figure 1. The light areas are alpha and the dark areas are beta.

Each of the specimens had a circumferential V-notch. The notch geometries and elastic stress concentration factors [7] of the specimens are shown in table 2. The minimum diameter of each specimen was 0.357 in.

TABLE 2. *Notch geometry and elastic stress concentration factors of specimens used*

Notch angle	Notch depth [a]	Root radius	Elastic stress concentration factors [b]
deg	%	*in*	
60	70	0.01	4.2
60	50	.01	3.9
60	50	.5	1.1
Unnotched	–	–	1.0

[a] Notch depth $= \frac{D^2 - d^2}{D^2} \times 100\%$

where D = reduced diameter

d = diameter at root of the notch.

[b] Elastic stress concentration factor is equal to the ratio of the maximum normal stress to the nominal normal stress. It is directly proportional to the notch depth and inversely proportional to the notch angle and root radius.

The numerical values for elastic concentration factors were derived from Peterson [7].

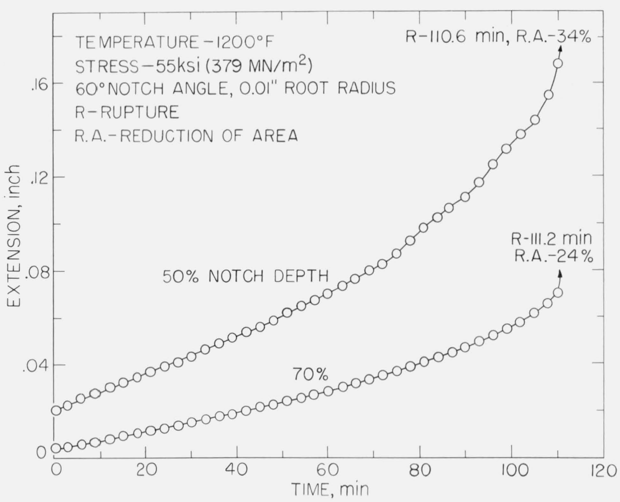


FIGURE 2. *Effect of notch depth on extension-time curves of two specimens tested in creep at 1200 °F (921 K) with a stress of 55 ksi (379 MN/m²).*

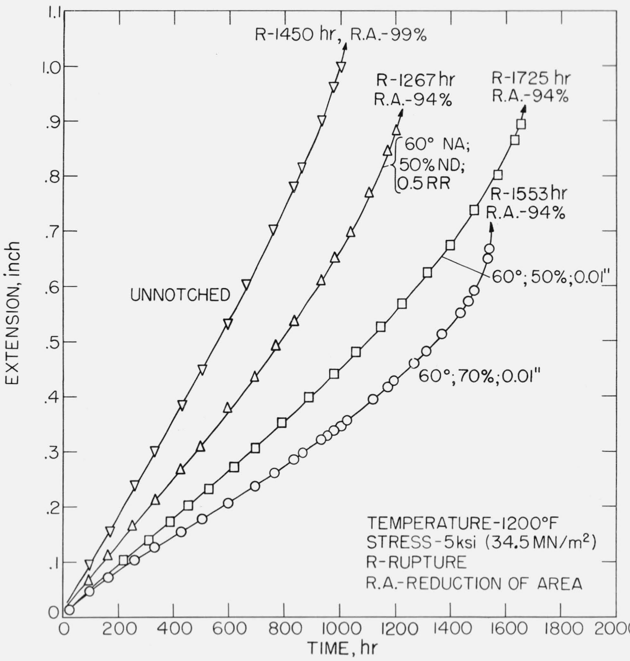


FIGURE 3. *Effect of notch geometry on extension-time curves for specimens tested in creep at 1200 °F (921 K) with a stress of 5 ksi (34.5 MN/m²).*

NA, notch angle in degrees; ***ND***, notch depth in percent; ***RR***, root radius in inches.

Prior to testing, each creep-rupture specimen was heated in air in a tube furnace to the desired temperature and equilibrated at temperature for 16 hr. It was tested at this temperature under constant load in a multi-lever creep-rupture machine equipped with motorized jack to alleviate shock loading. The loading time was 1 to 2 min. Test temperatures were controlled to an accuracy of ± 2 °F. Extension-time data were obtained from electric contact follow-up type extensometers attached to the shoulders of the specimens.

Metallographic examinations were made on selected ruptured specimens to ascertain the effects of notch geometry, temperature, and rupture time on micro- and macrocracking and changes in microstructure.

3. Results and Discussion

Test data obtained in the present investigation are shown in figures 2 through 10. Extension-time curves were constructed for all the specimens tested to complete fracture. It was observed that the curves for the notched specimens had the same general shape as those usually associated with creep of unnotched specimens. Each exhibited first stage (decreasing creep rate), second stage (constant rate), and third stage (increasing rate). The first stage is not evident in figures 2 and 3 as it lasted only a very short time as compared to the total test time. As might be expected for tests run at the same temperature and stress, the total strain decreased with increase in notch depth and decrease in root radius. However, as indicated in figures 2 and 3, rupture times and reduction of area values could not be predicted from strain-time data.

