Analysis of creep behavior of Alloy 617 for use of VHTR system

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Abstract

Alloy 617 is one of the leading candidate materials for intermediate heat exchangers (IHX) application of a Very High Temperature Reactor (VHTR) system for economic production of electricity and hydrogen. Creep rupture data for Alloy 617 were obtained from a series of creep tests with different applied stresses at 850°C, 900°C and 950°C. On the basis of a systematic analysis of the experimental data, creep behaviour for Alloy 617 was analyzed using various creep relationships and laws, such as Norton’s power law, Monkman-Grant Relationships (MGR), Modified Monkman-Grant Relationships (MMGR), creep damage tolerance factor $\lambda$, and Zener-Hollomon Parameter ($Z$), and the creep constants used in each equation were reasonably determined. The creep curve of Alloy 617 was somewhat different from those of typical heat-resistance steels, and it did not exhibit a textbook creep curve. The secondary creep stage is unclear, and it appeared to exhibit a predominantly accelerated creep rate from the start of a tertiary creep stage in short time ranges. The creep deformation was dominantly developed from the formation and growth of cavity in creep damage process. The MMGR appeared to be more narrowed in data scattering than the MGR, and it followed well a straight line of $m=1.0$ as $m=0.97$. In the plot of the $Z$ parameter vs. stress, it obeyed a straight line with a slope of $n'=5.87$ regardless of the three different temperatures. It would be inferred that the same creep mechanism was operative within the present stress and temperature ranges, and the creep damage tolerance factor of Alloy 617 was found to be 2.40.

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Keywords: Creep; Alloy 617; VHTR; Monkman-Grant Relationship; Creep damage tolerance factor; Zener-Hollomon parameter

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1. Introduction

A very high temperature reactor (VHTR) is one of the most promising Generation-IV reactor types for the economic production of electricity and hydrogen. Its major components are the reactor internals, reactor pressure vessel (RPV), piping, hot gas ducts (HGD), and intermediate heat exchangers (IHX), as shown in Fig. 1. The IHX among these is a key component, and Alloy 617 is a prime candidate material owing to its superior creep resistance above 800°C compared with other potential superalloys [Cook (1984), Dewson and Li (2005), Kim et al. (2013), Kim et al. (2010)].

At present, the Korea Atomic Energy Research Institute (KAERI) is developing a nuclear hydrogen development and demonstration (NHDD) plan of a capacity with 200 MWth in the thermal and core outlet temperature of 950°C. It has been carried out in a government funded project called “Development of Key Technologies for Nuclear Hydrogen” since 2006 [Chang et al. (2007), Kim et al. (2013)]. Since the VHTR system is designed for a life span of 60 years operating at 950°C and 7 MPa in helium impurities, creep behavior is considered as one of the most important mechanical properties. Of the existing alloys, nickel-based Alloy 617 is the leading candidate for use in the next-generation nuclear plant (NGNP) heat exchangers because it has the highest creep strength of solid solution alloys under consideration for temperature above 850°C. However, until now, the ASME design code for Alloy 617 was not developed for design use. Material works to complete the ASME Alloy 617 code case development are ongoing according to a next-generation nuclear plant research and development plan. Through this plan, a new Alloy 617 Code Case is planned to be approved by 2017. To do so, a number of creep data and creep constants are required to complete the new Code Case, and creep behavior should also be investigated from a systematical analysis with creep temperature and stress conditions of wide ranges.

In the present investigation, creep properties of Alloy 617 are obtained through a series of creep tests under different applied stresses at three temperature ranges of 850, 900, and 950°C at the Korea Atomic Energy Research Institute (KAERI). An analysis of creep rupture behavior is performed using various creep relations and laws, and the constants used in the creep equations are determined on the basis of the creep experimental data, and the results are given and discussed.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A, A', A_1$</td>
<td>Constants in power-law form</td>
</tr>
<tr>
<td>$C_{MG}$</td>
<td>Monkman-Grant constant</td>
</tr>
<tr>
<td>$C_{MMG}$</td>
<td>Modified Monkman-Grant constant</td>
</tr>
<tr>
<td>$E$</td>
<td>Modulus elasticity (GPa)</td>
</tr>
<tr>
<td>$m, m'$</td>
<td>Slope constants in Monkman-Grant and modified Monkman-Grant relationships</td>
</tr>
<tr>
<td>$n, n', n_1$</td>
<td>Creep exponent in power-law form</td>
</tr>
<tr>
<td>$Q$</td>
<td>Activation Energy (J/mol)</td>
</tr>
<tr>
<td>$R$</td>
<td>Universal gas constant (8.3 J/mol K)</td>
</tr>
<tr>
<td>$T$</td>
<td>Absolute temperature (K)</td>
</tr>
<tr>
<td>$t_r$</td>
<td>Rupture time (h)</td>
</tr>
<tr>
<td>$Z$</td>
<td>Zener-Holloman Parameter</td>
</tr>
<tr>
<td>$\varepsilon_f$</td>
<td>Strain in creep failure (%)</td>
</tr>
<tr>
<td>$\varepsilon_m$</td>
<td>Minimum creep rate (1/s)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stress (MPa)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Creep damage tolerance factor</td>
</tr>
</tbody>
</table>

