Effect of Frequency on Pulsating Stress Rupture Strength for Notched Bar Specimen†

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Abstract

Pulsating stress rupture tests (stress ratio A<1) in various frequency of stress cycle were performed for notched specimens at elevated temperature in order to study the influence of frequency on rupture strength.

Notched specimens are subjected to combined fatigue and creep damage by pulsating stress so that the rupture life considerably decreases with increase of frequency and the rupture characteristics are classified into 4 types.

Ruptures are not always dominated by a sum of fatigue and creep damage. In some cases, the creep behavior might prevent the development of fatigue damage. Therefore the linear life fraction rule in estimation of rupture life of materials subjected to combined fatigue and creep damage might be not always applicable.

1. Introduction

In materials subjected to a pulsating load at elevated temperature, both creep damage due to the instantaneous stress and fatigue damage by cyclic stress will occur.

In many previous investigations[1),2),3),4),5)] of pulsating stress creep rupture (stress ratio A<1) for unnotched specimen, the influence of fatigue for rupture characteristics has not been observed.

For the notched specimen, the creep behavior might be prevented in notch strengthening materials but the fatigue damage will be promoted. So that the notched specimen under the pulsating stress will be subjected to both fatige and creep damage. Creep damages depend on time and fatige damages depend on number of cycles of stress. The higher frequency of stress cycle, the larger fatigue damage per unit time may occur in materials.

In the viewpoint described above, the pulsating stress rupture tests for notched specimens were carried out for Cr-Mo steel at 550°C as well as mild steel at 450°C in various frequency of stress cycle in order to study not only the influence of notch on rupture life under the pulsating stress but also the rupture characteristics of materials subjected to combined fatigue and creep damage.

2. Experimental

The materials used in the current investigation are both 1Cr-1/2Mo steel and mild steel. Chemical compositions of them are shown in Table 1 and 2.

Both materials were received as rolled plate and heat treating were carried out respectively as follows prior to machining. Annealing was carried out with a condition of 930°C heating, 45 minutes keeping and 150°C/hr furnace cooling for the Cr-Mo steel, and 900°C heating, 30 minutes keeping then furnace cooling for the mild steel.

The Cr-Mo steel was chosen as an example of the material of which the rupture life under pulsating stress for

Table 1. Chemical composition of 1Cr-1/2Mo Steel (%)

C	Si	Mn	P	S	Cu	Ni	Cr	Mo
0.11	0.40	0.44	0.011	0.009	0.04	0.03	1.01	0.45

Table 2. Chemical composition of Mild Steel (%)

C	Si	Mn	P	S	Cu
0.23	0.29	0.80	0.016	0.023	0.09

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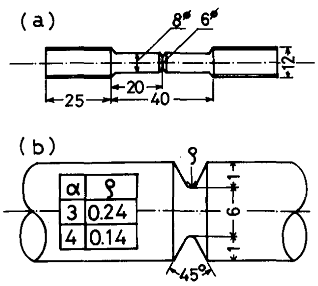
unnotched specimen is independent on frequency of stress cycle at 550°C (as shown in Fig. 5). On the other hand, the mild steel is an example of frequency dependent material for unnotched specimen at 450°C (as shown in Fig. 6).

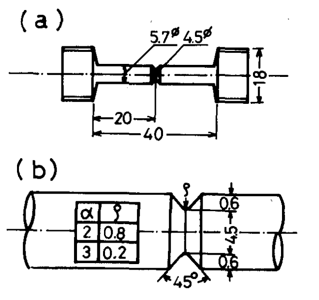
The test specimens are notched bar type as shown in Fig. 1 as well as Fig. 2 and were machined along the rolling direction of the plate. The stress concentration factor α=3 and 4 were employed for the specimen of Cr-Mo steel and α=2 as well as 3 for the mild steel specimens as shown in Fig. 1 and 2.

Pulsating stress rupture testing machine used in the investigation is the same as that used in the previous investigations.[1),2),3)] The rupture test under pulsating load were carried out at 550°C for Cr-Mo steel as well as 450°C for mild steel. The stress ratio A of pulsating stress ($A=\sigma_a/\sigma_m$, σ_a=stress amplitude, σ_m=mean stress) were employed for A<1. The stress wave induced by pulsating load in the test specimen is a sine wave.[1)] The frequency of stress cycle employed for the test are 0.38, 3.8, 38 and 380 c.p.m..



α : Stress Concentration Factor
ρ : Notch Root Radius

Fig. 1 Test specimen of Cr-Mo steel



α : Stress Concentration Factor
ρ : Notch Root Radius

Fig. 2 Test specimen of mild steel

3. Experimental results

Some of the test results for Cr-Mo steel at 550°C are shown in Fig. 3 and for mild steel at 450°C in Fig. 4. The both figures show the relationship between frequency of pulsating stress and rupture time for the notched specimens. Fig. 5 and 6 show the same relationship for the unnotched specimens of respective materials to be compared with the notched specimens.

