Study on Creep Rupture of Notched Cylindrical Specimens
of 1Cr-1Mo-1/4V Steel at Elevated Temperature*

By Masateru OHNAMI,** Kiyoshi UMEDA,***
Yoshiteru AWAYA**** and Mitsuo TAKADA*****

From the tensile creep rupture tests for unnotched and round notched bar specimens of 1Cr-1Mo-1/4V steel at 600°C and the numerical calculation results by using finite element method, the following are concluded: (1) The material tested has the transition phenomena from notch-strengthening to notch-weakening at elapsed time of about 120 hrs. The rupture ductility of the material remarkably decreases after elapsed time of this transition. (2) In the region of notch-strengthening, the levels of the equivalent stress and the strain at the notch root of the notched specimen are lower than those of the notched specimen under the same nominal stress. This holds also in the case of hydrostatic stress at the notch root. On the contrary, the quantitative relation mentioned above is reversed in the notch-weakening. The former is one of the important factors determining the notch-strengthening, while the latter is a factor for the notch-weakening.

1. Introduction

Although many studies have been reported on notch intensity of metallic creep at elevated temperatures, a universal rule on both notch-strengthening and notch-weakening has not been established yet. In order to clarify this problem, the necessity of a study from viewpoint of both mechanics and metallurgy is felt. From the former viewpoint, the reports written by W. Siegfried, (1)(2) Yu, N. Rabotnov,(3) L. M. Kachanov(4) F. K. C. Odqvist,(5) and those on the application of linear fracture mechanics to creep fracture of notched specimen have been presented. From the latter viewpoint, many studies on individual heat resistant metals have been reported. However, the studies which bridge both research fields were limited in the number. From this point of view, the approach of fracture mechanics considering with structural change of notch bottom of the specimen during creep will be an effectual method for a study on creep fracture of notched specimens at elevated temperatures.*

In the present paper, both the results of tensile creep rupture tests for notched cylindrical specimens of 1Cr-1Mo-1/4V steel cut from steam turbine rotor at 600°C and the numerical calculation results by use of finite element method are presented to clarify the notch-strengthening and the notch-weakening.

2. Material tested and test procedure

The notched specimens as shown in Fig. 1 were cut from the part of steam turbine rotor with a diameter of 1124 mm and a length of 210 mm. Table 1 shows the chemical composition and the heat treatment. The elastic stress concentration factor Kc of the notched specimen was 4.7. A combined type of notched and unnotched specimens of Fig. 1(c) was also used in the interruption creep tests to examine the crack initiation. The specimens were machined by tool after the heat treatment.

Test temperature was kept at a constant temperature 600°C. The interruption

*1 Although J-integral(7) is an effectual means in the calculation of initiation of cracks in materials having large yielding in the crack tip, it is worthy to notice that path independence of the integration not always holds when the density and the distribution of lattice imperfections are taken into account at the crack tip. Therefore, the fracture toughness G or J-integral of the material with microstructure shows the resultant force on both geometrical singularity and imperfections such as dislocations and micro voids at the crack tip.(8)
Table 1 Chemical composition and heat treatment of the material tested

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt(%)</td>
<td>0.29</td>
<td>0.28</td>
<td>0.75</td>
<td>0.013</td>
<td>0.006</td>
<td>0.13</td>
<td>0.44</td>
<td>1.05</td>
<td>1.07</td>
<td>0.23</td>
</tr>
</tbody>
</table>

1000°C×20hr A.C., 675°C×24hr F.C.

![Diagram](image1)

**Fig. 1** Size and shape of the specimens (dimension, mm)

tests were performed at a life fraction of 40 and 70 per cent of rupture time of the unnotched specimen under nominal tensile stress $\sigma$ of 31.0 kg/mm$^2$, and at 50, 70 and 85 per cent of rupture time under the stress of 21.0 kg/mm$^2$ in case of the notched specimen. Metallographic observation of creep cracks in the specimens was made by use of optical microscope of the longitudinal cross section including the specimen axis after the interruption tests.

