Nuclear Engineering and Technology xxx (2017) 1–11

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Influence of hold time and stress ratio on cyclic creep properties under controlled tension loading cycles of grade 91 steel

Q12 *Woo-gon Kim* [a,*], *Jae-Young Park* [a], *I.M.W. Ekaputra* [b], *Seon-Jin Kim* [b], *and*
Q1 *Jinsung Jang* [a]

[a] *Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yuseong-gu, Daejeon, 305-353, Republic of Korea*
[b] *Pukyong National University, 365 Shinsunro, Nam-gu, Busan, 608-739, Republic of Korea*

ARTICLE INFO

Article history:
Received 26 July 2016
Received in revised form
21 November 2016
Accepted 28 November 2016
Available online xxx

Keywords:
Cyclic creep
Grade 91 steel
Hold time
Sodium-cooled fast reactors
Stress ratio

ABSTRACT

Influences of hold time and stress ratio on cyclic creep properties of Grade 91 steel were systemically investigated using a wide range of cyclic creep tests, which were performed with hold times (HTs) of 1 minute, 3 minutes, 5 minutes, 10 minutes, 20 minutes, and 30 minutes and stress ratios (R) of 0.5, 0.8, 0.85, 0.90, and 0.95 under tension loading cycles at 600°C. Under the influence of HT, the rupture time increased to HT = 5 minutes at R = 0.90 and R = 0.95, but there was no influence at R = 0.50, 0.80, and 0.85. The creep rate was constant regardless of an increase in the HT, except for the case of HT = 5 minutes at R = 0.90 and R = 0.95. Under the influence of stress ratio, the rupture time increased with an increase in the stress ratio, but the creep rate decreased. The cyclic creep led to a reduction in the rupture time and an acceleration in the creep rate compared with the case of monotonic creep. Cyclic creep was found to depend dominantly on the stress ratio rather than on the HT. Fracture surfaces displayed transgranular fractures resulting from microvoid coalescence, and the amount of microvoids increased with an increase in the stress ratio. Enhanced coarsening of the precipitates in the cyclic creep test specimens was found under all conditions.

1. Introduction

Grade 91 steel (hereafter referred to as Gr. 91) is regarded as a prime candidate material for structural components such as steam generators, intermediate heat exchangers, and hot pipes in sodium-cooled fast reactors. The selection of Gr. 91 steel is mainly based on its high creep and low cycle fatigue resistance compared with those properties exhibited by its counterparts such as 9Cr–1Mo and 2.25–1Mo steels [1–9].

Cyclic creep (CC) behavior is very important in practice because high-temperature structural components are exposed under the cyclic conditions of repeated loading during design life reaching 60 years in a sodium-cooled fast reactor plant. The concept of CC has evolved to describe

---

* *Corresponding author.*
E-mail address: wgkim@kaeri.re.kr (W.-g. Kim).

http://dx.doi.org/10.1016/j.net.2016.11.007

Please cite this article in press as: W.-g. Kim et al., Influence of hold time and stress ratio on cyclic creep properties under controlled tension loading cycles of grade 91 steel, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2016.11.007

material behavior under various loading conditions, in which testing under the load control mode is involved and the applied cycling frequency simulates the creep/fatigue interaction. The parameters of cyclic loading can vary in broad regions of stress and time. There can be considerable interaction between creep and cyclic loading. The effect of cyclic loading can either accelerate or retard creep deformation depending on the material structure, temperature, and stress conditions [10–15]. Although in static loading, the response of the material is simply a static state of monotonic loading, cyclic loading is a kind of complex, dynamic loading. However, so far, data on CC response have rarely been reported, and CC behavior has not been understood well, whether accelerating or retarding, in terms of experimental variables that influence creep deformation and fracture behavior. In view of this, it is necessary to systematically clarify various test conditions, such as hold time (HT), cycling frequency, stress ratio, stress range, etc., influencing the creep deformation and fracture process.

In this study, CC tests of wide ranges were performed with HTs and stress ratios under tension–tension loading cycles of Gr. 91 steel. Influence of the HTs and stress ratios on the CC response was systemically investigated, and fracture surfaces in the CC tested specimens were observed and analyzed.