In the case of unnotched specimens, the rupture time take a almost constant vlue for the different frequency of stress cycles in Cr-Mo steel as shown in Fig. 5. For the mild steel, the rupture time increases with increasing in frequency of stress cycles and rupture life at 380c.p.m. reaches the rupture time which is calculated by equiva-

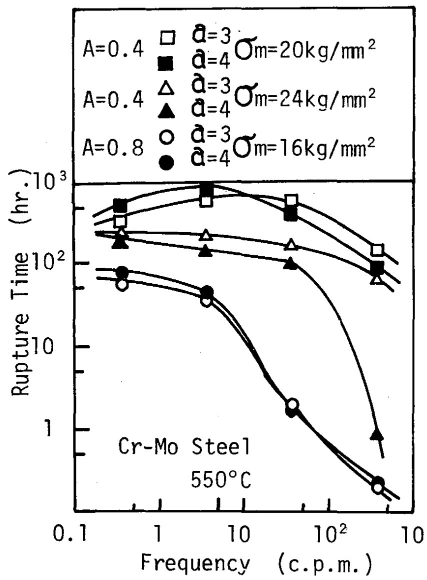


Fig. 3 Relation between frequency and rupture time

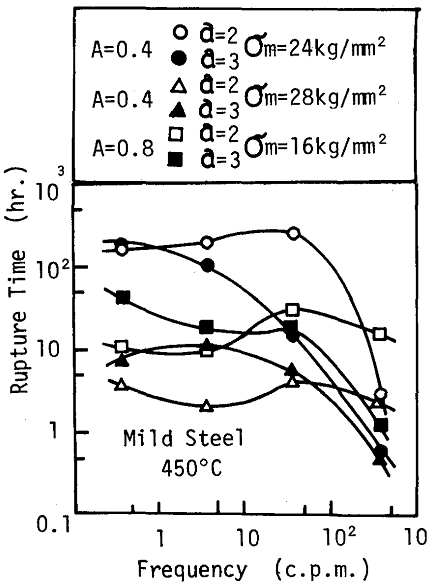


Fig. 4 Relation between frequency and rupture time

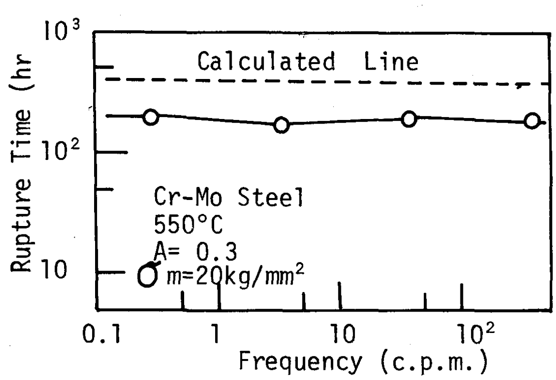


Fig. 5 Relation between frequency and rupture time for unnotched specimen (Cr-Mo)

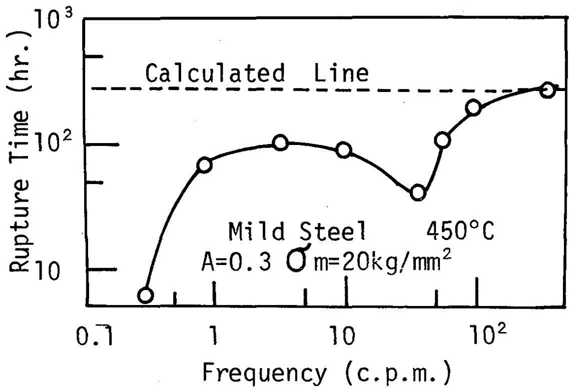


Fig. 6 Relation between frequency and rupture time for unnotched specimen (Mild steel)

lent static stress σ_{eq} [3] for pulsating stress creep rupture based on linear damage low, as shown in Fig. 6. A fatigue behavior to be dependent on number of stress cycles might not appear in failure of unnotched specimen subjected to pulsating stress.

For notched specimens, the rupture time decreases with increasing in frequency of stress cycles as shown in Fig. 3 and 4. These decreases in rupture time are remarkable in more sharp notch as well as for larger stress ratio A. With the experimental results as described above, it seems that both creep and fatigue damage occur in a notched specimen subjected to pulsating stress.

1. Relation between frequency and time to rupture

As shown in Fig. 3 and 4, both creep and fatigue damage may occur in a notched specimen under the pulsating load. Therefore, if the above mentioned equivalent static stress σ_{eq} for pulsating stress creep rupture are identical in the different stress ratio and frequency, pulsating stress will give the same creep damage for specimens.

Each diagram in Fig. 7 ~ 13 shows the relation between frequency and time to rupture for the same equivalent static stress σ_{eq}.

Fig. 7 and 8 show the results for the different σ_{eq} and the same stress concentration factor α=3 of Cr-Mo steel at 550°C. Except for the stress ratio A=0.8 in Fig. 8, rupture time for all specimens take a respective constant value in low frequency region so that the rupture behaviors are time dependent. This means that the rupture behavior is dominated by creep. As frequency increases, a fatigue damage per unit time increases so that the time to rupture decreases. The larger stress concentration factor α, the sooner decrease in time to rupture begins and the more drastic change in decreasing rate occurs.

