Journal of National Fisheries University 50 (1) 13−23 (2001)

Studies of Load Cycle Effects on Creep Fatigue Life at Elevated Temperatures

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The creep fatigue life of elevated temperature components such as combustion engines is said to depend on the mode of the thermal and mechanical load cycles. Creep fatigue tests of a modified JIS SUS 410L were performed in order to investigate the feasibility of the application to elevated temperature components. The experimental results are compared with data of the commer cial SUS304 and discussed with respect to the evaluation method of the creep fatigue load.

1. Introduction

A modified material from JIS SUS 410L, by annexing a very small amount of chemical elements, is surveyed to take place of the conventional stainless steels for elevated temperature components. This new material is intended to be more heat resistant and economical than the commercial ones. This material is called as Mod. SUS410L in this paper.

By using this new material, authors carried out three kinds of creep fatigue tests at elevated temperatures and confirmed the cycles to failure of this material is larger than those of SUS304. From the obtained data, the creep and fatigue effects are discussed by applying creep fatigue interaction approach, which is referred from Subsection NH Class 1 Components in Elevated Temperature Service of ASME B&PVC[1] (abbreviated as Subsection NH in this paper).

2. Testing Condition

2.1 Materials

Mod. JIS SUS 410L of the ferritic stainless steel is used for the material of the test specimen. The chemical compositions are shown in Table 1

Table 1. Chemical compositions of Mod. SUS410L and SUS410L (%)

Material	C	Si	Mn	P	S	Ni	Cr	Cu	Al	N	Ti
Mod.SUS410L	0.006	0.49	0.24	0.024	0.007	0.09	11.06	0.01	0.008	0.006	0.188
SUS410L	～0.03	～1.00	～1.00	～0.04	～0.03	—	11.0～13.5	—	—	—	—

Table 2. Mechanical properties of Mod. SUS410L and SUS304 at room temperature

Material	Proof stress (N/mm^2)	Tensile strength (N/mm^2)	Elong. (%)	Thermal expansion coefficient (1/°C)	Vickers hardness (HV)
Mod.SUS410L	304	451	31	11.7×10^{-6}	140
SUS304	242	666	68	12.2×10^{-6}	150

2001年３月22日受付. Received Mar. 22, 2001.
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with those of original JIS SUS410L. In this material, a very small amount of Cu, Al, N, and Ti were annexed to the original chemical compositions of SUS410L to improve the strength of the material at high temperature. The mechanical properties at room temperature are compared with the commercial SUS 304 in Table 2. The geometry and dimensions of the test specimen are shown in Fig.1.

2.2 Experimental conditions

The test parameters are summarized in Table 3. All of the creep and fatigue tests are performed at temperature, 550℃, 650℃ and 750℃, by using the hydraulic servo creep fatigue testing machine. Numbers of the cycles to failure are accounted by the rupture of the specimen.

The following creep fatigue tests are carried out at the strain control method.

① Triangle wave mode

② Trapezoidal wave mode

③ Combined wave mode

In the case of the triangle wave mode, 0.5%, 1.0% and 2.0% of the total strain range(ε_R) are applied . In the case of the trapezoidal wave mode, the hold time (H_T) of 600 sec is applied at the controlled maximum strain of 0.5%, 1.0% and 2.0%. But in the case of the combined wave mode, the sine wave of the frequency of 0.1Hz and 0.2Hz are laid on the base of the trapezoidal wave. Both amplitude ($2\varepsilon_A$) of the sine wave is set up at 25% and 50% strain of the total strain range (ε_R) of the trapezoidal wave.

The strain rates of the tension and compression of the triangle wave and trapezoidal wave are kept constant at 0.0001/sec. But in the case of the combined wave mode, the strain rate of the base trapezoidal wave is kept at the same 0.0001/sec, however the strain rate of the sine wave depend on the frequencies of the sine wave.

3. Test Results

3.1 Numbers of cycles to failure

Numbers of the cycles to failure (N_f) of the triangle wave and trapezoidal wave mode are listed in Table 4(a). Those of the combined wave mode are listed in Table 4(b). In the case of the combined wave mode, these are counted by the numbers of cycles to failure of the base trapezoidal wave.

