FRETTING FATIGUE UNDER VARYING LOADING BELOW THE FRETTING FATIGUE LIMIT

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Abstract

The fatigue limit diagram provides the critical conditions of non-failure against fatigue under constant stress amplitude. Therefore, the diagram is usually regarded to give the allowable stress if every stress component is kept below the fatigue limit diagram. In case of fretting fatigue, however, this report shows that fatigue failure occurs in case of variable amplitude loading even when every stress is below the fatigue limit diagram. The reason why such a phenomenon occurs was examined using multiple two-step loading. The first step stress was chosen as reversed loading and the second step stress was with high mean stress. A non-propagating crack was formed by the first step stress even well below the fatigue limit. Thus formed non-propagating crack functioned as a pre-crack for the second step stress. Consequently, fatigue failure did occur even when every stress was below the fatigue limit diagram of constant stress amplitude.

1. Introduction

In case of plain fatigue, the hatched area in the fatigue limit diagram [1] shown in Fig.1 describes the critical conditions of non-failure for constant amplitude fatigue loading. Therefore stresses below fatigue limit are considered to be harmless when every stress is below the fatigue limit diagram. Only when a mixture of stresses above and below fatigue limit is applied, it has been recognized that the stress below fatigue limit can also contribute to the fatigue damage [2, 3].

However, in case of fretting fatigue, it was predicted that fatigue failure can occur even when

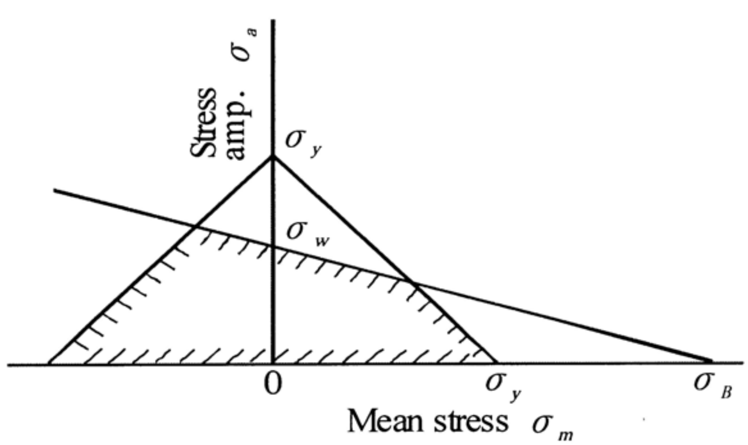


FIGURE 1. Fatigue limit diagram.

every stress is below the fretting fatigue limit diagram. The mechanism why such a phenomenon can occur was examined using multiple two-step loading.

2. Test method

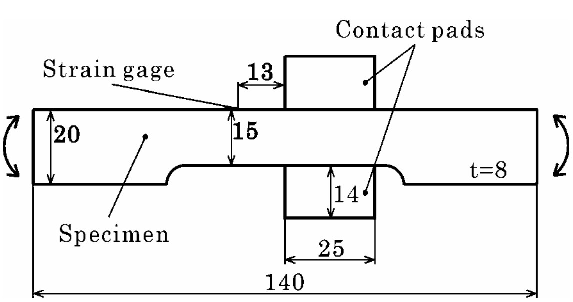
The test material is a low-alloy steel designated as SNCM435 in Japanese Industrial Standard with quenches and temper heat treatment. The chemical composition and mechanical properties are shown in Table 1 and 2, respectively. The test specimen and contact pad are shown in Fig. 2(a). The contact pad was made of the same material as the specimen. Contact conditions were achieved over the full length of the pad. The contact pressure was chosen as 196 MPa. Fatigue tests were done in air at an ambient temperature. Pure bending moment was cyclically applied to the specimen at 28.4Hz using a test rig shown in Fig. 2(b).

TABLE 1. Chemical composition of material (wt.%).