In the case of stress ratio A=0.8 in Fig. 8, the time to rupture decreases with the increase of c.p.m. without

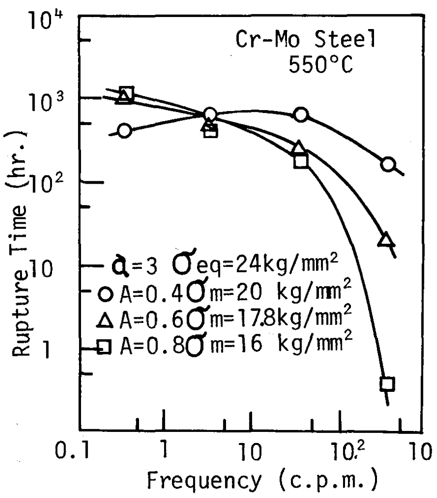


Fig. 7 Relation between frequency and rupture time for the same σeq

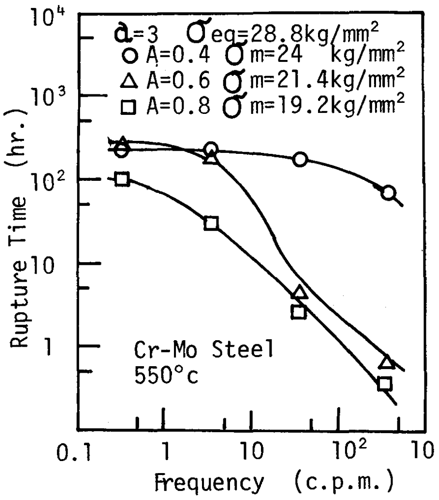


Fig. 8 Relation between frequency and rupture time for the same σeq

drastic change and it means that a fatigue behavior may dominate the fracture.

Fig. 9 and 10 show the results for stress concentration factor α=4. The similar characteristics as in Fig. 7 and 8 are observed. In case of larger equivalent static stress, σ_{eq}= 28.2 kg/mm² (Fig. 8), the stress ratio A=0.6 also shows the same characteristics as A=0.8 and both decrease in time to rupture in the lower frequency region compared with A=0.4.

The results for mild steel at 450°C are illustrated in Fig. 11 ~ 13.

In case of the lower equivalent static stress σ_{eq}=24 kg/mm² as shown in Fig. 11, all the rupture life are identical in the low frequency region where failures depend on time. As frequency increases, rupture lives for both A=0.4 and 0.8 decrease drastically exceeding 3.8 c.p.m. and

