Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Long-term Creep Life Prediction and Its Reliability on HAZ Failure Data 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 referred to as Grade 91 steel) is regarded as a promising candidate for structural materials such as steam generators (SG), intermediate heat exchangers (IHX), and hot pipes in sodium-cooled fast reactors (SFR). Grade 91 steel was developed by the addition of strong carbide/nitride forming elements such as V and Nb along with controlled addition of N in the plain 9Cr–1Mo steel, offers a good combination of high creep strength and ductility over prolonged exposures at elevated temperatures [1]. The choice of Gr. 91 steel for sodium-cooled fast reactor (SFR) applications is guided by its low thermal expansion coefficient and high resistance to stress corrosion cracking in water–steam systems compared to austenitic stainless steels [2,3]. French Nuclear Design Code RCC-MRx which provides the guideline for design and construction of fast reactors incorporates creep design curves up to 3×10^{5} h, i.e., ~35 years for Gr. 91 steel. In view of achieving economical and cleaner nuclear energy, Gen-IV SFR is being designed for 60 years. However, the creep strength in the weld joints of these steel has been significantly reduced from that of the base metals due to Type IV failure, which is the cracking observed in the fine grain region of heat affected zone (HAZ). The weldments typically exhibit failure in the weakest regions of the HAZ which is sandwiched between the base metal on one side and the weld metal on the other side.

In this study, a large number of creep-rupture data available world-wide was collected on Grade 91 HAZ-failure data at 500-700^{o}C. Using the data, long-term creep life prediction was performed by Larson-Miller parameter and its reliability was analyzed by SCRI (Service Condition-creep Rupture Interference) model based on Z parameter.

2. Methods and Results

2.1 HAZ failure database

Creep-rupture data of Grade 91 HAZ-failure data were meticulously collected from the various sources [4]. The database included only the data with chemical composition and the heat treatments that conformed to the ASTM standards [1] for Grade 91 steel. From this creep-rupture data of weld joints, the data that exhibited HAZ failure were separated and compiled. There were 280 data points comprising of creep-rupture data in the temperature range 500-700^{o}C. Typical plot of stress vs. rupture time at 500-700^{o}C is shown in Fig. 1. The creep-rupture data is well distributed having reasonable scatter at each temperatures in the range 500-700^{o}C. However, it may be observed that only a fewer data are available at the extreme temperatures of 500 and 700^{o}C.

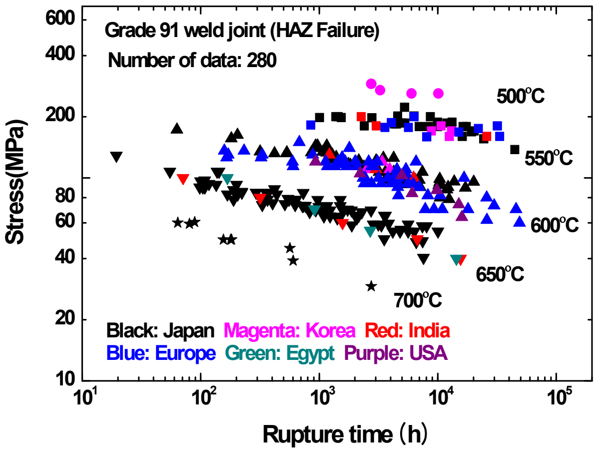

Fig.1. HAZ failure data at 500-700^{o}C of Grade 91 steel.

2.2 Creep life prediction and its reliability

The Larson–Miller (LM) parameter was used to predict the long-term creep life. An optimum value of material constant C_{LMP}=31 was obtained using least square regression analysis exhibiting the highest correlation coefficient. The master curve of the best fit is generally used with a polynomial form, but here at the highest temperature of 700^{o}C, the master curve of the 3rd polynomial resulted in an over estimation to creep-rupture data at lower stresses. To improve the creep life prediction at the low stress range of high temperature range, a master curve with a "sinh function" was newly proposed. The master curve with the sinh formulation conforms to the creep-rupture data of all the temperatures, as shown in Fig. 2. The master curve is given as

$$P(\sigma) = 37.04695 - 0.85\sinh(1.211\log\sigma) - 0.8795\log\sigma \quad (1)$$

The scatter in the experimental creep data describing the magnitude of data deviation from the obtained master curve is conveniently defined in terms of Z-parameter [5] as

$$Z_{i} = P_{i,exp} - P_{i,mean} \quad (2)$$

where Z_i is the deviation of experimental value $P_{i,exp}$ from the mean value $P_{i,mean}$ for i^{th} data (T_i, σ_i, t_{ri}). The values of $P_{i,mean}$ are obtained from the master creep-rupture relation represented by Eq. (1) and $P_{i,exp}$ values are evaluated using Eq. (2).

