

Creep-fatigue behavior of 2 1/4Cr-1Mo steel at 550°C in air and vacuum

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1. INTRODUCTION

Following studies on creep-fatigue behaviors of 304 steel at 650°C (Asada et al(1980) and Morishita et al(1984), (1985), (1987)), 2 1/4Cr-1Mo steel was studied on its creep-fatigue behaviors at 550°C in air and vacuum of 100 and 0.1 μ Pa. The present study intends to give a base for an evaluation of the environmental effect through obtaining a pure creep-fatigue behavior of this steel which is free from the environmental effect.

In the previous studies on 304 steel, tests were conducted in three kinds of environment of air, 100 and 0.1 μ Pa vacuum. It seemed to be plausible that the 0.1 μ Pa vacuum shows the pure creep-fatigue behavior of 304 steel at 650°C which is almost completely free from the environment. A creep-fatigue life in 0.1 μ Pa vacuum is almost one order of magnitude higher than that in air. The 100 μ Pa vacuum suggested that the environmental effect of air still remains but is so small that a creep-fatigue life in 100 μ Pa is same to that in 0.1 μ Pa in some strain wave forms.

Following characteristic features were observed with the creep-fatigue behaviors of 304 steel in a very high vacuum of 0.1 μ Pa which are able to be considered to be free from the environmental effect of air. The frequency effect diminished, that is, a symmetric continuous cycle showed a unique fatigue life independent of a strain rate. A F-S unsymmetric continuous cycle showed a same fatigue life to a symmetric one. These two wave forms gave an upper limit of a fatigue life at 550°C. Contrary to these, a S-F unsymmetric continuous cycle showed a life reduction from the former two wave forms and the life reduction was significant as a strain rate decreased in tension.

A tensile strain hold cycle showed a significant life reduction from the first two wave forms. However, a compressive strain hold cycle showed no life reduction and a tension-compression hold cycle showed no or little life reduction.

Following conclusions were derived from these observations with 304 steel at very high vacuum. A creep-fatigue life reduction occurs when a tension going time exceeds a compression going time. However, no life reduction occurs in other cases of a compression going-time equal to or longer than a tension going time.

A value of an internal back stress was determined based on an analysis of stress-strain hysteresis loops obtained in high vacuum environment. An overstress was defined by an applied stress subtracted by a back

stress and a time dependent behavior of the overstress was examined phenomenologically. A relaxation or recovery of the back stress occurs during unloading from a stress peak to a level of a stress at which a value of the back stress was determined. This recovery of the back stress diminishes at higher unloading strain rate exceeding 10^{*-3} 1/s. An experimental extrapolation was made based on this observation to obtain a value of the overstress just prior to unloading and was correlated with a value of an inelastic strain rate just prior to unloading. The relation showed a strain range dependency.

The authors assumed that this overstress-inelastic strain rate relation at stress peaks gives a universal stress-strain rate relation at an arbitrary moment of loading. This assumption resulted in a predicted overstress history of test data.

Damage analysis was made based on two damage factors. A time-independent damage factor is given by an inelastic strain integration of the overstress during one cycle. A time-dependent damage factor is given by a time integration of the overstress in a cycle. A linear combination of power expression of the factors gave a reasonable prediction of a creep-fatigue life in 0.1 μ Pa vacuum, that is, of a pure creep-fatigue life free from the environmental effect.

The present study intends to examine if similar observations are obtained with 2 1/4Cr-1Mo steel at 550°C. This paper describes the analysis of the overstress and damages, in addition to a creep-fatigue result.

2. CREEP-FATIGUE TESTS AND RESULTS

2.1 Test Procedure

The present study was made with a normalized and tempered 2 1/4Cr-1Mo steel (heat treatment 930°C x 3.5 Hr + 720°C x 7.5 Hr). Specimens were prepared from a hot-rolled plate with a thickness of 40 mm subjected to the heat treatment. Tables 1 and 2 give a chemical composition and mechanical properties of the material, respectively. Strain controlled creep-fatigue tests were conducted at 550°C in air and vacuum of 100 and 0.1 μ Pa. Same test facilities and procedures are employed here to those employed in the previous studies with 304 steel (Asada et al and Morishita et al). The strain wave forms employed are a symmetric continuous, unsymmetric continuous of S-F and F-S and a tension or compression hold cycle as employed in the previous studies.