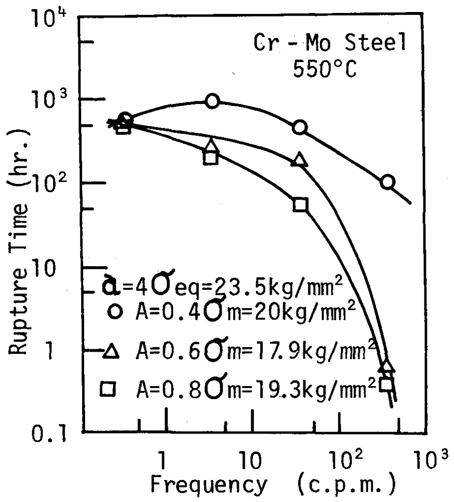


Fig. 9 Relation between frequency and rupture time for the same σeq

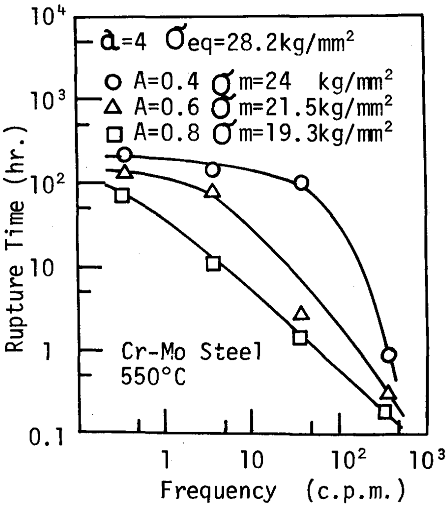


Fig. 10 Relation between frequency and rupture time for the same σeq

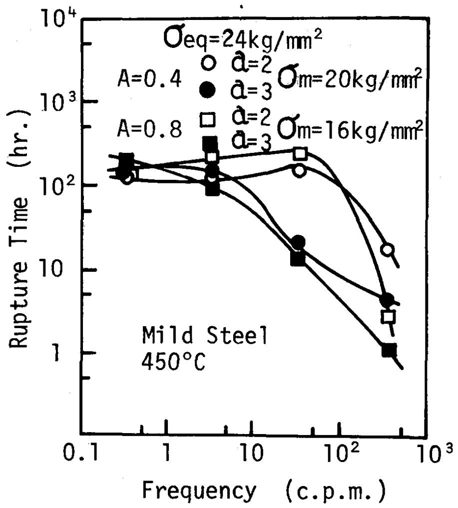


Fig. 11 Relation between frequency and rupture time for the same σeq

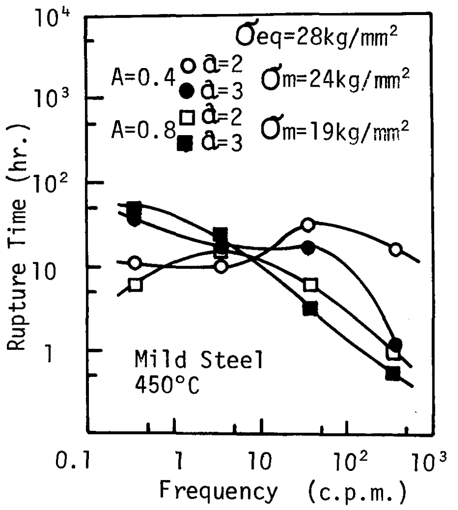


Fig. 12 Relation between frequency and rupture time for the same σeq

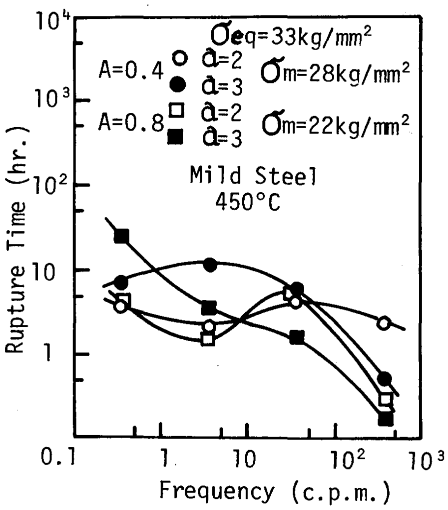


Fig. 13 Relation between frequency and rupture time for the same σeq

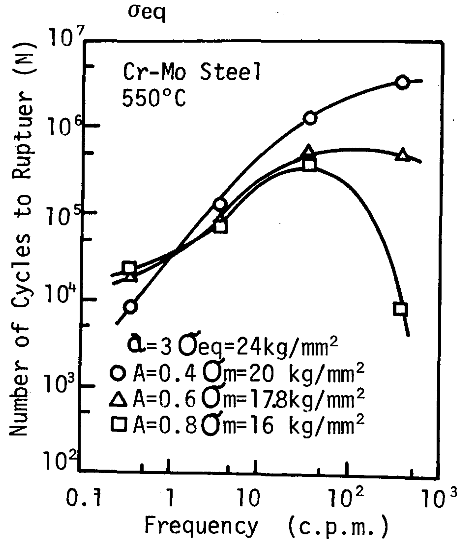


Fig. 14 N-c.p.m. curves for smaller σeq

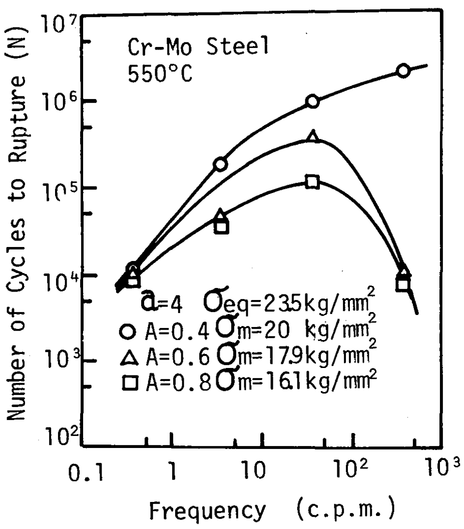


Fig. 15 N-c.p.m. curves for smaller σeq

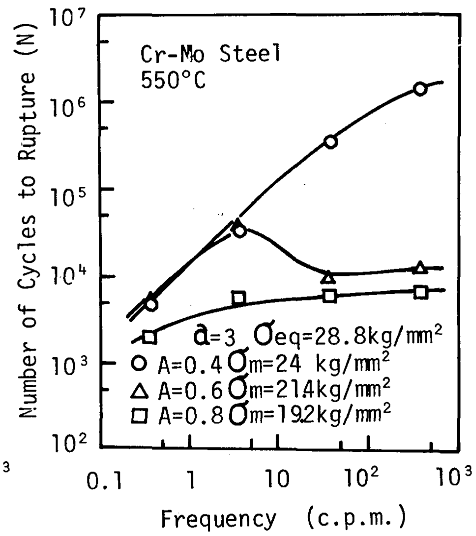


Fig. 16 N-c.p.m. curves for larger σeq

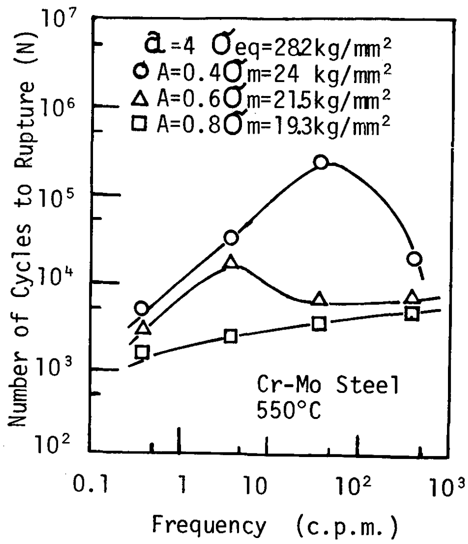


Fig. 17 N-c.p.m. curves for larger σeq

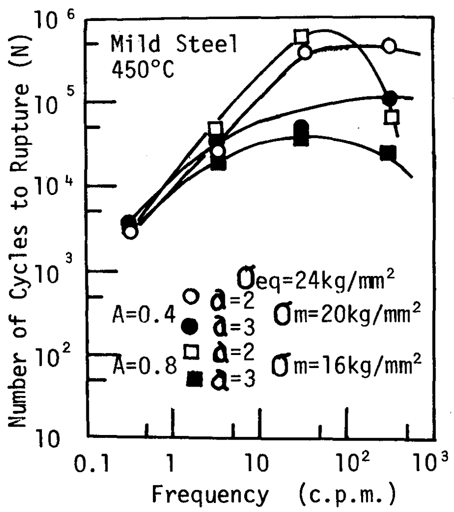


Fig. 18 N-c.p.m. curves for smaller σ_{eq}

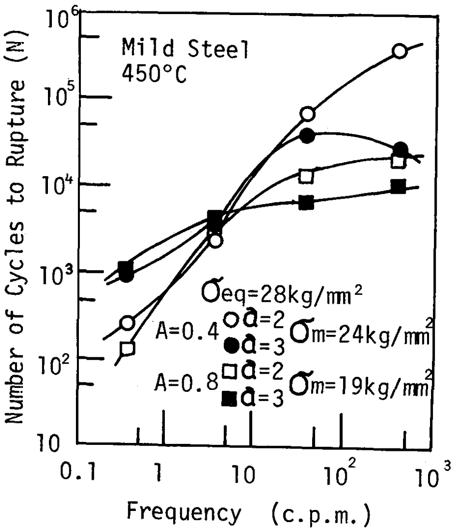


Fig. 19 N-c.p.m. curves for larger σ_{eq}

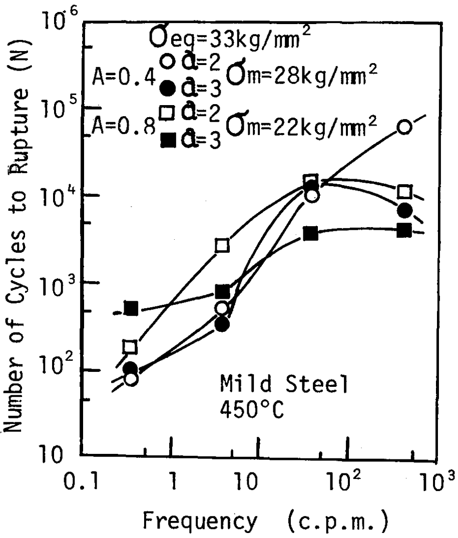


Fig. 20 N-c.p.m. curves for the largest σ_{eq}

rupture behavior seems to change into fatigue behavior in larger stress concentration factor α=3. As for the lower stress concentration factor α=2, the rupture lives depend on time up to 38 c.p.m. and the time to rupture decrease considerably at 380 c.p.m. where the rupture might be dominated by fatigue behavior.

In case of the higher equivalent static stress σ_{eq}, the rupture characteristics are slightly complicated as shown in Fig. 12 and 13. Both figures show that the rupture characteristics might be time dependent in the lower frequency region and the rupture lives decrease with the increase of c.p.m. in the higher frequency region where the failure might be dominated by fatigue behavior except for the case of α=3 in A=0.8.

In case of α=3 in A=0.8, the rupture lives decrease straight with the increase of c.p.m. as shown in Fig. 12 and 13. It is considered that a fatigue may dominate the failure over the whole frequency range.

