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Cyclic Creep Behavior with Hold Time under Tension-Tension Loading Cycles of Grade 91 Steel

Woo-Gon Kim[a*], Jae-Young Park[b], Jinsung Jang[a]
[a] *Korea Atomic Energy Research Institute, 989-111, Daedeokdaero, Yuseong, Daejeon, Korea, 305-353*
[b] *Pukyong National University, 100 Yongdang-dong, Nam-gu, Busan, 608-739*
[*] *Corresponding author: wgkim@kaeri.re.kr*

1. Introduction

Modified 9Cr-1Mo steel (ASME Grade 91, hereafter Gr. 91) is regarded as a promising candidate for structural materials of Gen-IV reactor types such as steam generators, intermediate heat exchangers, and hot pipes in sodium-cooled fast reactors (SFR). Korea Atomic Energy Research Institute (KAERI) has established an R&D program to develop the Gen-IV SFR system by 2028, and presently, key technologies for constructing a demonstration reactor are being developed step by step through the R&D program.

Cyclic deformation behavior is very important in practice because the high-temperature structural components are exposed under the cyclic conditions of repeated loading. In the case of static creep (SC), the response of the material is simple as a static state of monotonic loading. However, in the case of cyclic creep (CC), it is complex because of a dynamic loading. So far, cyclic creep data have been rarely reported and it has not been understood well whether the cyclic creep will accelerate or retard the creep rate and creep life compared with static creep, because not only is the plastic deformation under cyclic loading drastically different from that under monotonic loading, but the cyclic creep response is also dependent on the cycling frequency, stress range, stress ratio, and hold period 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 performed with various hold times and stress ratios under tension-tension loading cycles. Effect of the hold time and stress ratio on cyclic creep behavior was investigated and discussed.

2. Methods and Results

2.1 Experimental procedures

A commercial grade hot-rolled Gr. 91 steel 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 the cyclic creep tests were of a cylindrical form with a 30 mm gauge length and 6 mm diameter. The tension-tension cyclic creep tests were performed with the hold times of 1, 3, 5, 10, 20, and 30 min at four stress ratios (R) of R=0.8, 0.85, 0.90, 0.95 at 600 ^{o}C, as listed in Table 1. A value of mean stress in the loading cycles was constantly set at 160MPa. The mean stress (σ_{mean}), stress ratio (R), maximum stress (σ_{max}), and minimum stress (σ_{min}) are defined as follows:

$$\sigma_{mean} = \frac{1}{2}(\sigma_{max} + \sigma_{min}) \quad (1)$$

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (2)$$

$$\sigma_{max} = \frac{2\sigma_{mean}}{(1+R)} \quad (3)$$

$$\sigma_{min} = \frac{2\sigma_{mean}}{(1+1/R)} \quad (4)$$

Load-controlled tension-tension cyclic tests were performed using a universal testing machine with a 100KN capacity (Model No.: 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 main components are composed of a three-zone heating furnace, temperature controller, extensometer, strain gage, data acquisition system (PC and monitor), and program controller. The cyclic tests were automatically conducted according to a scheduled program. The real-time data of the strain and 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. Experimental procedures referred to the recommendations of ASTM E139.

Table 1. Cyclic creep test conditions at 600^{o}C.

Stress ratio (R)	Applied stress (MPa)	Mean stress (MPa)	Hold time (min.)
0.80	σ_{max}=178 MPa σ_{min} =142 MPa	160	1, 3, 5, 10, 20, 30
0.85	σ_{max} =173 MPa σ_{min} =147 MPa	160	1, 3, 5, 10, 20, 30
0.90	σ_{max} =168 MPa σ_{min} =152 MPa	160	1, 3, 5, 10, 20, 30
0.95	σ_{max} =164 MPa σ_{min} =156 MPa	160	1, 3, 5, 10, 20, 30

2.2 Cyclic creep behavior

From a series of cyclic creep tests at 600 ^{o}C of Gr. 91 steel, the cyclic creep data were obtained. The influence of the hold time and stress ratio on cyclic creep behavior was investigated.

Fig. 1 shows the variations of the cyclic creep rupture time with the hold times at each stress ratio. At the lower stress ratios of R=0.80 and 0.85, the rupture time slightly decreases with an increase in hold time. The influence of hold time at the lower stress ratios does not show a large difference in the rupture time. However, the rupture time at short hold times (1-3min) of the high stress ratios (R=0.90 and 0.95) is longer than the long hold times (10-30min) and sharply decreases for up to the hold time (5min). The reason for this is that R=0.90 and R=0.95 was lower in the amplitude of stress range (σ_{max}-σ_{min}) than R=0.80 and R=0.85.

