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Thermal Stress and Fatigue Analysis of Exhaust Manifold

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ABSTRACT

In this study, we investigated the reliability assessment of exhaust manifold used in thermomechanical condition. Overlay model proposed by Besseling[1] was modified to consider the strain range dependence on elastic limit. By combining geometrical relation in hysteresis loop and temperature dependence of elastic limit with isothermal overlay model, temperature dependent cyclic plasticity model was proposed. Continuous damage model based on isothermal fatigue data was generalized for non-isothermal condition. Finite element analysis and life prediction of exhaust manifold were performed under severe operating conditions.

1. INTRODUCTION

Automotive engine operates under severe thermomechanical loading condition: Operating temperature increases up to 800^{o}C from ambient temperature and large thermal stress is induced by temperature gradient and geometrical constraints. This thermomechanical coupling is one of critical problems in automotive engineering. For instance, most of the crack found in the stainless steel exhaust manifold were caused by out-of-phase thermal fatigue occurring at high temperature[2]. Hence, thermal fatigue analysis should be considered in design process of exhaust manifold. Since classical model of plasticity and life prediction is only applicable to isothermal condition, a new methodology for thermomechanical condition is necessary. We focused on the application of constitutive equation and damage model based on isothermal data into thermomechanical condition. Using proposed models, we performed the thermal stress analysis and life prediction of exhaust manifold made of 429EM stainless steel.

2. CONSTITUTIVE EQUATION

Among cyclic plasticity models, overlay model has been considered as physically motivated, as many real materials or mechanical systems can be thought of as having a similar structure [3]. For example, most of the engineering materials may have a crystalline structure that is made of a distribution of slip-planes or dislocations of different slip strengths. Moreover, the overlay model has definite advantages compared with the classical models in that it can be described qualitatively a variety of effects that the classical models are not able to describe, whereby the description remains fairly simple[4].

The basic assumption of overlay model is that material is composed of a series of so-called Jenkin's elements connected in parallel, each of which consists of a linear spring with "stiffness" E_i in series with a slip element (Coulomb damper) of strength, k_i as indicated in Fig.1 where ϕ_i denotes the fraction of each element. By using the classical plasticity theory, yield condition of each subelement can be defined by

$$f_i = J(\tilde{\sigma}(k_i)) - k_i = 0 \tag{1}$$

where $J(\boldsymbol{x})$ is second invariant of tensor variable $\boldsymbol{x}$. Macroscopic stress is the weighted sum of the stress applied to subelements

$$\sigma = \sum_{i=1}^{N} \phi(k_i)\tilde{\sigma}(k_i) \tag{2}$$

where $\tilde{\sigma}$ denotes applied stress on subelement. The sum of every fraction is assumed to be one. Each element in the model is subject to the same total-strain response as experienced by the model itself. Thus, the constitutive equation of subelement is defined

$$\tilde{\sigma}(k_i) = \mathbf{C}\left[\varepsilon - \tilde{\varepsilon}_p(k_i)\right] \tag{3}$$

where $\boldsymbol{C}$ is elastic stiffness matrix and $\tilde{\varepsilon}_p$ is plastic strain of subelements.

Overlay model of Eq.(1)~(3) is suitable for describing the hysteresis loop of Masing material. Fig.3 shows the cyclic stress-strain curves of 429EM stainless steel at 200^{o}C, which is obtained from matching the upper branch of the hysteresis loops through translating each loop along its elastic part. The common part of hysteresis loop is called 'master curve', but there exist differences in elastic region of hysteresis loops with respect to the strain amplitude. In order to consider non-Masing behavior of 429EM stainless steel, yield stress of subelement is divided into two parts

$$k_i = m_i(T) + R(\Delta\varepsilon, p, T) \tag{4}$$

where m_i is for describing master curve and R for representing the change of elastic limit. The detail explanation of determining m_i and R is referred in [5]. The hysteresis loops predicted by overlay model with 5 subelements show good agreements with the experiment shown in Fig.3.

