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The Effect of a "V" Notch on the Tensile Creep Behavior of Cr-Mo Steel

The effect of a "V" notch on the tensile creep behavior of Cr-Mo steel at elevated temperature was studied to elucidate the reasons for notch strengthening or notch weakening. Special attention was paid to changes in notch profile and dimensions, as well as to structural changes of the notched portion of the specimens with the lapse of time up to rupture.

Some interesting results were obtained which are different from those of an ordinary tensile test or a creep test on smooth bars, and which are useful to the complete analysis of the stress distribution at the notch-root section of the notched specimens at any time after loading and, in turn, to clarify reasons for notch strengthening.

Introduction

There is considerable information on the relative creep-rupture strength of notched and unnotched specimens in the literature on mechanical testing [1, 2],[1] but the reasons for notch strengthening or notch weakening have not yet been made clear, at least quantitatively, because of the complexity of those phenomena.

To elucidate the reasons, it is of utmost necessity to analyze the stress distribution at the notch-root section of the specimens. Besides general equations for such things as equilibrium of forces, compatibility of strains, constancy of volume in plastic deformations, and for creep deformations under triaxial stresses [3], some experimental relationships concerning the profile and dimension changes and the microstructure of the specimen at the notched part must be included for a complete interpretation of the problem in question. In this connection, the authors followed the change in notch profile and dimensions, as well as the structural change of the notched part, for specimens during their creep deformation up to rupture, taking the behavior of 5 Cr-0.5 Mo steel as an example.

Materials and Specimens

Three kinds of specimens were prepared (single-notched, double-notched, and smooth bars) as illustrated in Fig. 1. The latter two types of specimen were used only for comparison with the first.

All the specimens were made by tool-cutting rods of $^3/_4$-in. diameter rolled from the same ingot of 5 Cr-0.5 Mo steel with the following chemical composition:

C 0.15%, Si 0.25%, Mn 0.45%, P 0.013%, S 0.007%,
Cr 5.27%, M 0.59%

The notched part was then finished by a grinder with special accuracy and its profile and dimensions were examined by a shadowgraph, enlarging to the 50× scale.

With regard to heat-treatment, the specimens were first annealed at 900 deg C for one hour before machining and then vacuum annealed at the same temperature for 30 minutes after machining and grinding.

Experimental Results and Discussion

Stress-Rupture Curves. Creep-rupture tests were carried out on the above-mentioned specimens of three kinds, under several nominal stresses (12–29 kg/mm^2) at a temperature of 600 deg C.

All the test results are shown in Fig. 2 as stress-rupture curves. Under the conditions of the present tests, the figure shows that both the single-notched and the double-notched specimens are much stronger than the unnotched bars. In other words, they are all notch strengthened.

Furthermore, it is obvious that the nominal elongations of the single-notched and the double-notched specimens are much smaller than those of the unnotched bars and that the smallest in elongation are the double-notched specimens.

But, if we notice the local elongation at the notch-root section of the specimens, i.e.,

Nomenclature

a = radius of a specimen at the notch-root section, at any time t (Fig. 15)
a_0 = initial radius of a specimen at the notch-root section
r = distance from the axis of a specimen at the notch-root section, at any time t (Fig. 15)
r_0 = initial distance from the axis of a specimen at the notch-root section
R = notch radius of a specimen at any time t (Fig. 15)
R_0 = initial notch radius of a specimen
ρ = radius of curvature of an intermediate trajectory of the principal stresses, at any time t (Fig. 15)
ρ_0 = initial radius of curvature of an intermediate trajectory of the principal stresses
A = sectional area of a specimen at the root of the notch, at any time t
$= \pi a^2$
A_0 = initial sectional area of a specimen at the root of the notch
$= \pi a_0^2$
P = axial tensile force
$\sigma_r, \sigma_t, \sigma_z$ = radial, tangential, and axial stress, respectively, at any time t
$\bar{\sigma}_z$ = average axial stress
$\epsilon_r, \epsilon_t, \epsilon_z$ = radial, tangential, and axial natural strain, respectively, at any time t
$\epsilon_r'', \epsilon_t'', \epsilon_z''$ = radial, tangential, and axial natural creep-strain, respectively, at any time t

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[1] Numbers in brackets designate References at end of paper.

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$$\bar{\epsilon}_z'' = \ln\left(\frac{A_0}{A}\right) = 2\ln\left(\frac{a_0}{a}\right) \qquad (1)$$

it must be recognized that all the notched specimens of both kinds were locally stretched to a considerable degree. This also suggests that they were all ductile-fractured.