A number of investigators [4] have predicted that a linear relation exists between stress-rupture time, stress-log rupture time, or log stress-log rupture time. Data obtained in the present investigation were plotted in each manner, and linear relations were observed only over limited ranges of stresses at each temperature except 600 °F. At this temperature, little or no creep was apparent even at stresses in excess of 95 percent of the short-time tensile strength. Difference in behavior may be due in part to (1) the relaxation of stress concentration at the root radius of the notch as a result of plastic yielding, (2) time at temperature, (3) formation of a compound such as Ti_3Al, or (4) the healing of internal voids. Stress-log rupture time curves for some of the Ti–8Al–1Mo–1V specimens are shown in figure 4. In general, the relative positions of the curves are affected by notch geometry more at low temperatures and high stresses than at high temperatures and low stresses. For example, at 1200 °F and very low stresses, notch geometry appeared to have no effect on the stress-rupture time relations. At 800 °F, an inflection point must occur at stresses below those used in these tests or the stress could be zero for extremely long rupture times. Conversely, at 1200 °F, an inflection point must occur for stresses higher than those shown in figure 4. At 1000 ° F, the inflection points are clearly shown, and the time of their occurrence appears to be affected by notch geometry.

According to elastic theory, root radius has a more dominating influence on the stress concentration at the base of the notch than does the notch depth. The influence of each of these variables on rupture times at different stresses is shown in figures 5 and 6 for the present tests. Although no exact equivalence between notch depth and root radius could be established for the specimens (table 2), each of these variables had a marked effect on the rupture behavior. The effect of each is more apparent at the low temperatures and high stresses than at the high temperatures and low stresses.

Engineering design curves, showing stress-temperature relations to produce rupture of the specimens in 1, 10, 100, and 1000 hr, are presented in figure 7. Within the range of temperatures used in the tests, no inflection points are evident in the 1-hr and 10-hr curves (figs. 7A and 7B). Obviously, these points must occur at higher values of temperature than those used in this investigation or the specimens would have to rupture in 1 or 10 hr at zero stress. As indicated in figures 7C and 7D, the

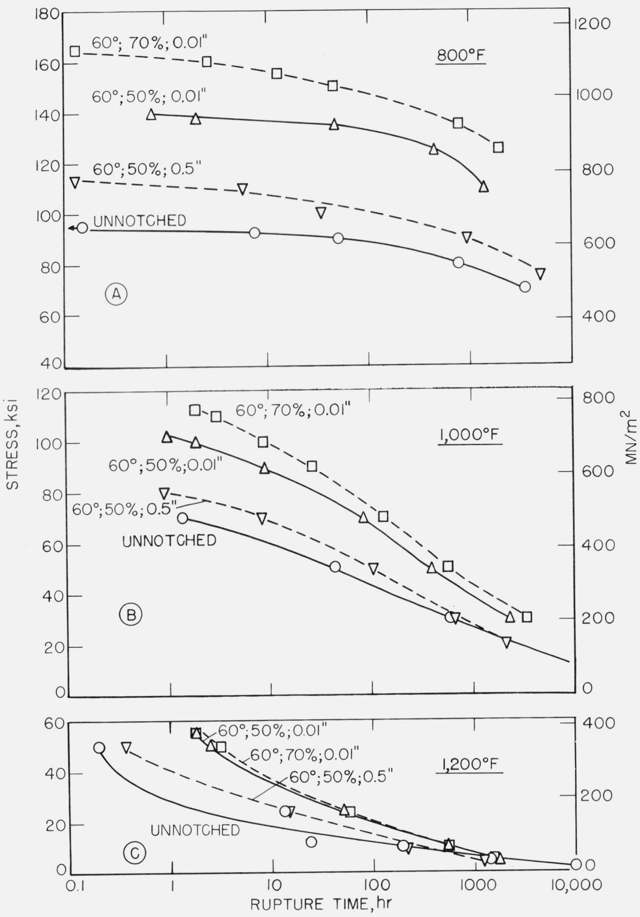
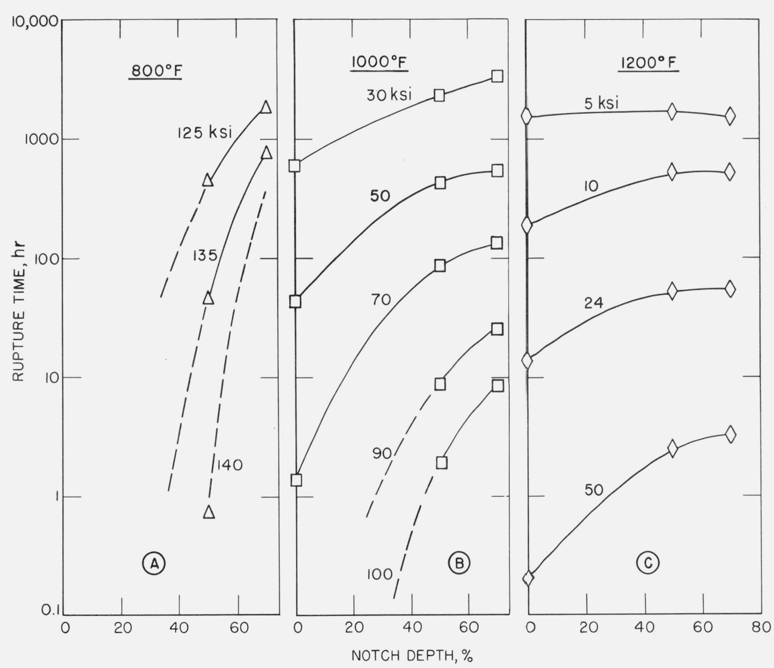


FIGURE 4. *Effect of notch geometry on stress-rupture time relations for specimens tested at 800, 1000, and 1200 °F (699, 811, and 921 K).*

Numbers adjacent to curves indicate notch angle in degrees, notch depth in per cent, and root radius in inches.