For describing cyclic behavior in thermomechanical condition, we introduced the geometrical relation among the nonlinear part in hysteresis loop at different temperature as shown in Fig.4. This relation of reversed stress with reversed plastic strain can be formulated as

$$\sigma_r = \sigma_y(T) + K(T)H(\varepsilon_r^p) \tag{5}$$

where σ_r and σ_y are the reversed stress and stress magnitude of linear region in hysteresis loop and $K(T)$ and $H(\varepsilon_r^p)$ denote influence factor and hardening function respectively. It is noteworthy that hysteresis loop at the intermediate temperature can be predicted by interpolating hysteresis loops at high and low temperature through Eq.5 and thermal softening or hardening which takes place during temperature change can be considered as well. The minimum yield stress with respect to temperature is shown in Fig. 5. Combining Eq.5 and modified overlay model, we derive thermomechanical overlay model which gives a good prediction of TMF hysteresis loop as shown in Fig. 6.

3. CONTINUOUS DAMAGE MODEL

The authors reported that the Morrow model is suitable for life prediction of 429EM stainless steel since continual cyclic hardening was observed from isothermal low cycle fatigue[6]. The relation of the isothermal fatigue lifetime with plastic strain energy density is

$$\Delta w_p \left(N_f\right)^m = C \qquad (6)$$

where Δw_p and N_f are the plastic strain energy density and number of cycles to fracture. C and m are temperature dependent material constants.

Transforming Eq.6 and assuming a linear damage evolution, we obtain the expression for damage per cycle as shown in Eq.7.

$$\Delta D = \frac{1}{N_f} = \left(\frac{\Delta w_p}{C}\right)^{1/m} \qquad (7)$$

In case of 429EM stainless steel, the exponent m in Eq.6 approaches to 1 at temperature range from room temperature to 600^{o}C. Hence, the relation of Eq.7 can be approximated with linear relation of damage with plastic energy density and the isothermal fatigue data shown in Fig.7 serves as an evidence of this approximation.

By using damage conversion factor which denotes the slope of damage-plastic work curve, the fatigue damage corresponding to plastic strain energy occurred at arbitrary temperature can be calculated directly. Fig.7 shows temperature dependence on damage conversion factor of 429EM stainless steel. The TMF damage per cycle is calculated by integrating damage induced by every increment of plastic work for the whole TMF stabilized loop through the following equation

$$D_{TMF} = \int C^*(T) dw_p \qquad (8)$$

where $C^*(T)$ is the damage conversion factor at temperature T.

Though this model is not verified experimentally because of the lack of TMF data, the similar model proposed by Shi et al.[7] gave a good prediction for TMF life of 316L stainless steel. At present, TMF test on 429EM stainless steel is performing for verifying the proposed model and the results will be published in near future.

This method was originally developed to predict TMF damage of material which has the nonlinear relation of plastic work with damage per cycle by considering the influence of reversed plastic strain on damage accumulation. So, the case of 429EM stainless steel is a special case of TMF damage model.

4. FINITE ELEMENT ANALYSIS

The thermal stress analysis was performed in ABAQUS/Standard. The thermomechanical overlay model and TMF damage model was implemented into ABAQUS through UMAT subroutine. The assembly considered is a four-tube exhaust manifold fastened to an engine head by eight bolts acting on four flanges. The materials of engine head and bolt are aluminum and steel respectively. The bolts and engine head were modeled as elastic materials; the manifold was modeled as an elastic-plastic, temperature-dependent material described by thermomechanical overlay model.

The analysis consists of two parts, heat transfer analysis and thermal stress analysis. The temperature distribution obtained from transient heat transfer analysis was used as an input of the thermal stress analysis. The stress analysis consists of three steps. First, prescribed bolt loads fasten the manifold to the head at room temperature. Then, the assembly is heated to an operating condition, shown in Fig.9, and is cooled to a uniform ambient temperature. After repeating heating-cooling cycle two times, the damage contour was obtained as shown in Fig.10 and critical region was found in the junction of tube. As the calculated damage is strongly depending on the mesh size, the fatigue damage calculated at the centroid of element was used to predict the crack initiation life. Because the linear damage evolution was assumed in continuous damage model, it is reasonable to calculate the expected life from a reciprocal of damage. The expected life of exhaust manifold was 5500 ~ 6000 cycles, which is very short than the actual life. The accelerated life may be caused by the severe loading condition used in analysis and low resistance to thermal fatigue of 429EM stainless steel.

5. CONCLUSION

In this research, we developed a methodology for reliability assessment under thermomechanical condition using constitutive equation and damage model based on isothermal data. By considering geometrical relation in hysteresis loop and temperature dependence of elastic limit, temperature dependent overlay model was proposed. The concept of damage conversion factor was introduced to calculate the TMF damage. Using proposed models, thermal stress analysis and life prediction of exhaust manifold was performed and expected life was determined through the simple procedure.