The detailed description of finite element method for creep stress analysis is omitted here, but a brief description of the analysis and the calculation procedure is given. The analysis is based on time incremental method. The calculation procedure by computer is as follows;

1. An elastic calculation is made at t=0;
2. A creep strain increment $\Delta C_t$ is determined, by assuming that the stress is kept constant during time interval $\Delta t$;
3. Regarding $\{\Delta C_t\}$ as an initial strain the elastic calculation is made in succession, and then a displacement increment $\{\Delta u\}$, a strain increment $\{\Delta e\}$ and a stress increment $\{\Delta \sigma\}$ are calculated, and
4. the numerical values of $\{\Delta u\}$, $\{\Delta e\}$ and $\{\Delta \sigma\}$ mentioned above are added to the prior value at time t, respectively, and the individual values of $\{\Delta u\}$, $\{\Delta e\}$ and $\{\Delta \sigma\}$ at time of $t+\Delta t$ are determined.

The analysis was made by repeating the procedure from (1) to (4). The following steady state creep rate versus stress relation was also adopted,

$$\dot{\varepsilon} = b \sigma^\alpha$$

where $\sigma$ and $\dot{\varepsilon}$ are the equivalent stress and the creep rate on the basis of Mises-Mises criterion, respectively. In the present study, $b=2.062\times10^{-8}$ and $\alpha=14.2$ were used from the tensile creep rupture tests of the unnotched specimen, where the conventional strain and time dimension of hour were used. Moreover, in the present analysis the geometrical change of the specimen shape during creep was also taken into account. **Fig. 2** shows the finite element division of the specimen, the minimum distance of the element in the notch bottom being 5μ.

![Diagram](image2)

**Fig. 2** Finite element division of the round notched bar specimen (dimension, mm)

Number of elements 398, Number of nodes 239
3. Experimental and analytical results

Fig. 3 shows the nominal stress $\sigma_n$ versus rupture time $t_r$ curves of the unnotched and the notched specimens at 600°C. It is found from the figure that the material tested has the transition phenomena from notch-strengthening to notch-weakening at elapsed time of about 120 hours and also that the rupture ductility of the unnotched specimen remarkably decreases after the elapsed time of this transition as shown in the parentheses near the data points.

Fig. 3 Transition phenomena from notch-strengthening to notch-weakening in the tensile creep rupture of round notched bar specimen of 1Cr-1Mo-1/4V steel at 600°C in atmosphere (numerical value in the parenthesis shows the rupture elongation %).

Fig. 4 shows the variation of distributions of both the axial stresses $\sigma_2$ and the equivalent stresses $\sigma^*$ on the cross section of notch root with elapsed time during creep under nominal stress $\sigma_n$ of 31.0 kg/mm². In this case, the stress of 31.0 kg/mm² was the level in the region of notch-strengthening as shown in Fig. 3. It is seen from the present numerical calculation that the stresses near notch root of the notched specimen remarkably relax in the early state of creep and reach the steady state and also that at this steady state the level of the equivalent stress $\sigma^*$ at the notch root is lower than that of the nominal tensile stress $\sigma_n$. They are in good agreement with those of other calculations including notched plate (9)(11)(12)(13) and also with those of experimental examination (10)(11). (12) Fig. 5 shows the variation of the equivalent stress $\sigma^*$ at the notch root of the notched specimen with time elapsed during creep under nominal stress $\sigma_n$ of 21.0 kg/mm² and 31.0 kg/mm², respectively. The level of nominal stress of 21.0 kg/mm² was in the region of notch-weakening as shown in Fig. 3. It is found from the comparison of two stress levels that at higher stress level in the region of notch-strengthening the equivalent stress $\sigma^*$ rapidly becomes lower than that of the nominal stress but not lower than the stress level in the region of notch-weakening. Intergranular creep cracking in both the unnotched and the notched specimens was examined through the metallographic observation.

![Graph showing transition phenomena from notch-strengthening to notch-weakening](image)

![Graph showing variation of distributions](image)

![Graph showing variation of equivalent stress](image)

4. Discussions

The controlling factors of both the notch-strengthening and the notch-weakening were discussed from a viewpoint of mechanics as follows.

