Developing UMAT to predict thermo-mechanical fatigue lifetime of Aluminum

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Abstract: *The improvement of fuel efficiency and the development of high power engines have been increasing the thermal load of the engine parts. This is increasing the cases of the thermal-mechanical fatigue damage. Thermo-mechanical fatigue (TMF) failure is caused by the cumulative plastic strain due to cyclic thermal loads, unlike mechanical fatigue failure. In order to predict the TMF lifetime, a nonlinear material equation including viscoelastic plasticity behavior under high temperature thermal load conditions should be constructed and appropriate tests should be conducted to obtain appropriate material parameters. And then the crack propagation model is linked to derive the lifetime prediction formulas.*

In this paper, an aluminum material model for TMF lifetime prediction is developed. Theoretical formulas were constructed through the process described above, and material parameters were obtained through testing. Also, the derived lifetime prediction equation was composed of ABAQUS UMAT so that it can be used for the lifetime analysis of aluminum.

As a result of this study, it is possible to predict thermos-mechanical fatigue failure and quantitative lifetime prediction of aluminum which is insufficient by existing analysis.

Keywords: *TMF (Thermo-mechanical fatigue), LCF (Low cycle fatigue) Aluminum, engine, Chaboche model, ABAQUS, UMAT*

1. Introduction

The thermal load is increasing due to the improvement of fuel efficiency and the development of high power engine, and as a result, thermal fatigue damage is increasing. Thermal fatigue failure occurs when a thermal load is applied due to temperature in a high temperature environment. In particular, among the components that make up the automobile, the engine is operated under the harshest condition that is repeatedly influenced by a high and a low temperature environment.

The aluminum material treated in this study is for the piston which is exposed to the combustion chamber of the engine and is directly affected by the flame. It is important to predict TMF (Thermo-mechanical fatigue) failure of the piston in accordance with the development trend of high power engine, but a current common TMF analysis is still a qualitative evaluation with plastic strain amplitude. Needed is a quantitative evaluation with lifetime not a qualitative evaluation for the optimization and cost saving in the initial design stage.

A FEA (Finite-element analysis) process in developed for the quantitative evaluation for TMF lifetime of an aluminum alloy in form of ABAQUS material user-subroutine (UMAT) based on Gologanu and Chabeche model. The material characteristics to simulate the nonlinear material behavior are extracted with the TMFs and LCFs tests under various temperature ranges.

2. Theoretical approach

The aluminum material, which is the subject of this stud, not only contains pores originating from the process but also exhibits a time and temperature dependent behavior. Therefore, the development of the material behavior model should consider the effect of microscopic pores on the aluminum material, that is, the advancement of the pores due to the deformation and also simulate the visco-plastic behavior for time-dependent deformation of such pores.

The yield function of the aluminum material uses Gologanu model considering the characteristics of the porous material, not the von Mises function, and the Chu model is used for pore generation, growth and coalescence. Other material based models for tensile and compression are based on the hardening theory presented by Chaboche and can simulate the deformation behavior of materials by cyclic loading based on the correlation between path dependent behavior and time dependent behavior.

2.1 Basic constitutive equation

The material strains based on elastic, plastic and thermal effects can be expressed as :

$$\varepsilon^{total} = \varepsilon^{e} + \varepsilon^{p} + \varepsilon^{th}$$

ε^{e} is elastic strain rate, ε^{p} is plastic strain rate and ε^{th} is thermal strain rate.

