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A Research Status on High-Temperature Creep of Alloy 617 for Use in VHTR System

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1. Introduction

A very high temperature reactor (VHTR) is one of the most promising Gen-IV reactors for the economic production of electricity and hydrogen. Its major components are the reactor internals, reactor pressure vessel (RPV), hot gas ducts (HGD), and intermediate heat exchangers (IHX). Since the VHTR components are designed to be used for a 60 year lifetime at a high temperature, above all, creep behavior is one of the most important properties for design use because the creep strength are reduced owing to creep damage during long service life at elevated temperatures [1-2].

The Korea Atomic Energy Research Institute (KAERI) is developing a nuclear hydrogen development and demonstration (NHDD) plan with a capacity of 200MWth and core outlet temperature of 950 °C. Till date, the ASME design code for Alloy 617 was not developed for design use, and the draft Code Case for Alloy 617 was only prepared for the design of high-temperature Alloy 617 nuclear components. The draft Code Case is a modification from ASME Section III Subsection NH that was put forth by a special task force of the ASME subgroup that deals with elevated temperature design. The primary intended application of the draft Code Case is a VHTR. Presently, various creep data for Alloy 617 are being accumulated through Generation-IV forum (GIF) Material Handbook Database of a next-generation nuclear plant research and development. As per this, a new Alloy 617 Code Case is planned to be approved by 2017. However, to do so, various creep data and creep constants in air/helium environments, and base/weld metals etc. should be obtained to help draft the new Code Case, and creep behavior should be investigated through systematic analysis of a wide range of creep temperature and stress conditions.

In this study, a research status on creep works of Alloy 617 conducting at KAERI was introduced and summarized. Various experimental creep data and creep constants obtained in the air/helium environments and base/weld metals were presented and discussed using various creep equations and parameters.

2. Method and Results

2.1 Creep tests

To investigate the creep behavior between air and He environments, commercial grade Alloy 617 a hot-rolled plate with a thickness of 15.875 mm was used. Creep specimens in the air and He environments were fabricated in cylindrical form with a 30 mm gauge length and 6 mm diameter. The gage section was parallel to the longitudinal rolling direction. Creep data were obtained the creep tests performed with different stresses in air and He environments at 800, 850, 900, and 950°C. In the creep tests of the He environment, a vacuum chamber made for the quartz tube was used. Pure He gas of 99.999% was supplied to the specimens equipped in the quartz tube. Impurity concentration in pure He gas was O_2< 1.0 ppm, N_2< 5.0 ppm and H_2O < 1.0 ppm. Flow rate of the He gas during the creep test was controlled under 20 cm^3/min. Creep testing apparatus in the He environment is shown in Fig. 1, which consists of the quart tube, He flow meter, strain indicator, specimen and jigs, furnace controller, and data acquisition PC.

Fig. 1. Creep testing apparatus of He environment installed at KAERI.

In addition, to investigate the creep behavior for the base metal (BM) and weld metal (WM), Alloy 617 of a hot-rolled plate with a thickness of 25 mm was used. Welded specimens were fabricated by a gas tungsten arc welding (GTAW), and a filler metal was used for KW-T617 (brand name), manufactured by KISWEL Company. Presently, the creep tests are ongoing with different stress levels at 800, 850, 900, and 950°C. Long-term creep tests for the weld metals are running for 32,000h (3.6y) and 29,000h (3.3y) at 800°C. After the creep tests, fracture micrographs and oxidation layer for the crept specimens were comparatively investigated.

2.2 Analysis of creep tested data

Based on experimental creep data, the creep constants are determined using various creep laws; Norton's power law, Monkman-Grant Relation (MGR), Modified Monkman-Grant Relation (MMGR), and Zener-Hollomon Parameter (ZHP). Furthermore, new methods for predicting long-term creep life (or strength) were demonstrated, and improved methodologies were proposed and developed. The obtained creep data were contributed to the GIF Materials Handbook Database (DB) (ORNL website in USA) every year.