(1) Factor of the equivalent stress $\sigma^*$ and that of the hydrostatic stress $\sigma_n$

From the experimental results of Fig. 5, both the notch-strengthening and the notch-weakening of the material can be interpreted as shown in Fig. 6, on the common basis of the equivalent stress $\sigma^*$ of the unnotched specimen and that at the notch root of the notched specimen. It is seen from Fig. 6 that at comparatively higher stress level $\sigma_m$ the time to the crack initiation in the notched specimen $t^*_t$ becomes longer than that of the unnotched specimen $t_0$ because the level of the equivalent stress $\sigma^*$ of the notched specimen is lower than that of $\sigma_m$ of the unnotched specimen in the majority of the rup-
ture lives of the material. On the contrary, at comparatively lower stress level \( \sigma_{11} \) the time to the crack initiation in the notched specimen \( \varepsilon_1 \) becomes shorter than that of the unnotched specimen \( \varepsilon_1 \) because the level of the equivalent stress curve \( b_1 \) of the notched specimen is higher than that of \( a_1 \) of the unnotched specimen. In this case, it is assumed that the curve \( A_1 \) is at higher level than the curve \( A_0 \) due to precipitation hardening of the material exposed to elevated temperatures. It is worthy to note that the configuration of the curves \( a_0 \), \( a_1 \), \( b_0 \) and \( b_1 \) is in good agreement with the calculation results by use of finite element method. Therefore, it can be concluded that a lower level of the equivalent stress \( \sigma^* \) at the notch root of the notched specimen than that of the nominal tensile stress \( \sigma_0 \) in the majority of the rupture lives is one of the important factors determining the notch-strengthening of the material. On the contrary, the quantitative relation mentioned above is reversed in the notch-weakening.

It seems that time to the crack initiation of the metallic materials at elevated temperatures becomes longer and the crack propagation rate becomes smaller in accordance with smaller positive value of the hydrostatic stress \( \sigma_{11} \) under a constant nominal stress. As a matter of fact, in the previous paper of the authors on pure commercial copper at \( 270^\circ \)C under hydrostatic pressure of 1500 kg/cm², both the tensile creep rupture time and the time to the crack initiation of the material under the hydrostatic pressure were 22 and 17 times longer than those in atmosphere, respectively. The crack propagation rate of the material under the confining pressure was \( 1/20 \) times smaller than that in atmosphere. Therefore, it can be also concluded that the hydrostatic stress is an influential factor in the notch-strengthening or the notch-weakening.

(2) Factor of the equivalent total strain \( \varepsilon^* \)

In connection with Fig.6, a schematic representation of both the notch-strengthening and the notch-weakening on the common basis of the equivalent total strain \( \varepsilon^* \) can be drawn as shown in Fig.7. In the figure, \( a_0 \) and \( b_0 \) show the creep curves of the unnotched and the notched specimens under the stress \( \sigma_{10} \) mentioned in Fig.6, respectively. In the same way, \( a_1 \) and \( b_1 \) show the creep curves of both the specimens under the stress \( \sigma_{11} \), respectively. The creep curves of the notched specimen represent the equivalent total strain \( \varepsilon^* \) at the notch root. It is seen from the figure that under the stress \( \sigma_{10} \) in the region of the notch-strengthening the equivalent creep rate \( \varepsilon^* \) at the notch root of the notched specimen is smaller than that of the unnotched specimen due to a lower level of the equivalent stress than that of the nominal stress \( \sigma_{10} \). It is also seen that the equivalent total strain \( \varepsilon^* \) at the notch root of the notched specimen is smaller than that of the unnotched specimen in the majority of the rupture lives, even if the strain concentration at the notch root is taken into consideration. On the contrary, under the stress \( \sigma_{11} \), in the region of the notch-weakening the quantitative relation mentioned above is reversed. Assuming that the crack occurs when the value of the equivalent total strain \( \varepsilon^* \) at the notch root of the notched specimen reaches a critical one and also that the critical strain curve is represented by curve C in Fig.7 in connection with a monotonous decrease of rupture ductility of the material with time of rupture, it is clearly noted that the time to the crack initiation of the notched specimen \( t_1 \)'s becomes longer than that of the unnotched specimen \( t_0 \) at the stress level of the notch-strengthening. On the contrary, at the stress level of the notch-weakening, it is also noted that the time to the crack initiation of the notched specimen \( t_1 \) becomes shorter than that of the unnotched specimen \( t_0 \).

