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Thermo-Mechanical Fatigue Life Prediction for Austenitic Stainless Steel

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1. Introduction

Powertrain components of automobiles operating in high pressure and high temperature environments undergo a cyclic thermo-mechanical load. This kind of fatigue behavior affects the durability of components, and therefore a methodology that can analytically predict the material behavior and thermo-mechanical fatigue life is required to ensure the reliability of component.

In this study, low cycle fatigue(LCF) tests were performed under 25°C, 200°C, 400°C, 600°C, 800°C, and 900°C, respectively to develop the constitutive model together with fatigue life prediction of austenitic stainless steel used in turbine housing of automotive. In addition, thermo-mechanical fatigue tests were carried out under the in-phase and the out-of-phase conditions as well.

Based on the Chaboche's rate-dependent cyclic viscoplasticity theory, a fatigue life prediction model was developed and implemented into the ABAQUS UMAT subroutine. Finally by comparing the experimental data with prediction results the reliability of the model was verified.

2. Constitutive equations

In order to predict the material behavior of austenitic stainless steel, the following constitutive equation was employed:

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{C}:\left(\boldsymbol{D} - \boldsymbol{D^P} - \boldsymbol{D^{th}}\right) + \left(\frac{\partial \boldsymbol{C}}{\partial T}\dot{T}\right):\boldsymbol{C^{-1}}:\boldsymbol{\sigma} \quad (1)$$

$$\boldsymbol{D^{th}} = \alpha^{th}\dot{T}\boldsymbol{1} \quad (2)$$

$$\boldsymbol{D}^P = \left(\frac{|\boldsymbol{\sigma} - \boldsymbol{X}| - \left(\sigma_{y0} + R\right)}{K}\right)^n sgn(\boldsymbol{\sigma} - \boldsymbol{X}) \quad (3)$$

In Eq. (1), $\boldsymbol{D}$, $\boldsymbol{D^P}$, and $\boldsymbol{D^{th}}$ are total strain rate tensor, plastic strain rate tensor, and thermal strain rate tensor respectively. Also, $\mathbf{C}$, and T are elasticity tensor and temperature respectively. The $\boldsymbol{D^{th}}$, thermal strain rate tensor, can be expressed by Eq. (2) where α^{th} is the thermal expansion rate and $\mathbf{1}$ is the 2nd order identity tensor. In addition, the plastic strain rate tensor, $\boldsymbol{D^P}$, of Eq. (3) was used to predict the cyclic hardening, softening, creep, and stress relaxation based on Chaboche's rate-dependent cyclic viscoplasticity theory [1]. In Eq. (3), $\boldsymbol{X}$, R, and σ_{y0} are the backstress tensor, isotropic hardening variable, and initial yielding stress respectively. Also, K and n are the viscosity variables.

3. Fatigue life prediction

The equation for predicting the fatigue life of austenitic stainless steel is as shown in Eq. (4).

$$\frac{1}{N_f} = \frac{1}{N_{TMF}} + \frac{1}{N_{Oxidation}} \quad (4)$$

$$N_{TMF} = A(d'_{\bar{N}} D_{TMF})^B \quad (5)$$

$$N_{Oxidation} = \frac{1}{\left[\dfrac{h_{cr}\delta_o}{B\Phi^{ox}\left(K_{peff}^{oxi} + K_{peff}^{\gamma'}\right)}\right]^{-1/\beta} \dfrac{2(\Delta\varepsilon_{mech})^{(b/\beta)+1}}{\dot{\varepsilon}^{1-\alpha/\beta}}} \quad (6)$$

The Fatigue life N_f consists of the thermo-mechanical fatigue life N_{TMF} , and the oxidation fatigue life $N_{oxidation}$. Eq. (5) was proposed by Riedel and Seifert as a prediction of the thermo-mechanical figure life [2], where the $d'_{\bar{N}}$ proposed by Shih is the function of the Ramberg-Osgood's exponents, and D_{TMF} is the function of thermo-mechanical fatigue damage variable. In addition, Eq. (6) was applied to account for fatigue life due to the oxidation as a Neu-Sehitoglu model [3].

4. Experiments

In this study, the low cycle fatigue tests and the thermo-mechanical fatigue tests were performed to extract the variables for material behavior model and also identify the fatigue life which is depend on the temperatures.

The low cycle fatigue tests were performed under 0.4% and 0.5% strain amplitude conditions with strain rate 0.2s^{-1} as shown in Fig. 1, where the each test was performed under 25°C, 200°C, 400°C, 600°C, 800°C, and 900°C temperature conditions. In addition, the thermo-mechanical fatigue tests were performed under the in phase and out of phase conditions as shown in Table 1.