2. *Relation between frequency and number of cycles to rupture*

Rupture should depend on number of cycles when the failures are dominated by fatigue behavior so that the number of cycles to rupture in a given stress condition reaches a constant value independent of c.p.m. when the strength of fatigue is independent on frequency or the constant value fixed by c.p.m. when its strength depends on frequency.

In such a view point, relation between frequency and number of cycles to failure are shown in Fig. 14~20 from the test results.

In Fig. 14~17 for the Cr-Mo steel, it is found that the rupture characteristics for the smaller σ_{eq}, shown in Fig. 14 and 15, are different from those for the larger σ_{eq}, shown in Fig. 16 and 17.

In the case of smaller σ_{eq} shown by Fig. 14 and 15, the number of cycles to rupture for the larger stress ratio A=0.8 of both α=3 and 4 as well as for the stress ratio A=0.6 of α=4 take a maximum value around 38 c.p.m..

As for the smaller stress ratio A=0.4, number of cycles to rupture increases continuously with the increase of c.p.m. over the whole frequency range, although the rate of increase in number of cycles to rupture slightly falls in the higher frequency region.

In the case of the larger σ_{eq}, number of cycles to rupture in stress ratio A=0.8 slightly increases with the increase of c.p.m. for both α=3 and 4 as shown in Fig. 16 and 17 respectively. These curves are different from others and it seems to be a fatigue rupture curves. As for the A=0.6 for both α=3 and 4, curves have the same characteristics as that of the A=0.8 in smaller σ_{eq} (Fig. 14 and 15) in the low frequency region, taking a maximum around 3.8 c.p.m. and it may approach the respective fatigue curve beyond the maximum value in number of cycles to rupture. In case of A=0.4, there are two types of curve. One of them is the curve of α=3 which increases continuously in number of cycles to rupture with the increase of c.p.m. same as that of A=0.4 in smaller α_{eq} and the other type is in the case of α=4 which takes a remarkable maximum like the curve of A=0.8 in smaller σ_{eq} .