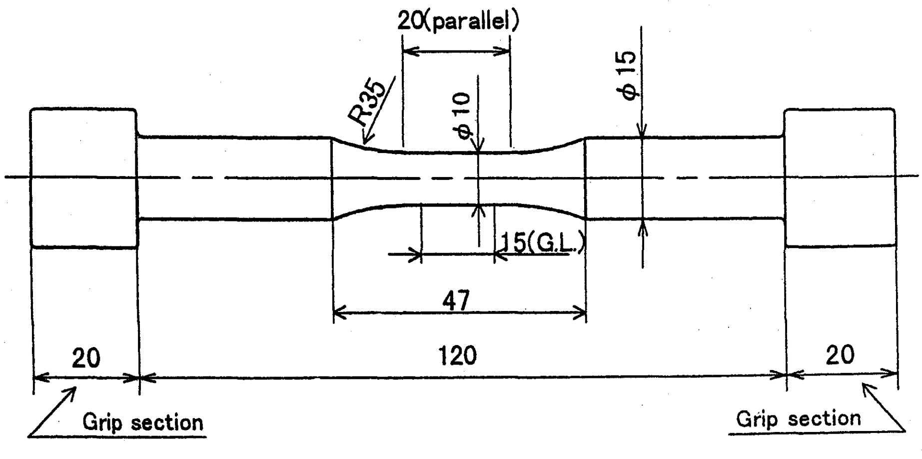
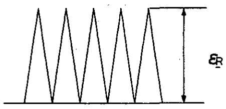
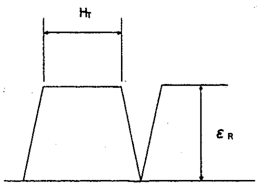
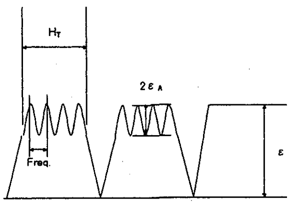


Fig.1. Test specimen configuration (unit : mm)

Table 3. Test parameters

Test modes	Test parameters
	$\varepsilon_R \times$ Temp. $\times T_H \times 2\varepsilon_A \times$ Freq.
Triangle wave mode 	$\begin{Bmatrix} 0.5\% \\ 1.0\% \\ 2.0\% \end{Bmatrix} \times \begin{Bmatrix} 550℃ \\ 650℃ \\ 750℃ \end{Bmatrix} \times \{-\} \times \{-\} \times \{-\}$
Trapezoidal wave mode 	$\begin{Bmatrix} 0.5\% \\ 1.0\% \\ 2.0\% \end{Bmatrix} \times \begin{Bmatrix} 550℃ \\ 650℃ \\ 750℃ \end{Bmatrix} \times \{600s\} \times \{-\} \times \{-\}$
Combined wave mode 	$\begin{Bmatrix} 0.5\% \\ 1.0\% \\ 2.0\% \end{Bmatrix} \times \begin{Bmatrix} 550℃ \\ 650℃ \\ 750℃ \end{Bmatrix} \times \{600s\} \times \begin{Bmatrix} 0.25\varepsilon_R \\ 0.50\varepsilon_R \end{Bmatrix} \times \begin{Bmatrix} 0.1Hz \\ 0.2Hz \end{Bmatrix}$
	$\{0.5\%\} \times \begin{Bmatrix} 550℃ \\ 650℃ \\ 750℃ \end{Bmatrix} \times \{600s\} \times \{1.00\varepsilon_R\} \times \begin{Bmatrix} 0.1Hz \\ 0.2Hz \end{Bmatrix}$

3.2 Creep and fatigue effect on failure

Cycles to failure of the triangle wave mode and the trapezoidal wave mode are shown in Fig.2, which shows that N_f decreases with the temperature rise at the same strain range, and N_f decreases with increase of the strain range at the same temperature. These decrease are thought to be the fatigue effect. N_f of trapezoidal wave mode decreases at the lower strain range than that of the triangle wave mode. The decrease of N_f of the trapezoidal wave mode is thought to be caused by the hold time effects of 600 sec., namely the creep effect.

