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Low Cycle Fatigue Life Assessment of Alloy 617 Weldments at 900℃ by Coffin-Manson and Strain Energy Density-Based Models

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Abstract: This work aims to investigate on the low cycle fatigue life assessment, which is adopted on the strain-life relationship, or better known as the Coffin-Manson relationship, and also the strain energy density-based model. The low cycle fatigue test results of Alloy 617 weldments under 900^{o}C have been statistically estimated through the Coffin-Manson relationship according to the provided strain profile. In addition, the strain energy density-based model is proposed to represent the energy dissipated per cycle as fatigue damage parameter. Based on the results, Alloy 617 weldments followed the Coffin-Manson relationship and strain energy density-based model well, and they were compatible with the experimental data. The predicted lives based on these two proposed models were examined with the experimental data to select a proper life prediction parameter.

Key Words : Alloy 617, Low Cycle Fatigue (LCF), Weldment, Life Prediction, Coffin-Manson, Strain Energy

— Nomenclature —

E : Modulus elasticity [GPa]
c : Fatigue ductility exponent
b : Fatigue strength exponent
N_f : Number of cycles to failure [cycles]
N_T : Transition of fatigue life [cycles]
K' : Cyclic strength coefficient [MPa]
n' : Cyclic strain hardening exponent
A : Material energy absorption capacity

Greek Symbols

$\Delta\varepsilon_T$: Total strain range
$\Delta\varepsilon_P$: Plastic strain range
$\Delta\varepsilon_e$: Elastic strain range
ε_f' : Fatigue ductility coefficient
σ_f' : Fatigue strength coefficient
$\Delta\sigma$: Stress amplitude [MPa]
ΔW_T : Total strain energy density [MJ/m^3]
ΔW_P : Plastic strain energy density [MJ/m^3]
ΔW_e : Elastic strain energy density [MJ/m^3]
α : Fatigue exponent

1. Introduction

Extensive investigations have been conducted to develop advanced materials which can be used in the nuclear fusion reactors. Nowadays, Pukyong National University(PKNU) and Korea Atomic Energy Research Institute(KAERI) are investigating the Nickel-based superalloy Alloy 617, which will

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be utilized in the Very High Temperature gas-cooled Reactor (VHTR). In the VHTR system, the primary components incorporate the reactor internals, reactor pressure vessel (RPV), piping, hot gas ducts (HGD), and intermediate heat exchangers (IHX) are the principal components.[1-3] On the existing Nickel-based alloy which will be utilized in the IHX component, Alloy 617 is considered as a leading material because of its high temperature strength, such as creep, fatigue, or combined creep-fatigue phenomena at high temperatures, it also has excellent superior to a comprehensive oxidation and corrosive environments.[2-3]

This study deals with the low cycle fatigue (LCF) deformation which indicates a major damage in the reactor components from a temperature alteration caused by thermal strain through operation, such as startups and shutdowns, and to power transients of VHTR coolant with a low loading rate.[3] Hence, the significant concern of LCF failure mechanism is necessary in the engineering structure and life estimation of such material design that worked on extreme condition.[2-3]

Comprehensive researches have been made in the past decades on Alloy 617. However, it is still less data and research progress concerning on the weldments material. The weldments are also considerable concern in the engineering structure because of the heterogeneity link in components and probably have a few original flaws, which could form the initial location of failure.[3] In this study focuses on the LCF life assessment models of Alloy 617 under temperature of 900°C. An analysis of fatigue life was implemented using the strain-life relationship, or better known as the Coffin-Manson (C-M) relationship and strain energy density-based model. The material constants are determined through the fatigue life models and its variations are evaluated by comparing it with the experimental data.

2. The low cycle fatigue life assessment models

For reliability design aspect, fatigue life assessment is very important and it can be done through the experimental data. In this paper, most of the fatigue evaluation methods for predicting material constants are particularly based on experimental results. The statistical evaluation of the existing C-M relationship and strain energy density based model are presented. The studied model will estimate the universal slope.

2.1 Coffin-Manson (C-M) relationship

The well-known C-M fatigue life evaluation relationship regulates the number of cycles to failure, N_f, with the provided strain profile. At the moment, the C-M relationship can be adopted in the LCF issue, when the plastic strain range, $\Delta\varepsilon_P$, is equal or in fact is bigger than the elastic strain range, $\Delta\varepsilon_e$. The C-M relationship can be arranged with the stress-strain behavior, as though the Ramberg-Osgood formula, to consider the cyclic stress response behavior of the material during cyclic deformation.[4] The equation is used;

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\epsilon_p}{2} + \frac{\Delta\epsilon_e}{2} = \frac{\Delta\sigma}{E} + \left(\frac{\Delta\epsilon_p}{2K\prime}\right)^{n\prime} \quad (1)$$