Fig. 2 shows a typical result of log (stress) vs. log (rupture time) of Alloy 617 tested in air and He environments at 950°C. As the rupture time increases, it shows clearly that the stress of He environment was more reduced than that of air one. The reason for this was investigated that the creep rate was faster in the He environment compared with the air one.

Fig. 3 shows a typical plot of Norton's power law of $\dot{\varepsilon}_s = A\sigma^n$ tested in the BM and WM at 950°C. As the stress increases, the creep rate of WM was significantly lower than that of BM. The reason for this was investigated that the rupture elongation of WM was largely reduced compared with that of BM.

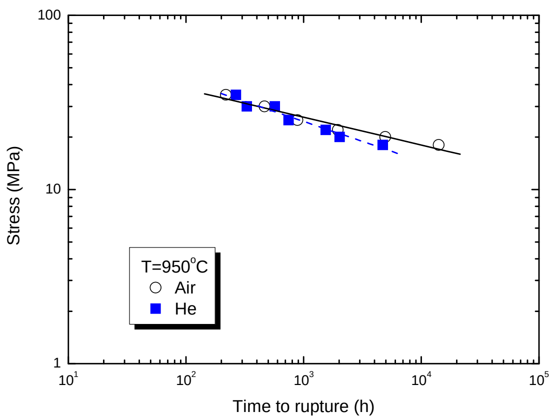

Fig. 2. A typical plot of stress vs. time to rupture tested in air and He environments at 950°C.

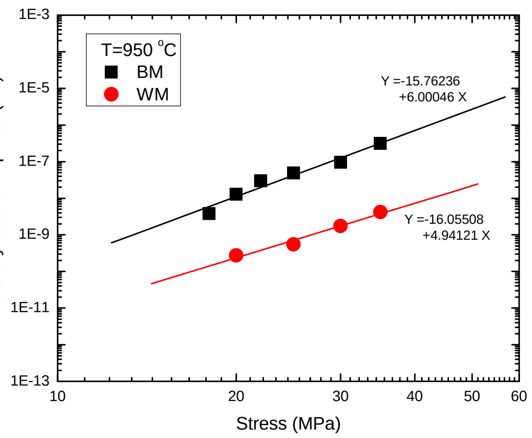

Fig. 3. A typical plot of creep rate vs. stress tested in the base metal (BM) and weld metal (WM) at 950°C.

Fig. 4 shows a plot of log stress vs. log time to rupture of Alloy 617 tested at 850 °C, 900 °C, and 950°C. It is obvious that there was a temperature effect in the creep stress with rupture times. A plot of Norton's power law revealed clearly a temperature effect, as $n \cong$ 5-6.

Fig. 5 shows a typical plot obtained for modified Monkman-Grant Relation (MMGR) of $\log(t_r/\varepsilon_f) + m\log\dot{\varepsilon}_s = C_{MMGR}$. The MMGR reduced the data scattering, and it showed a good fit with a straight line of m=0.97 regardless of the different temperatures. It was identified that the MMGR showed good agreement compared with the Monkman-Grant Relation (MGR).

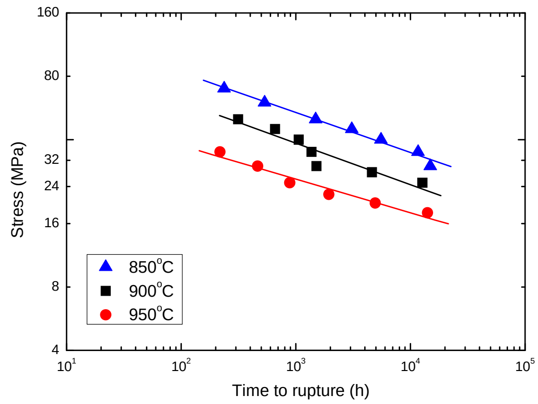

Fig. 4. Plot of stress vs. time to rupture of Alloy 617 tested at 850 °C, 900 °C, and 950°C.