FIGURE 5. *Effect of notch depth on rupture time of specimens tested at different temperatures and with different stresses.*

Dashed curves indicate extrapolated data. Zero notch depth indicates unnotched specimens. Notched specimens have 60° notch angle and 0.01 in root radius.



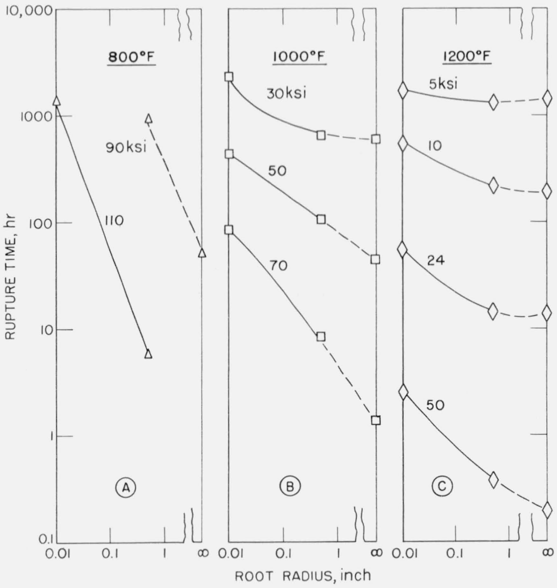


FIGURE 6. *Effect of root radius on rupture time of specimens tested at different temperatures and with different stresses.*

Infinite root radius indicates unnotched specimens. Notched specimens have 60° notch angle and 50 percent notch depth.

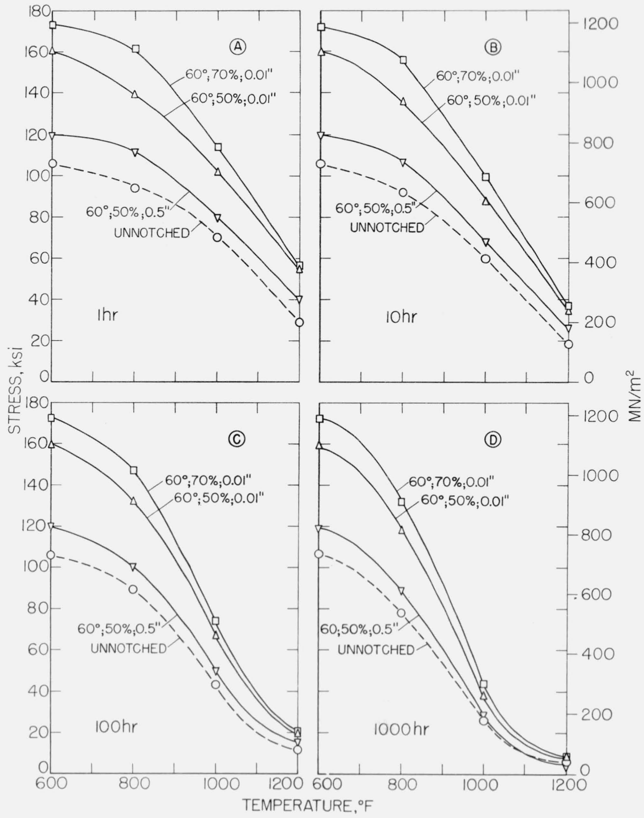


FIGURE 7. *Variation of stress with temperature required to cause rupture at various times, of specimens with different notch geometries.*

Numbers adjacent to curves indicate notch angle in degrees, notch depth in percent, and root radius in inches.

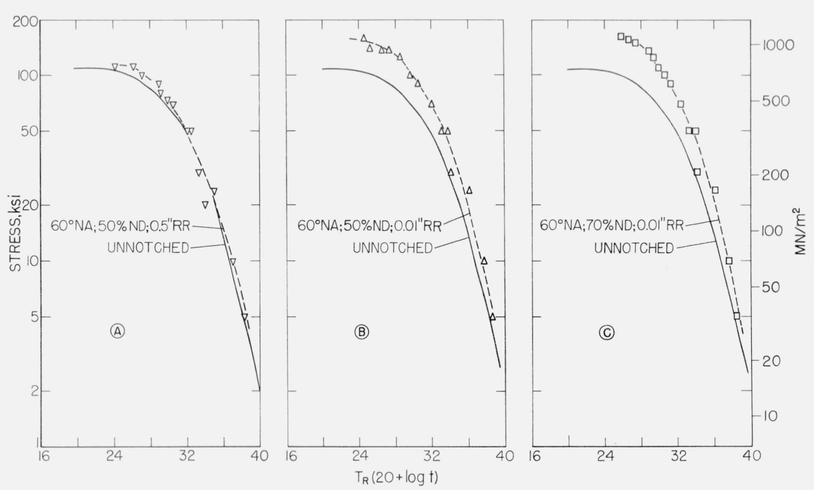


FIGURE 8. *Relation between stress and a temperature-time parameter for specimens having various notch geometries.*

Numbers adjacent to curves indicate notch angle in degrees, notch depth in percent, and root radius in inches.

T_R = temperature in degrees Rankine divided by 1000.

t = rupture time in hours.