2.2 Test Results

Creep-fatigue test results are given in Figs.1 to 3 for a test in air, 100 μ Pa vacuum and 0.1 μ Pa vacuum, respectively. A very interesting feature is shown in these figures. The data in air shows a very narrow scatter band despite that tests were made with various strain wave forms. A wide scatter is observed in data in vacuum, although a life itself is about one order of magnitude higher in vacuum than in air. The 100 μ Pa vacuum gives almost same fatigue life to that in 0.1 μ Pa although the former gives a little bit shorter life than the latter.

Figure 4 summarizes a trend of life reduction in three environments, with respect to a strain range and strain wave form. As easily seen, the highest life is given by a symmetric continuous cycle of 10^{*-3} 1/s strain rate in 0.1 μ Pa vacuum. A symmetric continuous cycle of 10^{*-3} 1/s

strain rate in 100 μ Pa vacuum comes next although a difference in life is small between these vacuum environments.

Visual and SEM observations showed that no indication of oxidation was observed on specimen surfaces tested in 100 and 0.1 μ Pa vacuum. The authors considered that the environmental effect of air was eliminated almost in 100 μ Pa and almost completely in 0.1 μ Pa vacuum, although there still exists a small discrepancy as seen in Fig.4.

A symmetric continuous cycle of 10^{*-4} and 10^{*-3} 1/s strain rate gives a very similar fatigue life. A scatter can be considered to be within an experimental error in high vacuum. The authors considered that a frequency effect diminished in high vacuum environment as 304 steel at 650°C. The F-S cycle gives a very similar fatigue life to that of a symmetric continuous cycle in high vacuum environment. However, there observed a trend of shorter life in F-S cycle than in a symmetric continuous cycle though the difference is small. This observation is different from that with 304 steel. The discrepancy can be explained by an effect of a mean stress suggested by Coffin (1980). A positive mean stress was developed in the F-S cycle but not in other wave forms except for a compression hold cycle in the present study.

The S-F cycle showed a remarkable life reduction compared with former two wave forms. The life reduction in S-F cycle became noticeable as a strain rate in tension going decreases as seen in Figs. 2 and 3. In air, this observation is quite ambiguous. A large reduction of life was again observed with a tensile hold time cycle in vacuum but not in air. A compression hold cycle was tested in air which showed a remarkable life reduction. This can be attributed to the effect of a positive mean stress.

Through these observations on creep-fatigue behaviors of various wave forms and environments, a similar conclusion can be deduced with this steel as obtained with 304 steel, that is, a life reduction due to the pure creep-fatigue interaction occurs with 2 1/4Cr-1Mo steel when a tension going time exceeds a compression going time. Differing from 304 steel, a life reduction is affected by a positive mean stress in 2 1/4Cr-1Mo steel as seen in F-S cycle in vacuum and possibly in a compression hold cycle.

Above conclusions are derived in an environment free condition. In air, a situation becomes complex due to a superposition of a mean stress effect and the environmental effect which may prevent a life reduction by a formation of oxide films on specimen surfaces which covers matrix from further oxidation under slow loading rate.

Summarizing above, a symmetric continuous cycle shows a unique fatigue strength independent of time or strain rate, in high vacuum environment. In high vacuum, that is, pure creep-fatigue condition, a life reduction occurs when a strain wave form has a longer tension going time than a compression going time. The opposite case of a strain wave form shows basically no life reduction of time/rate dependent. An additional effect is introduced by a positive mean stress to reduce a creep-fatigue life. A positive mean stress is developed by a strain wave form of F-S or compressive strain hold cycle in which a slight life reduction is seen even in high vacuum. In air environment, the mean stress effect superposes upon the environmental effect to shade a pure creep-fatigue behavior and to show a complex behavior.

3. STRESS-STRAIN RESPONSE AND OVERSTRESS

3.1 Stress-Strain Response in Various Environment

The present normalized and tempered 2 1/4Cr-1Mo steel shows a typical

cyclic strain softening behavior. In order to check an effect of environment on a stress-strain response of this steel, a cyclic strain softening curve was compared among three test environments as shown in Fig.5. The figure shows a maximum tensile and minimum compressive stress versus number of cycles relation of a symmetric continuous cycle with a strain rate of 10^{-3} 1/s with a strain range of 0.01.

