Accelerated Stage Creep and Creep Rupture under Temperature Cycling

By Shuji Taira** and Masateru Ohnami***

In the present paper, the influence of temperature cycling on the accelerated stage creep and the rupture life is discussed by employing AISI 318 type stainless steel. In this discussion, the strength of material under temperature cycling was compared with that under steady temperature by introducing the idea of the equivalent steady temperature for the rupture life of material under temperature cycling.

Embrittlement of a creeping material subjected to temperature cycling is significantly larger than in the case of steady temperature. It would probably be because of a difference in the metallographic structure change occurring during the tertiary stage of creep, for both series of tests.

1. Introduction

In the preceding papers of the authors(1)(2), it was found that temperature cycling does not give a serious influence on transient or steady state stage creep for application in mechanics problems. However, it was noted that the accelerated stage creep or creep rupture life might be greatly affected by the change of structure during the tertiary stage of creep, such as nucleation of micro crack or recrystalization(5). Therefore, knowledge on the influence of temperature history on the tertiary stage creep of material is wanted. The study on the influence of temperature history on creep rupture is also necessary, in order to predict, the rupture life of a material under cyclic variation of temperature from the information on creep rupture of the material under steady temperature. In this line, some investigations have been reported by E. L. Robinson(4) and J. Miller(5).

In the present paper, the influence of temperature cycling on the accelerated stage creep and the creep rupture life is discussed by employing AISI 318 type stainless steel. In the discussion, the strength of material under temperature cycling is compared with the strength at steady temperature on the basis of the equivalent steady temperature for rupture life.

2. Influence of temperature history on creep rupture life

Denoting the period of temperature cycling as $p$, the temperature at infinitesimal time interval $dt$ as $T'$ and rupture life for a steady temperature of $T'$ as $L'$, the life consumption during a fragment of time $dt$ is represented by

$$dE = \frac{dt}{L'}$$

Assume that the material subjected to periodic temperature variation fractures when

$$\int_0^{t} \frac{dt}{L'} = 1$$

is satisfied, and also take the temperature dependency of creep rupture life as

$$L' = B_0\exp\left(\frac{Q}{T'}\right)$$

where $L$ is the life time of material subjected to temperature cycling and $B_0$ and $Q$ are constants. Eq. (3) is initially intended to represent the dependency of creep rupture life on test temperature. In order to study the rupture life of a material under cyclic temperature variation, it is here assumed that the equation is applicable to this case, according to the assumption that the life consumption is determined by its "state value", i.e., elapsed time $t$ and temperature $T$ at that instant, independent of the past temperature history that the material has experienced.

Therefore, the rupture life of a material under temperature cycling $T(t)$ with a period of $p$ is introduced from Eqs. (2) and (3) as

$$L = B_0 \rho \left[ \int_0^{\rho} \exp\left(-\frac{Q}{T(t)}\right) dt \right]$$
Thus, the equivalent steady temperature for creep rupture life under periodic temperature variation $T(t)$ with period $p$ is represented as

$$T_{e, r} = -Q / \ln \left[ \frac{1}{p} \int_0^p \exp \left( -\frac{Q}{T(t)} \right) dt \right] \quad \cdots (5)$$

From Eq. (5) it is shown that the creep rupture life under periodic variation of temperature with period $p$ is equivalent to the rupture life at steady temperature of $T_{e, r}$.

If temperature history does not affect the life consumption at any moment, the material would fracture at the life time determined by Eq. (4). In this case, the life time is equal to the rupture life in static creep at the steady temperature determined by Eq. (5). If there were any influence of temperature history, the life consumption at any moment would be increased or decreased and it leads to elongated or shortened rupture life.

Denoting the life consumption under the condition which includes the influence of temperature history as $dE^*$, and also assuming

$$dE^* = \alpha \cdot dE \quad (\alpha: \text{constant}) \quad \cdots (6)$$

Eq. (5) would be represented, in this case, as

$$T_{e, r} = -Q / \ln \left[ \frac{\alpha}{p} \int_0^p \exp \left( -\frac{Q}{T(t)} \right) dt \right] \quad \cdots (7)$$

When $\alpha = 1$, Eq. (7) reduces to Eq. (5).

The equivalent steady temperature for creep rupture life under the absence of the influence of temperature history is equal to the equivalent steady temperature for creep $T_{e, r}^{(0)}$, if $Q = K/m$ is satisfied. This is approximately satisfied because the following relation hold for most of the metallic materials$^{(8)}$:  

$$\kappa \cdot L \equiv \text{constant} \quad (8)$$

$$n \equiv -\frac{1}{2}$$

where $\kappa$ is steady state creep rate, $A_0'$ and $K$ are constants, and $T$ is absolute temperature.