N_f of 0.1Hz and 0.2Hz combined wave mode are plotted in Fig.3 and Fig.4 respectively. It shows that N_f decreases with increase of the amplitude of the sine wave. The decrease is thought due to the creep fatigue effect.

Table 4. Test results of the cycles to failure

(a)Results of the triangle wave and trapezoidal wave tests

Strain range ε_R (%)	Temperature (°C)	Cycles to failure Tria. w.	Trape. w.
0.5	550	10100	3302
	650	7887	4379
	750	3844	1300
1.0	550	2691	2100
	650	1657	1412
	750	1117	862
2.0	550	775	885
	650	556	556
	750	392	392

(b)Results of the combined wave tests

Both amplitudes of sine wave ($2\varepsilon_A$)	Max. strain ε_R(%)	Temperature (°C)	Cycles to failure 0.2Hz of sine wave	0.1Hz of sine wave
$0.25\varepsilon_R$	0.5	550	1040	2450
		650	830	1503
		750	320	268
	1.0	550	311	739
		650	281	205
		750	98	56
	2.0	550	69	137
		650	56	69
		750	34	19
$0.50\varepsilon_R$	0.5	550	403	646
		650	281	227
		750	191	179
	1.0	550	80	289
		650	71	95
		750	49	81
	2.0	550	26	61
		650	22	48
		750	15	31
$1.00\varepsilon_R$	0.5	550	66	233
		650	46	92
		750	—	59

4. Discussions

4.1 Comparison of cycles to failure between Mod. SUS410L and SUS304

In Fig.5, cycles to failure of the triangle wave mode of Mod. SUS410L are compared with those of SUS304, which are referred from of Refs.2), 3) and 4). The comparison shows cycles to failure of Mod.SUS410L seem stronger than those of SUS304.

4.2 Evaluation method of creep fatigue

According to the background criteria[5] of Subsection NH, the ASME Code Committee chose the creep fatigue interaction approach for the creep fatigue evaluation from various approaches, wherein damage due to creep was accounted for on a time fraction basis (Robinson Taira rule)

