Initiation and Growth Behavior of Creep Voids in an Austenitic Steel with High Ductility under Multi-axial Stresses

Li-Bin NIU, Akihide KATSUTA1), Mitsuyuki KOBAYASHI and Hiroshi TAKAKU

Faculty of Engineering, Shinshu University, Wakasato, Nagano City, 380-8553 Japan. E-mail: niulibn@gips.shinshu-u.ac.jp
1) Graduate School, Shinshu University, Wakasato, Nagano City, 380-8553 Japan.

(Received on August 27, 2002; accepted in final form on October 2, 2002)

This study aims mainly to clarify the effects of the multi-axial stress components on the initiation and growth behavior of creep voids. For this purpose, creep tests, particularly creep interrupt tests are conducted in tension, torsion and in combined tension-torsion stress states at 700°C, using tubular specimens of the austenitic steel SUS310S with high ductility. Creep voids formed in the specimens are examined in detail by observation with the scanning electron micrographs. It is found that creep voids in the torsional creep specimens form easily to a certain size in the primary creep, but they grow difficultly to rupture. While from torsional stress state to tensile one, creep voids become easy to grow. The initiation and growth behaviors of creep voids under the multi-axial stress conditions are discussed. It is further suggested that the von Mises equivalent stress is a dominant component for the initiation of creep voids, and the mean stress component strongly promotes their growth.

KEY WORDS: creep; creep interrupt test; void; initiation and growth; multi-axial stress; fracture.

1. Introduction

Creep rupture properties of high-temperature materials in the uniaxial stress state or in the multi-axial stress states have been widely studied up to now. Many investigations1–4) have been made upon the various factors controlling creep rupture life for the materials under multi-axial stress conditions. In these factors, the initiation and growth behavior of creep voids has been known to be a very important mechanism of creep fracture for many high-temperature materials.5–8) And it is strongly influenced by the multi-axial stress components, such as the von Mises equivalent stress, the mean stress and so on.9,10) However, the initiation and growth behavior of creep voids, which is closely related with the creep rupture life, has not been made clear for the materials with different characteristics under multi-axial stresses. So, it is necessary to clarify the effects of the multi-axial stress components and the material characteristics on the initiation and growth behavior of creep voids.

In order to clarify the multi-axial creep fracture mechanisms, in this study using tubular specimens of the austenitic steel SUS310S with high ductility, creep tests, particularly creep interrupt tests are conducted in tension, torsion and in combined tension-torsion at 700°C. The initiation and growth behaviors of creep voids in the specimens under multi-axial stresses are investigated in detail.

2. Experimental Procedures

The material used in this work is a commercial austenitic steel with high ductility and high metallographic stability, SUS310S (0.05% C–0.42% Si–1.19% Mn–0.03% P–0.025% S–19.36% Ni–24.36% Cr–bal. Fe). Steel bars with 16mm diameter were solution treated at 1 100°C for 1 h and then air cooled to room temperature. Figure 1 is an optical micrograph showing the austenitic microstructure of the steel after heat treatment. Table 1 lists the mechanical properties of the steel after the heat treatment. An average grain size is about 45 μm.

As shown in Fig. 2, tubular specimens were machined to 8mm external diameter with 1.5 mm wall thickness by a gauge length of 10 mm. In order to clarify the multi-axial
creep fracture mechanisms, creep tests were conducted in tension, torsion and in combined tension–torsion stress states using the tubular specimens. In the combined tension–torsion stress states, the ratios of applied tensile stress \( \sigma \) to applied shear stress \( \tau \) on the external surface of specimens are 1:1 and 2:1. These tests were performed in air using a tensile–torsional creep test machine. The test temperature was kept at 700 ± 1°C and monitored with a thermoelectric couple attached on the external surface of each specimen. Tensile creep elongation and torsional creep rotation angle were measured continuously, using a dial gauge and a rotary encoder device respectively. Thus, the von Mises effective strain of the specimen at any time can be calculated by

\[
\varepsilon = \sqrt{\frac{2}{3} \left(\varepsilon^2 + \frac{3}{2} \gamma^2\right)}
\]

where \( \varepsilon \) and \( \gamma \) are the nominal tensile strain and the nominal shear strain, respectively.

To investigate the effects of multi-axial stress components on the initiation and growth behavior of creep voids, 2 kinds of the creep interrupt tests for the specimens loaded at a given maximum principal stress \( \sigma_1 \) were carried out: (1) The creep tests were interrupted at the initial and final stages of steady state creep. (2) The creep tests were interrupted as their effective strains reached the same.