Change of Profile and Dimensions of the Necked Part of the Specimens With the Lapse of Time. The relation between a/R and $\bar{\epsilon}_z''$ or $\ln(A_0/A)$ obtained in a creep-rupture test on the unnotched bars, which denotes a characteristic feature of the progress of necking, represents almost the same trend as in an ordinary tensile test on such specimens [4–7].

On the contrary, in the case of the single-notched specimens, the notch radius R increases with the lapse of time or the progress of necking, while the notch-root diameter decreases. As a result, a/R decreases markedly as the necking goes on. This is the most remarkable feature in the necking of the notched specimens.

Fig. 3 represents these opposite trends in the curves of a/R versus $\bar{\epsilon}_z''$. In Figs. 4–7, some results concerning the change of profile and dimensions of a single-notched specimen, which fractured at 15.8 hours after loading under the stress of 22 kg/mm² and the temperature of 600 deg C, are also represented in detail.

Fig. 7 shows that the well-known relation [4] obtained in the case of smooth bars

$$\frac{\rho}{R} = \frac{a}{r} \qquad (2)$$

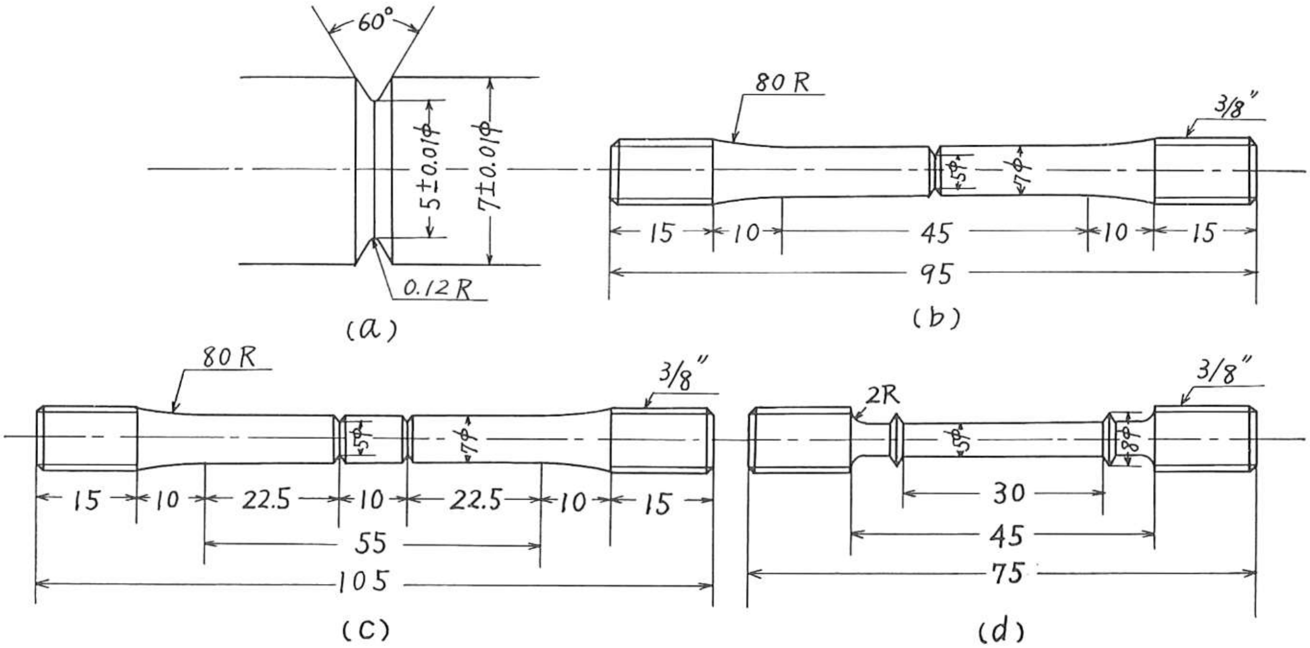


Fig. 1 Three kinds of specimens

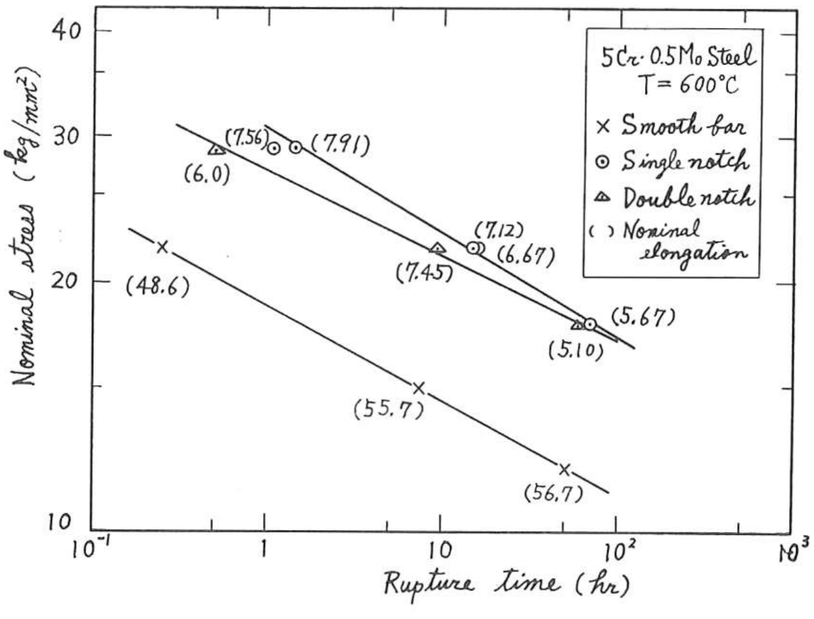


Fig. 2 Stress-rupture curves for notched and unnotched specimens of 5 Cr-0.5 Mo steel at 600 deg C

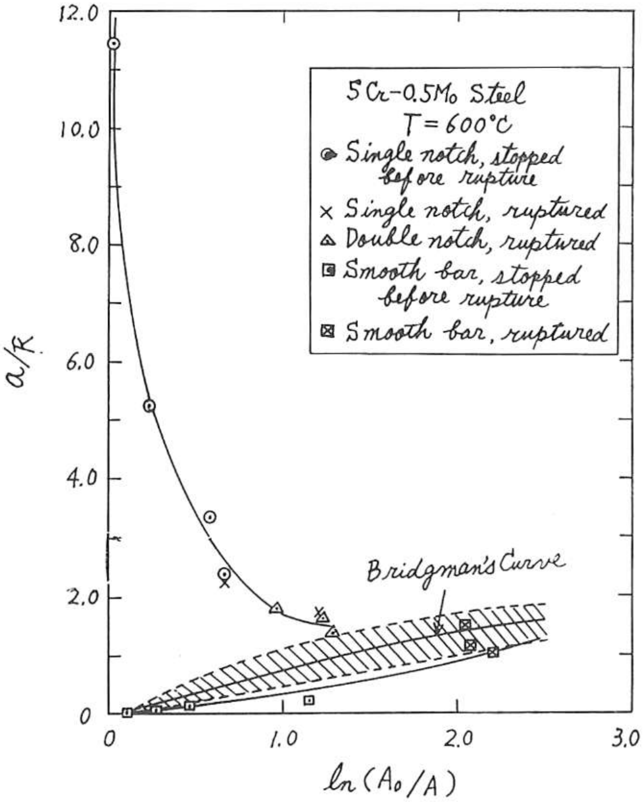
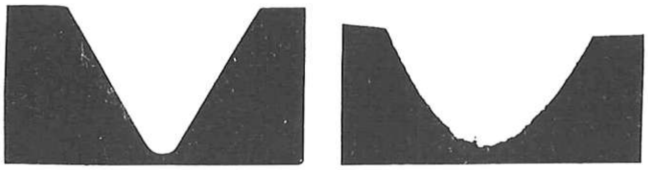


Fig. 3 Relation between a/R and $\bar{\epsilon}_z$



(*a*) Before testing (*b*) After rupture

Fig. 4 Change in profiles and dimensions of a specimen before testing and after rupture