LCF problem under fully reversed condition can be expressed as a connection with the total strain range, $\Delta\varepsilon_T$, and N_f as follows;[4-5]

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\epsilon_p}{2} + \frac{\Delta\epsilon_e}{2} = \frac{\sigma_f{}'}{E}\left(2N_f\right)^b + \epsilon_f{}'\left(2N_f\right)^c \quad (2)$$

Eq. 2 mathematically represents the Fig. 1. Under high total strain range, we noticed that the plastic regime governed the fatigue process, otherwise, the low total strain range is generated in the elastic regime. The domain in the point of contact among plastic and elastic straight line is interpreted by the transition of the fatigue life, N_t. The region to the left of the N_t is defined by the plastic deformation dominant region, otherwise is the elastic deformation dominant region.

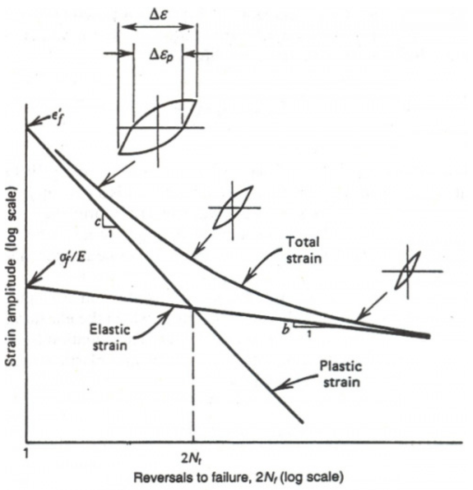

Fig. 1 Definition of strain-life relationship diagram

2.2 Strain energy density model

In recent years, numerous studies have been reported for estimating the variance on fatigue life prediction corresponded with the approach models. One of the proposed model that seem to be more complex, the so-called strain energy density-based model. The LCF life analysis based on this energy concept that has been used to separate the influence of microstructures on the fatigue life. Morrow and Halford[6-7] proposed the total dissipated energy is the summation of the plastic and the elastic strain energy in J/m^3. This damage parameter is saturated when subjected to the cyclic hardening or softening phase.[6)] Therefore, it is thought that the strain energy density is a better parameter for extreme hardening or softening conditions.

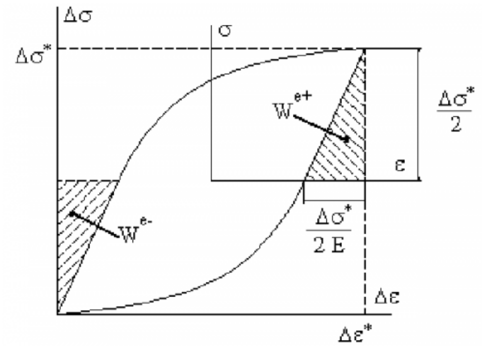

Fig. 2 Schematic interpretation of plastic and elastic strain energy density parameter

Fig. 2 shows a description of the stable hysteresis loop. The plastic strain energy is a definition of the inside area within the hysteresis loop and the elastic strain energy as described in Fig. 2. In this study, assuming this material exhibiting the Masing behavior[8)], the hysteresis loop at half-life is evaluated for the plastic strain energy, ΔW_P, and the elastic strain energy density, ΔW_e, respectively, use the following equation;

$$\Delta W_p = \int_0^{\epsilon} \Delta\sigma d\epsilon_p = \left(\frac{1-n'}{1+n'}\right)\Delta\sigma\Delta\epsilon_p$$

$$\Delta W_p = 4\left(\frac{1-n'}{1+n'}\right)\sigma_f{}'\epsilon_f{}'\left(2N_f\right)^{b+c} \tag{3}$$

Nevertheless the elastic strain energy is defined with;

$$\Delta W_e = \int_0^{\epsilon} \Delta\sigma d\epsilon_e = \frac{1}{2E}\left(\frac{\Delta\sigma}{2}\right)^2 \tag{4}$$

Therefore, the total strain energy as the summation of the plastic and elastic energy is described by the following equation;

$$\Delta W_T = 4\left(\frac{1-n'}{1+n'}\right)\sigma_f{}'\epsilon_f'\left(2N_f\right)^{b+c} + \frac{1}{2E}\left(\frac{\Delta\sigma}{2}\right)^2 \tag{5}$$

The total strain energy density can be related to the N_f (or number of reversals to failure, $2N_f$) through the power law and it can be described as the following equation;

$$\Delta W_T = A\left(2N_f\right)^{\alpha} \tag{6}$$

The material parameters A and α can be evaluated and the predicted lives also can be calculated too through the strain energy density and the energy parameters as follows;

$$2N_f = \left(\frac{\Delta W_T}{A}\right)^{1/\alpha} \tag{7}$$

In this study, the stabilized hysteresis loop was used to define the universal slope of this Alloy 617 weldments at 900℃ condition in any desired total strain controlled.