For the tested specimens, longitudinal sections were etched with the chemical solution \((25\text{vol}\% \text{HNO}_3 + 50\text{vol}\% \text{HCl} + 25\text{vol}\% \text{Glycerin})\) after mechanical polishing. The specimens were then observed in detail with a scanning electron microscope (SEM). The “fraction of creep voids on grain boundary lines”, i.e. a fraction of total length of creep void areas on the grain boundary lines, was measured on the SEM micrographs. Also, the “average diameter of creep voids” was calculated because each void area observed on the longitudinal sections was just only a cutting plane of a spherical void, in this work the average diameter of the spherical creep voids was calculated approximately from these cutting planes using Fullman’s method. And for each tested specimen, about 100 creep voids were measured for the calculation.

### Results and Discussion

#### 3.1. Creep Rupture Properties

Typical creep curves, showing the relationship between effective strain and time, of the specimens at the 4 stress states under a given maximum principal stress \( \sigma_1 \) of about 100 MPa are shown in Fig. 3. From these curves the effective strains at the initial and final stages of steady state creep as well as the creep rupture strains of the specimens are plotted in Fig. 4. It can be found that the torsional creep specimen showed larger deformations than the others, and at every stages of creep the effective strain decreased from the torsional stress state to the tensile one. Figures 5(a)–5(d) are the SEM micrographs showing the fracture surfaces of the creep ruptured specimens. All of these specimens exhibited a ductile fracture mode, especially the torsional creep specimen showed a complete transgranular fracture of shear type. On the other hand, it can be also noticed that from the torsional stress state to the tensile one the grain boundary facets, which show a brittle intergranular fracture, occur easily on the fracture surfaces.

#### Table 1. Mechanical properties of the steel used.

| Temperature (°C) | 0.2% Proof Stress \( \sigma_{0.2} \) (MPa) | Tensile Strength \( \sigma_b \) (MPa) | Elongation \( \epsilon \gamma \) (%) | Reduction of Area \( \psi \) (%) |
|-----------------|------------------|------------------|------------------|------------------|
| 20°C            | 255.0            | 608.0            | 54.0             | 73.0             |
| 700°C           | 122.5            | 325.4            | 67.6             | 47.3             |

© 2003 ISIJ
3.2. Initiation and Growth Behavior of Creep Voids

Creep voids in the specimens loaded at about 100 MPa of the maximum principal stress were examined in detail with SEM micrographs. As typical examples, Figs. 6(a)–6(d) are a part of the SEM micrographs showing the longitudinal sections of the specimens interrupted at final stages of steady state creep. Many creep voids can be clearly observed in these specimens. With the SEM micrographs, fractions of creep voids on grain boundary lines and their average diameters were measured. The results are plotted in Fig. 7, in which the abscissas show the torsional stress state \( \sigma/\tau = 100\), \( t/\tau = 100\) MPa, and the uniaxial tensile one \( t/\sigma = 0\), \( \sigma/\tau = 100\) MPa. It can be found that from torsion to tension, i.e., with decreasing the applied shear stress \( \tau \) and increasing the applied tensile stress \( \sigma \), at initial stages of steady state creep the fraction of creep voids on grain boundary lines as well as the average diameter decreased. And in each stress state both of them became larger. They showed larger values in the specimens loaded under larger tensile stresses (specimens C and D in the figures). On the other hand, using above results the average number of creep voids on per 100 \( \mu m \) of grain boundary lines was calculated \( = \text{Fraction on grain boundary lines}/100 \mu m \times \text{Average diameter} \). For contrasting with the average diameter, it was also plotted in Fig. 9. From this figure, the average number of creep voids can be found to decrease with increasing the applied tensile stress, showing a just converse tendency to the average diameter.

3.3. Discussion

Authors have reported that the initiation and growth behavior of creep voids is a dominant creep fracture mechanism of the austenitic steel SUS310S used in this work, and that the maximum principal stress component determines the creep rupture life of the steel at multi-axial stresses.14) As shown in Fig. 7, the fractions of creep voids on grain boundary lines for the specimens ruptured at the 4 stress states reached almost the same. At the initial and final stages of steady state creep, however, the fraction on grain boundary lines, the diameter of creep voids as well as the creep strain changed with the applied stress state. Therefore the initiation and growth behaviors of creep voids at each stress state should be discussed separately.
Generally, the von Mises equivalent stress has been assumed to control creep rate and govern the nucleation of creep voids. And it has been reported that many creep voids nucleate in the early stages of creep tests. In this work, the von Mises equivalent stress in the torsional specimen was the largest and it decreased from the torsional stress state to the tensile one, even though the maximum principal stresses in these specimens were almost the same. By the above reasons, the creep deformation as well as the fraction on grain boundary lines of creep voids formed in the periods of primary creep exhibited the largest in torsion and decreased from torsion to tension. On the other hand, it has also been assumed that the mean stress component promotes the growth of creep voids or cracks. As stated above, in this work the von Mises equivalent stress in the specimen in torsion was larger than those in the other stress states and it became smaller from the torsion to tension. However, the mean stress was 0 in the torsional specimen and it became larger conversely with increasing applied tensile stress. Therefore, it may be suggested that in specimens loaded under the same maximum principal stress, creep voids nucleate easily in torsion and grow easily in tension. For this reason, the average number of creep voids on per 100 µm of grain boundary lines, as shown in Fig. 9,