An attention should be paid to the fact that three kinds of data points coincide with each other regardless the test environment. It is suggested that a stress-strain response is not affected by an environment of air or vacuum. Same observations are obtained with stress-strain hysteresis loops obtained under a same wave form and strain range when loops are measured at a same number of cycles. However, different shapes of loops are obtained in various environments when we compare those at a half life cycle as a level of cyclic softening differs from environment to environment.

3.2 Unloading Curve

As made with 304 steel, unloading curves of the present test results were examined to determine an internal stress and then the overstress. Figure 6 shows a schematical illustration of a shape of the hysteresis loop of this steel at 550°C.

The unloading curve shows a bowing out shape to a direction of an acting stress during the very beginning of unloading. This implies an increase of an inelastic strain just after unloading starting, although the increment of an inelastic strain is very small. Then we observe a linear unloading curve with a gradient equal to a value of Modulus of Elasticity of the material at the temperature. After then a decrease of an inelastic strain is observed against a direction of the stress acting at a start of unloading.

Figure 7 shows an example of unloading curves from a tensile peak of a symmetric continuous cycle of 10^{-3} 1/s strain rate. In the figure, an upper and lower bound of the linear part are indicated with solid lines. As seen in the figure, a size of this linear part increases as a strain range increases. A same unloading curve was obtained in unloading from a compression peak, in this wave shape. In other wave forms of S-F, F-S and hold time cycles, unloading curves differed in tension and compression, usually.

However, a prescribed linear part was observed in all unloading curves of various wave forms in the present study with 2 1/4Cr-1Mo steel. This observation is quite different from 304 steel in which a linear part was not observed in its unloading curve.

The authors considered that this linear part is an elastic core in which the material behaves as a completely elastic body and that a radius of this part is to be a drag stress D as indicated in Fig.6. The authors defined a back stress R by a value of a stress corresponding to a center of this part also indicated in Fig.6. As a result, 2 1/4Cr-1Mo steel has two kinds of an internal stress. A total internal stress is given by a summation of R and D.

3.3 Overstress

The authors defined a value of the overstress of 2 1/4Cr-1Mo steel by the following equation, that is, the overstress in this case is given by a difference of the applied stress $\bar{\sigma}$ and R+D.

$$(1) \quad \sigma_e = \sigma - R - D$$

where, σ_e and σ are the overstress and applied stress, respectively. Based on a similar procedure to the dip test by Ahlquist et al (1969), an experimental value of the overstress $\sigma_{e \text{ exp}}$ is evaluated on the unloading curve as,

$$(2) \quad \sigma_{e \text{ exp}} = \sigma_{\text{peak}} - R - D,$$

where, σ_{peak} corresponds to a maximum or minimum stress. Values of R and D are those determined experimentally, as shown in Fig.6.

Figure 8 shows that thus determined value of $\sigma_{e \text{ exp}}$ depends upon the strain rate during unloading. A remarkable reduction of this value is observed as the unloading strain rate increases. This implies that a relaxation or recovery of R and D occurs during unloading, as observed with 304 steel. A lowest saturated value of $\sigma_{e \text{ exp}}$ should coincide with a correct value of the overstress at the stress peak as illustrated in Fig.6. Figure 8 suggests that the correct overstress at peak can be determined at a strain rate higher than 10^{-3} l/s for this steel at 550 °C. The authors assumed a value of $\sigma_{e \text{ exp}}$ at 10^{-3} l/s to be a value of the overstress at a peak in the present study. The authors assumed further that the overstress is independent of a strain wave form and a sign of a stress although it depends upon an inelastic strain rate just prior to unloading.

Thus determined value of the overstress at a peak was examined with its change due to cyclic strain softening. It showed an increase during first several cycles, that is, hardening occurred in the overstress. But the hardening saturated very rapidly to show almost constant values till failure. Above observations were obtained from data tested in 0.1 μ Pa vacuum. But the results can be extended to other environments based on the description in 3.1.

3.4 Overstress-Inelastic Strain Rate Relation

The overstress at a stress peak was correlated with an inelastic strain rate just prior to a strain reversal as shown in Fig.9. The figure shows a characteristic feature that a overstress is held constant between the experimental strain rate of 10^{-6} to 10^{-3} l/s and is independent of a strain range. The feature is characterizing 2 1/4Cr-1Mo steel but is different from 304 steel.

