Low cycle fatigue properties of Alloy 617 base metal and weld joint at room temperature

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Abstract

Alloy 617 is one of the leading candidate materials for intermediate heat exchangers (IHX) of a Very High Temperature Reactor (VHTR). System start-ups and shut-downs as well as power transients will produce low cycle fatigue (LCF) loadings of components. As a series of the work to better understand the LCF properties of Alloy 617 weld joints at high temperature, firstly, in this work, strain-controlled LCF testing of Alloy 617 base metal (BM) and weld joint (WJ) by a gas tungsten arc weld process (GTAW) were carried out. Fully reserved total-strain controlled LCF tests have been conducted at room temperature with four total strain ranges of 1.5, 1.2, 0.9, and 0.6\%. For the LCF tests triangular test waveforms with a frequency of 0.25Hz were applied. The present paper is to characterize the LCF properties for Alloy 617 base metal (BM) and weld joint (WJ) from the cyclic stress response behavior and fatigue fracture behavior, with the comparative method. The cyclic stress response behavior was influenced by the level of total strain ranges and the material properties. Though base metal (BM) had shown higher plastic strain accumulation, the observed fatigue life of the weld joint (WJ) is lower than the base metal (BM). Coffin-Manson relationship and energy-life models can be used to determine the fatigue life.

Keywords: Low cycle fatigue (LCF); Alloy 617; Weld joint; Cyclic stress response; Fatigue life

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1. Introduction

The Very High Temperature Reactor (VHTR) is one of the most promising Generation-4 reactor types for the economic production of electricity and hydrogen. Its major components are the reactor internals, reactor pressure vessel (RPV), piping, hot gas duct (HGD), and intermediate heat exchangers (IHX). The IHX is a key component. Alloy 617 provides good properties for components of power generating plants with high temperature strength, a wide range of corrosive environment, and oxidation resistance. Therefore, Alloy 617 is being considered as a primary candidate due to its creep strength at elevated temperature above 800°C [Kim et al. (2013)].

System start-ups and start-downs as well as power transients will produce low cycle fatigue (LCF) loadings of components [Carroll et al. (2013)]. This consideration is used to determine the material resistance of the cyclic loadings and properties of Alloy 617. Generally, some of the components are combined with welding techniques. Therefore welded joints are inevitable in the construction of mechanical structures [Prasad et al. (2008)]. As well know, the welded joint is more brittle than base metal and may have several original defects, the fatigue life is predicted shorter than the base metal [Carroll et al. (2013)].

A series of research and development activities on the Alloy 617 weld joints has been carried out in KAERI. Meanwhile the reported data on LCF properties of the Alloy 617 weld joints need furthered investigation. In order to better understand fatigue properties of the Alloy 617 weld joints at high temperature, the main purpose of this paper is to investigate the cyclic stress response and fatigue life behavior for Alloy 617 base metal (BM) and weld joint (WJ). Thereafter in this investigation, the LCF properties of the Alloy 617 BM and WJ at room temperature in air is being compared.

In the present paper, strain-life curves are derived from fatigue tests under completely reversed ($R = -1$) cyclic loading between constant strain limits with measurement of stress amplitude, as listed in ASTM Standard No. 606. This study investigated the LCF behavior and fatigue life were also examined and compared using two different models which is very commonly used by researcher, such as Coffin-Manson relationship and energy-life to find the best model for life prediction.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| $\Delta \varepsilon_T$ | total strain range |
| $\Delta \varepsilon_p$ | plastic strain range |
| E | modulus elasticity (GPa) |
| $\varepsilon_f$ | fatigue ductility coefficient |
| $\sigma_f$ | fatigue strength coefficient |
| c | fatigue ductility exponent |
| b | fatigue strength exponent |
| $N_f$ | number of cycles to failure (cycles) |
| $\Delta \sigma$ | stress range (MPa) |
| $n'$ | cyclic strain hardening exponent |
| $\Delta W_T$ | total strain energy (MJ/m³) |
| A | material energy absorption capacity |
| $\alpha$ | fatigue exponent |

2. Experimental Details

The chemical composition of the Alloy 617 is given in Table 1. The amount of each element was well within the ASTM standards E606 specifications. The BM was a hot rolled plate a thickness of 25 mm. Afterward, welded plate cuts prepared for the WJ specimen which has a single V-groove with an angle of 80° from the GTAW process. A filler metal was used for KW-T617 (brand name) that was prepared according to AWS specifications. Details of the welding method can be found in Kim et al. (2013). Cylindrical samples, used for LCF testing, were machined from weld pad as shown in Fig. 1 and Fig. 2 is a schematic geometry of LCF specimen.
Table 1. The Chemical composition of Alloy 617 plate (wt%).