The following rate constitutive equation can be expressed as follows when a completely solid material without pore effect is subjected to visco-plastic behavior under the uniaxial stress condition based on the above equation.

$$\dot{\varepsilon}^{total} = \frac{\dot{\sigma}}{E} - \frac{\partial E}{\partial T}\frac{1}{E^{2}}\dot{T}\sigma + \dot{\varepsilon}^{p} + \dot{\varepsilon}^{th}$$

The elastic modulus (E) in the constitutive equation depends on the temperature (T). In the above equation, the first term and the second term represent the elastic region, and the other two terms are the plastic strain rate and the thermal strain rate, respectively. The rate constitutive equation considering pore characteristics can be expressed as follows.

$$\dot{\varepsilon}^{total} = \frac{\dot{\sigma}}{E} - \frac{\partial E}{\partial T}\frac{1}{E^2}\dot{T}\sigma - \frac{\partial E}{\partial f}\frac{1}{E^2}\dot{f}\sigma + \dot{\varepsilon}^{p} + \dot{\varepsilon}^{th}$$

The rate of stress change associated with such strain rate can be expressed as:

$$\dot{\sigma} = E(\dot{\varepsilon}^{total} - \dot{\varepsilon}^{p} - \dot{\varepsilon}^{th}) + \left(\frac{\partial E}{\partial T}\dot{T} + \frac{\partial E}{\partial f}\dot{f}\right)\frac{1}{E}\sigma$$

2.2 Elastic Behavior Characteristics

In general, ductile materials such as aluminum lead to breakage through the formation, growth and coalescence of pores, and exhibit behavior characteristics due to the advancement of pores in the material. In this study, we use the Mori-tanaka model, which assumes elastic effective physical properties based on Eshelby's elastic tensor for such materials. It is possible to express the micro-mechanical average stress tensile and strain tensor of a matrix material considering porosity by connecting macroscopic effective stress tensor and strain tensor.

2.3 Yield function considering porosity

To simulate the behavior of the porous material, a model including elliptical pores was assumed using a modified Gologanu model based on the Gurson model considering isotropic pores.

$$\Phi = \frac{{\sigma_{eq}}^2}{\sigma_M^2} + 2q \cdot f \cdot \cosh\left[\kappa \frac{\sigma_h}{\sigma_M}\right] - 1 - q^2 f^2$$

2.4 Cyclic plastic deformation and viscous-plastic behavior

The Chaboche model is widely used to simulate the Baussinger effect, cyclic hardening and softening, strain rate sensitivity and creep stress relaxation based on cyclic plasticity behavior. The Chaboche model for visco-plastic behavior analysis is as follows.

$$\mathbf{D^p} = \dot{\varepsilon}_e^p \operatorname{sgn}(\boldsymbol{\sigma} - \mathbf{X}) \; and \; \dot{\varepsilon}_e^p = \left\langle \frac{|\boldsymbol{\sigma} - \mathbf{X}| - (\sigma_{y0} + R)}{K} \right\rangle^n$$

The visco-plastic Chaboche model uses a number of material constants to simulate actual material behavior based on isotropic and nonlinear hardening theory. These material constants are all temperature-dependent values and can be obtained based on the stress-strain relationship obtained through the load history experiment.

2.5 Model to predict Thermal Mechanical Fatigue lifetime

The fatigue crack growth rate is affected by several variables such as the experimental temperature T, the frequency f, the average stress and the crack length,and can be expressed as follows.

$$\frac{da}{dN} = f\left(\Delta\sigma, a, \ldots\right)$$

The crack tip opening displacement due to cyclic loading is proposed as follows.

$$\frac{da}{dN} = \beta \Delta CTOD = \beta \frac{\Delta K_{eff}{}^{2}}{2\sigma_0 E}$$

The above equation can be modified to define the damage parameter D_{TMF} in thermal mechanical Fatigue Test(TMF).

$$D_{TMF} = \frac{Z_D}{\sigma_{CY}} F(t, \sigma, T)$$

It is possible to develop a model to predict thermal fatigue lifetime based on material tests on aluminum material.

3. Experimental approach

3.1 Low Cycle Fatigue (LCF) Test

Based on the stabilized curve in the half failure cycle, the isotropic hardening and the kinematic hardening parameters of aluminum material are extracted according to plastic strain amplitude.

Stabilized curve and fatigue life according to temperature and strain amplitude conditions are compared and analyzed as shown in the figure below.