The authors assumed that the relation of Fig.9 can be extended to a general overstress-strain rate relation at an arbitrary moment of loading although the relation itself was obtained at strain reversals. This assumption leads us to a prediction of the overstress at an arbitrary moment of loading of specimens. This means a constant overstress develops during strain cycling, as shown in Fig.6, where the authors assumed a cut off of the overstress at a start of reloading in order that a R+D line starts at the end of the elastic core. Figure 10 shows an example of a prediction of a locus of R+D for S-F cycle of 10^{-5} / 10^{-3} l/s strain rate and 0.01 strain range.

4. DAMAGE ANALYSIS BASED ON OVERSTRESS

4.1 Concept of Model

In the present study, an examination was tried to check if a damage model

developed for 304 steel is applicable to 2 1/4Cr-1Mo steel. The model was developed to describe a pure creep-fatigue behavior observed in very high vacuum where a time/rate dependent life reduction was observed. A life prediction equation is given by Eq.(3).

$$(3) \quad N_f (C_1 D_I^{n1} + C_2 D_D^{n2}) = 1$$

N_f is a fatigue life in pure creep-fatigue condition free from the environmental effect.

D_I and D_D are a time-independent and -dependent damage factor and are given by Eqs.(4) and (5), respectively.

$$(4) \quad D_I = \int_{\text{cycle}} \sigma_e d\epsilon_p$$

$$(5) \quad D_D = \int_{\text{cycle}} \sigma_e dt$$

D_I and D_D are an inelastic strain ϵ_p and time t integration of the over-stress for one cycle, respectively. D_D is imposed following restriction.

$$(6) \quad D_D = 0$$

if Eq.(5) gives a negative value of D_D . Equation (6) restricts an over increase of fatigue life estimation of F-S cycle or compression hold cycle exceeding the upper limit of a fatigue life given by a symmetric continuous cycle experimentally.

4.2 Damage Analysis of 2 1/4Cr-1Mo Steel

A creep-fatigue life prediction was tried with data obtained in 0.1 μ Pa vacuum, which are considered to be free from the environmental effect. Figure 11 shows a relation of D_I versus life fraction $1/N_{f0}$, where N_{f0} means a life of a symmetric continuous cycle. The figure shows results of F-S cycle, additionally although it showed a life reduction due to a mean stress effect. A very reasonable relation is observed with data of a symmetric continuous cycle expressed by following Eq.(7), empirically.

$$(7) \quad 1/N_{f0} = C_1 D_I^{n1}$$

where, C_1 equals to 1.45×10^{-4} and $n1$ equals to 1.81, when a stress is measured in MPa.

A positive value of D_D is obtained for S-F cycle and tension hold cycle. Based on Eq.(7), D_D is correlated a time-dependent life fraction $1/N_f - 1/N_{f0}$, where N_f means a life of S-F and tension hold cycles.

$$(8) \quad 1/N_f - 1/N_{f0} = C_2 D_D^{n2}$$

A result of evaluation of Eq.(8) is given in Fig.12 to result in a following value for C_2 and $n2$. $C_2 = 4.21 \times 10^{-8}$ and $n2 = 0.965$, when a stress and time are measured in MPa and s, respectively.

A result of life prediction based on Eqs.(3), (7) and (8) is shown in Fig.13 for 2 1/4Cr-1Mo steel at 550°C in very high vacuum. A scatter of prediction is within a factor of 2. However, this prediction does not take into account the effect of positive mean stress on a pure creep-fatigue life reduction. This should be considered for an evaluation of pure creep-fatigue life reduction of 2 1/4Cr-1Mo steel.

Figure 12 shows a wide scatter as is observed. This situation may be improved by taking into account the effect of mean stress in the present damage model, but is a future problem.

Figure 11 means the Coffin-Manson equation rewritten by a damage factor D_I in place of an inelastic (plastic) strain range. The relation was held good both in 304 steel and 2 1/4Cr-1Mo steel.

5. Discussion

Although the life prediction equations were derived from data in environment free condition, the relation can be used to give a base for evaluation of the environmental effect. An example is shown in Fig.14 in which predicted lives of tests in air and 100 μ Pa vacuum are correlated with experimental lives. The off-set of life from the prediction means the effect of particular environments on creep-fatigue behaviors of this steel.