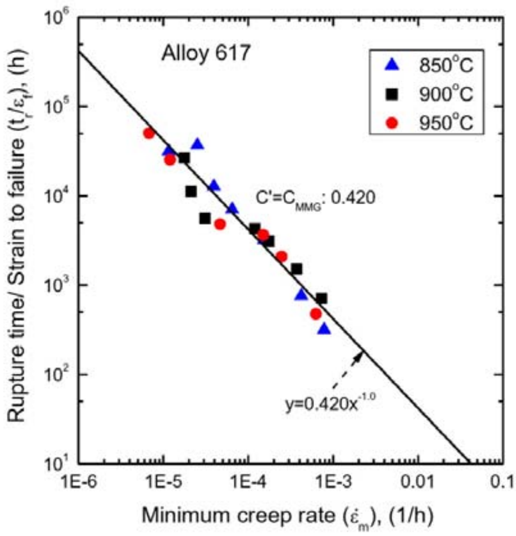

Fig. 5. Plot of the MMGR of the tested data at 850-950°C.

Fig. 6 shows a plot of the Zener-Holloman Parameter as a function of stress (σ/E) of Alloy 617 tested temperature. The creep strain rate is expressed as [3]

$$\dot{\varepsilon}_s = A_1\sigma^{n'}\exp(-Q/RT) \quad (1)$$

$$Z = \dot{\varepsilon}_s\exp(Q/RT) \quad (2)$$

where Q is the activation energy, A_1 and n' are the experimentally determined constants, and quantity Z is called the Zener-Hollomon parameter. A straight line can be seen well with a slope of n'=5.87 regardless of the three different temperatures. It can be inferred that the same mechanism is operative in the temperature range of the current study.

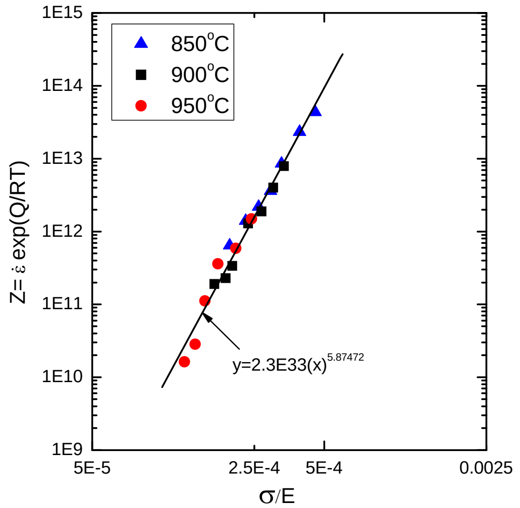

Fig. 6. Plot of the Zener-Holloman Parameter as a function stress (σ/E) of Alloy 617 tested at 850-950°C.

In addition, based on a continuum creep damage mechanics approach, λ was defined as the ratio of strain failure ε_f to MGR, $\dot{\varepsilon}_m \cdot t_r$, *i.e.*, the secondary creep strain. The λ equation can be given by [4, 5]

$$\lambda = \frac{\varepsilon_f}{\dot{\varepsilon}_m \cdot t_r} = \frac{\dot{\varepsilon}_{avg}}{\dot{\varepsilon}_m} \tag{3}$$

Alloy 617 was investigated to take λ=2.40, as shown in Fig. 7, which was a plot of the average creep rate (ACR) vs. the minimum creep rate (MCR) of the data tested at 850, 900, and 950°C of Alloy 617. For λ=1.5-2.5, the creep damage mechanism corresponds to cavitation, and for λ=1.5 or more, it corresponds to microstructural degradation such as a coarsening of the precipitates and/or dislocation substructural softening. It is known that Grade 91 steel of typical heat resistance steel has λ≅5 and more [6]. Thus, creep damage mechanism for Alloy 617 can be reasonably inferred by "cavitation" because Alloy 617 exhibits λ=2.40.