In the case of mild steel at 450°C, rupture characteristics are different from that of Cr-Mo steel at 550°C.

The results for smaller σ_{eq}=24kg/mm^2 are illustrated in Fig. 18. All the number of cycles to rupture increase in proportion to the frequency up to 3.8c.p.m. independent of stress ratio A. Beyond 3.8 c.p.m., in the sharp notch, α=3, rate of increase in number of cycles to rupture decreases in A=0.4 and the curve for A=0.8 takes only a maximum around 38 c.p.m. As for the blunt notch, both A=0.4 and 0.8 show linear increase in number of cycles to rupture up to 38 c.p.m.. Beyond 38 c.p.m., the curve of A=0.4 holds a constant value and that of A=0.8 takes a maximim around 38 c.p.m. in number of cycles.

The results for larger σ_{eq} are illustrated in Fig. 19 and 20. In case of the small stress ratio A=0.4 and blunt notch α=2, number of cycles to rupture increases in proportion to frequency as shown in the both figures respectively. In the same stress ratio A=0.4, as for the sharp notch, number of cycles to rupture increases in proportion to frequency up to 38 c.p.m. and then reaches a maximum around 38 c.p.m. followed by slight decrease in number of cycles to rupture.

In case of the larger stress ratio A=0.8, for the blunt notch α=2, number of cycles to rupture increases linearly in proportion to frequency up to 38 c.p.m. and afterward increases slightly with increase of c.p.m. in the smaller σ_{eq}=28kg/mm^2 as shown in Fig. 19 but in the larger σ_{eq}=33kg/mm^2, N-c.p.m. curve takes a maximum value around 38 c.p.m. and then slightly decreases at 380 c.p.m. as shown in Fig. 20.

For the sharp notch α=3 in the same stress ratio A=0.8, the N-c.p.m. curves for both σ_{eq}=28 and 33 kg/mm^2 take a gradual increasing with the increase of frequency as shown in Fig. 19 and 20. These characteristics are same as those for A=0.8 and σ_{eq}=28 kg/mm^2 in both α=3 and 4 of Cr-Mo steel and it seems that these curves show the fatigue strength curve for the mild steel at 450°C, increasing with increase of frequency.

4. Discussion

Notched specimens under the pulsating stress will receive a combined fatigue and creep camage. Different frequency may give a different contribution of fatigue and creep damage to the specimens because a fatigue damage per unit time will be fixed by frequency. It is, therefore, considered that the rupture characteristics under pulsating stress will be changed by frequency of stress cycle.

In the current test results for notched specimens, the rupture characteristics suffered from combined fatigue and creep damage are classified into the following 4 types.

Type 1. Rupture characteristics are dominated by fatigue behavior over the whole frequency range so that the N-c.p.m. curve has gently slope line to abscissa as shown in Fig. (a).

Type 2. Rupture characteristics are shown by the N-c.p.m. curve in which a clear maximum appears in number of cycles to rupture as shown in Fig. (b). Time dependent rupture behavior in lower frequency region

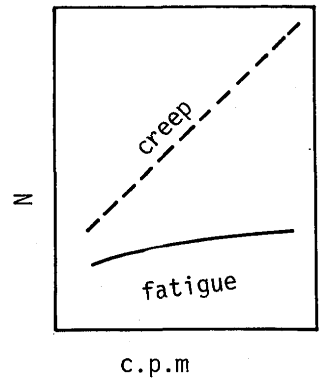


Fig. (a)
Schema of Type 1

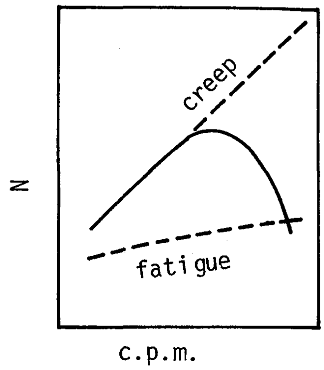


Fig. (b)
Schema of Type 2

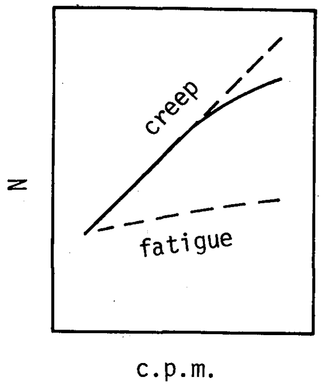


Fig. (c)
Schema of Type 3

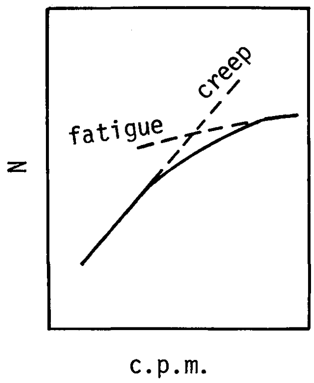


Fig. (d)
Schema of Type 4

shifts to fatigue rupture behavior which has lower strength than that of time dependent rupture in higher frequency region.