In the figure, values of DI and DD were computed with the data of corresponding environments. Eqs.(3), (7) and (8) were used again to obtain the predicted life of data in corresponding environments. Data points of 100 μ Pa vacuum fall within a scatter band of the pure creep-fatigue data in 0.1 μ Pa, although there observed a small off-set of about 1.5.

The data in air shows about one order of magnitude off-set. This means a life reduction of about one order of magnitude due to the environmental effect of air. A scatter band of data in air shows enlargement from that observed in Fig.1. This implies that a large life reduction may occur in very high vacuum under loading condition of S-F cycle as seen in Fig.14. A trend of scatter of data in air is almost parallel to a trend of high vacuum data. This can be considered that the effect of air environment is independent of a strain range.

A caution should be paid to a point that these results do not include the particular effect of a mean stress. This is a point of discussion and further studies are necessary regarding this effect.

6. Conclusion

Creep-fatigue tests were conducted with 2 1/4Cr-1Mo steel at 550°C under various strain wave forms in air and vacuum of 100 and 0.1 μ Pa. No indication of environmental effect of air was observed in 0.1 μ Pa vacuum in which a strain rate effect diminished. However, there observed still a time/rate dependent life reduction in a case of wave forms with a longer tension going time than compression. In addition, there observed an effect of mean stress with this steel.

An analysis of stress-strain response showed the response is not affected by the test environment. Internal stresses of back and drag stress were obtained with this steel and an overstress was predicted based on phenomenology.

A pure creep-fatigue life reduction was predicted based on a damage model composed of the overstress. The prediction showed a scatter of a factor of two. An effect of air environment was evaluated based on the prediction procedure. The method should be improved to include the effect of mean stress on creep-fatigue behavior of this steel.

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References

Ahlquist, C. Norman and Nix D. 1969, A technique for measuring mean internal stress during high temperature creep, Scripta Met. 3,679-682

Asada, Y. and Mitsuhashi, S. 1980, Creep-fatigue interaction of 304 and 316 stainless steel in air and vacuum, Proc. 4th I.C.P.V.T. II, I. Mech E., 321-327

Asada, Y. and Mitsuhashi, S. 1980, Creep-fatigue interaction of type 304 stainless steel in air and vacuum, I. Mech. E. Conf. Publ. 1980-5 I 199-202

Coffin, L.F. 1980a, Damage processes in time-dependent failure - a review Creep-Fatigue-Environment Interaction, Pelloux, R.M. and Stoloff, N.S. Ed. AIME, 1-23

Morishita, M. and Asada, Y. 1984, Creep-fatigue interaction - a data base analysis and applications, Nucl. Eng. Design 83, 367-377

Morishita, M., Taguchi, K., Satake, M., Ishikawa, A. and Asada, Y. 1984, Creep-fatigue behavior of 304 stainless steel in vacuum, Proc. 5th I. C..V.T. II, ASME, 1109-1120

Morishita, M. and Asada, Y. 1985, An evaluation of creep-fatigue behavior of 304 stainless steel in a very high vacuum environment, Bull. JSME 28, 7-12

Morishita, M., Taguchi, K., Asayama, T., Ishikawa, A. and Asada, Y. 1987 Application of the overstress concept for creep-fatigue evaluation of 304 steel in vacuum, ASTM STP 942(to be published)

Table 1 Chemical Composition of 2 1/4Cr-1Mo Steel (wt%)

C	Si	Mn	P	S	Ni	Cr	Cu	Mo
0.15	0.28	0.55	0.10	0.06	0.14	2.38	0.07	0.98

Table 2 Mechanical Properties of 2 1/4Cr-1Mo Steel NT* at R.T.