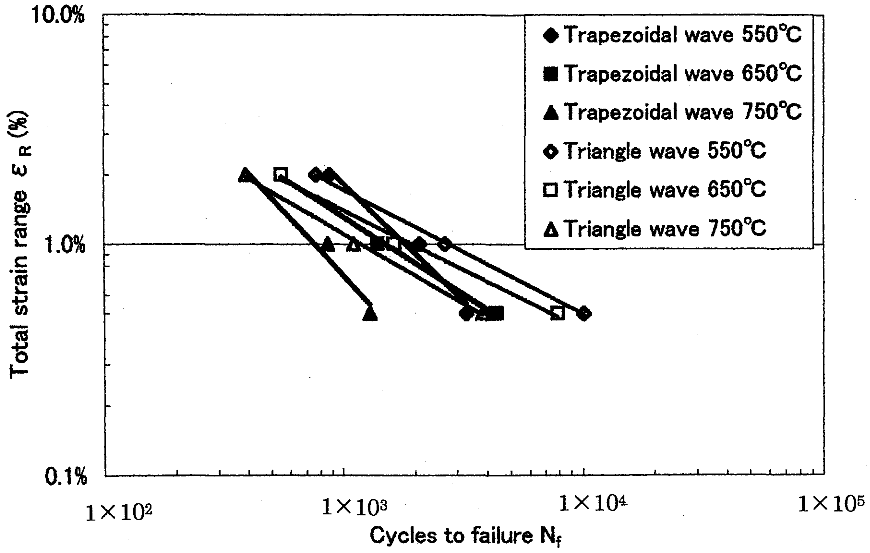


Fig.2. Cycles to failure of the triangle wave and the trapezoidal wave tests

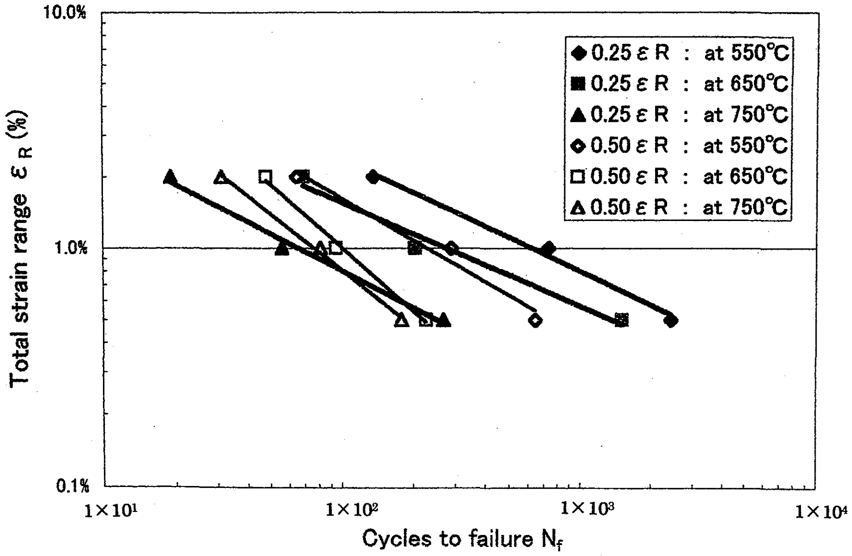


Fig.3. Strain vs. cycles to failure by combined wave test at 0.1Hz

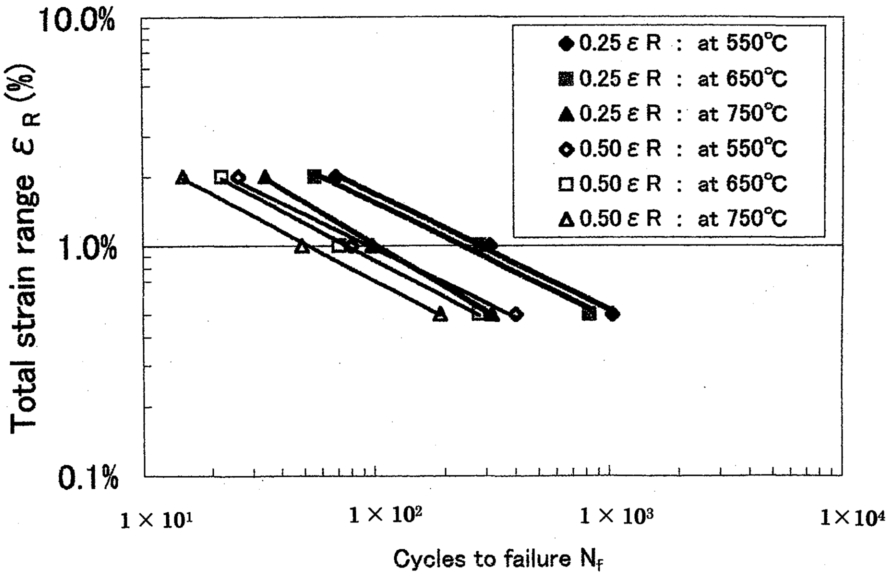


Fig.4. Strain vs. cycles to failure by combined wave tests at 0.2Hz

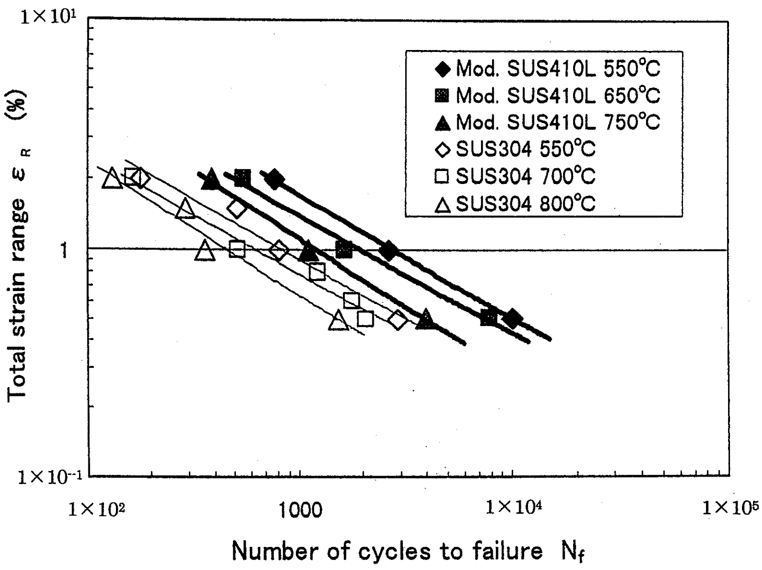


Fig.5. Comparison of cycles to failure by no-holdtime test between Mod. SUS410L and SUS304