Type 3. The relation between fatigue and creep strength of this type is similar to the Type 2 and it seems that the N-c.p.m. curve has the same characteristics as that of lower frequency region up to a maximum in Type 2, as shown in Fig. (c).

Type 4. Rupture behavior dependent on time in lower frequency region changes gradually to fatigue behavior dependent on number of cycles of stress as c.p.m. increasies as shown in Fig. (d).

These 4 types of rupture characteristics are closely related to the ratio of fatigue and creep damage which is induced in the specimen by different pulsating stress.

The rupture characteristics of Type 1 appears when the specimen has a sharp notch as well as larger stress ratio so that the creep behavior is extremely preceded by fatigue as shown in Fig. 21. These N-c.p.m. curves are considered to be a fatigue strength curve for each stress condition respectively. It is repôrted[6] that the fatigue strength at high temperature increases with c.p.m. as shown in this figure.

Rupture characteristics of Type 2 is a interesting

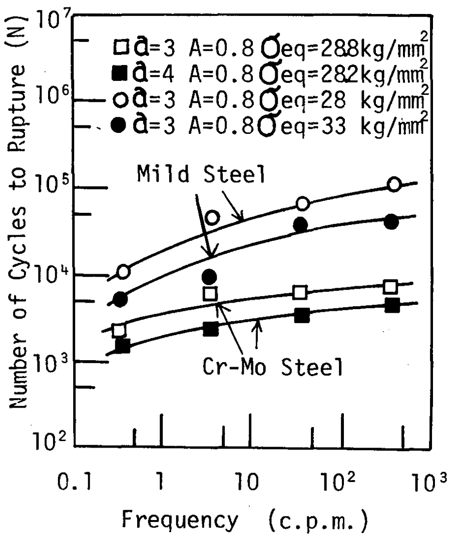


Fig. 21 N-c.p.m. curves of Type 1

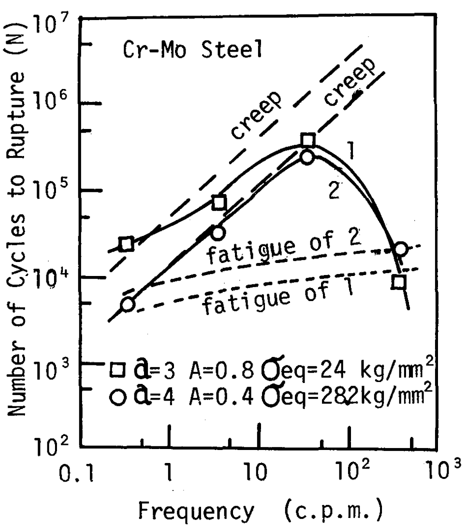


Fig. 22 N-c.p.m. curves of Type 2

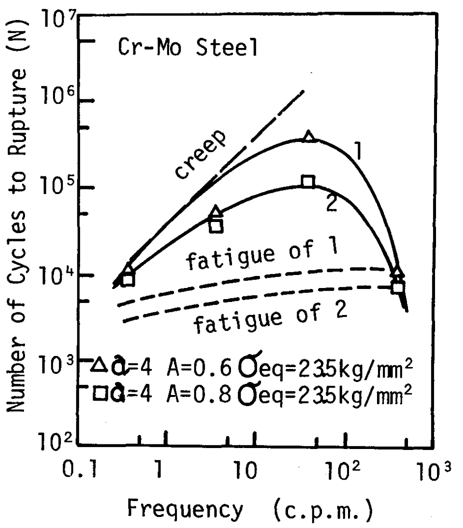


Fig. 23 N-c.p.m. curves of Type 2

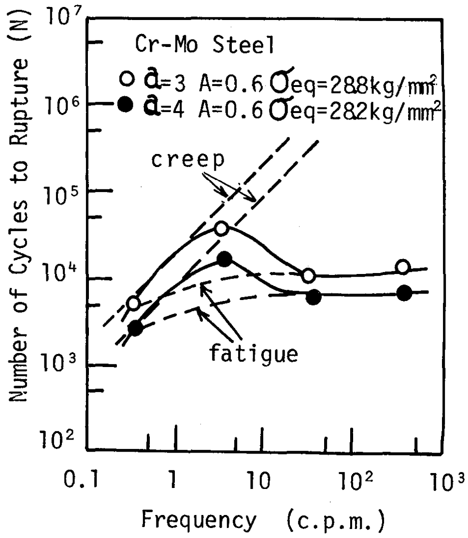


Fig. 24 N-c.p.m. curves of Type 2

phenomenon. It appears when the fatigue strength is considerably low compared with the creep strength in higher frequency region as shown in Fig. 22, 23 and 24. Fatigue curves shwon by the dotted line in these figures are the fatigue strength curve expected for each stress condition.

