SMiRT-12 / K. Kussmaul (Editor)

L07/4

EFFECT OF AIR ENVIRONMENT ON CREEP-FATIGUE OF SOME COMMERCIAL STEELS

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ABSTRACT

The environmental effect of air on the creep-fatigue behaviour of 304 stainless steel, 2 1/4Cr-1Mo steel and Modified 9Cr-1Mo steel is discussed. The creep-fatigue tests were conducted with these materials in high vacuum and air environment and the environmental effect of air on the creep-fatigue damage is analyzed through the creep-fatigue life evaluation model based on the overstress concept. It is found that the fatigue damage is highly affected with the air environment resulting in a life reduction controlled by a strain rate or a time duration during the compression going stroke. As to the creep damage, the analysis suggests that the air environment accelerates the creep damage in 304 stainless steel, gives quite little effect in Modified 9Cr-1Mo steel but reduces the creep damage in 2 1/4Cr-1Mo steel.

1. INTRODUCTION

It should be considered that the creep-fatigue data obtained in air reflect a particular effect of the air environment. However, most of high temperature components are operated in other service environments than air and the environmental effect is not always the same as in the air environment. Therefore, in developing a precise creep-fatigue life prediction method of practical components operated at high temperature, it is important to evaluate the environmental effect of air separately. For this necessity, the authors have made a series of creep-fatigue experiments with 304 stainless steel (Morishita and Asada, 1984; Morishita et al., 1985; Morishita et al., 1985, Morishita et al., 1987), 2 1/4Cr-1Mo steel (Asayama et al., 1987; Asayama et al., 1988; Cheng et al., 1988; Asayama and Asada, 1989) and Modified 9Cr-1Mo steel (Okamoto et al., 1991; Asada et al., 1992) in air and in a very high vacuum environment of 0.1μPa, and investigated the environmental effect of air in 2 1/4Cr-1Mo steel (Yang et al., 1991) and in Modified 9Cr-1Mo steel (Asada et al., 1992). In this study, the environmental effect of air on the creep-fatigue behaviour of 304 stainless steel is discussed as well as those of 2 1/4Cr-1Mo steel and Modified 9Cr-1Mo steel, and the comprehensive scope will be given for these commercial steels. The particular features of creep-fatigue behavior of these materials in air and vacuum are briefly described at first and then, the creep-fatigue damage analysis based on the overstress concept is applied to give a creep-fatigue life evaluation in vacuum. Finally, this damage model is applied to the data obtained in air, and the effect of air environment upon the creep-fatigue interaction is discussed.

2. CREEP-FATIGUE EXPERIMENTS

In the authors' previous studies, push-pull uniaxial creep-fatigue experiments have been conducted with three kinds of materials; (1) solution annealed 304 stainless steel at 650℃, (2) normalized and tempered 2 1/4Cr-1Mo steel at 550℃ and (3) normalized and tempered Modified 9Cr-1Mo steel at 600℃. Electro-hydraulic closed-loop systems were used with being equipped the induction heating systems. The diametric strain at the minimum cross section of the hourglass type specimen was measured to control with an extensometer using an LVDT. For the experiments in vacuum, a turbo-molecular pump was used. This vacuum system establishes a high vacuum environment of 0.1μPa. It has been shown that no environmental effect of air remains in this vacuum environment, that is, no Oxide was observed by SEM on the fracture surfaces.

The strain wave forms were a symmetric continuous cycle, a unsymmetric continuous cycle and a tension or compression hold-time cycle. The axial strain range covered from 0.005 to 0.02 m/m and the axial strain rate from 10^{-5} to 10^{-3} s^{-1}. A hold-time up to 600 s was superposed at the tension or compression peak of each cycle for strain hold-time cycles.

3. EXPERIMENTAL RESULTS

3.1 Results in vacuum

Figures 1, 2 and 3 show the results of creep-fatigue tests for 304 stainless steel, 2 1/4Cr-1Mo steel and Modified 9Cr-1Mo steel, respectively. In each figure, open symbols show the results in vacuum and the solid and the half-solid ones show the data obtained in air.

The following features are obtained.

(a) A symmetric continuous cycle shows about the same fatigue life being independent of a strain rate.That is, the frequency effect diminishes.