2. Experimental procedures

A commercial-grade hot-rolled Gr. 91 steel plate with a thickness of 16 mm was used for the CC tests. The chemical composition is listed in Table 1. The heat treatment condition of the steel was normalized at 1,050°C/1 min/mm (this means an HT of 1 min/mm at 1,050°C) followed by tempering at 770°C/3 min/mm (this means an HT of 3 min/mm at 770°C). Identical round specimens with a 30 mm gauge length and 6 mm diameter were used for the CC specimens, as shown in Fig. 1.

To clarify the cyclic loading behavior, the five-case CC test conditions were widely employed from 1 minute to 30 minutes in HT and from 0.5 to 0.95 in stress ratio (R), such that HT = 1 minute, 3 minutes, 5 minutes, 10 minutes, 20 minutes, and 30 minutes, and R = 0.5, 0.8, 0.85, 0.90, and 0.95 at 600°C, as listed in Table 2. The load schedules in the tension–tension CC tests are shown in Fig. 2. In the figure, t_p is the time of a period cycle, and t_h is the HT. HT is identically taken at the maximum stress (σ_{max}) and minimum stress (σ_{min}) in the loading cycles. In all CC tests, the crosshead speed of loading and unloading was controlled at 200 mm/min. The loading pattern was almost rectangular. The value of mean stress in the loading cycles was fixed at 160 MPa. Terminologies in cyclic loading are defined as follows: the mean stress ($\sigma_{mean} = 1/2(\sigma_{max} + \sigma_{min})$, stress range ($\sigma_R = \sigma_{max} - \sigma_{min}$), and stress ratio ($R = \sigma_{min}/\sigma_{max}$). It should be noted that the values of the maximum stress (σ_{max}) and minimum stress (σ_{min}) at each stress ratio were obtained by calculating the relationships given by $\sigma_{max} = 2\sigma_{mean}/(1+R)$ and $\sigma_{min} = 2\sigma_{mean}/(1+1/R)$, respectively.

Load-controlled tension–tension cyclic tests were performed using a universal testing machine with 100 kN capacity (Model No.: RB Unitech-M), manufactured by R&B Company in Korea. The cyclic loading of the maximum and Q2 minimum stresses was applied to a specimen using an AC servomotor; this process was periodically repeated in the clockwise and counterclockwise directions. The main components were a three-zone heating furnace, a temperature controller, an extensometer, strain gage, a data acquisition system, and a program controller. The cyclic tests were automatically conducted by a scheduled program. The real-time data of the strain and stress at the elapsed times were monitored and collected by a PC through a high-precision extensometer attached to the specimen. The steady-state creep rate was as taken as a mean value of the secondary creep strain data. The CC testing apparatus is given in detail in the authors' previous study [16]. All experimental procedures referred to the recommendations of ASTM E139 [17]. Fracture surfaces in the CC tested specimens were observed using an optical microscope and a scanning electron microscope (SEM).

Table 1 – Chemical compositions of Gr. 91 steel (wt%).

C	Si	Mn	P	S	Ni	Cr	Mo	Cu	V	Al	N	Nb
0.115	0.23	0.415	0.012	0.0014	0.22	8.9	0.869	0.038	0.194	0.020	0.0513	0.073

Gr., grade.

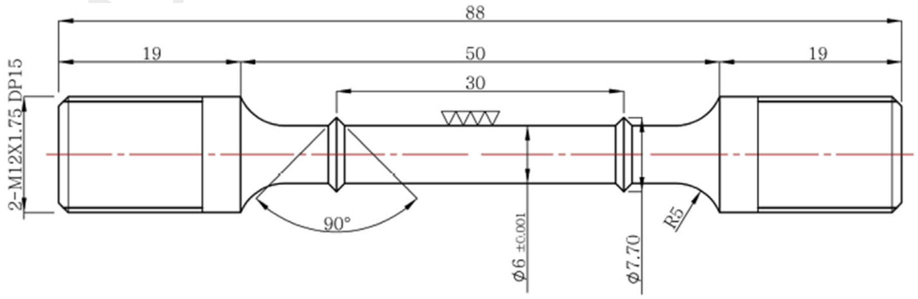

Fig. 1 – Dimensions of the CC test specimen (unit: mm). CC, cyclic creep.

Please cite this article in press as: W.-g. Kim et al., Influence of hold time and stress ratio on cyclic creep properties under controlled tension loading cycles of grade 91 steel, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2016.11.007