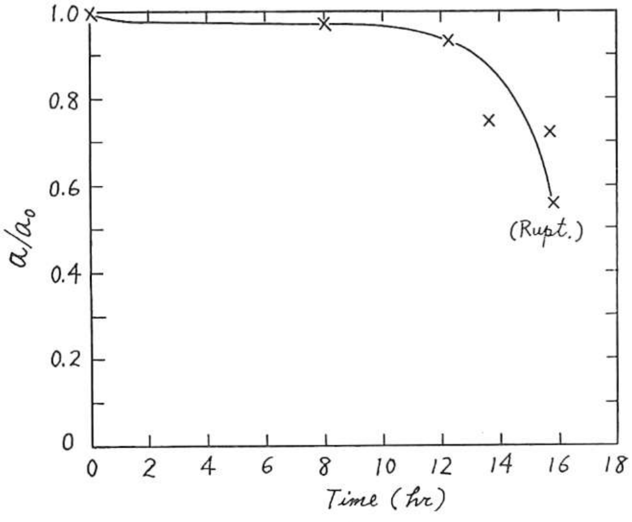


Fig. 5 Relation between a/a_0 and elapsed time t

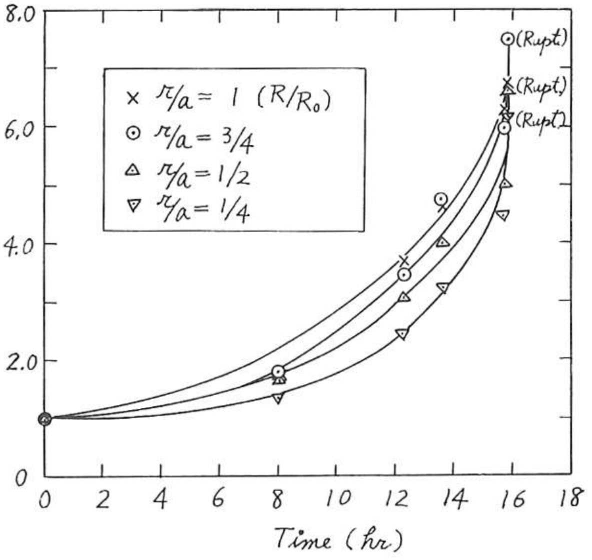


Fig. 6 Relation between ρ/ρ_0 and elapsed time t

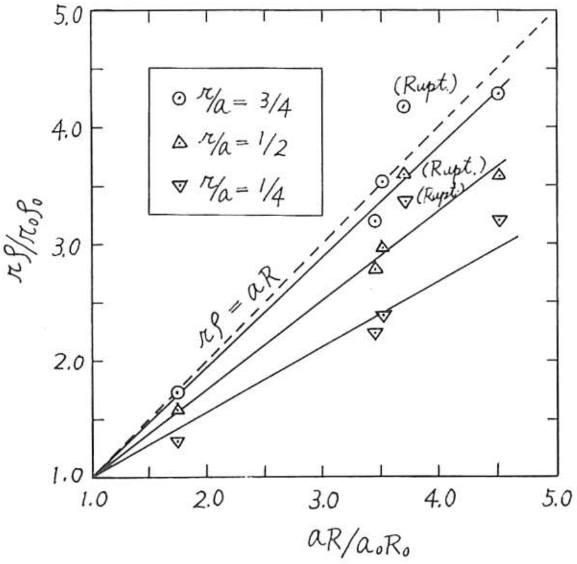


Fig. 7 Relation between $r\rho/r_0\rho_0$ and aR/a_0R_0

does not hold for the single-notched specimens, and the following relations must hold:

$$\frac{r\rho}{r_0\rho_0} - 1 = \left(\frac{r}{a}\right)^{0.4}\left[\frac{aR}{a_0R_0} - 1\right] \qquad (3)$$

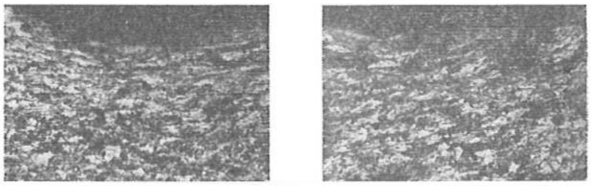
or

$$\frac{\rho}{R} = \left(\frac{a}{r}\right)^{m} \qquad (4)$$

where $m = 0.73 - 0.78 < 1$

Structural Change of the Necked Part of the Specimens With the Lapse of Time. Fig. 8(a–c) represents the longitudinal microstructures (at times of 12.25, 13.6, and 15.7 hours after loading, respectively) for the notched part of a specimen which broke at 15.8 hr under a stress of 22 kg/mm² and a temperature of 600 deg C.