(b) An unsymmetric continuous cycle of fast-slow (F-S) gives the same fatigue life as that of the symmetric continuous cycle except for the case of 2 1/4Cr-1Mo steel. In this case, a slight life reduction is observed. A transgranular crack was observed by the SEM observation, which indicates that this life reduction was not cased by creep but was caused by a positive mean stress developed in this wave form.

(c) In case of 2 1/4Cr-1Mo steel and Modified 9Cr-1Mo steel, the fatigue life of a compression hold-time cycle slightly reduces from those of the symmetric continuous cycle. The SEM observation also indicates that this life reduction is caused by a positive mean stress.

(d) An unsymmetric continuous cycle of slow-fast (S-F) and a tension hold-time cycle show a drastic life reduction from the symmetric continuous cycle. This life reduction depends on a strain rate and/or a strain hold-time in tension, that is, time/rate-dependent. It is also noted that the intergranular crack was observed in this case for each material.

3.2 Results in air

The following trends are observed in air.

(a) For the strain wave forms of the symmetric continuous cycle, the unsymmetric continuous cycle of fast-slow (F-S) and the compression hold-time cycle, the fatigue life in air is reduced from those obtained in vacuum. This life reduction depends on a strain rate and a hold time.

(b) The unsymmetric continuous cycle of slow-fast (S-F) and the tension hold-time cycle, which show the time/rate-dependent life reduction in vacuum, have the same trend in air, too. However, it is less remarkable than that in vacuum.

4. DAMAGE MODEL BASED ON OVERSTRESS CONCEPT

In the previous studies of the creep-fatigue interaction, the authors have developed a creep-fatigue life evaluation model based on the overstress concept. This model was originally proposed and developed to evaluate the creep-fatigue life in high vacuum environment and the good agreements have been found between the predicted and the experimental creep-fatigue life (Asada et al., 1991).

The overstress is defined as the exceeding part of the stress over the internal back stress and is considered to be the primary driving force of the inelastic deformation. Asada proposed a method to measure the overstress experimentally by analyzing the cyclic stress-strain hysteresis loop and such a measured overstress has been used in the following creep-fatigue damage model (Asada et al., 1991, Okamoto et al., 1991).

The proposed model includes two kinds of damage parameters D_I and D_D, the time/rate-independent and -dependent damage parameter, respectively.

(1) 304 stainless steel:

$$D_I = \int_{cycle} \sigma_e \, d\varepsilon_p \qquad (1a)$$

$$D_D = \int_{cycle} \sigma_e dt \qquad (1b)$$

(2) 2 1/4Cr-1Mo steel:

$$D_I = \int_{cycle} (\sigma_e + |\sigma|) \, d\varepsilon_p \qquad (2a)$$

$$D_D = \int_{cycle} |R|^{\alpha} sgn(R) \, dt \qquad (2b)$$

(3) Modified 9Cr-1Mo steel:

$$D_I = \int_{cycle} (\sigma_e + |\sigma|) \, d\varepsilon_p \qquad (3a)$$

$$D_D = \int_{cycle} |\sigma_e|^{\beta} \, sgn(\sigma_e) \, dt \,, \qquad (3b)$$

where σ_e and R are the overstress and the back stress respectively. α and β are constants, sgn(x) is the sign function, ε_p is an inelastic strain and t is a time in s. In calculating D_D with eqs.(1b), (2b) or (3b), we take D_D = 0 when it gives a negative value.

These two damage parameters are correlated to the time-independent (fatigue) damage per a cycle and the time-dependent (creep) damage per a cycle respectively, as shown in eqs.(4) and (5), where Nf0 is the fatigue life observed for the symmetric continuous, F-S and compression hold-time cycles, and Nf is the creep-fatigue life.

$$1 / N_{f0} = C_1 \, D_I^{\,n1}, \qquad (4)$$

$$1 / N_f - 1 / N_{f0} = C_2 \, D_D^{\,n2}, \qquad (5)$$

where C1, C2, n1 and n2 are constants.

