Cyclic Creep Behavior of Modified 9Cr-1Mo Steel at 600°C

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1. Introduction

Cyclic deformation behavior is important in practice because high-temperature structural components are exposed under the cyclic conditions of repeated loading. In static creep (SC), the response of the material is simple as a static state of monotonic loading. However, in cyclic creep (CC), it is complex as dynamic loading. Cyclic creep data have been rarely reported until now. In particular, it is not understood well whether cyclic creep will accelerate or retard the creep rate compared with static creep, because it is not only the plastic deformation under cyclic loading is drastically different from monotonic loading, but also the cyclic response is dependent on the cycling frequency, stress range, stress ratio, and hold periods of cycling [1-5]. Therefore, it is necessary to clarify the cyclic creep behavior influencing the creep deformation and fracture process.

In this study, a series of cyclic creep tests was carried out using magnitudes of stress range of constant stress ratio (*R*=0.1) under continuous tension-tension loading cycles at a hold time of 10 minutes. Cyclic curves were monitored and obtained with time variations, and the properties of the cyclic creep tests were compared with those of static creep tests. The fracture microstructures were observed and analyzed.

2. Methods and Results

2.1 Experimental procedures

A commercial grade hot-rolled modified 9Cr-1Mo steel (Gr. 91) plate was used for the testing material. The heat treatment condition of the steel was normalized and tempered at 1050 °C/1 mim/mm and 770 °C/3 mim/mm. The plate thickness was 16 mm. The specimens for cyclic creep tests were of a cylindrical form with a 30 mm gauge length and 6 mm diameter.

The cyclic creep tests were conducted with applied stress ranges (σ_R) at a constant stress ratio of *R*=0.1 ($\sigma_{min}/\sigma_{max}$) of 20MPa($\sigma_{min.}$)/200MPa($\sigma_{max.}$), 19MPa/190MPa, 18MPa/180MPa, and 17MPa/170MPa at a fixed hold time of 10 minutes (t_h) at 600°C. The stress range ($\sigma_R = \sigma_{max} - \sigma_{min}$) was chosen as variable parameter. The stress ranges at *R* = 0.1 were 180MPa (σ_{R1}), 171MPa (σ_{R2}), 162MPa (σ_{R3}), and 153MPa (σ_{R4}). The σ_R values were chosen for a lower value than the yield stress of 247.5MPa, which was obtained by the tensile tests for Gr. 91 steel at 600°C. In the cyclic creep tests, the cross-head moving speed to a maximum stress from a minimum stress was fixed at 3,920N/min. Load-controlled tension-tension cyclic tests were performed using a universal testing machine with a 100KN capacity (Model: RB Unitech-M), manufactured by R&B company in Korea. The cyclic loading of the maximum and minimum stresses was applied to a specimen using an AC servomotor type, which can be periodically repeated in the clockwise and counterclockwise rotations. The cyclic tests were automatically performed according to a scheduled program. The real-time data of the strain-stress at elapsed times were monitored and collected by a PC through a high-precision LVDT. The steady state creep rate in the cyclic creep was taken as a mean value of the secondary creep strain data.

In this work, to reasonably determine the creep properties in the CC, the steady state creep rate and rupture time were determined by taking the half value of the total elapsed time, as the unloading time during a minimum stress of cycling does not practically contribute to creep deformation.

2.2 Comparison of the SC and CC properties

The cyclic curve showed the well-defined primary creep stage, the secondary creep stage, and the tertiary creep stage, as generally reported in the static creep curves. The cyclic creep curves were no differences in the shapes compared with the static creep curves. An enlarged profile for the primary and secondary creep strains is shown in Fig. 1. The stress-strain profiles with time variations were accurately monitored.

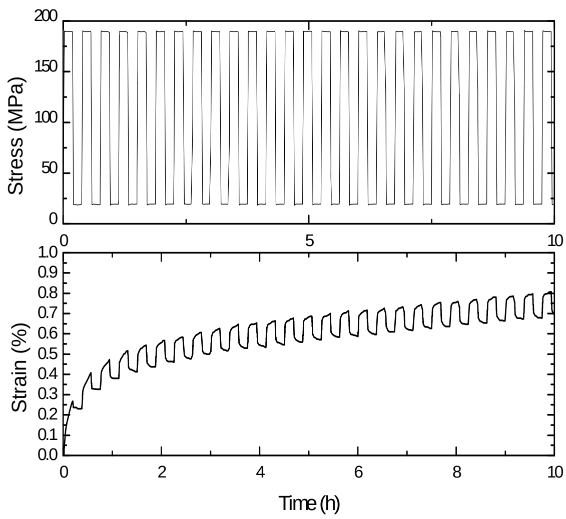

Fig. 1. Enlarged profiles at the primary creep region under the stress range (19MPa/190 MPa) for 10min hold time at 600°C.