2. Experimental Details

Commercial grade nickel-based superalloy, Alloy 617 (Inconel 617), was used in this study. The material was a hot-rolled plate with a thickness of 15.875 mm. Creep test specimens 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. Circular
grooves were machined at both ends beyond the shoulder region of these specimens to attach a high-precision extensometer for monitoring the elongation during creep testing.

The loading frames used in the creep tests had a lever arm ratio of 20:1. A split furnace was used to heat the specimens of Alloy 617 in dry air at 850, 900, and 950°C. The pull rod and jig used for the creep tests were manufactured with a nickel-based superalloy material to sufficiently endure oxidation and thermal degradation during creep. Creep strain data with elapsed times were taken automatically through a PC. K-type thermocouples were used to monitor temperatures within the gage section of the specimens. Creep strain-time curves were obtained, and the value of the minimum creep strain rate was obtained by calculating the secondary creep stage from the strain–time creep curves. The creep properties of the rupture time, minimum creep rate, rupture elongation, and reduction of area were obtained in dry air at 850, 900, and 950°C of Alloy 617. The creep data were analyzed using the plots of various creep equations, and the constants in these creep equations are determined on the basis of a systematic analysis of the experimental data.

3. Results and Discussion

3.1. Creep curves of Alloy 617

The creep properties of Alloy 617 such as the rupture time, minimum creep rate, rupture elongation, and reduction of area were obtained at 850°C, 900°C, and 950°C. The creep data were analyzed using the plots of various creep equations, and the constants in these creep equations are reasonably determined on the basis of a systematic analysis of the experimental data.

Fig. 1 shows creep curves of typical heat-resistance steels. The creep curve of Alloy 617 seems to be somewhat different from those of typical heat-resistance steels, such as 2.25Cr-1Mo steel, 9Cr-1Mo steel, and austenitic stainless steel (type 316LN). The creep curves of low and high-Cr ferritic steels plot well distinct primary, secondary, and tertiary creep stages (called “textbook creep curve”), but Alloy 617 does not exhibit a textbook creep curve, as shown well in Figs. 2. The secondary creep stage is unclear, and it seems to exhibit a predominantly accelerated creep rate from the start of a tertiary creep stage in short time ranges.

3.2. Analysis of creep rupture data

A plot of log stress vs. log rupture time showed temperature dependence in the creep strength tested at 850, 900, and 950°C. A higher temperature results in a lower creep strength. The creep rate and rupture time can be given by stress dependence of the power law form, as follows.
The minimum creep rate obeys the stress dependence of the power law form at 850°C, 900°C, and 950°C. The slope is \( n \approx 5-6.8 \), as shown in Fig. 3. In addition, creep rupture time obeys stress dependence of the power law form at 850°C, 900°C, and 950°C. The slope is \( n' \approx 4.5-6.0 \), as shown in Fig. 4. Material constants of \( A \), \( A' \), \( n \), and \( n' \) values are almost the same regardless of the temperature changes, but the \( n \) and \( n' \) values have a decrease with increase in temperature. It means that closer values of respective \( n \) and \( n' \) had similar creep deformation and fracture mechanisms. The four constants are summarized in Table 1.

\[
\dot{\varepsilon}_m = A \sigma^n \\
I_r = A' \sigma^{n'}
\]

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Table 1 Material constants of \( A \), \( A' \), \( n \), and \( n' \) obtained for a power-law form at each temperature for Alloy 617.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>( A )</th>
<th>( n )</th>
<th>( A' )</th>
<th>( n' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>2.98x10^-13</td>
<td>5.10</td>
<td>9.28x10^11</td>
<td>5.17</td>
</tr>
<tr>
<td>900</td>
<td>1.83x10^-13</td>
<td>5.63</td>
<td>1.53x10^10</td>
<td>4.52</td>
</tr>
<tr>
<td>950</td>
<td>1.98x10^-14</td>
<td>6.87</td>
<td>3.11x10^11</td>
<td>6.00</td>
</tr>
</tbody>
</table>

Figs. 5 and 6 show the plots of the Monkman-Grant Relationships (MGR) of Eq. 3 and modified Monkman-Grant Relationships (MMGR) of Eq. 4 [Phaniraj et al. (2003)]. The equations are given as follows, respectively.