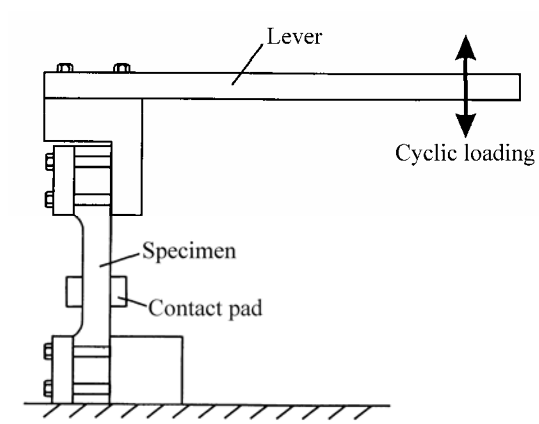
Material	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
SCM435	0.35	0.19	0.75	0.022	0.014	0.02	1.09	0.19	0.02

TABLE 2. Mechanical properties of material.

Material	$\sigma_{0.2}$ (MPa)	σ_B (MPa)	δ (%)	φ (%)	HV
SCM435	870	989	22.4	65.4	305



Dimensions are in mm.
(a) Test specimen



(b) Loading type

FIGURE 2. Test specimen and loading type.

3. Fretting fatigue test under constant amplitude loading

The fretting fatigue *S-N* curves are shown in Fig.3. The fatigue limit diagram is shown in Fig.4. The mean stress has only a little effect on the fretting fatigue limit and the fatigue limit diagram is almost horizontal. Open symbols show fatigue fracture before 10^7 cycles and solid symbols show fatigue limits. Fatigue limit specimens were heat tinted after fatigue test and opened to observe non-propagating cracks. Micro-structural sectioning was also used for the inspection of non-propagating cracks. As indicated by (a) in Fig.4, a 20μm deep non-propagating crack was observed only in the specimen tested at zero mean stress. Non-propagating crack was not found at positive mean stresses as indicated by (b) and (c) in Fig.4. What should be mentioned here is that non-propagating cracks are difficult to be formed at positive mean stress also in fretting fatigue just like in plain fatigue.

A comparison of mean stress effect on the fatigue limit diagrams of fretting fatigue and short pre-cracked specimen are shown in Fig.5. Each diagram was normalized by each fatigue limit for zero mean stress. The fatigue limit of a 170μm deep pre-cracked specimen shown by ■ was substantially decreased by the application of positive mean stress. This is the inherent

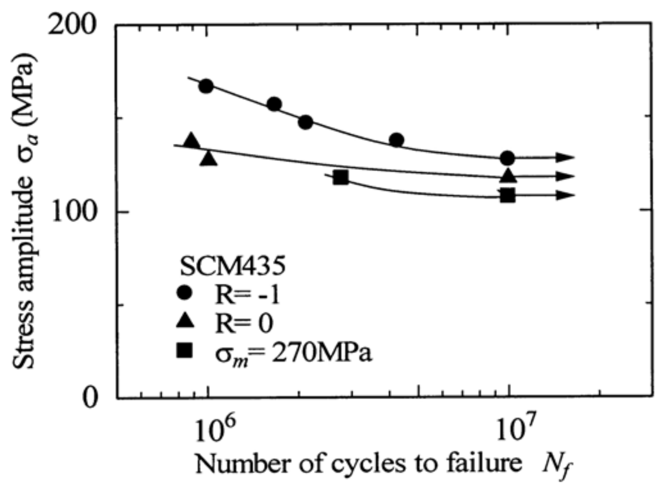


FIGURE 3. Constant stress amplitude fretting fatigue *S-N* curves.