Creep rupture life of the CC was higher than that of the SC. The creep rate was decelerated due to the CC effect. This reason can be verified from the plot of Norton's power law, as shown in Fig. 2. The cyclic creep rate was slower than the static creep rate. The constants of Norton's power law can be obtained. In the CC, the *A* values was 2.72x10^{-15} (MPa^{-n} s^{-1}) and the n value of the slope was 1.086, and in the SC, the A values was 4.30x10^{-16} (MPa^{-n} s^{-1}), and the n value of the slope was 1.103.

Fig. 3 shows the comparison of the SC and CC by Monkman-Grant (M-G) plot presenting the relation between the creep rupture time and steady state creep rate. The M-G plot revealed a good linearity for both the SC and CC. At the same rupture time, the creep rate of the CC was lower than that of the SC. In this cyclic test condition, the creep rate was retarded when compared with the SC. This reason for this is believed to be that the material was recovered during the hold time of 10 minutes at the minimum stress. Also, an accelerated effect in the CC did not occur because the value of the minimum stress in the maximum and minimum of cycling stresses was so much lower.

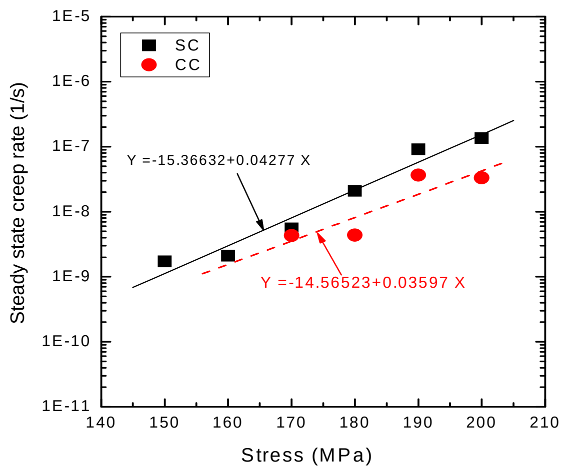

Fig. 2. Comparison for the SCR and CCR by Norton's law.

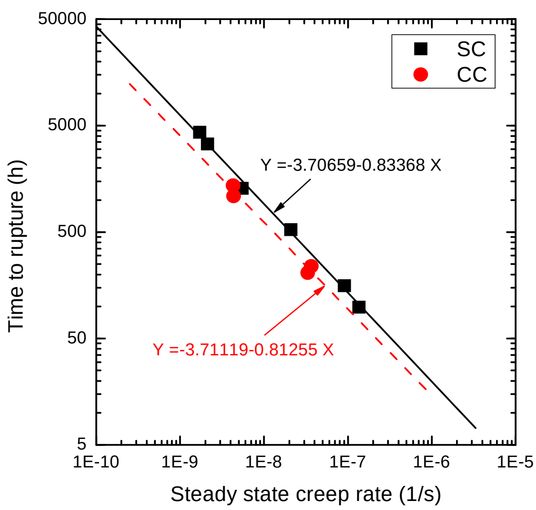

Fig. 3. Comparison of the SC and CC by M-G relation.

In addition, the comparison results between the CC and SC for the rupture ductility did not show any differences for the CC and SC. SEM fractographs for four specimens (20/200MPa), 19/190MPa, 18/180MPa, 17/170MPa ruptured by the cyclic creep tests were observed. The final creep fracture was preceded by necking as in the static creep fracture. Many creep voids (or dimples) occurred near the necking area. These voids occurred from cyclic creep damage, and the size and area of the voids decreased with a decrease in the stress ranges. The shapes of the higher stress specimens were more irregular than those of the lower stress specimens.

3. Conclusions

The results of the creep rupture time and creep rate showed retardation when compared with those of static creep. The reason for this is believed to be that the material was recovered during the 10 minute hold time corresponding to the minimum of cycling stress, and it is also believed that the value of the minimum stress was much lower. The cyclic creep results followed well the plot of the Norton's power law and Monkman-Grant relation. The creep rupture ductility decreased with a decrease in stresses, and there was no difference between the CC and SC. It was observed that the final fracture in the cyclic creep tests was preceded by necking as in the static creep fracture. Many creep voids (or dimples) occurred near the necking area. However, the size and area of the voids decreased with decreasing the magnitude of the σ_R, and the shapes of the higher stress specimens were more irregular than those for the low stress specimens.

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