6. ACKNOWLEDGEMENT

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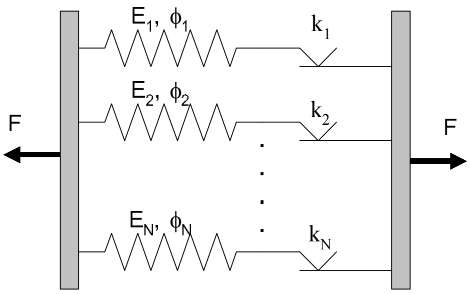


Fig. 1 One-dimensional overlay model

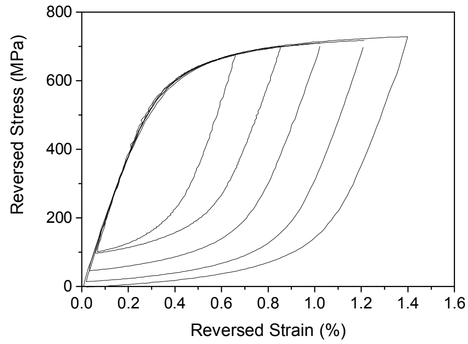
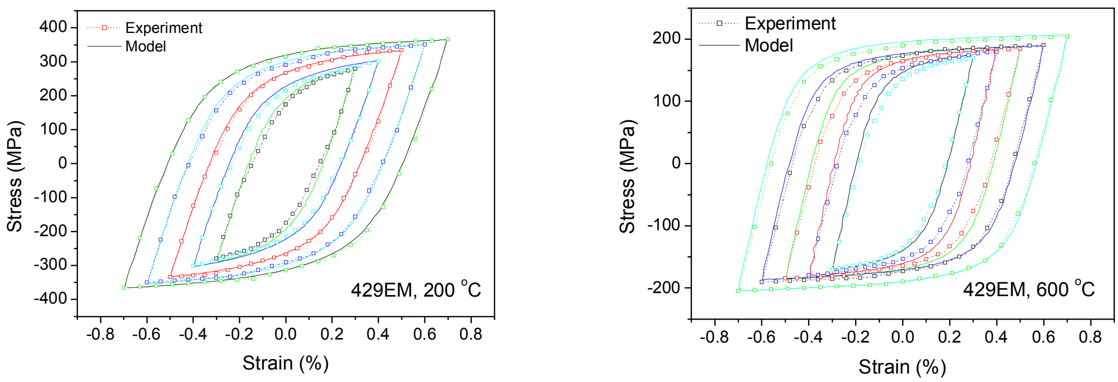


Fig. 2 Stabilized hysteresis loop in relative coordinate (200°C).



(a) (b)

Fig. 3 Comparison of stabilized hysteresis loop obtained by the calculation and the experiment, (a) 200°C, (b) 600°C

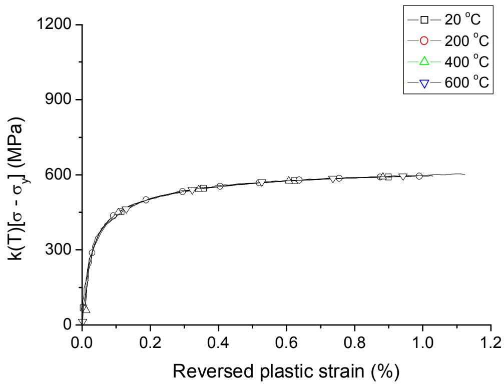


Fig. 4 Temperature dependence of nonlinear part in hysteresis loop.