0.2% Yield Stress MPa	U.T.S. MPa	Elongation per cent	Reduction in Area per cent
431.2	619.4	29.5	68.6

* Normalized and Tempered, 930°C x 3.5 Hr + 720°C x 7.5 Hr, 40 mm Plate

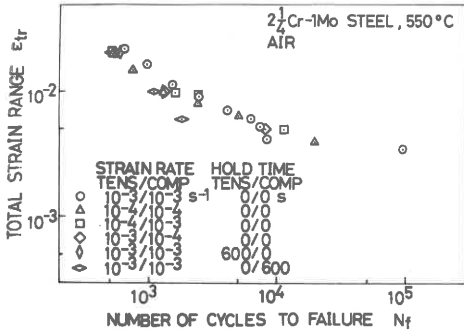


Fig.1 Creep-fatigue test result in air

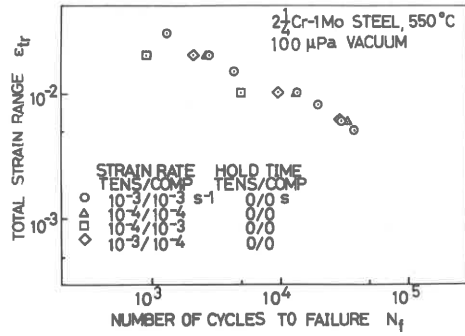


Fig.2 Creep-fatigue test result in 100 μPa vacuum

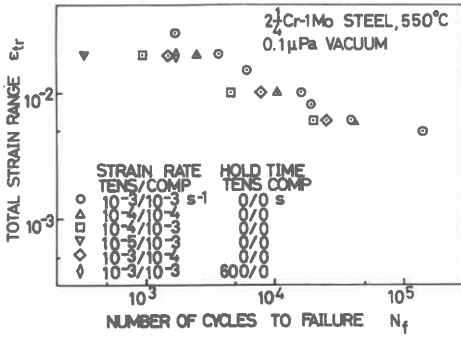


Fig.3 Creep-fatigue test result in 0.1 μPa vacuum

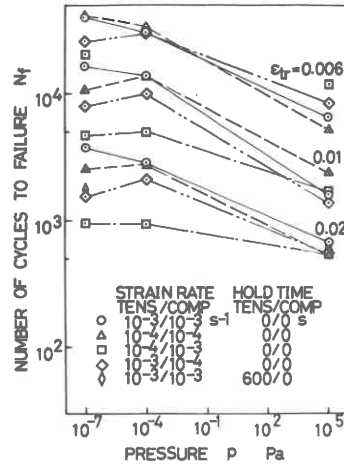


Fig.4 Fatigue life of various environments

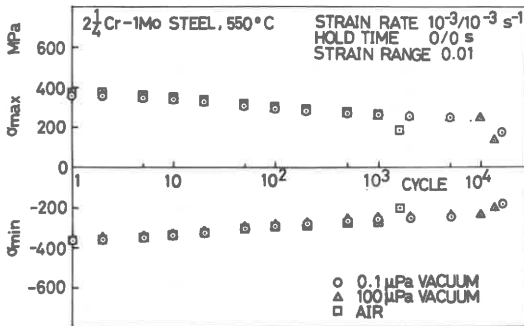


Fig.5 Cyclic strain softening behavior in various environments

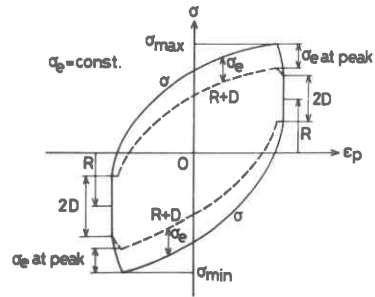


Fig.6 Schematic illustration of hysteresis loop

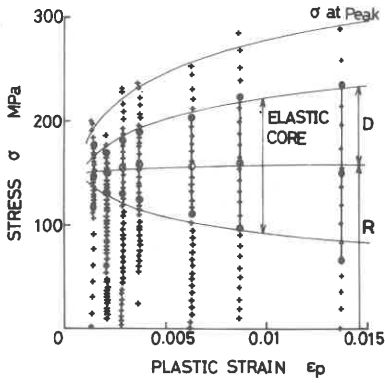