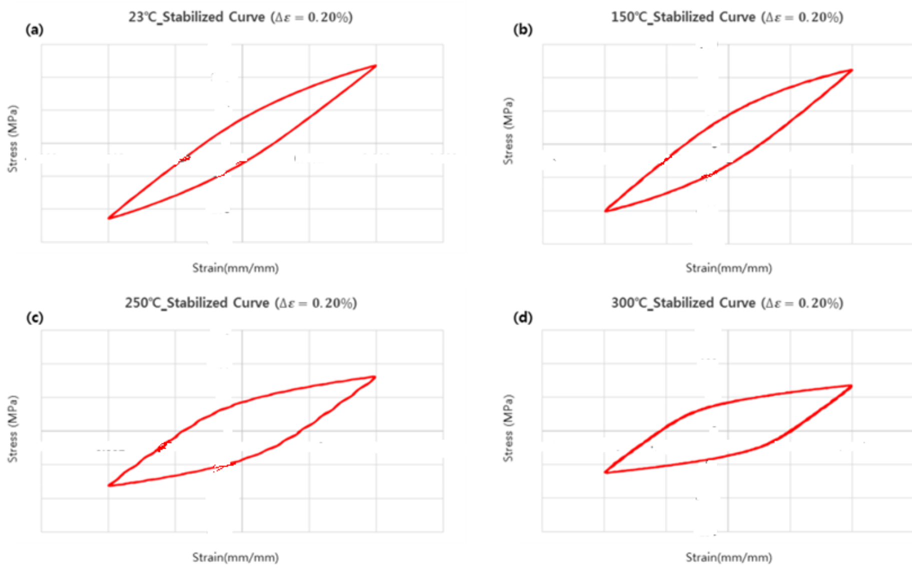

Figure 1. Stress vs. strain stabilized curve of △stain 0.20% LCF test at (a) 23℃ (b) 150℃ (c) 250℃ (d) 300

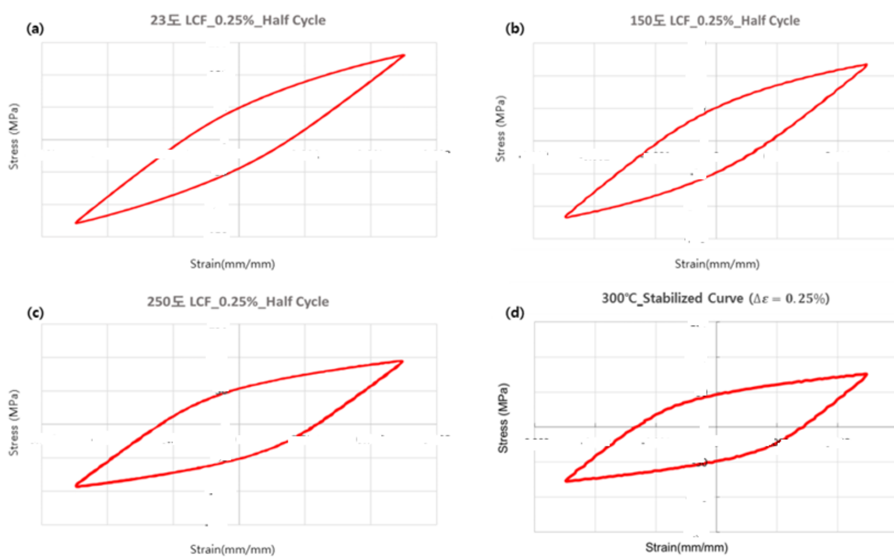

Figure 2. Stress vs. strain stabilized curve of ▵stain 0.25% LCF test at (a) 23℃ (b) 150℃ (c) 250℃ (d) 300℃

The stress hysteresis shows that the absolute value of the maximum stress and the minimum stress gradually decreases and the plastic strain width increases as the temperature increases in the stress stabilization curves of Fig.1 and Fig.2. As the material properties deteriorate, The maximum compressive stress value becomes small. This is because as the temperature increases, the values of the yield stress and elastic modulus decrease, and as the temperature-dependent kinematic hardening and isotropic hardening parameters become smaller, the amount of hardening of the material decreases as a result.