![SEM micrographs showing creep voids in the specimens interrupted at final stages of steady state creep.](image)

![Fractions on grain boundary lines and average diameters of creep voids in specimens loaded under the same maximum principal stress.](image)

(a) \( \tau = 98 \text{MPa}, \ 220 \text{h tested}; \)  
(b) \( \sigma = 60 \text{MPa}, \ \tau = 60 \text{MPa}, \ 220 \text{h tested}; \)  
(c) \( \sigma = 82.8 \text{MPa}, \ \tau = 41.4 \text{MPa}, \ 240 \text{h tested}; \)  
(d) \( \sigma = 100 \text{MPa}, \ 250 \text{h tested}. \)
decreased from the torsional stress state to the tensile one, while their average diameter exhibited a converse tendency. Consequently, in a torsional creep stress state with larger von Mises equivalent stress, creep voids nucleated easily and grew to a certain extent in the period of primary creep. But because the mean stress was 0, the creep voids grew difficultly till the rupture, even though they initiated continuously to the final rupture. While from torsional stress state to tensile one, creep voids were found to become easy to grow.

4. Conclusions

Using tubular specimens of the austenitic steel SUS310S with high ductility, creep tests, particularly creep interrupt tests were conducted in tension, torsion and in combined tension–torsion stress states at 700°C. The initiation and growth behaviors of creep voids for the steel under multi-axial stresses were investigated. The results obtained are summarized as follows:

(1) With decreasing applied shear stress and increasing applied tensile stress, the fraction on grain boundary lines and the average diameter of creep voids in specimens loaded under the same maximum principal stress were found to become smaller in the periods of primary creep. However, alone with further testing to ruptures they grew fast conversely.

(2) In torsional stress state, it was found that creep voids formed easily to a certain size in the primary creep, but they grew difficultly till the rupture, even though they initiated continuously to the final rupture. While from torsional stress state to tensile one, creep voids were found to become easy to grow.

(3) It is further suggested that at a multi-axial stress state the von Mises equivalent stress component and the mean stress component promote the initiation and the growth of creep voids, respectively.

REFERENCES

1) C. R. Kennedy, W. O. Harms and D. A. Douglas: Trans. ASME, D81 (1959), 599.
2) W. Sawert and H. R. Voorhees: Trans. ASME, D84 (1962), 228.
3) W. D. Nix, J. C. Earthman, G. Eggerler and B. Ilschner: Acta Metall., 37 (1989), 1067.
4) Y. H. Hsiao, H. Zhang and G. S. Daehn: Metall. Mater. Trans., 27A (1996), 891.
5) C. W. Weaver: J. Inst. Met., 88 (1959–60), 296.
6) R. Rai and M. F. Ashby: Acta Metall., 23 (1975), 653.
7) S. E. Stanzl, A. S. Argon and E. K. Tschegg: Acta Metall., 23 (1975), 653.
8) K. Kobayashi, H. Imada and T. Majima: Trans. JSME Int., 41A (1998), 218.
9) A. Yousefiani, F. A. Mohamed and J. C. Earthman: Metall. Mater. Trans., 31A (2000), 2807.
10) L.-B. Niu, M. Nakamura, A. Futamura and M. Kobayashi: ISIJ Int., 40 (2000), 511.
11) N. Tada, T. Kitamura and R. Ohtani: J. Soc. Mater. Sci. Jpn., 45 (1996), 110.
12) R. L. Fullman: Trans. Metall. Soc. AIME, 197 (1953), 447.
13) J. Kyono, N. Shinya, H. Kushima and R. Horiiichi: Tetsu-to-Hagané, 79 (1993), 604.
14) L.-B. Niu, M. Kobayashi and H. Takaku: ISIJ Int., 42 (2002), 1156.
15) M. M. Abo El Ata and I. Finnie: Creep in Structures 1970, ed. by J. Hult, Springer-Verlag, Berlin/Heidelberg, (1972), 80.
16) F. C. Monkman and N. J. Grant: Proc. Am. Soc. Test. Metals, 56 (1956), 295.
17) H. E. Evans and J. S. Waddington: Philos. Mag., 20 (1969), 1075.
18) D. Hull and D. E. Rimmer: Philos. Mag., 4 (1959), 673.
19) R. T. Ratcliffe and G. W. Greenwood: Philos. Mag., 12 (1965), 59.