|        | C   | Ni  | Fe  | Si  | Mn  | Co  | Cr  | Ti  | P   | S   | Mo  | Al  | B   | Cu  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| ASTM Spec. | Min | 0.05 | Bal. | -   | -   | 10.0 | 20.0 | -   | -   | 8.0 | 0.8 | -   | -   | -   |
|         | Max | 0.15 | Bal. | 3.0 | 0.5 | 0.5 | 15.0 | 24.0 | 0.6 | 0.015 | 0.015 | 10.0 | 1.5 | 0.006 | 0.5 |
| Alloy617 |     | 0.08 | 53.11 | 0.949 | 0.084 | 0.029 | 12.3 | 22.2 | 0.41 | 0.003 | <0.002 | 9.5 | 1.06 | <0.002 | 0.0268 |

Fully reversed total axial strain controlled LCF tests were conducted at room temperature in the air at four different total strain-controlled ranges, i.e. 1.5, 1.2, 0.9 and 0.6% using a servo hydraulic machine equipped at a constant frequency of 0.25Hz. The waveform is chosen in triangular shape as we know that no hold time applied in this experiment. The fatigue life was taken as the cycle number corresponding to a 100% drop in the peak tensile stress.

3. Results and Discussion

3.1. Low cycle fatigue properties of Alloy 617

From experimental results, the tests under different total strain-controlled versus number of cycles to failure of LCF were summarized in Fig. 3. The given results are for total strain-controlled 1.5, 1.2, 0.9 and 0.6%, respectively. The figure evidently shows similar behavior for both BM and WJ specimens decreasing in fatigue life according to increasing in total strain range. In consequence of small deformation that occurred when the amplitude stress also smaller in the specimens. The grain movement proportionally leads to deformation and generate strength of material rapidly decreasing. Therefore, the dislocations of grain boundaries play a major role in the fatigue crack initiation [Paul et al. (2010)].

In engineering materials usually exhibits cyclic hardening or softening to some level in cyclic plastic deformation process. The higher stress is generating a crack is to nucleate. For higher total strain ranges cyclic softening are observed until the rapid stress drop to failure. At the lower total strain ranges more likely constant saturation phases...
is stabilized during the cyclic loading and decreasing slowly until failure [Carroll et al. (2013)]. Fig. 4 presents four conditions fully reversed total strain-controlled LCF tests (Left) is the cyclic stress response curves of the Alloy 617 for BM and WJ at room temperature. While, increase in stress amplitude with number of cycles for total strain controlled showed cyclic hardening and contrarily the decreasing in stress amplitude means cyclic softening. Alloy 617 showed a combination of cyclic hardening and softening followed by final fracture, almost without reaching its saturated values except on lower total strain ranges. Therefore, the cyclic hardening and softening phases on material also depend on loading conditions [Paul et al. (2010)]. Afterward, (Right) is a comparison of peak stress as a function of cycle between four total strain range conditions. For consideration, the cyclic loading must contain maximum and minimum peak stress level. The peak stress may be compression and tension and may change depend on time. The stress-strain hysteresis loops at half-life were identified and compared for Alloy 617 BM and WJ, as shown in Fig. 5. So far, from this figure we can clearly see the WJ showed a longer narrow and thin hysteresis loop, and the BM showed a short and fat hysteresis loop that reflects the characteristic of BM being low strength and high ductility, otherwise the WJ being high strength and low ductility. Furthermore, the higher plastic strain enhances the growth of crack [Bannantine et al. (1990)].
3.2. Fatigue life evaluation

The results from half-life of LCF tests were obtained for Alloy 617 BM and WJ. The Coffin-Manson relationship, Eq. (1), shows the experimental relationship between plastic strain, elastic strain, and total strain range and number of cycles to failure with log-log coordinates in four conditions of fatigue tests. It can be obtained from the correlation between Eq. (1) to find the constants value from the best fit line using a least square method approach.

\[
\frac{\Delta \varepsilon_f}{2} = \varepsilon'_f (2N_f)^c + \frac{\sigma'_f}{E} (2N_f)^b
\]

(1)

Where \( E \) is the modulus elasticity, and \( \sigma'_f \) and \( \varepsilon'_f \) are the fatigue strength and fatigue ductility coefficients. \( b \) and \( c \) are material exponents measured in fully alternated tension-compression fatigue tests. The results of analysis for regression coefficients of Alloy 617 BM and WJ at room temperature for strain-life parameter are given in Table 2, respectively [Bannatine et al. (1990); Burke et al. (2006); Meggiolaro et al. (2004); Dowling (2007)].

The predicted life obtained by employing the present parameter and also compared to the experimental data of fatigue life shows in Fig. 6. It shows that the proposed models can correlate the experimental data and all predictions are within range by factor of 2.

Halford and Morrow [Morrow (1964)] provide an analysis procedure for LCF of metals based on plastic energy concept. The plastic strain energy density which is defined as the inner area of the cyclic stress-strain hysteresis loop. Generally, the plastic strain energy calculated at half-life. The plastic energy can be calculated based on components of stress and plastic strain range, because the value of elastic energy is very small or negligible. For a Masing material, the cyclic plastic strain energy as the area of hysteresis loop can be expressed as in Eq. (2). Where \( n' \) is the cyclic hardening exponent.

\[
\Delta W_p = \left( \frac{1-n'}{1+n'} \right) \Delta \sigma \Delta \varepsilon_p
\]

(2)

Thus, the hysteresis plastic strain energy is related to the number of cycles to failure by a Power law function. Because of this consideration, the similar relationship can be derived for total energy dissipated or number of cycles to failure in Eq. (3). Where, \( A \) and \( \alpha \) are material constants, representing material energy absorption capacity and fatigue exponent. The coefficients value can be determined from the best fit line of experimental data.