5. ENVIRONMENTAL EFFECT

5.1 Environmental effect on time-independent damage

The environmental effect of air is evaluated by applying the creep-fatigue damage model based on the overstress. This damage model was originally developed for the creep-fatigue damage evaluation in vacuum and the same model is employed to the creep-fatigue data obtained in air. The parameters D_I and D_D are computed by using eqs.(1a) to (3b) based on the stress-strain hysteresis curves obtained in air. It should be noted that the stress-strain response is the same in air and vacuum. Then, the inconsistency will be derived, representing the environmental effect of air superposing upon the creep-fatigue damage.

Figures 4, 5 and 6 show the relation between D_I and 1/Nf0 obtained from data in air for each material. The trend of the vacuum data is also plotted in the figures with broken lines. In these figures, all of the results in air are shown below the data of vacuum. This indicates that the time-independent damage (fatigue damage) remarkably increases due to the air environment. Furthermore, as the value of D_I decreases, the data distribution in air diverges from the line of vacuum data. This divergence is dependent on a strain rate in the compression going stroke as shown by the solid lines. The life reduction in air from the fatigue life in vacuum becomes more remarkable as the compressive strain rate becomes lower. These features are common to these three materials.

5.2 Environmental effect on time-dependent damage

The relations between D_D and 1/Nf-1/Nf0 obtained from the experiments in air are shown in Figs.7, 8 and 9. The trend from the vacuum experiments are also shown by the broken lines. Comparing these figures with each other, it can be found that the air environment has different effects on the time-dependent (creep) damage for the different materials. In case of 304 stainless steel (Fig.7), the air data are shown in the lower region than the vacuum data, indicating that the air environment increases the time-dependent damage in the creep-fatigue interaction. In case of 2 1/4Cr-1Mo steel, all data in air appear in the upper region than the vacuum data (Fig.8), which indicates that the environmental effect of air makes down the development of the time-dependent damage. The result for Modified 9Cr-1Mo steel is shown in Fig.9. The data of both air and vacuum appear in almost the same region. This indicates that the air environment has quite little effect on the time-dependent damage of this material.

Finally, it is noted that the present damage model evaluates the creep-fatigue life in both air and vacuum for the three steels within the error of factor of two.

6. CONCLUSION

304 stainless steel, 2 1/4Cr-1Mo steel and Modified 9Cr-1Mo steel were subjected to the creep-fatigue tests in air and in a very high vacuum environment at high temperature. Applying the damage model based on the overstress concept, the following features were obtained on the environmental effect of air on the creep-fatigue interaction behaviour.

(1) In the air environment, the fatigue damage (time-independent damage) increases for all of these materials. The air environment reduces the fatigue life. This life reduction is mainly dependent on a strain rate and/or a time duration in the compression going stroke.

(2) The environmental effect of air on the creep damage (time-dependent

damage) is different for different materials. The air environment intensifies the creep damage of 304 stainless steel, restrains that of 2 1/4 Cr-1Mo steel and has little effect in Modified 9Cr-1Mo steel.

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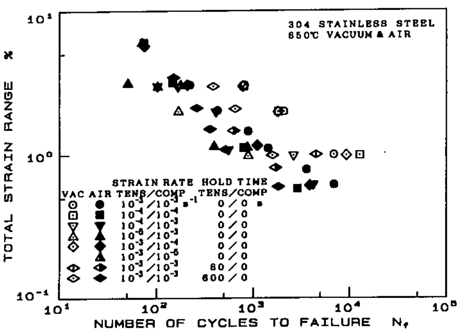