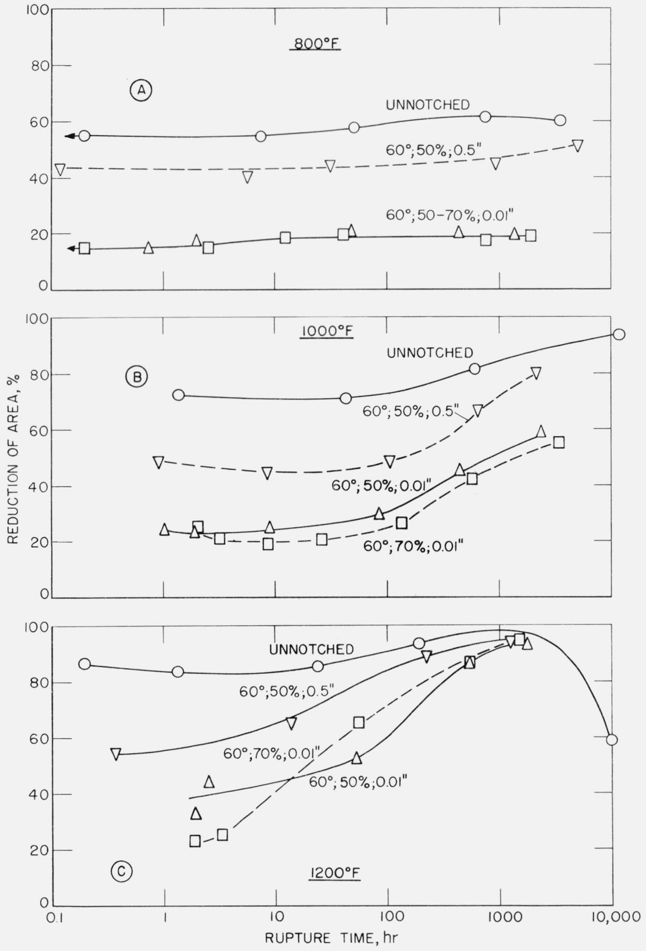


FIGURE 9. *Relation between rupture time and reduction of area values for specimens having various notch geometries and tested at 800, 1000, and 1200 °F (699, 811, and 921 K).*

Numbers adjacent to curves indicate notch angle in degrees, notch depth in percent, and root radius in inches.

occurrence of these inflection points is affected both by notch geometry and test time.

A number of "parametric" expressions have been developed to evaluate creep-rupture data for specific materials over wide ranges of stresses and temperatures [4]. It was previously shown that creep data for the unnotched specimens of this Ti–8Al–1Mo–1V alloy [6] could be described by a single curve. The time-temperature parameter used was derived by Larson and Miller [8]. As shown in figure 8 for the present tests, a single curve can also describe stress-"parameter" relations for each group of notched specimens; however, no simple translation was available to cause all the curves to coincide. The difference in the shape of these curves from those previously shown [6] is due to the fact that the stress values in figure 8 are plotted on a log instead of a linear basis. This method of analysis is recommended for comparing and storing engineering data obtained over wide ranges of test conditions, even though the theoretical significance of the relations is suspect.

The relation between reduction of area values and rupture-time is shown in figure 9. Rupture time had little or no effect on ductility, as defined by reduction of area values, at 800 °F (fig. 9A), whereas a large effect was observed at 1000 and 1200 °F (figs. 9B and 9C). Although, at the latter two temperatures, the ductility appeared to increase with increase in rupture time, inflection points and a reversal in one ductility-time curve are shown. One point at 1200 °F and 1450 hr was omitted for the unnotched curve as it nearly coincided with the notched data. These indicate the possibility of a change in the mode of deformation. Introduction of a notch tended to lower reduction of area values below those of the unnotched specimens. Moreover, decreasing the root radius caused the reduction of area values to decrease even more. However, increasing the notch depth from 50 to 70 percent had little effect on reduction of area.

The influence of prior thermal-strain history on creep-rupture behavior of specimens tested at 1000 °F with a stress of 30 ksi (207 MN/m^2) is shown in figure 10. Although the number of tests are limited, several general observations can be made concerning the effect of prestraining. (1) The rate of extension is significantly changed from that of the unstrained material. (2) Reduction of area values were not seriously affected. (3) Rupture times were decreased by prestraining at temperatures above and below 1000 °F. (4) Prestraining at 1200 °F relieved the stress at the root of the notch to such an extent that the rupture time was increased above that of the metal strained at 800 °F (curves 10B and 10C). This occurred even though the amount of prestraining at 1200 °F was greater than that at 800 °F.

4. Metallography

Metallographic examinations were made on a number of selected specimens after rupturing in creep. Little or no difference in microstructure from that observed in short-time tensile tests [3] was apparent for specimens tested at 600 or 800 °F. This was not totally unexpected since it was indicated, in figure 9 of the present paper, that the reduction of area values for specimens tested at 800 °F were independent of rupture time. Photomicrographs of several specimens tested to rupture at 1000 and 1200 °F are shown in figures 11 through 14. Specimens, shown in figures 11 and 12, were lightly etched to remove any surface effects due to metallographic preparation of the samples. At 1000 °F, increasing the root radius from 0.01-in (figs. 11A and 11B) to 0.5-in (fig. 12A) tended to cause an increase in the number of internal cracks that did not link up to become a part of the main fracture surface. At 1200 °F, however, no significant differences in the number of internal cracks were observed for the specimens even though the increase in elastic stress concentration factor (from 1.1 to 3.9) appeared to cause an increase in the tendency toward surface cracking (figs. 11C and 11D and 12B, 12C, and 12D). Increasing the temperature from 1000 to 1200 °F increased the number and size of cracks in regions away from complete fracture. However, the relation between the number or size of cracks and test time was different at 1000 from that at 1200 °F. At 1000 °F, tendency to form