![Table 2. Regression coefficients for analysis of Alloy 617 at room temperature for strain-life parameter.](image)

![Fig. 6. Life prediction evaluation for strain-life based parameter.](image)

![Fig. 7. Life prediction evaluation for energy dissipated parameter.](image)
\[ \Delta W_T = A(2N_f)^\alpha \]  

The values of material energy absorption capacity and fatigue exponent for Alloy 617 were identified, which is for BM are 56860.41 and -0.54727 and for WJ are 104059.08 and -0.67608, respectively. These values can be used to find the predicted life for Alloy 617 based on energy density parameters. Generally, the prediction of fatigue life have been investigated and compared with experimental data in Fig. 7. Where all predictions are within range by factor of 2 of the experimental data [Abdalla et al. (2009); Lagoda (2001); Jahed et al. (2006)].

4. Conclusions

The LCF properties of Alloy 617 BM and WJ at room temperature for four different total strain range conditions, i.e. 1.5, 1.2, 0.9, 0.6% and fatigue life for different two models using Coffin-Manson relationship and energy-life have been investigated and determined. The observed fatigue life of the WJ is lower than BM. The BM shown elastic strain is dominant at long lives. The BM had longer transition fatigue life than the WJ. It can be found that Coffin-Manson relationship further shown its value is more appropriate when compared with data experimental life. The error accuracy were identified for Coffin-Manson relationship and energy-life are 18.4% and 25.3%, respectively.

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References

Kim, W.G., Park, J.Y., Ekaputra, I.M.W., Hong, S.D., Kim, S.J. and Kim, Y.W., 2013. Comparative Study on the High-Temperature Tensile and Creep Properties of Alloy 617 Base and Weld Metals, Journal of Mechanical Science and Technology, 27 (8): 2331–2340.
Carroll, L.J., Cabet, C., Carroll, M.C. and Wright, R.N., 2013. The Development of Microstructural Damage during High Temperature Creep-Fatigue of a Nickel Alloy, International Journal of Fatigue, 47: 312–321.
Prasad Reddy, G.V., Sandhyaya, R., Valsan, M. and Bhanu Sankara Rao, M., 2008. High Temperature Low Cycle Fatigue Properties of 316(N)/316(N) Weld Joints, International Journal of Fatigue, 30: 538–546.
Chen, X., Sokolov, M.A., Sham, S., Erdman, D.L., Busby, J.T., Mo, M. and Stubbins, J.F., 2013. Experimental and Modeling Results of Creep-Fatigue Life of Inconel 617 and Haynes 230 at 850°C, Journal of Nuclear Materials, 432: 94–101.
ASTM E 606-92. 2002. "Standard Practice for Strain-Controlled Fatigue Testing". In: Annual Book of ASTM Standards. Vol. 03.01. Printed in Baltimore, MD, U.S.A., pp.569.
Paul, S.K., Sivaprasad, S., Dhar, S, Tarafder, S., 2010. Cyclic Plastic Deformation and Cyclic Hardening/Softening Behavior in 304LN Stainless Steel, Theoretical and Applied Fracture Mechanics, 54: 63–70.
Julie A. Bannatine, Jess J. Comer, and James L. Handrock. 1990. "Fundamentals of Metal Fatigue Analysis". Prentice Hall, Englewood Cliffs, New Jersey, pp.46–66.
Burke, M.A. and Beck, C.G., 1987. The High Temperature Low Cycle Fatigue Behavior of the Nickel Base Alloy IN-617, Vol. 15A.
Meggioro, M.A., Castro, J.T.P., 2004. Statistical Evaluation of Strain-Life Fatigue Crack Initiation Predictions. Int. J. of Fatigue. 26: 463–476.
Norman E. Dowling. 2007. ‘Mechanical Behavior of Materials’. Pearson Prentice Hall, USA, pp.718–750.
Morrow JD. 1964. Cyclic Plastic Strain Energy and Fatigue of Metals, Internal Friction, Damping, and Cyclic Plasticity. ASTM STP 378.
Philadelphia (PA): American Society for Testing and Materials.
Abdalla, J.A., Hawileh, R.A., Oudah, F., Abdelrahman, K., 2009. Energy-Based Prediction of Low-Cycle Fatigue Life of BS 460B and BS B500B Steel Bars, Materials and Design, 30: 4405–4413.
Lagoda, T., 2001. Energy Models for Fatigue Life Estimation under Uniaxial Random Loading, Part I: The Model Elaboration, International Journal of Fatigue, 23: 467–480.
Jahed, H., Varvani-Faharani, A., 2006. Upper and Lower Fatigue Life Limits Model Using Energy-Based Fatigue Properties, International Journal of Fatigue, 28: 467–473.