These fatigue curves are drawn as follows. It is assumed that the rupture strength A=0.8 at 380 c.p.m. for respective stress concentration factor α is a strength for 100% fatigue. Fatigue strength expected for respective stress ratio at 380 c.p.m. are obtained from the assumption mentioned above assuming the fatigue strength is given by 2 σ_a (σ_a= stress amplitude) respectively. Passing through these fatigue strength point for respective stress ratio at 380 c.p.m., fatigue strength curves are drawn parallel to the respective fatigue curve in Fig. 21.

Fatigue curves in Fig. 25 and 26 are also drawn in the same way.

These rupture characteristics mean that the fracture of materials suffered from combined fatigue and creep damage does not always depend on a sum of both damage, and also that the strength of materials is not always equal to the less one either fatigue or creep.

In Fig. 22 and 23, all specimens are fractured by fatigue behavior at 380 c.p.m. Decreasing of the frequency to 38 c.p.m., number of cycles to rupture increase drastically and fracture does not occur even though the number of stress cycles has exceeded the fatigue life expected at 380 c.p.m.. For smaller stress ratio A=0.6, the type of fatigue rupture appears at 380 and 38 c.p.m. and number of cycles to rupture takes a maximum value arround 3.8 c.p.m. as shown in Fig. 24.

These phenomena may appear more often in Cr-Mo steel at 550°C than mild steel at 450°C. It seems to be caused by a strain aging due to creep strain. For higher

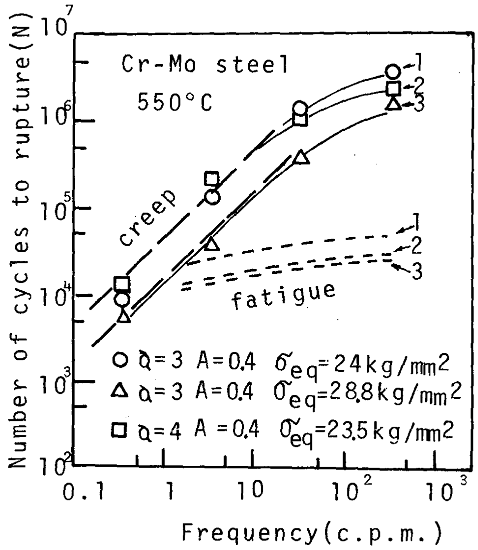


Fig. 25 N-c.p.m. curves of Type 3

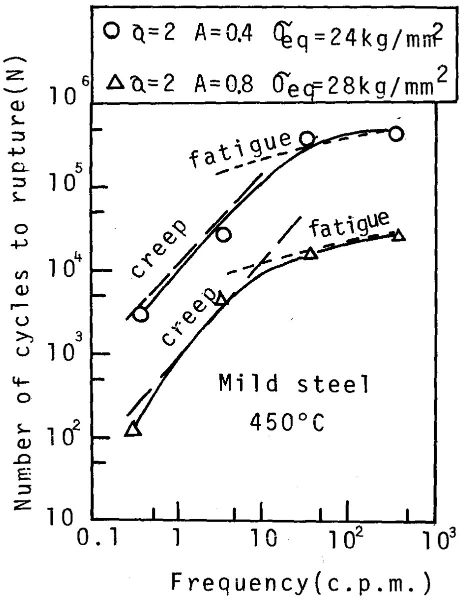


Fig. 26 N-c.p.m. curves of Type 4

frequency, number of cycles to rupture reaches a critical value in fatigue failure before the strain aging occurs enough because of relatively short time for creep. When the frequency becomes lower, the strain aging by creep which may prevent the development of fatigue damage progresses enough before the number of cycles reaches a critical value in fatigue failure, so that the rupture is mainly dominated by creep behavior and takes a time dependent characteristics.

The rupture characteristics of Type 3 is the same as that of time dependent behavior in low frequency region of Type 2, as shown in Fig. 25 for smaller stress ratio A=0.4 in Cr-Mo steel at 550°C.

The Type 4 is characterized by the conditions in which the creep strenght is lower than that of fatigue in lower frequency region and the fatigue strength is lower in higher frequency region as shown in Fig. 26. So the rupture mode changes to cycle dependent behavior from time dependent behavior with increase of frequency.

In these case, cases of Type 4 the linear life fraction rule [7] as shown by equation (1) for combined fatigue and creep damage may be applicable.

$$N/N_f + \Sigma t/t_c = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where N is a number of stress cycles to rupture, N_f is a number of stress cycles to rupture by pure fatigue, t is a time to rupture and t_c is a time to rupture by pure creep.

5. Conclusion

Notched specimens subjected to a pulsating stress may suffer both fatigue and creep damage so that the rupture time of them decreases as the frequency of stress cycle increases.

In the relation between number of cycles to rupture and frequency for a given stress condition and notch sharpness, it was found that failure does not always occur when a sum of fatigue and creep damage reaches a critical value fixed for materials and temperature. Some of specimens do not fracture with a number of stress cycles beyond the fatigue rupture life and it is considered that the strain aging by creep may prevent the development of fatigue damage.

In the current experiment the rupture characteristics are classified into 4 types, however the combined effect of creep and fatigue is complicated and make it impossible to apply the linear life fraction rule to the most of results in order to estimate those rupture life.

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