3.2 Thermal Mechanical Fatigue Test (TMF)

In order to perform the thermal fatigue test, the condition of cyclic repetition of the temperature was applied and the change of the thermal fatigue behavior according to the mechanical strain was confirmed by experimental the various mechanical strain amplitude.

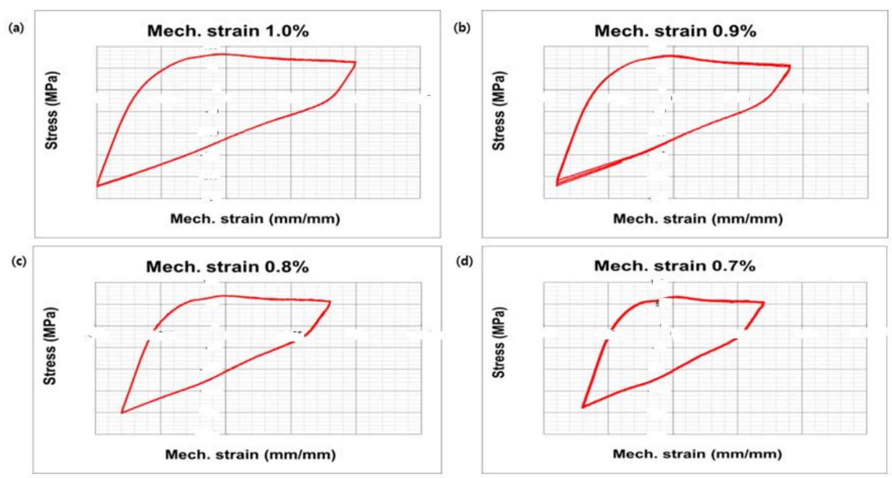

Figure 3. Stress vs. mechanical strain stabilized curve of In-Phase TMF test (a)1.0% (b)0.9% (c)0.8% (d)0.7%

4. FEA Approach

4.1 Chaboche model material variable extraction

In order to develop the material behavior model based on the Chaboche theory, kinematic hardening and isotropic hardening parameters and visco-plastic parameters were obtained by applying recursive approximation algorithm based on least squares method and differentiation method to material variables for each temperature.

4.2 FEA of material behavior model based on Chaboche theory

In order to determine the rationality of UMAT, a FEA model with the same conditions as the test is constructed. As shown in the figure below, the ABAQUS of the specimen shape is constructed and the previous test is implemented as an analysis.

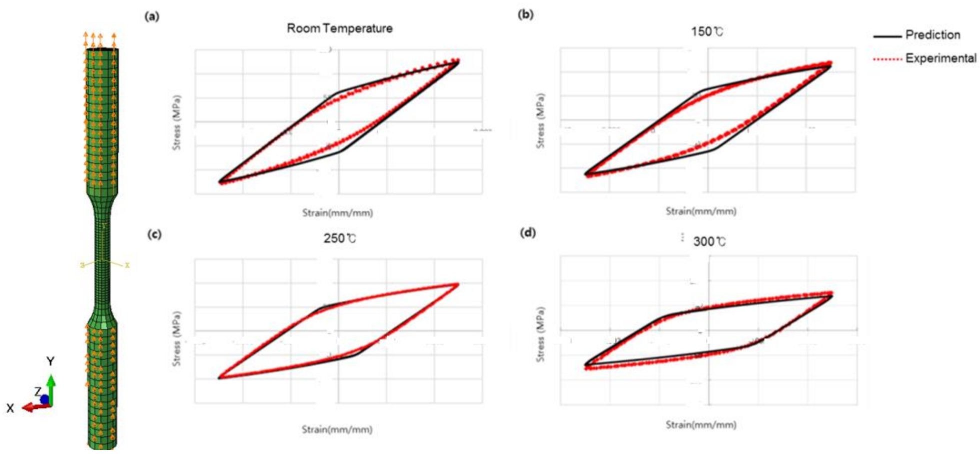

Figure 4. Measured and Simulated Strain-Stress Stabilized Curve of LCF Test (a) 23℃(b) 150 ℃(c) 250 ℃(d) 300 ℃