With these photographs and profile-change diagrams of Figs. 5 and 6, we can easily recognize the fact that the structural change has already occurred considerably in the first part of the third stage of creep; that is, the notch-root and its vicinity are strongly



(a) Earlier middle part of the third stage

(b) Middle part of the third stage

(c) End part of the third stage

Fig. 8 Longitudinal microstructures of a rupture specimen at the notched part

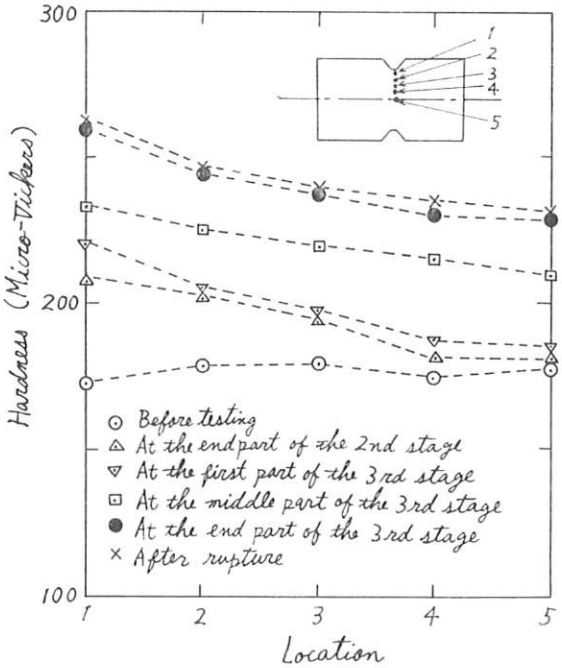


Fig. 9 Change in hardness due to stretching (notched specimen)

stretched to the fibrous structure, even accompanied by some cracks, while the central part far from the notch-root does not undergo such severe stretching. Also, we are sure to recognize that the stretching becomes more and more marked with an increase in the number of cracks and in their size as the deformation goes on to rupture.

Furthermore, these matters are quantitatively illustrated in Fig. 9, as a relationship between micro-Vickers hardness and the locations measured. (Compare to Fig. 10 for a smooth bar.)

Davidenkov and Spiridonova [5] demonstrated in an ordinary tensile test on smooth bars, by microscopic inspection of the specimens, that the strain in the grains in the radial and tangential directions is practically the same and, therefore, the corresponding stresses are also equal. Namely,

$$\epsilon_r = \epsilon_t$$

and (5)

$$\sigma_r = \sigma_t$$

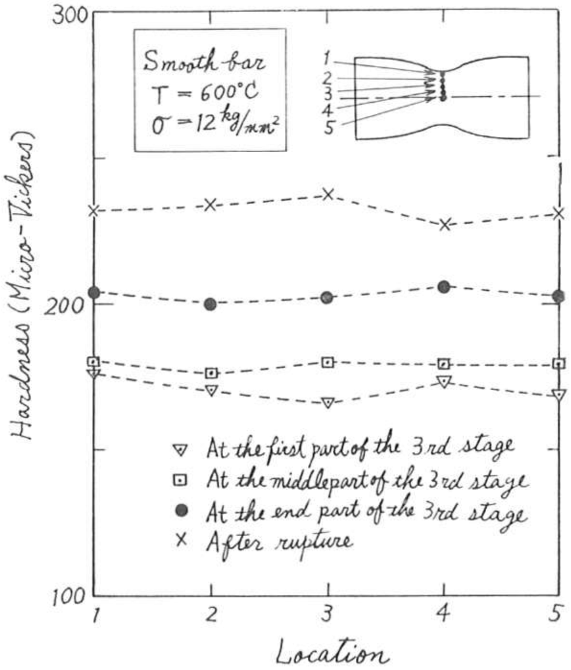


Fig. 10 Change in hardness due to stretching (smooth bar)

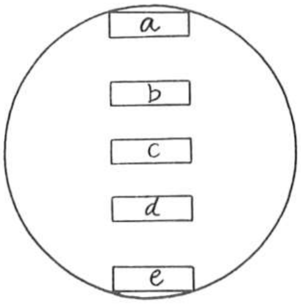


Fig. 11 Locations where microphotographs were taken

These relations are valid also in our tensile creep tests on the unnotched specimens. Microstructures taken at the several positions shown in Fig. 11 close to the ruptured section of the specimens do not differ from each other, as Fig. 12 illustrates.

On the contrary, the circumstances are somewhat different in the tests on the notched specimens. Fig. 13 shows some microstructures of the notched specimens taken at the same positions as above. This illustrates a difference in structure between the central part and the boundary. The structures of the boundary part are undoubtedly stretched and orientated to the circumferential direction, while the central remain almost unchanged. Therefore, at least in creep-rupture tests for the case of high stress or short rupture time, the relations expressed by Eq. (5) do not hold for the notched specimens. This fact must be kept in mind for a complete solution of the problem in question.