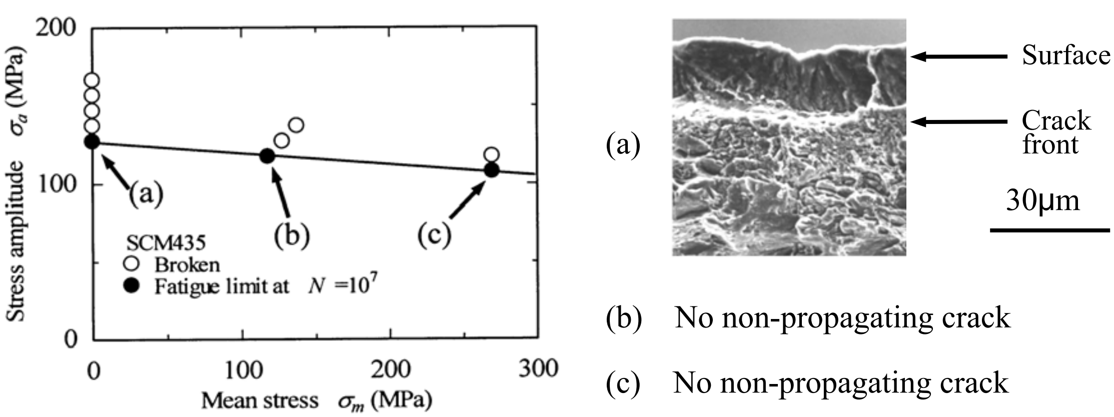


FIGURE 4. Fretting fatigue limit diagram of constant amplitude loading.

characteristic of a cracked material [4] In case of short pre-cracked material, crack closure phenomenon [5] is significantly developed at low mean stress, which increases the ability to withstand applied stress and results in relatively higher fatigue limit. As the positive mean stress increases, the crack becomes free from crack closure, which results in lower fatigue limit. To the contrary, the fretting fatigue limit shown by ● showed different behavior at positive mean stress. There was no non-propagating crack in these specimens, which means that the fretting fatigue limit at positive mean stress was governed by the crack initiation characteristic and not by the crack propagation.

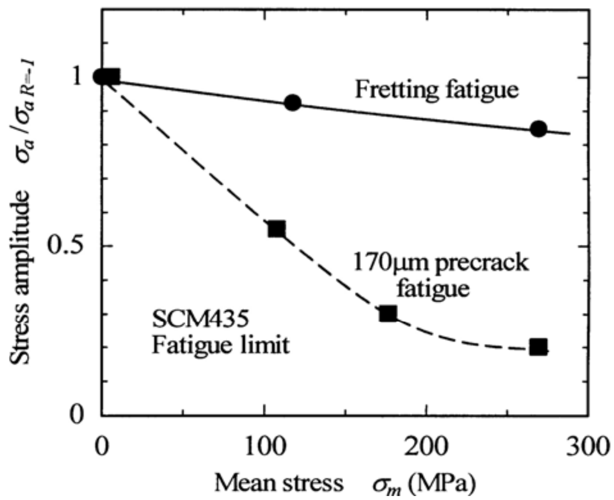


FIGURE 5. Comparison of fatigue limit diagrams between constant amplitude fretting fatigue and short pre-cracked fatigue specimen.

4. Varying loading fretting fatigue test

Multiple two-step loading sequence shown in Fig.6 was used. The 1st step stress (σ_1) was with zero mean stress and the 2nd step stress (σ_2) was with positive mean stress (σ_{m2}). The number of cycles n_1 was 5×10^4 and n_2 was 2×10^5 in each loading block. The fatigue limit under varying loading condition was defined by the no-break after 200 blocks, which means the total number of cycles at fatigue limit is $\Sigma n_1=1\times 10^7$ cycles and $\Sigma n_2= 4\times 10^7$ cycles.

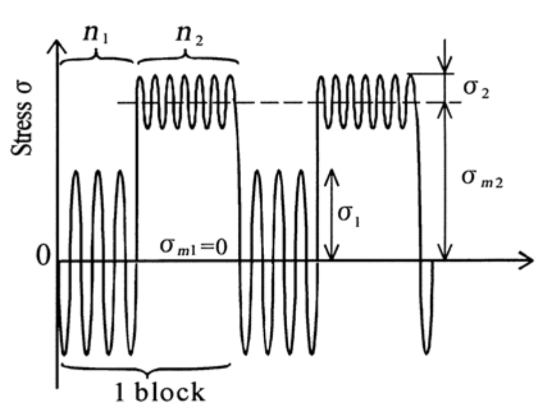
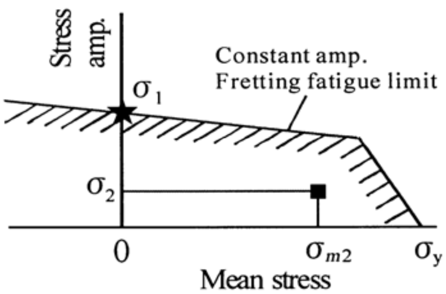