and damage due to fatigue was accounted for by using Miner's cumulative criteria. The allowable total damage was based upon observed material behavior and was a function of the calculated damage for both creep and fatigue. The following Eq. (1) in Subsection NH was adopted largely upon a life fraction concept which was based on several alloys.

Authors tried to evaluate creep and fatigue lives from the obtained data to assess the evaluation method of Eq. (1)

$$\sum_{j=1}^{P}\left(\frac{n}{N_d}\right)_j+\sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k \leq D \qquad \cdots(1)$$

where, D=total creep-fatigue damage =1.0

$(N_d)_j$ =number of design allowable cycles for cycle type, j

$(T_d)_k$ =allowable time duration during the time interval, k

$(n)_j$ =number of applied repetitions of cycle type, j

$(\Delta t)_k$=duration of the time interval, k

As Subsection NH does not show practically how to analyze loading histogram, authors set up the analysis procedure of the calculation as follows.

(1) Analysis of trapezoidal wave mode

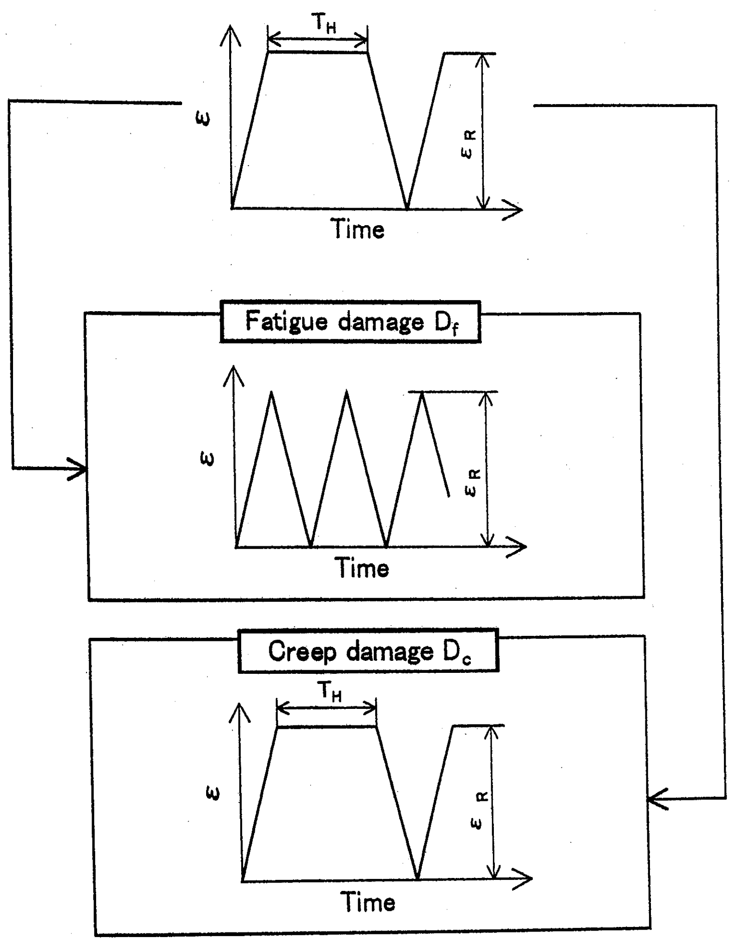
The trapezoidal wave mode is separated into the triangle wave and the trapezoidal wave for the calculation of fatigue damage and creep damage respectively, as shown in Fig.6 (a). The fatigue damage (D_f) is obtained by the following equation.