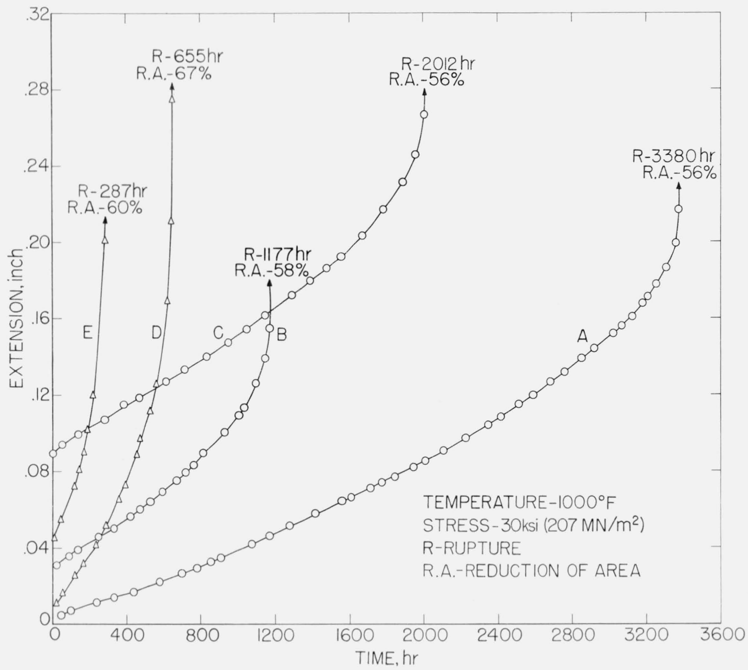


FIGURE 10. *Effect of prior thermal-strain history on extension-time relations of specimens tested at 1000 °F with a stress of 30 ksi (207 MN/m^2).*

Curve	Notch angle	Notch depth	Root radius	Prestrain Temp.	Prestrain Time
	deg	*%*	*in*	° F	*hr*
A	60	70	0.01	None	None
B	60	70	.01	800	2350
C	60	70	.01	1200	403
D	60	50	.5	None	None
E	60	50	.5	800	1539

cracks increased with increase in test time (figs. 11A and 11B) while at 1200 °F the opposite was observed (figs. 11C and 11D).

In order to find a solution to some of the anomalies associated with the previous observations, a metallographic examination was made by deep-etching the specimens (figs. 13 and 14), and attempts were made to relate changes in microstructure to changes in mechanical behavior and fracture characteristics of the alloy. Previously, it has been shown that at high temperatures in short-time tensile tests [3] and in some creep tests made by Soltis [9] on another similar alloy that voids could be initiated at alpha boundaries in the vicinty of beta particles. In addition, Seagle and Bartlo [10] have indicated that an intermediate ordered phase (Ti_3Al) can form in titanium alloys containing 5 percent or more of aluminum at temperatures less than 1300 to 1500 °F. They also showed that elongation and short-time tensile strength increased with decrease in cooling rate. As shown in figure 13A for a short-time creep-rupture test, the microstructure appeared to be nearly unchanged from the starting material (fig. 1). Apparently, as the test time was increased, recovery caused a weakening of the grain boundaries and a reduction in the number of beta particles located at the alpha grain boundaries (figs. 13B and 14B). Good ductility, associated with these specimens, can be attributed to relief of stress by plastic deformation at the root of the notches. The presence of some beta and weakening of the grain boundaries could contribute to the increase in the number of internal cracks, previously shown in figures 11 and 12, as the test time was increased. Microstructures of specimens tested at 1200 °F also indicated that the amount of beta decreased as the test time increased (figs. 13C and 13D and 14B, 14C, and 14D). Apparently, an additional reaction also occurs and results in the formation of a new phase (possibly Ti_3Al) at this temperature. The relative amounts of this phase increased with increase in test time and with increase in root radius at the base of the notch (figs. 13 and 14). Decrease in beta and increase in the amount of this new constituent could contribute to increased ductility, a decrease in the number of internal cracks, and the presence of inflection points in the stress-temperature curves.