\[
\log t_r + m \log \dot{\varepsilon}_m = C_{MG} \\
\log \left( \frac{t_r}{\varepsilon_f} \right) + m' \log \dot{\varepsilon}_m = C_{MMG}
\]

In the plot of MGR, the data show some scattering at the three temperatures, and the slope on average is \( m=0.87 \). On the other hand, the MMGR reduced the data scattering, and it follows well a straight line with about unity as \( m=0.97 \) regardless of the temperature changes. The MMGR is superior in creep data plots to the MGR. In the MMG and MMGR, Alloy 617 have values of \( C_{MG}=0.52 \) and \( C_{MMG}=0.420 \). In addition, creep damage tolerance factor, \( \lambda \), provides a measure of the susceptibility of a material to localized cracking at stress and strain concentrations. It is considered to be a material performance characteristic. Based on a continuum creep damage mechanics approach, \( \lambda \) is defined as the ratio of strain failure \( \varepsilon_f \) to MGR, \( \dot{\varepsilon}_m \cdot t_r \), i.e., the secondary creep strain. The \( \lambda \) equation can be given by

\[
\log(\lambda) = \frac{\log \left( \frac{t_r}{\varepsilon_f} \right) + m' \log \dot{\varepsilon}_m - C_{MMG}}{m'}
\]
Alloy 617 was investigated to take $\lambda=2.40$, as shown in Fig. 7 showing the plot of average creep rate vs. minimum creep rate of Alloy 617 at 850-950°C. For $\lambda=1.5-2.5$, the creep damage mechanism corresponds to cavitation, and for $\lambda=1.5$ 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 $\lambda \approx 5$ and more [Phaniraj et al.(2003)].

Fig. 5. Plot showing the MGR of the creep data tested at 850, 900, and 950°C of Alloy 617.

Fig. 6. Plot showing the MMGR of the creep data of tested at 850, 900, and 950°C of Alloy 617.

Fig. 7. Plot of average creep rate vs. minimum creep rate tested at 850, 900, and 950°C of Alloy 617.

Fig. 8. Plot of the Zener-Holloman Parameter as a function of stress ($\sigma/E$) at 850, 900, and 950°C of Alloy 617.

Fig. 8 shows a plot of the Zener-Holloman Parameter ($Z$) as a function of stress ($\sigma/E$) of Alloy 617 tested at 850, 900, and 950°C. The creep strain rate is expressed as [Deter and Bacon (1988)]
\[
\dot{\varepsilon}_m = A_1 \sigma^{n_1} \exp(-Q/RT) \quad (6)
\]

\[
Z = \dot{\varepsilon}_m \exp(Q/RT) \quad (7)
\]

\[
Z = A_1 \sigma^{n_1} \quad (8)
\]

where \( Q \) is the activation energy, \( A_1 \) and \( n_1 \) 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 \( n' = 5.87 \) for Alloy 617 regardless of the three different temperatures. It can be inferred that the same mechanism is operative in the temperature range of the present creep conditions.

Fracture micrographs were also investigated from creep rupture specimens. Creep deformation of Alloy 617 was dominantly developed from the formation and growth of cavity in creep damage process. The creep cracks were initiated by linking and incorporating with the cavities, and were then developed along the cavities formed on the grain boundary. A failure occurred by the growth and interconnections of the cavities rather than a necking failure generated in the tertiary creep region. Failure mode was dominant for a typical intergranular fracture. The precipitates in creep ruptured specimens were formed coarsely on the grain boundaries and scattered throughout matrix. Cylindrically-shaped coarse carbides of Cr-rich M23C6, were mainly formed on the grain boundaries [Jang et al. (2008)].

**Conclusions**

To investigate the creep rupture behavior of Alloy 617, a series of creep tests was performed with different applied stresses at 850, 900, and 950°C. Creep behaviors were analyzed using creep data various creep laws on the basis of experimental creep rupture data. The creep curve of A617 was somewhat different with typical heat-resistance steels, and the secondary creep was unclear, and the tertiary creep stage was started at the early stage of creep time. Creep failure was due to the generation, growth and linking of cavities. The MMGR reduced the data scattering and presented a good straight line as \( m = 0.97 \). The MMGR showed a better plot than the MGR. Creep damage tolerance factor (\( \lambda \)) for Alloy 617 was found to be 2.4. This was in agreement with materials exhibiting typical cavitation damage. In the plot of \( Z \) parameter vs. stress, a straight line was found for \( n' = 5.87 \) regardless of the three different temperatures. It would be inferred that the same creep mechanism was operative within the current temperature ranges.

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