3. Experimental section

Commercial grade Nickel-based Alloy 617 was used for this study, which was a hot-rolled plate that has been approved by ASME code. Fig. 3 shows the geometry of cylindrical LCF specimens, and the LCF test specimens has 12 mm of the gauge length. The gauge section of the LCF specimen only covering a weld metal (WM) with dendritic structure and heat affected zone (HAZ) materials. Fully reversed LCF tests were performed at 900℃ under various total strain ranges applied, 0.6, 0.9, 1.2, and 1.5%, and a constant strain rate of 10^{-3}/s. The experimental results of LCF life are shown in Fig. 4. The criteria of the N_f, was determined as a 20% rapidly drop in the peak stresses ratio (peak tension and compression stresses). The details of the experimental preparation can be found in reference.[2)]

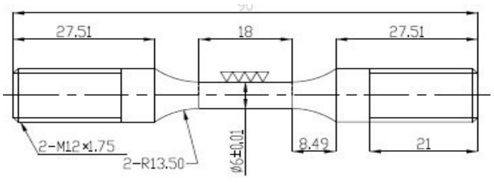

Fig. 3 Geometry of the cylindrical weldment specimen (All dimensions in mm)

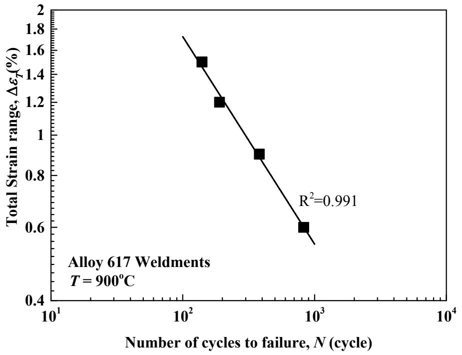

Fig. 4 The effect of total strain range controls on the LCF behavior of Alloy 617 weldment

4. Results and analysis

4.1 The C-M relationship

The cyclic stress-strain response is evaluated through the Ramberg-Osgood equation (Eq. 1). The linear plot of stress amplitude and plastic strain magnitude at half-life is shown in Fig. 5. From the figure, the plastic strain magnitude is increased with increasing in cyclic stress amplitude during LCF loadings. The linear regression can be taken and provides a measure to cyclic straining. Furthermore, the values of K' and n' are also shown in Fig. 5.

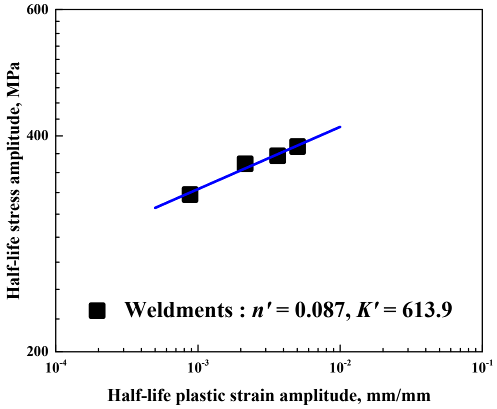

Fig. 5 The Ramberg-Osgood plots of the Alloy 617 weldments at 900℃

First, the C-M relationship is examined. Fig. 6 shows the C-M plots of total strain ranges and a number of reversals to failure. The results show a good correlation for this Alloy 617 weldment under isothermal condition. The fatigue parameters are determined using eq. 2, and by using a least square fit method to specify the universal slope. The C-M parameters are shown in Table 1. The universal *c* slope of -0.96 is obtained according to experimental data.

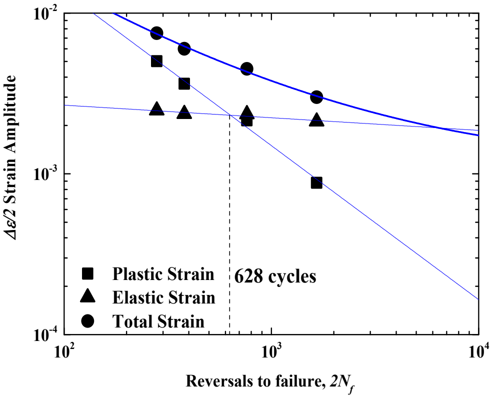

Fig. 6 C-M plots of the Alloy 617 weldments at 900℃ with reversals to failure

Table 1 The C-M parameters for the Alloy 617 weldments at 900℃

Parameters	Alloy 617 Weldment
εf’, Fatigue ductility coefficient	1.12
c, Fatigue ductility exponent	-0.958
σf’, Fatigue strength coefficient	572.2
b, Fatigue strength exponent	0.078
E, Modulus elasticity [GPa]	149

The model is used for the fatigue life validation. Fig. 7 indicates an effective method using C-M relationship over all total strain ranges condition, in fact that the predicted lives and experimental data are in preferential compatibility within factor of 1.0, and the validation value of accuracy is equal to 92.92%.