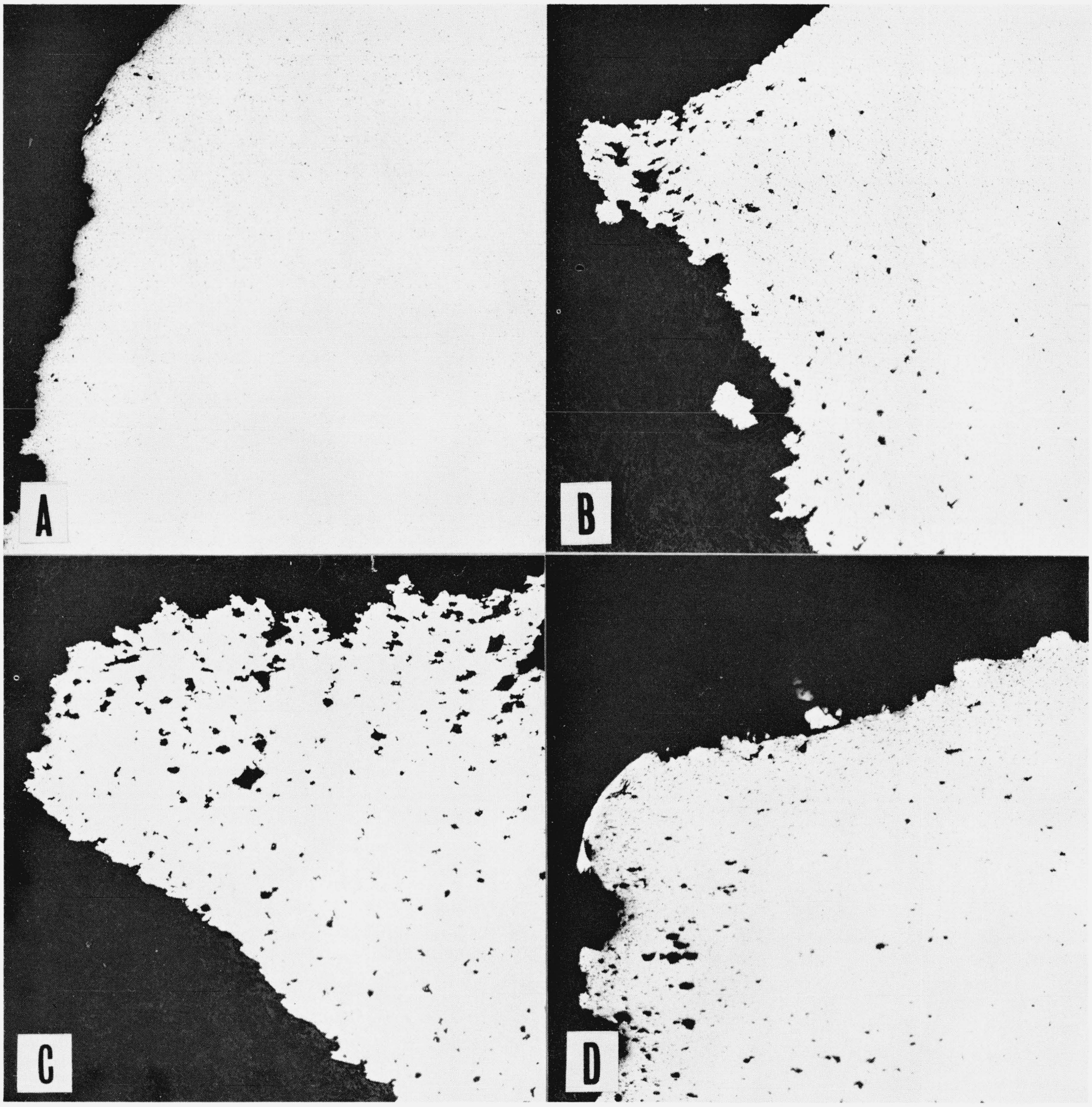


FIGURE 11. *Photomicrographs of sections of fractured specimens after testing to complete rupture in creep.*
Initial notch geometry—60° notch angle, 50 percent notch depth, and 0.01-in root radius. Longitudinal sections near outer surface near fracture, Lightly etched in a solution containing 1.5 ml HF, 3.5 ml HNO_3, and 95 ml H_2O. × 40.

Specimen	Test		Reduction of area
	Temperature	Time	
	° F	*hr*	%
A	1000	9	24
B	1000	2311	58
C	1200	52.5	52
D	1200	1725	94