$$D_f=\frac{n_i}{N_i} \qquad \cdots(2)$$

where, n_i=cycles to failure of the separated triangle wave

N_i=cycle to failure of the triangle wave mode in Fig.2

As the stress arisen in the test specimen decreases on the progress of the cycles when the strain is kept constant, the measured stress of the half cycles to the failure is used for the estimation of the creep rupture time as shown in Fig.7. Creep rupture curves of Fig.8[4] are used



(a)Separation of trapezoidal waves

Fig.6. Separation of waves for the calculation of the creep and fatigue damages

for the calculation of the creep damage (D_c), which is calculated by the following equation.

$$Dc=\frac{t_H\times n_f}{T_r} \quad \cdots(3)$$

where, t_H=hold time of the separated trapezoidal wave
n_f=cycles to failure of the trapezoidal wave
T_r=creep rupture time

Since D_c is thought to be caused largely in the period of the maximum strain holding of the trapezoidal waves, the creep generation time is calculated by $t_H\times n_f$.

(2) Analysis of combined wave mode

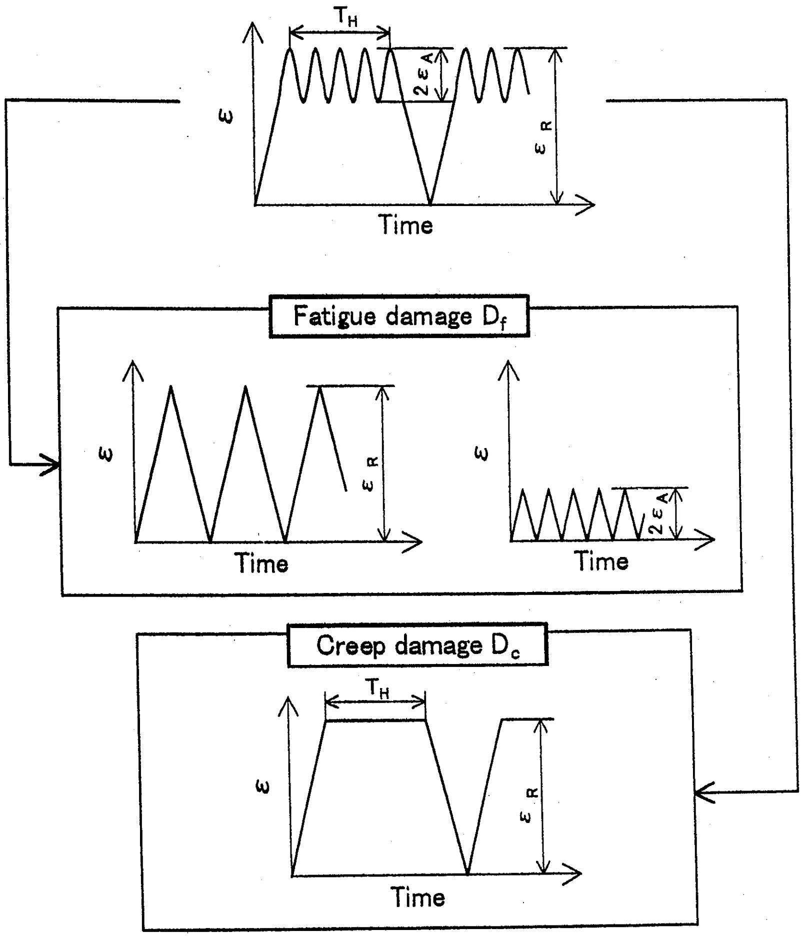
To calculate the creep and fatigue damages, the combined wave mode is separated into the large triangle wave, small triangle wave and trapezoidal wave as shown in Fig.6(b).

The fatigue damages (D_f) are obtained by the following equation,

$$D_f=\frac{n_{i1}}{N_{i1}}+\frac{n_{i2}}{N_{i2}} \quad \cdots(4)$$

where, the definition of n_i and N_i is the same as Eq.(2), but sub 1 and sub 2 indicate the separated large triangle and the small triangle respective ly.

The calculations of the creep damages are performed as those of the trapezoidal wave mode.