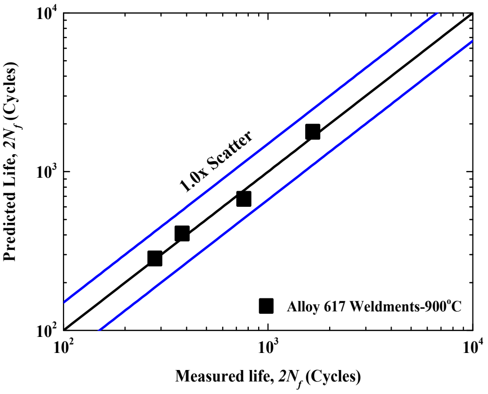

Fig. 7 Validation of lives predicted by C-M relationship for Alloy 617 weldments at 900℃

4.2 The strain energy density-based model

In this study, the Alloy 617 weldment specimens exhibit the Masing behavior. Li et. al.,[8] reported that the stabilized hysteresis loops derived from total strain range conditions are drawn, and the lower left tips of the hysteresis loops are coincided with its common origin. It is found that the upper right tips almost coincide each other. Fig. 8 shows the damage parameter of strain energy density with reversals to failure, through the eq. 3 to 5. Thus the material properties are listed in Table 2.

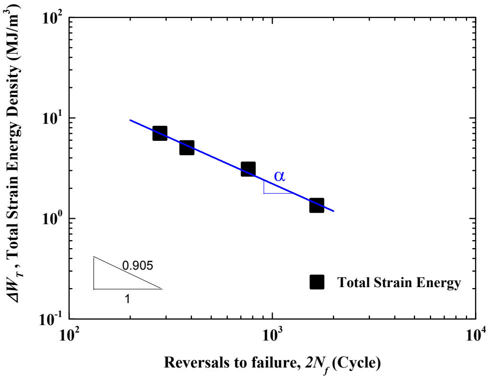

Fig. 8 Strain energy density-based plots of the Alloy 617 weldments 900℃ with reversals to failure

Table 2 The Strain energy density coefficients for the Alloy 617 weldments at 900℃

Parameter	Alloy 617 Weldment
A, Material energy absorption capacity	1149.1
α, Fatigue exponent	-0.905

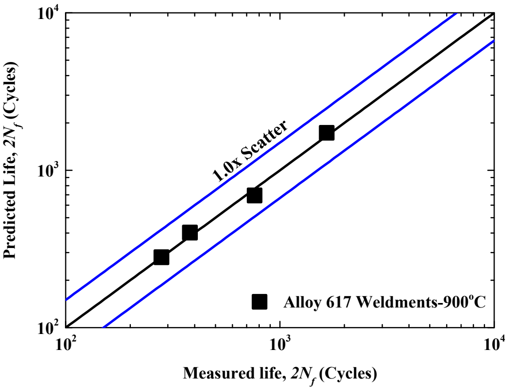

Fig. 9 Validation of lives predicted by Strain energy density-based model for Alloy 617 weldments at 900℃

As shown in Fig. 8, a fairly good correlation is found in energy damage parameter and fatigue life. The strain energy density is decreased as well as a total strain range applied decreases. And the fatigue exponent is obtained from the experimental data, the α slope of -0.91. The calculated life predictions are in a good agreement for the Alloy 617 weldments showing a Masing behavior. A difference tendency between the calculated lives and experimental data are noticed at the highest total strain range, i.e. 1.5%.

The validation between the predicted lives and the experimental data is shown in Fig. 9. The comparison data are in well suitability within factor of 1.0. The more successful result can be evaluated for the strain energy density-based model with a better accuracy of 95.08%, when it is compared with the C-M relationship. The strain energy density is found to be more promising for the Alloy 617 weldments as a fatigue damage parameter with its consistency of properties during high temperature. However, this model is evaluated only in the present investigated condition. Further study is required whether this life evaluation can be applied to other materials and conditions.

5. Conclusions

In this paper, most of the existing methods for predicting material parameters, namely the C-M relationship and the strain energy density based model were presented on the Alloy 617 weldments under LCF loadings at 900°C. Both methods showed an excellent suitability between the predicted lives and experimental data. The material parameters were well characterized by the C-M relationship and strain energy density-based model, the c slope was -0.96 and theα slope equalled to -0.91. They were well matched with the experimental data within factor of 1.0. The validations of the C-M relationship and strain energy density-based model were obtained, 92.92 and 95.08% of accuracy, respectively. Consequently, the results showed that the strain energy density-based model is found to be more promising than the C-M relationship.

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