The quantitative relation of creep curves of both the notched and the unnotched specimens can be examined from the nu-
Fig. 7 Schematic representation of both notch-strengthening and notch-weakening of the material on the common basis of the equivalent total strain $e^*$

- $a_0, a_1$: Creep curves of unnotched specimen
- $b_0, b_1$: Creep curves at the notch root of notched specimen
- $c$: Critical strain curve of crack initiation

Fig. 8 Analytical comparison of both creep curves of the round notched and the unnotched bar specimens by finite element method ($\sigma_0=31.0$ and $21.0$ kg/mm$^2$)

Fig. 9 Comparison between mode of crack initiation of the round notched and unnotched parts of the combined type bar specimen ($\sigma_n=21.0$ kg/mm$^2$)
order to clarify metallographically that the time to the crack initiation of the notched specimen is shorter than that of the unnotched specimen under nominal stress $\sigma_N$ of 21.0 kg/mm$^2$, a series of interruption tests were performed by using the combined type of specimen of Fig.1(c). Fig.9 shows a typical example of the metallographic observations of the notched and unnotched parts of the specimen under the nominal stress. It is found from the observations that there is no creep crack in the unnotched part interrupted at a life fraction of 70 percent but the intergranular cracks are observed in the notched part as shown in Fig.9(a). Moreover, it is found from the result of the interruption tests at a life fraction of 85 percent that there are intergranular cracks in both the parts of the specimen as shown in Figs.9(b) and (c). Therefore, it is seen that the time to the crack initiation of the notched cylindrical specimen is shorter than that of the unnotched one.

Fig.10 shows the experimental relation between the steady state creep rate $\dot{\varepsilon}$ and the rupture time $t_r$ of both the notched and the unnotched specimens where the steady state creep rate at the notch root of the notched specimen represents the equivalent creep rate $\dot{\varepsilon}^*$ calculated by use of finite element method. It is found from the figure that there are inflection points on the data lines and also that the transition from ductile fracture to brittle fracture occurs at these points. This is in agreement with the transition phenomena in the gradient of the curves of both the unnotched and the notched specimens as shown in Fig.4. It is also seen from Fig.10 that the fracture ductility of the notched specimen becomes smaller than that of the unnotched one because $\dot{\varepsilon}$-$t_r$ curve of the notched specimen is lower than that of the unnotched specimen. In addition to $\dot{\varepsilon}$-$t_r$ curve, the steady state creep rate $\dot{\varepsilon}$ or $\dot{\varepsilon}^*$ - time to the crack initiation $t_c$ curves are shown in the figure and it is also considered that the average crack propagation rate of the notched specimen is larger than that of the unnotched one, provided that $\dot{\varepsilon}$ or $\dot{\varepsilon}^*$ - $t_c$ curve is the same one for both the unnotched and the notched specimens.

5. Conclusions

From the tensile creep rupture tests for unnotched and round notched (60°V-shape, $kt=4.7$) bar specimens of Inconel 601-1/4V steel at 600°C in atmosphere and the numerical calculation results by use of finite element method, the following are concluded.

(1) The material tested has the transition phenomena from notch-strengthening to notch-weakening at elapsed time of about 120 hrs. The rupture ductility of the material remarkably decreases after elapsed time of this transition.

(2) Under the same nominal stress in the region of the notch-strengthening, both the level of the equivalent stress and that of the equivalent total strain at the notch root of the round notched bar specimen are lower than those of the unnotched bar specimen. This quantitative relation holds also in the case of hydrostatic stress at the notch root. On the contrary, the quantitative relations mentioned above are reversed in the notch-weakening. The former is one of the important factors determining the notch-strengthening, while the latter is a factor for the notch-weakening and this is seen from the interruption creep tests under the nominal stress in the region of the notch-weakening.

Acknowledgement

The authors express their thanks to the research institute of Muroran plant, the Japan Steel Works Ltd., for providing the test material cut from the steam turbine rotor. The numerical calculation by finite element method was performed by using FACOM 230-60 in Kyoto University.

References

(2) Siegfried, W., Proc. NPL Symp. on Creep and Fracture of Metals at High Temperature(1954), p.333, H.M.S.O.
(4) Kachanov, L.M., Ibid., Chap. 2.
(5) Odqvist, P.K.G., Ibid., Chap. 3.

*2 This assumption means that the creep crack initiates when the equivalent total strain at the notch root reaches a critical one.