Simulated result shows that the maximum and minimum stresses and stresses of experimental and prediction are in good agreement and that the stable curve is well followed. This confirms that the material parameters are properly extracted and that the material behavior UMAT model is well constructed.

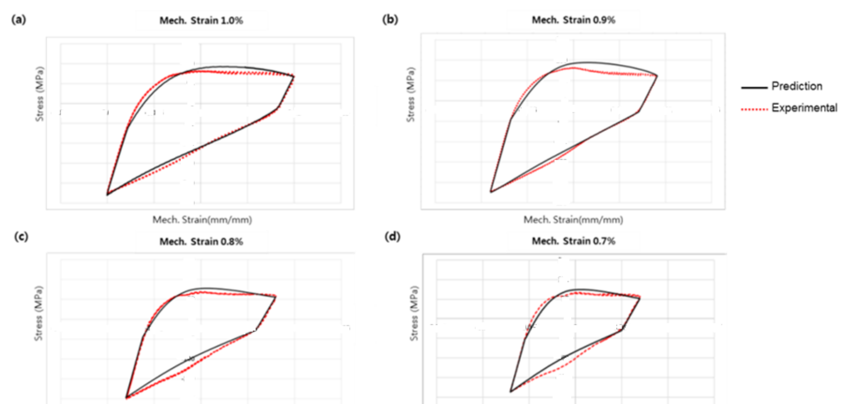

Figure 5. Measured and simulated mechanical strain-stress stabilized curve of TMF test at condition (a)1.0% (b)0.9% (c)0.8% (d)0.7%

4.3 Thermal fatigue life prediction model analysis

The table 1 and 2 compare the prediction of the numerical simulation with measured data. The difference in the predictions and measurements is generally less than 20%. It shows the UMAT could use the prediction lifetime all kind of condition.

Table 1. Results of LCF test life prediction

strain 0.2%	Experimental results	Prediction
23℃	6934	6202
250℃	2672	2801
strain 0.25%	**Experimental results**	**Prediction**
23℃	3974	4285
150℃	2224	2682
250℃	1790	1859
300℃	1520	1615

Table 2. Results of TMF life prediction

TMF In Phase	Experimental results	Prediction
$\Delta\varepsilon_{mech} = 1.0\%$	172	195
$\Delta\varepsilon_{mech} = 0.9\%$	244	256
$\Delta\varepsilon_{mech} = 0.8\%$	374	322
$\Delta\varepsilon_{mech} = 0.7\%$	482	451

5. Conclusion

Through this study, the material behavior model based on Chaboche theory is formulated and the UMAT code is developed together with the thermal fatigue life prediction model for aluminum.

The material behavior model uses the Gurson yielding function to account for the pores present in the cast aluminum alloy, and the Chaboche theory is applied to consider the repeated visco-plastic behavior.

The parameters of material behavior model were obtained through low cycle fatigue test and thermal fatigue test and applied to material behavior model UMAT. The results of the stress stabilization curves for the low cycle fatigue test and thermal fatigue test were compared and analyzed with the material behavior model UMAT code. The accuracy of the developed material behavior model was confirmed.

In addition, the UMAT code based on the Chaboche theory based thermal fatigue life prediction model was developed to predict the low cycle fatigue test and the fatigue life of the thermal fatigue column. The UMAT accuracy was confirmed by comparing the fatigue life and predicted values in the low cycle fatigue test and the thermal fatigue test.

6. References

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