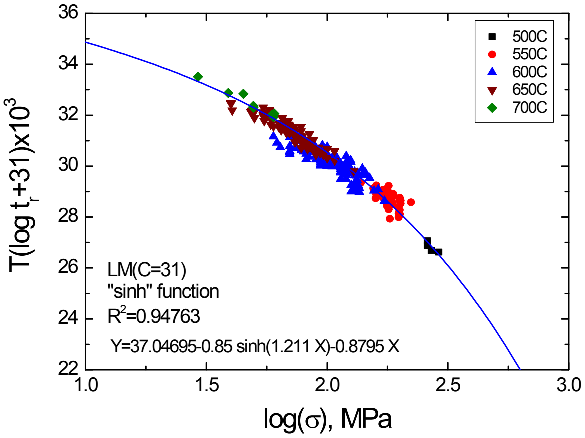

Fig. 2. A master curve of "sinh" function in the LM parameter.

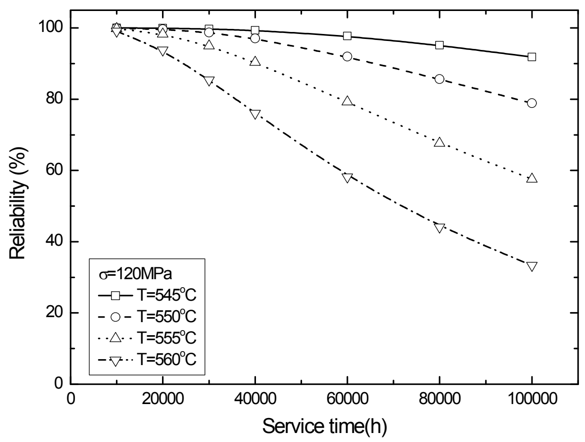

Fig. 3. Influence of increase in temperature on the reliability of creep life for different durations at σ=120 MPa.

The distribution of Z parameter followed normal distribution. For the normal distribution, the mean value, μ=0.11231 and standard deviation, S_{cr}= 0.29756 were obtained. The evaluation of the distribution of Z_S arising from the fluctuations in service condition becomes difficult using analytical method due to the fluctuations in at least two factors, i.e., the variations in operating temperature and stress. In view of this, the Monte-Carlo simulation (MCR) is used to evaluate reliability in the SCRI model and the details of this simulation are described in Ref. [5]. Large numbers of random variables are generated using MCR from the normal distribution of the Z-parameter. For a set of service conditions (T_i, σ_i, t_{ri}), the values of Z_S are calculated using Eq. (2). Meanwhile, the values of Z_{cr} are generated randomly in a normal distribution. The condition $Z_S<Z_{cr}$ defines the safe state of the material, whereas $Z_S>Z_{cr}$ indicates failure under the particular service condition. For total number of simulation (N), the reliability (R) is obtained as

$$R = \frac{n}{N} \tag{3}$$

where n is the number of safe states displaying $Z_S<Z_{cr}$ in the total number of simulation. Here, 30,000 random variables were generated for Z_S and Z_{cr} under certain conditions with fluctuations in the service temperatures and stresses, and reliability percentage was evaluated.
Following Z-parameter concept, the deviations in the experimental rupture data from the master curve are obtained using Eq. (2) as

$$Z = T(35 + \log t_r) \times 10^{-3} - (37.04695 - 0.85 \sinh (1.211 \log \sigma) - 0.8795 \log \sigma) \tag{4}$$

To account for the influence of increase in the operating temperature and stress conditions, a service temperature T=550°C and service stress σ=120MPa are chosen to assess reliability prediction up to 10^5 h. Reliability assessment was made using the chosen service temperature and stress conditions. The variations in reliability percentage with change in temperature in the range 545-560°C for the intervals of 5°C at constant stress of 120MPa for different durations are typically shown in Fig. 3. A larger decrease in reliability with increase in the service durations is observed for all the conditions.

3. Conclusion

Long-term creep life prediction on Grade 91 HAZ failure data was performed by LM parameter, and its reliability was successfully demonstrated using SCRI model based on Z-parameter. To improve the creep life prediction at the low stress range of high temperature range, the master curve with a "sinh" function was newly proposed. By Monte-Carlo simulation, reliability assessment was made using the chosen service temperature and stress conditions.

REFERENCES

[1] Standard Specification for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes, ASTM Standards A213/ A213M-11a, ASTM Inter., Pennsylvania, 2011.
[2] B.K. Choudhary and E. Isaac Samuel, Creep Behavior of Modified 9Cr–1Mo Ferritic Steel, J. Nucl. Mater., Vol. 412, pp. 82~89, 2011.
[3] W.G. Kim, J.Y. Park, S.N. Yin, D.W. Kim and S.J. Kim, Reliability Prediction of Long-term Creep Strength of Gr. 91 Steel for Next Generation Reactor Structure Materials, Kor. J. Met. Mater., Vol. 29, pp. 275~280, 2011.
[4] W.G. Kim and E. Isaac Samuel, Private Document, KAERI-IGCAR-2015-HAZ01, 2015.
[5] W.G. Kim, J.Y. Park, S.J. Kim and J. Jang, Reliability Assessment of Creep Rupture Life for Gr. 91 Steel, Mater. Des., Vol. 51, 1045~1051, 2013.