Fig. 2 shows the variations of the creep rate with the hold times at each stress ratio. The creep rate slightly increases with an increase in hold time. At the higher stress ratios of R=0.90 and 0.95, the creep rate sharply increases at the hold times of 1, 3, and 5 min. It is identified well that the creep rate and creep rupture time were closely related in the present investigation.

Fig. 3 shows the variations of number of cycles as a function of stress ratio at each hold time. At the hold times (HT) of HT=1 and 3 min, the number of cycles sharply increases with an increase in stress ratio. It means that both of the number of cycles and stress ratio was closely related to the rupture time.

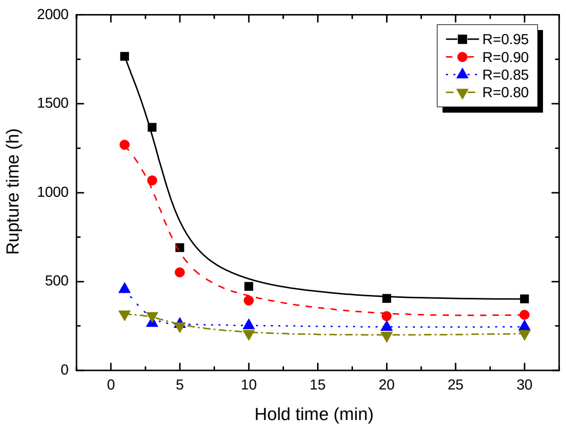

Fig. 1. Variations of the cyclic creep rupture time with the hold times at each stress ratio.

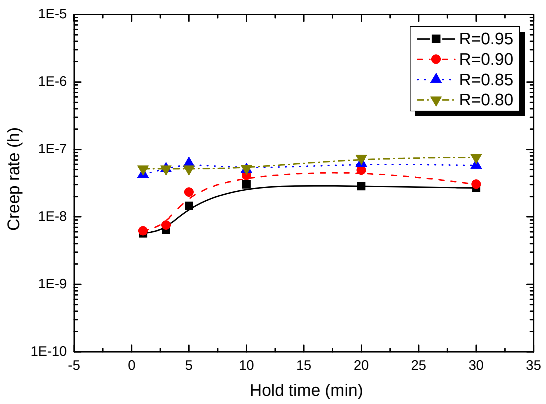

Fig. 2. Variations of the creep rate with the hold times at each stress ratio.

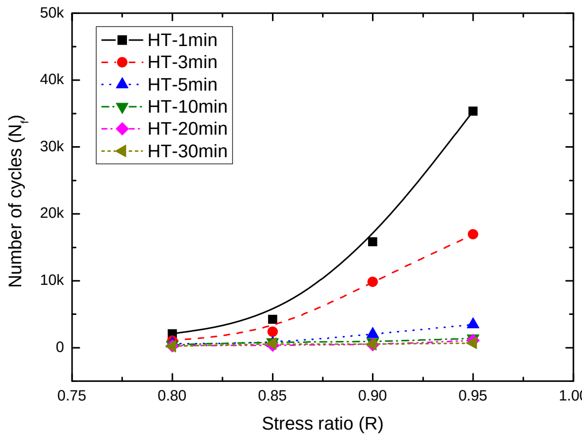

Fig. 3. Variations of number of cycles as a function of stress ratio at each hold time.

Accordingly, in the present investigation, it appeared that at the test conditions of the short hold time (HT=1 and 3 min) and higher stress ratios (R=0.90 and 0.95), the creep rupture time increased sharply and the creep rate decreased largely. At the other test conditions, the cyclic creep behavior was almost similar without a large difference regardless of the variations of the hold times and stress ratios.

3. Conclusions

The cyclic creep behavior for Gr, 91 steel was investigated from a series of cyclic creep tests which was performed with various hold times and stress ratios under tension-tension loading cycles. The results showed that at the test conditions of the short hold time (HT=1 and 3 min) and higher stress ratios (R=0.90 and 0.95), the cyclic rupture time increased sharply and the creep rate decreased largely. At the other test conditions, cyclic creep behavior was almost similar without a large difference regardless of the variations of the hold times and stress ratios.

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