(b)Separation of the combined waves

Fig.6. Separation of waves for the calculation of the creep and fatigue damages

4.3 Feasibility of Mod. SUS410L to the creep fatigue evaluation

The obtained D_c and D_f are plotted on Fig.9, which shows the totals of D_c and D_f values of the left side of Eq.(1) are distributed between 0.4 and 6.5 as shown below.

$$0.4 < D_c + D_f < 6.5 \quad \cdots(5)$$

In these calculations, the mean trend curve of the fatigue cycle and the creep rupture time are used. But in the case of the Subsection NH, the design curves of the creep and the fatigue are to be used. Referring the background[5] of Subsection NH, the design curve of the creep rupture time was derived from the mean curve by subtracting 1.65 multiples of the standard deviation of the sample. The design curve of the fatigue was constructed by enveloping whichever minimum values of reduced ones of the best fit curve of continuous cycling fatigue data (a) by a factor of 2 on total strain range and (b) by a factor of 20 on life cycle.

The creep and fatigue data of this new material are not obtained yet enough to perform the statistical calculation for the design allowable. Accordingly, the mean trend curves are used provisionally as mentioned above. D value of unity in Eq.(1) was determined on the basis of many evaluations of the experimental data by ASME Code Committee[5]. The actual failure data of 304

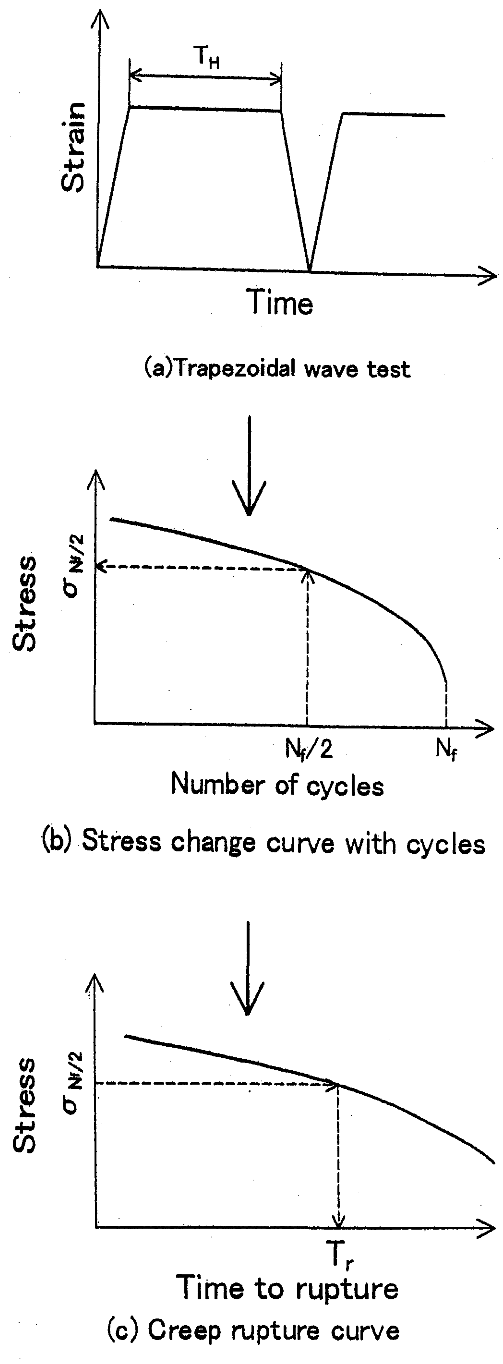


Fig. 7. Calauation of creep damages

and 316 stainless at 1100° F(593℃) were compared with design allowable points of the draft of the Subsection NH, and showed the total damage varies from a minimum of four to greater than40, even though there was considerable scatter.

The total damages of this new material can be estimated to be more than 8 to 130 by reducing the best fit curve of the fatigue only by a factor of 20 on life cycle. Therefore, it can be thought this evaluation method be conservative for Mod. SUS410L. And Mod.SUS410L seems to be feasible to apply Eq.(1).

5. Summary

From the three kinds of the creep fatigue tests, authors obtained the following results.