3. Material tested and the testing apparatus

Material tested was AISI 318 type stainless steel, and its chemical composition and mechanical properties at room temperature and elevated temperature are shown in Tables 1 and 2, respectively. The diameter of the specimen was 10 mm and the gauge length was 100 mm.

Temperature cycling was performed by combined use of conventional temperature controller and mechanical relay mechanism. A saw-tooth like temperature cycling was obtained by using such an apparatus. In this case, the period of every cycle was 2 hours. The temperature distribution in the radial direction of the specimen during temperature variation was very small and its influence was neglected. Setup to measure the elongation of the specimen is the same as that used in the previous study by the authors.

4. Discussion

Fig. 1 shows the results of experiment on AISI 318 type stainless steel in the case of saw-tooth cycling of temperature. The temperature range of variation was 600°C to 700°C, and the equivalent steady temperature $T_{e, r}$, was determined as 680°C. Besides, static creep rupture tests were performed.

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>Cu</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.059</td>
<td>1.77</td>
<td>0.32</td>
<td>0.012</td>
<td>0.015</td>
<td>14.17</td>
<td>16.73</td>
<td>2.38</td>
<td>0.78</td>
<td>0.08</td>
<td>1 100°C, W. Q.</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties of the material at room temperature and high temperature

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Yield point kg/mm²</th>
<th>Tensile strength kg/mm²</th>
<th>Elongation %</th>
<th>Area contraction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temp.</td>
<td>--</td>
<td>56.0</td>
<td>48.0</td>
<td>74.0</td>
</tr>
<tr>
<td>600</td>
<td>--</td>
<td>46.0</td>
<td>34.0</td>
<td>55.0</td>
</tr>
<tr>
<td>650</td>
<td>--</td>
<td>39.0</td>
<td>33.0</td>
<td>63.0</td>
</tr>
<tr>
<td>700</td>
<td>--</td>
<td>33.0</td>
<td>41.0</td>
<td>63.0</td>
</tr>
</tbody>
</table>

(Tensile test at high temperature was performed under strain rate of 1 mm/min.)
by fixing the temperature at 680°C under various stress levels. The experimental results are shown by the stress-rupture time relation in semi-logarithmic scale. The closed circles are the results for cyclic temperature, open circles for steady temperatures of 650°C, 680°C and 700°C.

As is known from the figure, the life time for periodic cycling is a little longer than that for a steady temperature of 680°C which is equal to the equivalent steady temperature for cyclic temperature. Thus, in this case, the value of \( \alpha \) in Eq. (7) becomes smaller than unity.

Fig. 2 shows another representation of the experimental creep curves under temperature cycling and those under constant temperature as shown in Fig. 2. These curves show the results under the stress of 25.0, 20.0 and 17.0 kg/mm², respectively. From the figure it is found that the creep strain under periodic temperature variation (closed circles) is smaller than that under a steady temperature of 680°C (open circles) in the accelerated stage of creep. Creep rupture strain under cyclic temperature becomes approximately half of that under steady temperature. It would probably be because of the difference in the metallographic structure change during the tertiary stage of creep, for both series of tests.

On the other hand, Fig. 3 shows transient stage creep curves under a fixed stress of 15.0 kg/mm² in both series of tests. The equivalent steady temperature for rupture life in this case of temperature cycling was determined as 650°C and 680°C, which were nearly equal to that for creep strain. Therefore, static creep tests under the same stress were carried out at steady temperature of 650°C and 680°C. From the figure, it is found that both curves in two series of tests are close even at an elapsed time of 1000 hours. It substantiates the propriety of the prediction of creep strain before the beginning of the tertiary stage, that is, the adoption of the equivalent steady temperature for estimating creep strain before the beginning of the accelerated creep stage under periodic temperature variation.

The difference in the strain of tertiary stage creep and the rupture life was also studied from the following experiments, studying the change of the ductility of material and the metallographic structure change during creep.

Figs. 4 and 5 show the changes of hardness and impact values of creep specimen in both series of tests, respectively. The hardness of specimens surface was measured by the Vickers hardness tester. For the impact test of the creep specimen, a Charpy's
notched specimen as shown in Fig. 6 was employed. As is known from these figures, the change of hardness and impact value in the case of cyclic temperature (closed circles) is larger than in the case of steady temperature (open circles). Fig. 7 shows the relation of the decrease of impact value to the time ratio \( t/L \), which is the ratio of elapsed time \( t \) to the rupture life \( L \) in two series of tests. The figure shows that the decrease of impact value under cyclic temperature becomes larger than in the case of steady temperature in the range of time ratio over ten per cent.