Fig. 7 Behavior of unloading curves

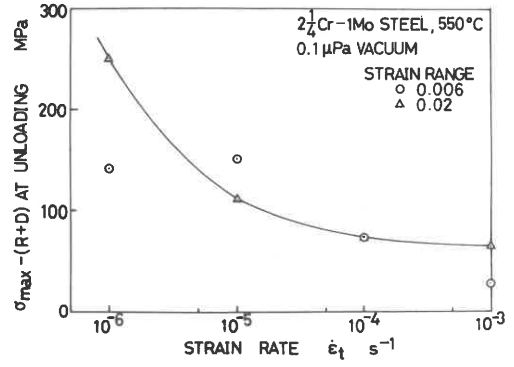


Fig. 8 Rate dependent reduction of experimental overstress

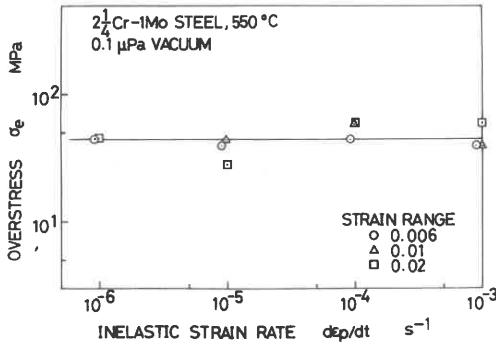


Fig. 9 Overstress-inelastic strain rate relation

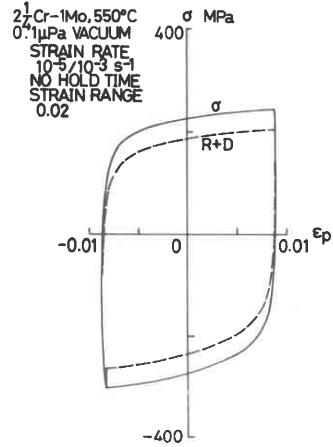


Fig. 10 Prediction of Back and drag stress

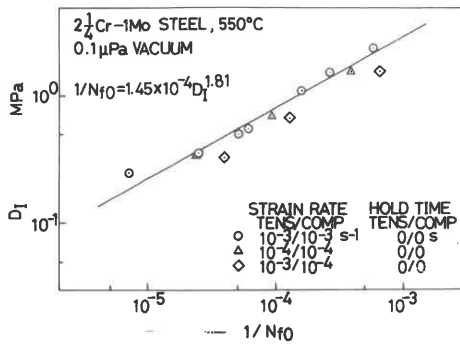


Fig. 11 Time-independent damage factor and life fraction

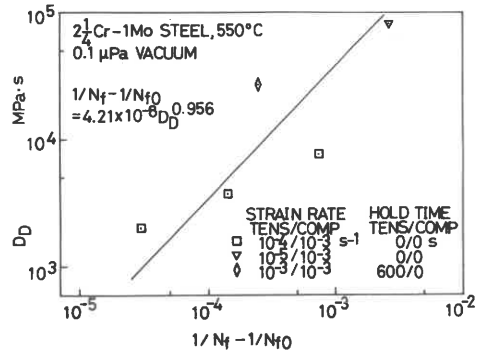


Fig. 12 Time-dependent damage factor and life fraction

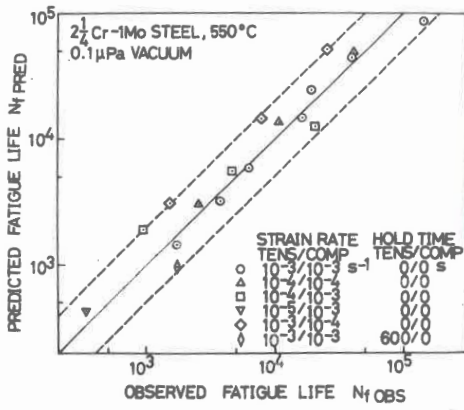


Fig.13 Life prediction result of data in 0.1 μPa vacuum

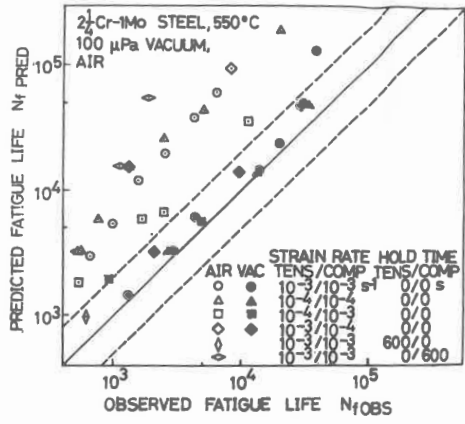


Fig.14 Life prediction and environment effect prediction for air and 100 μPa vacuum