Fig.1 Creep-fatigue Test Result 304 Stainless Steel, 650℃

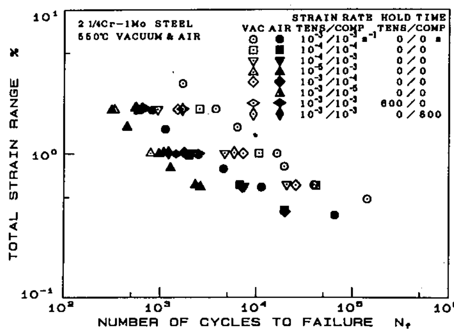

Fig.2 Creep-fatigue Test Result 2 1/4Cr-1Mo Steel, 550℃

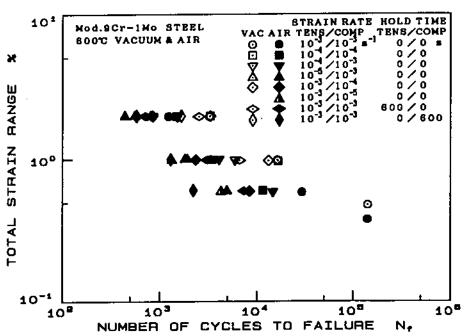

Fig.3 Creep-fatigue Test Result Mod.9Cr-1Mo Steel, 600℃

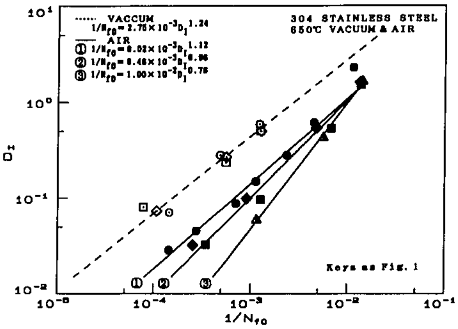

Fig.4 Environmental Effect on Time-independent Damage 304 Stainless Steel, 650℃

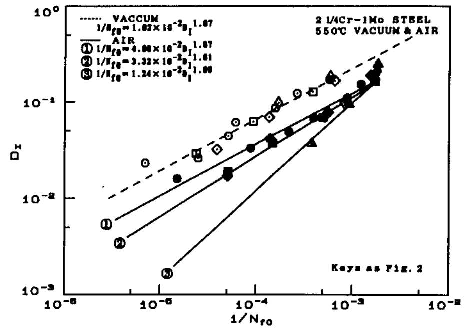

Fig.5 Environmental Effect on Time-independent Damage 2 1/4Cr-1Mo Steel, 550℃

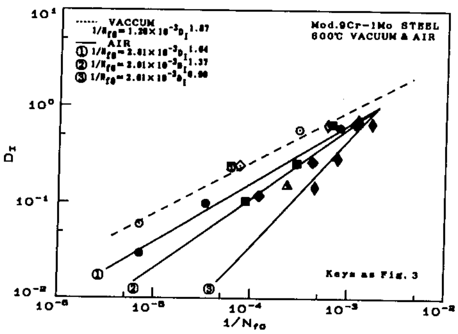

Fig.6 Environmental Effect on Time-independent Damage Mod.9Cr-1Mo Steel, 600℃

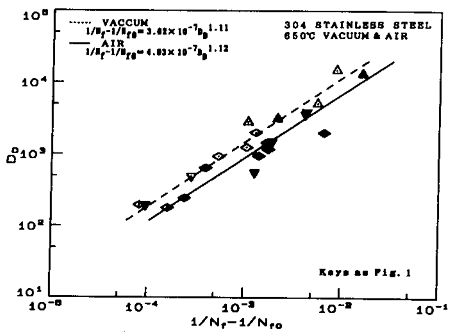

Fig.7 Environmental Effect on Time-dependent Damage 304 Stainless Steel, 650℃

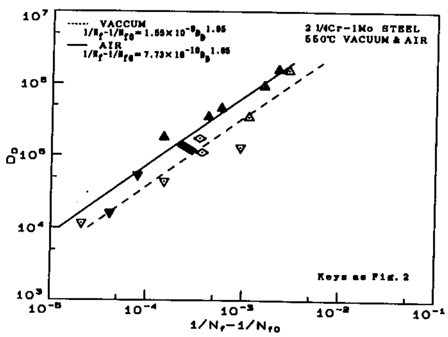

Fig.8 Environmental Effect on Time-dependent Damage 2 1/4Cr-1Mo Steel, 550℃

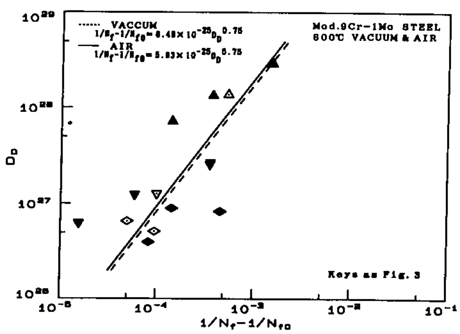

Fig.9 Environmental Effect on Time-dependent Damage Mod.9Cr-1Mo Steel, 600℃