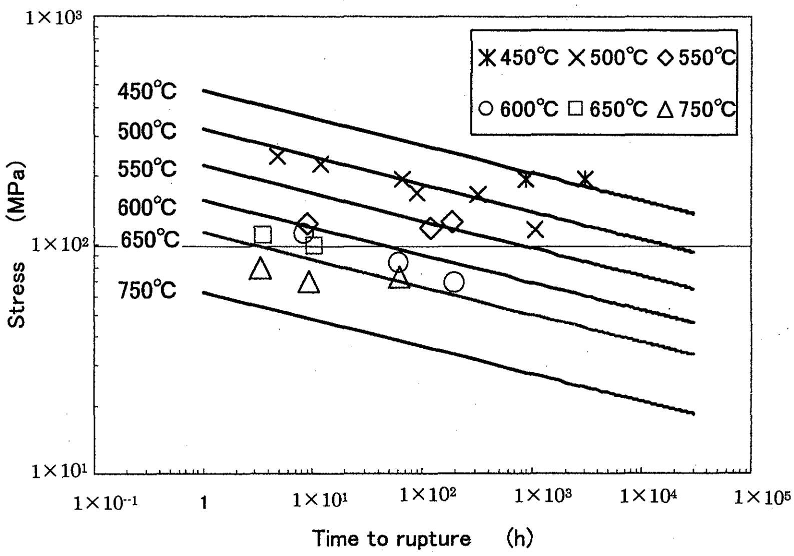


Fig.8. Master creep curve[4]

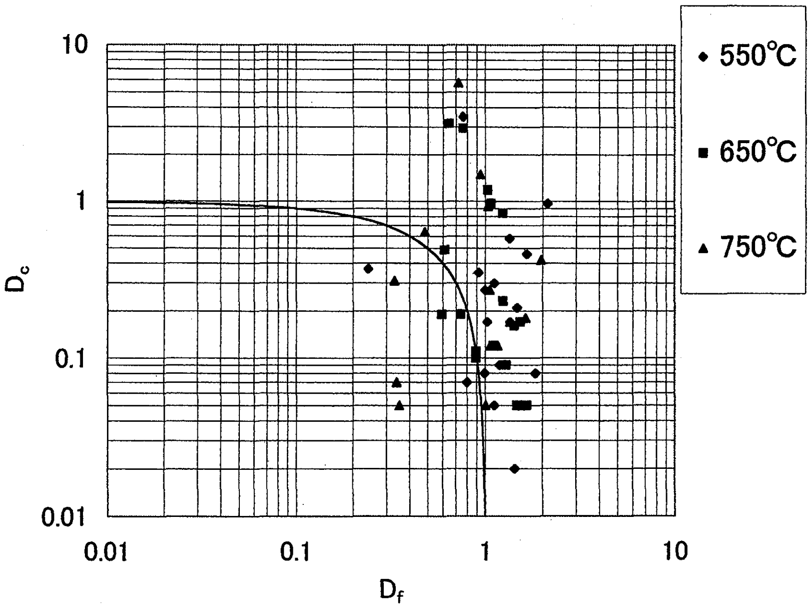


Fig.9. Plot of creep and fatigue damages

(1) Cycles to failure of Mod.SUS410L seem to be stronger than those of SUS304 at elevated temperatures from the triangle wave mode.
(2) The evaluation method of the Subsection NH seems to be feasible to Mod. SUS410L for the elevated temperature component.

Acknowledgments

Authors would like to thank Mr. Yoshihisa Miwa and Mr. Nobuhide. Takeshige of Mazda Motor Corporation for the support of this study. Authors would like to acknowledge the generous support of Miss Chie Hamasaki, Mr. Tohru Kaihara, Miss Noriko Yagi and Mr. Takahiro Gotoh of the students of National Fisheries University in performing the experiments.

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高温におけるクリープ疲労寿命に及ぼす荷重サイクル効果に関する研究

小畑清和・田中辰彦・阿部清三・中嶋大輔
平野尊之・小松和也・古谷哲二

船用内燃機関などの高温高圧機器においては、定常及び変動負荷時に各種の熱応力サイクルを受けクリープ疲労寿命を低下させることになり，正確な寿命予測することをむつかしくしている。本研究では各種の荷重サイクルをひずみ制御の重畳波形におきかえて，新開発の耐熱材料に対してクリープ疲労試験を行い，米国機械学会高温設計基準の寿命評価式の適用性を検討した。