Fig. 8 shows a plot of long-term creep life prediction for Alloy 617 at 950°C. This result which was newly developed by author used the multi-constants C values in Larson-Miller Parameter (LMP) method. This method is to apply different values for a C value in the short-time region (high stress) and long-time region (low stress), because activation energy value is changed in the high and low stress regions. For 10^5h at 950°C, the single-constant value of C=18 was predicted as 7.2 MPa, but the two-constant value with C=12 and 20 revealed a good prediction to experimental data as 4.2 MPa. In addition, our KAERI's tested data were contributed to GIF Materials DB, and the technical reports were uploaded to website of GIF Materials DB every year. KAERI uploaded and issued 45 technical reports from 2009y to 2015y. A typical result contributed to GIF Database of KAERI's creep data is shown in Fig. 9.

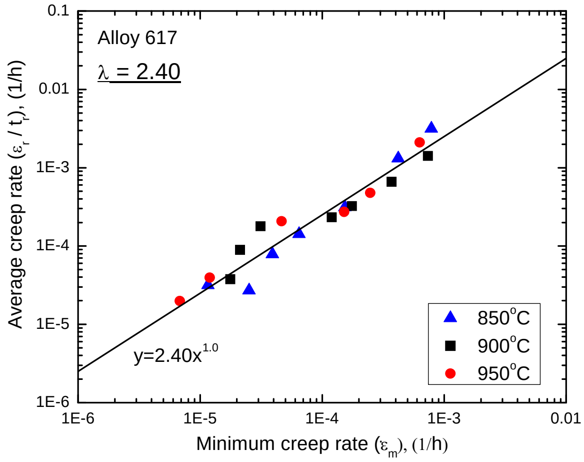

Fig. 7. Relationship of average creep rate and minimum creep rate tested of Alloy 617.

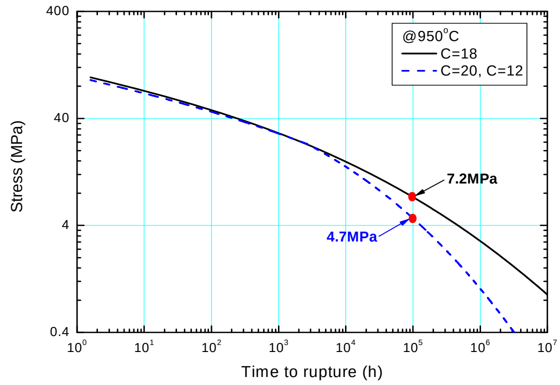

Fig. 8. Result of creep life prediction extrapolated using the single-and two-C values of Alloy 617 for 10^5h at 950°C.

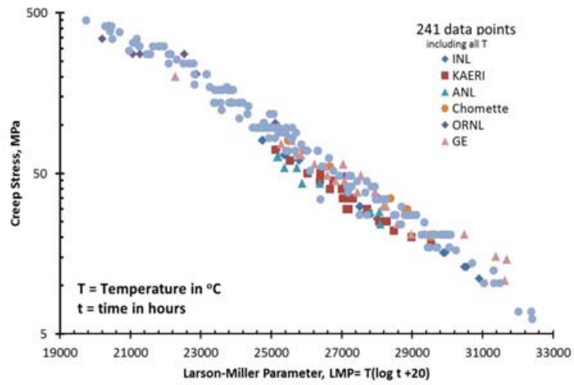

Fig. 9. A typical result contributed to GIF Material Handbook Database of KAERI's creep data.

3. Conclusions

A research status on creep works of Alloy 617 conducting at KAERI was introduced and summarized. Various experimental creep data in the air/helium environments and base/weld metals were obtained and database. Using various creep equations and parameters, the creep constants were determined for design use of Alloy 617. The stress of the He environment was more reduced than that of the air one. As the stress increases, the creep rate of WM was significantly lower than that of BM. The reason for this was that the rupture elongation of WM was largely reduced compared with that of BM. The MMGR reduced the data scattering, and it showed a good fit for straight line of m ≅ 1.0 as m=0.97. In the plot of ZHP and stress, a straight line was for $n^{'}$=5.87 regardless of the tested temperatures. Thus, it is inferred that the same creep mechanism was operative within the tested temperature ranges.

Acknowledgements

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