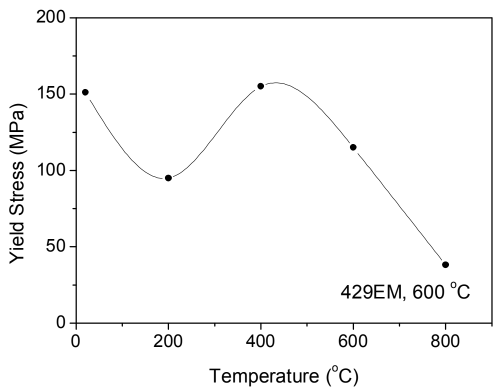
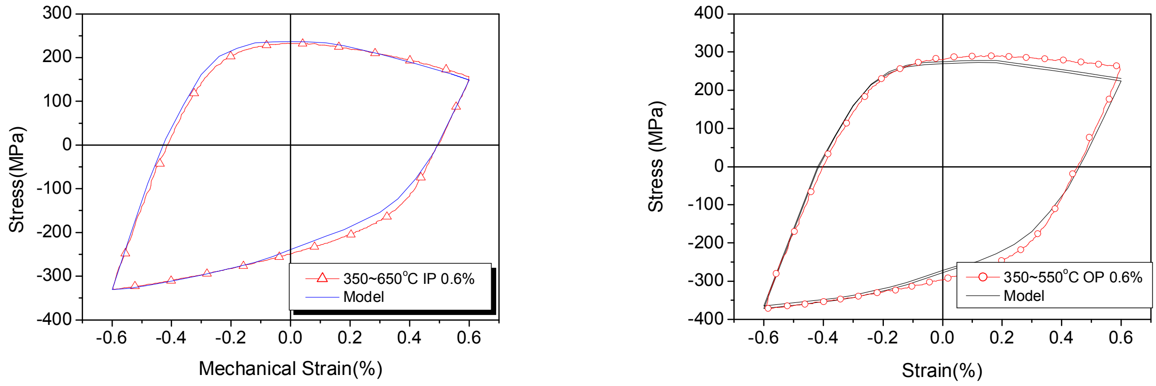


Fig. 5 Minimum elastic limit versus temperature.



(a) (b)

Fig. 6 Prediction of stabilized hysteresis loop in TMF,
(a) In phase TMF, 350C~650°C, (b) Out of phase TMF, 350C~550°C

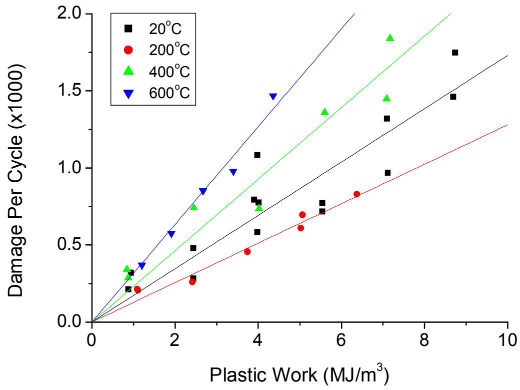


Fig. 7 Relation of plastic work with damage per cycle at several temperatures

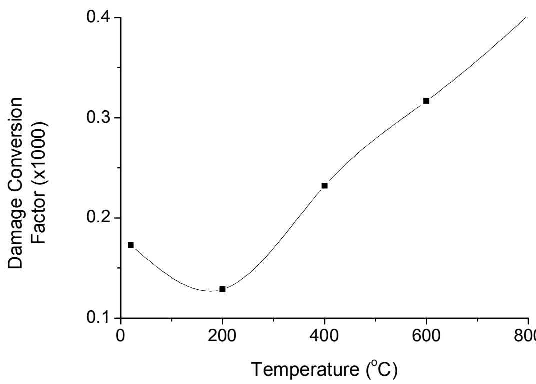


Fig. 8 Damage conversion factor versus the temperature

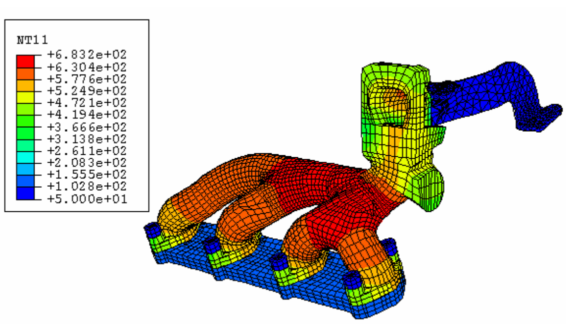


Fig. 9 Temperature distribution at the operating temperature

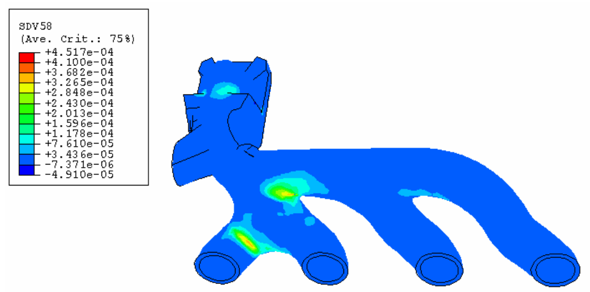


Fig. 10 Damage distribution after thermal cycles