In practical cases of creep of this sort of material, the tertiary stage creep begins at the time ratio between ten to twenty per cent. Therefore, the difference of decrease of impact value in both series of tests would appear in the tertiary stage of creep. It would be reasonable to think that the material subjected to temperature cycling might be embrittled during the tertiary stage of creep. Surveying the metallurgical study concerning the embrittlement during the creep of this sort of material, the embrittlement leads to shortened creep rupture strain and to elongated rupture life. Therefore, considering that the life consumption is affected by change of the ductility of a material during creep, the relation of \( \alpha < 1 \) in Eq. (7) would be explained by the fact that the life consumption at any moment is decreased by the embrittlement of a material during the tertiary stage of creep.

The difference in the embrittlement of a material during creep between two series of tests was also verified by the following metallographic studies. Photographs from 1 to 4 show the microstructures of specimens before and after the creep tests. In these photographs the areas enclosed by circles were subjected to electron-diffraction analysis to study the structure of precipitates appearing after the tests. From Photo. 2 it is found that temperature cycling is likely to accelerate the precipitation of chromium carbide near the grain boundary. Photo. 3 shows the crack of specimen after creep rupture.
in both series of tests. It is found from Photo. 3 that a crack appearing in the case of temperature cycling has sharp jogs along grain boundary, where for the case of rupture at steady temperature the cracks look like continual vacancies having a round corner. Therefore, from Photos. 2 and 3, it is likely that the embrittlement of a creeping specimen subjected to temperature cycling is due to the increase of strength of the vicinity of crystal boundary caused by preferable precipitation of chromium carbide near the grain boundary, which restricts deformation. On the contrary, in Photo. 4 which shows the microstructure of a specimen tested in transient creep stage, no difference in the precipitation between two series of tests is observed.

As is understood from the experiment, the estimation of the creep rupture life of a material subjected to periodic temperature variation is rather uncertain as compared with that of creep strain. It is presumably because the fracture might be greatly affected by the change of metallographic structure during the tertiary stage of creep.

5. Conclusion

In the present paper, the influence of temperature cycling on the accelerated stage creep and the rupture life is discussed by employing AISI 318 type stainless steel. From the creep rupture tests under saw-teeth cycling of temperature the following are concluded:

(1) Embrittlement of a creeping material subjected to temperature cycling is significantly larger than that of one subjected to steady temperature. The rupture life of a material subjected to periodic temperature variation is nearly twice as much as that of one subjected to steady temperature and the rupture elongation under temperature cycling is approximately half of that under constant temperature. It is probably because of a difference in the metallographic structure change occurring during the tertiary stage of creep, for both series of tests.

(2) In the case of transient and steady state stages of creep, the influence of temperature cycling is negligibly small. It is probably due to the absence of any difference in the structure change during such stages of creep for both temperature cycling test and steady temperature test.

Acknowledgement

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References

(1) S. Taira and M. Ohnami: This Bulletin, p. 1.
(2) S. Taira and M. Ohnami: ibid, p. 6.
Dynamic Creep and Fatigue of an 18-8 Mo-Cb Steel at Elevated Temperature

By Shuji TAIRA** and Ryoichi KOTERAZAWA***

Dynamic creep and fatigue tests were carried out with an 18-8 Mo-Cb steel at a temperature of 650°C. The results were discussed from the standpoint of the analysis, which had been proposed by the authors previously, concerning the prediction of dynamic creep and fatigue strength from the information on static creep and creep rupture tests together with reversed stress fatigue data. The prediction by the analysis showed a satisfactory agreement with the experimental results as for a practical purpose, although a little discrepancy was observed due to the acceleration of the precipitation hardening by alternating stress.

In order to contribute to clarification of the relation between the precipitation hardening characteristics of the material and its strength characteristics, the electron-microscopic observation of structure, hardness test and creep rupture test after the dynamic creep were carried out. Their results were discussed in connection with the discrepancy between the analysis and experiments.

1. Introduction

One of the most important problems for the design of elevated temperature devices is the evaluation of strength characteristics of their members under a dynamic load. For this purpose, it is necessary to find the relation between the dynamic and the static strengths of a material, because it offers us the means of prediction of the dynamic strength from the readily available data on static strength. Concerning this problem, the authors have proposed a method of analysis and proved its validity for some materials; low carbon steel, 13 chromium steel and commercially pure titanium(1)-(5). This paper is a continuation of the previous papers and is intended to examine the applicability of the analysis to an austenitic steel, which shows precipitation hardening during the creep process, using an 18-8 Mo-Cb steel of AISI 318 type.

2. Testing apparatus, test material and test specimen

The testing machine used in this study is the same as the one described in the previous report(3). The test material is an 18-8 Mo-Cb steel of AISI 318 type and its chemical composition, condition of heat treatment and mechanical properties at room temperature are given in Table 1. Two different

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