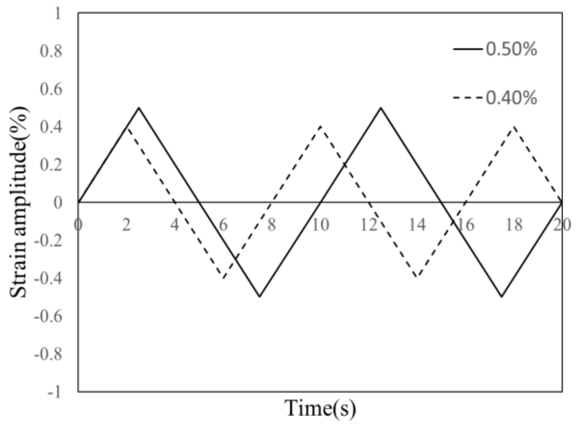

Fig.1 Strain history of low cycle fatigue test.

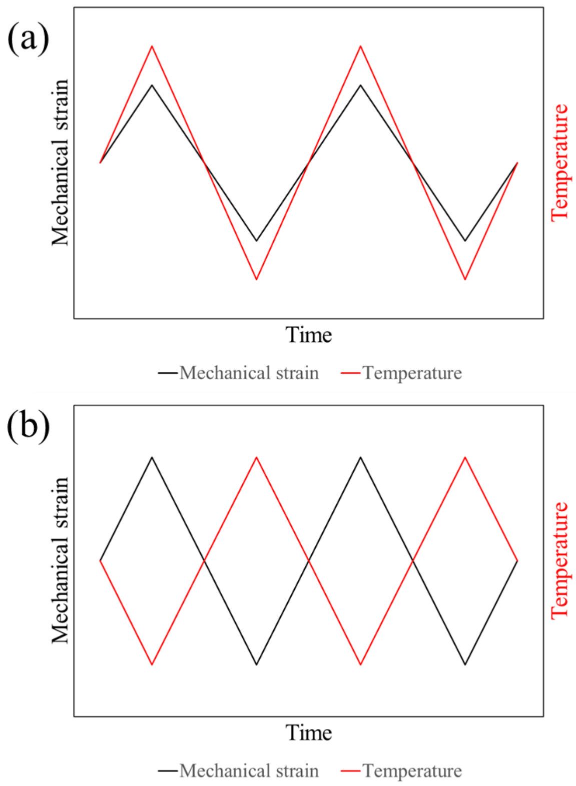

Fig.2 Schematic of strain and temperature history of TMF test. (a) In-phase (b) Out-of-phase

Table 1 Conditions of TMF test

Test	$\Delta\varepsilon_{mech}$	Temperature	Strain rate
In phase	0.65%	300~600℃	**0.00008125s^{-1}**
	0.65%	600~900℃	**0.00008125s^{-1}**
Out of phase	0.65%	300~600℃	**0.00008125s^{-1}**
	0.65%	300~600℃	**0.00008375s^{-1}**
	0.67%	300~600℃	**0.00008125s^{-1}**

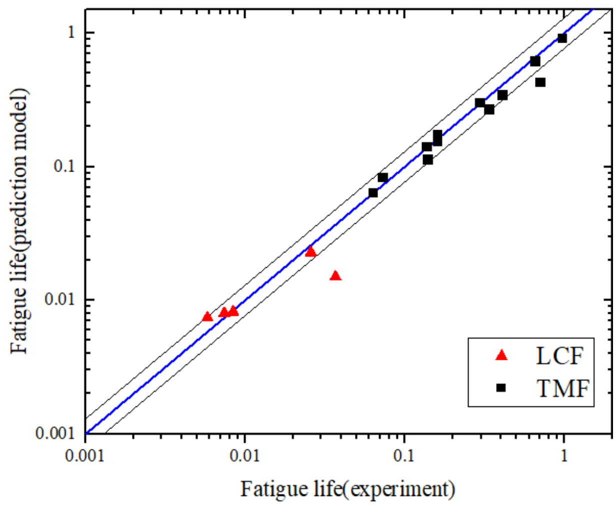

Fig.3. Measured cycles to failure and lifetime model prediction for the TMF test.

5. Results and conclusion

In order to verify the material behavior and the fatigue life prediction model of austenitic stainless steel, the results of the numerical analysis and the experimental values were compared.

Depending on the temperatures, the Chaboche model reflecting the material properties of austenitic stainless steel could be simulated such as cyclic hardening, softening and viscous behavior, within 10% error. The low cycle fatigue life and the thermo-mechanical fatigue life could also be predicted to be within 2 factors as shown in Fig. 3.

As a result, the thermo-mechanical fatigue life prediction model based on the Chaboche's rate-dependent cyclic viscoplasticity theory was developed and found to be valid. It is expected that the model could be sufficiently applicable to the analytical evaluation of the thermo-mechanical fatigue life as well as the low cycle fatigue life for austenitic stainless steel.

Based on the proposed methodology, the thermo-mechanical fatigue life of the powertrain components of automobile therefore can be evaluated in advance and hence the reliability of the components can be secured at design step early.

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