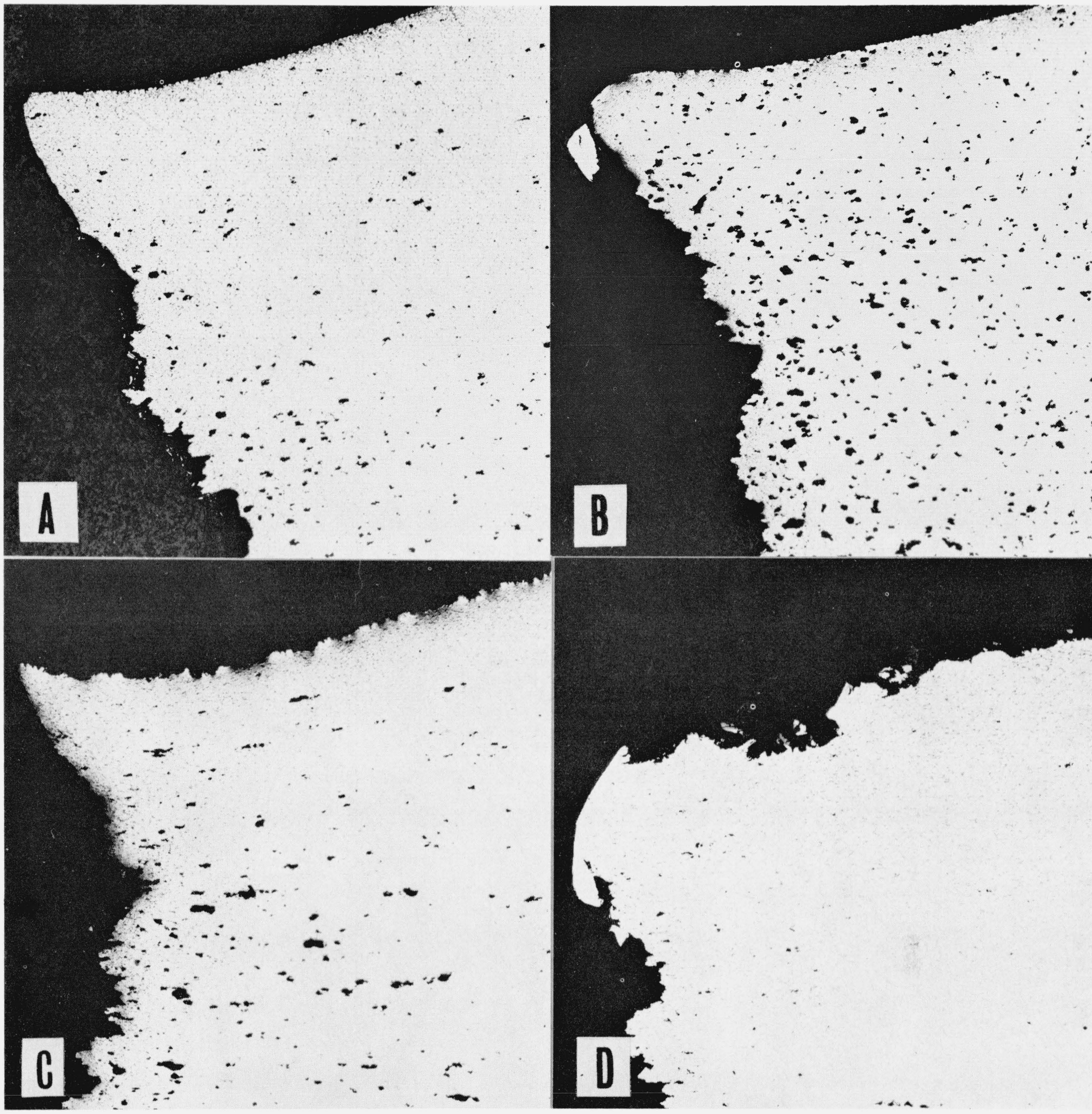


FIGURE 12. *Photomicrographs of sections of fractured specimens after testing to complete rupture in creep.*
Initial notch geometry—60° notch angle, 50 percent notch depth, and 0.5-in root radius. Longitudinal sections near outer surface near fracture. Lightly etched in a solution containing 1.5 ml HF, 3.5 ml HNO_3, and 95 ml H_2O. × 40.

Specimen	Test		Reduction of area
	Temperature	Time	
	° F	*hr*	%
A	1000	655	67
B	1200	14	65
C	1200	222	89
D	1200	1267	94

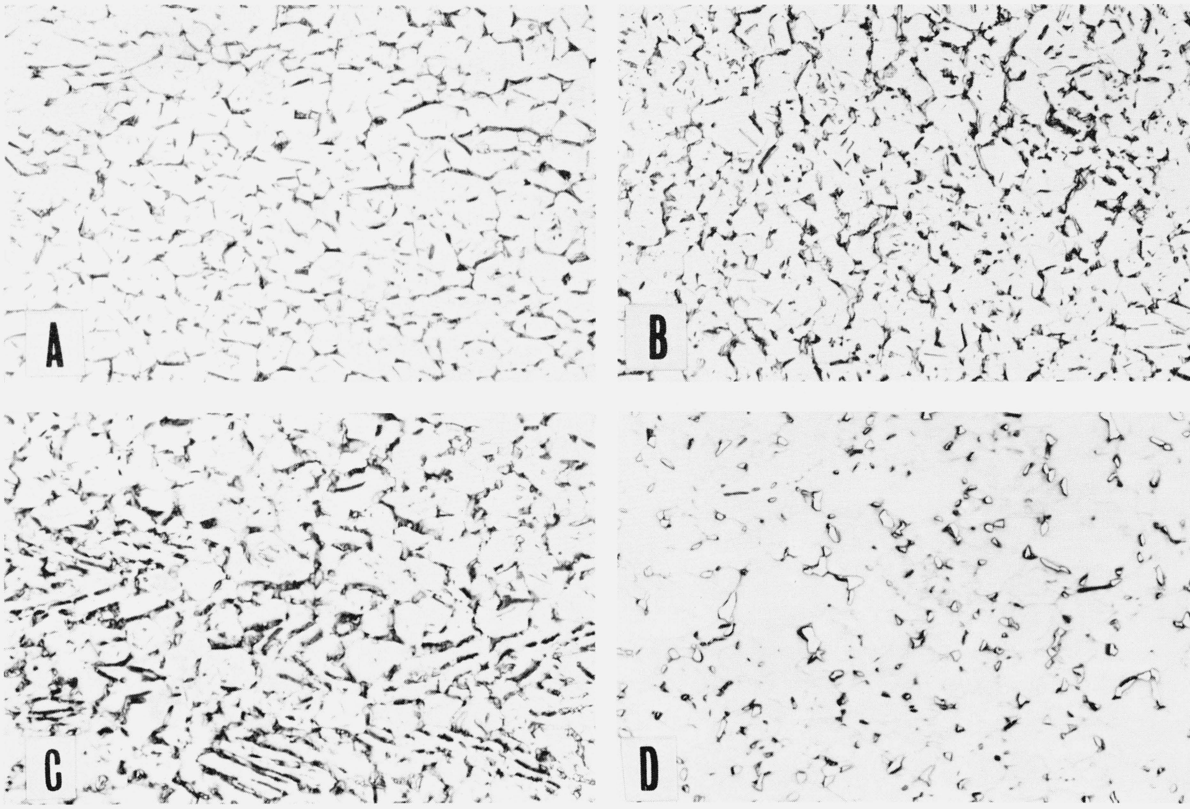


FIGURE 13. *Photomicrographs of sections of fractured specimens after testing to complete rupture in creep.*
Initial notch geometry—60° notch angle, 50 percent notch depth, 0.01-in root radius. Longitudinal sections near axis, 0.1 in from fracture. Etched in a solution containing 3 ml HF, 6 ml HNO_3, and 100 ml H_2O. × 500.

Specimen	Test		Reduction of Area
	Temperature	Time	
	° F	*hr*	%
A	1000	9	24
B	1000	2311	58
C	1200	52.5	52
D	1200	1725	94

5. Summary

A. Creep-rupture tests were made to determine the effects of notch geometry on the creep-rupture behavior of duplex-annealed Ti–8Al–1Mo–1V alloy at temperatures of 600, 800, 1000, and 1200 °F (588, 699, 811, and 921 K).