Fig. 14 shows the longitudinal structures taken near the ruptured and the unfractured notch, respectively, of a double-notched specimen which ruptured at 58.2 hour under stress of 18 kg/mm² at a temperature of 600 deg C.

Conclusions

In this paper, the effect of a "V" notch on the tensile creep behavior of Cr-Mo steel at elevated temperatures was studied, paying special attention to the change of notch profile and dimen-

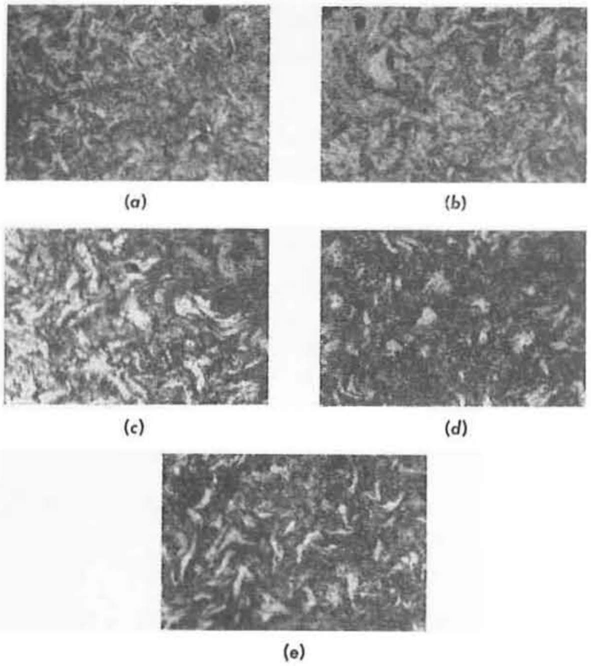


Fig. 12 Microstructures of a creep-ruptured smooth bar

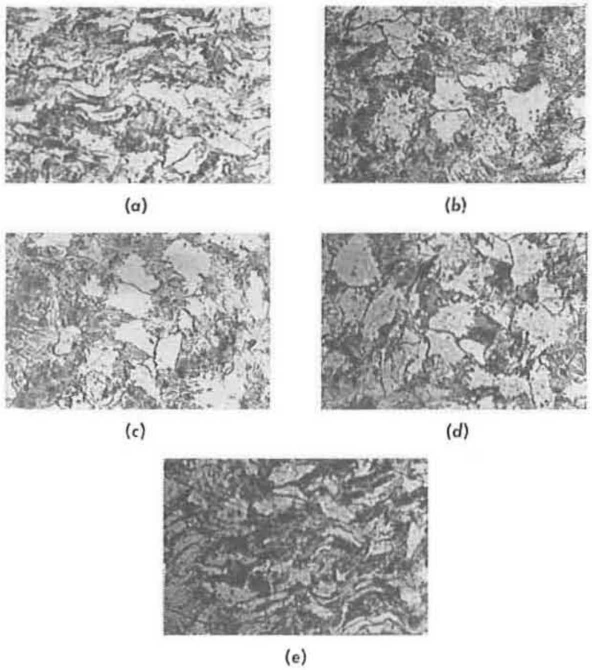
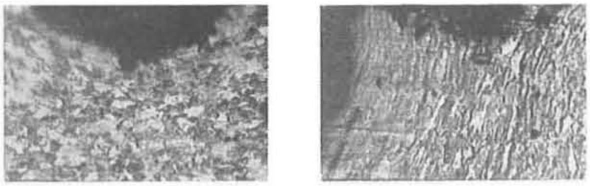


Fig. 13 Microstructures of a creep-ruptured notched specimen



(a) Unruptured notch

(b) Ruptured notch

Fig. 14 Longitudinal microstructures of a creep-ruptured double-notched specimen

sions as well as the structural change of the notched part of the specimens, with the lapse of time up to rupture.

Some interesting results (Fig. 3, Eq. (3) or (4), Fig. 9, and Fig. 13) were obtained which are different from those of an ordinary tensile test or a creep test on smooth bars.

To analyze completely the stress distribution at the notch-root section of the notched specimens at any time after loading and finally to elucidate quantitatively the reasons for notch strengthening, we have to set some adequate assumptions deduced from the above-mentioned results, using simultaneously several fundamental equations concerned with the problem in question.

Acknowledgments

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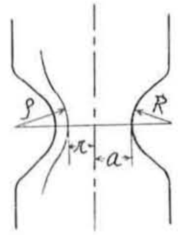
Fig. 15 Illustrative diagram for profiles and intermediate trajectories



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