B. When specimens were tested at the same temperature and stress, the total extension at any given time decreased with increase in notch depth and with decrease in root radius. However, no accurate predictions of rupture time or reduction of area values could be made on the basis of extension-time data.

C. The slopes of the stress-log rupture time curves decreased with decrease in stress at 800 °F, whereas the opposite behavior was observed at 1200 °F. At 1000 °F, inflection points in the curves were observed at intermediate stresses.

D. At constant load, rupture times generally increased with increase in notch depth and decrease in root radius. This phenomenon was more apparent at high stresses and low temperature than at low stresses and high temperatures.

E. The elastic stress concentration factor was a consistent index for predicting rupture times.

F. The shape of the "engineering design" curves indicate that extrapolations should not be made to temperatures higher than those used in determining stress-temperature relations.

G. A single curve was used to describe the stress temperature, rupture-time relations for each group of specimens having the same notch geometry. However, no single curve could describe all the data.

H. With few exceptions, reduction of area values increased with increase in temperature and decrease in elastic stress concentration factor.

I. Creep-rupture behavior was markedly affected by prior strain history.

J. Microstructures of specimens after fracture were greatly influenced by initial notch geometry and test conditions. Decrease in the amounts of beta structure and the formation of a compound (probably Ti_3Al) was evident in microstructures of specimens tested at 1200 °F. The amount of the compound increased and the number of internal cracks decreased as the rupture time increased.

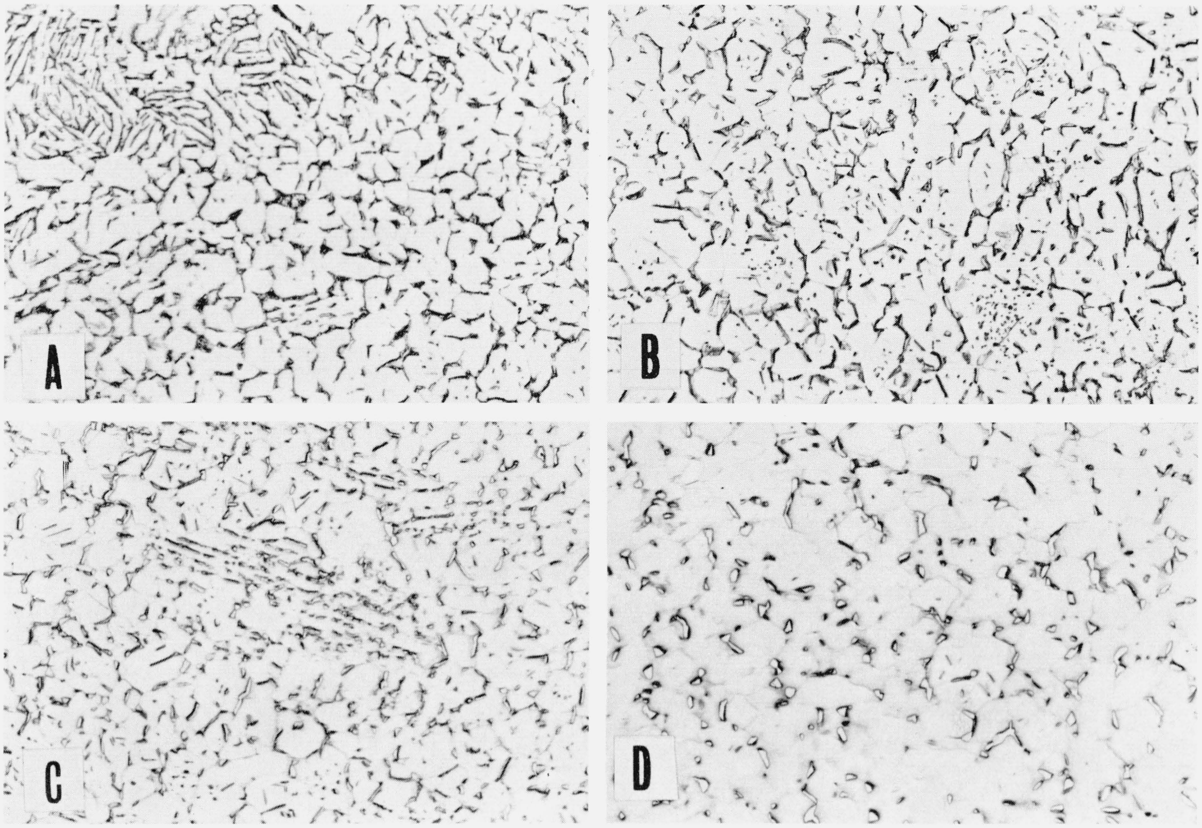


FIGURE 14. *Photomicrographs of sections of fractured specimens after testing to complete rupture in creep.*
Initial notch geometry—60° notch angle, 50 percent notch depth, 0.5-in root radius. Longitudinal sections near axis, 0.1 in from fracture. Etched in a solution containing 3 ml HF, 6 ml HNO_3, and 100 ml H_2O. × 500.

Specimen	Test		Reduction of area
	Temperature	Time	
	°F	*hr*	%
A	1000	655	67
B	1200	14	65
C	1200	222	89
D	1200	1267	94

The authors gratefully acknowledge the helpful discussions with G. W. Geil and the excellent technical assistance of D. E. Harne and L. C. Smith during this investigation.

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