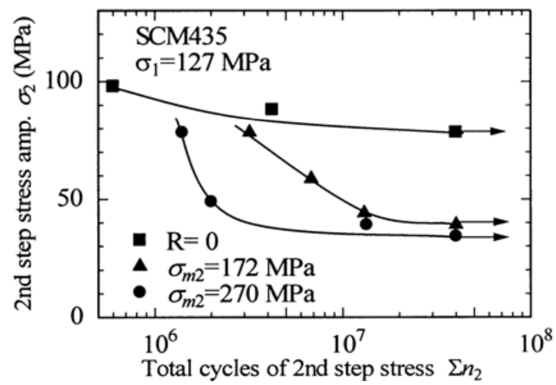
FIGURE 6. Multiple two-step loading.

4.1 Test result for pattern A

Every stress was chosen as equal to or below the constant fatigue limit as shown in Fig. 7(a). The σ_1 was set at 127 MPa, which is equal to the fatigue limit for zero mean stress. The σ_2 was changed

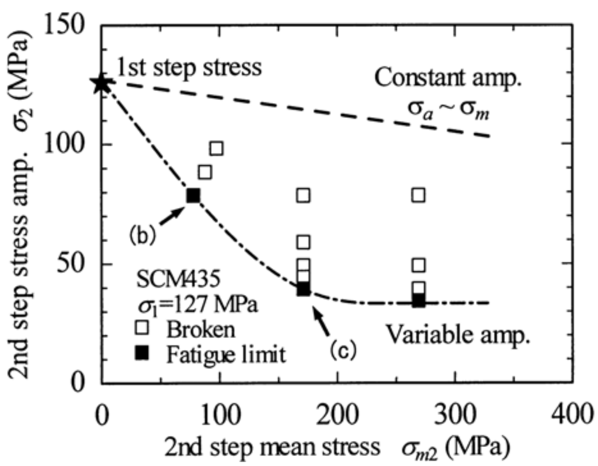


(a) Loading condition A

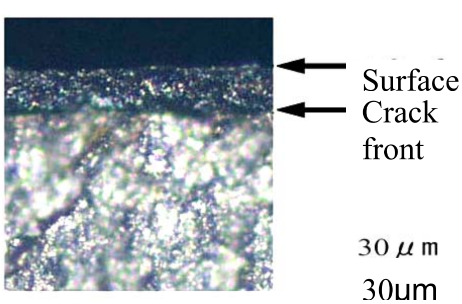


(b) *S-N* curves

FIGURE 7. *S-N* curves of varying loading fretting fatigue test for loading condition A.

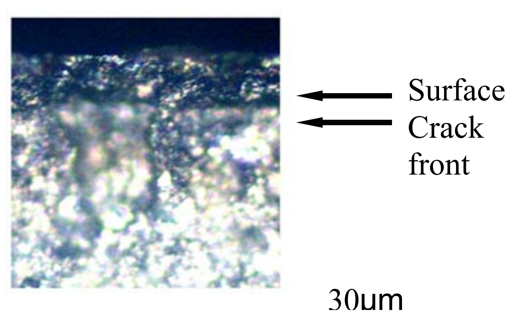


(a) Fretting fatigue limit diagram of varying loading condition A



(b) $\sigma_1 = 127$ MPa (R = -1)

$\sigma_2 = 78$ MPa (R = 0)



(c) $\sigma_1 = 127$ MPa (R = -1)

$\sigma_2 = 40$ MPa (σ_{m2}=172MPa)

FIGURE 8. Fretting fatigue limit diagram and non-propagating crack of condition A.

at each σ_{m2}. Fig- 7(b) shows the *S-N* curves. Fig. 8(a) shows the fatigue limit diagram of varying amplitude and constant amplitude fretting fatigue. Fatigue failure occurred even when every stress was below the constant amplitude fretting fatigue limit diagram.

This difference was caused by the difference in the formation of non-propagating crack in constant amplitude and varying loading conditions. Non-propagating crack was not found at a positive mean stress in constant amplitude fatigue limit, which resulted in relatively high fatigue limit for constant amplitude. The fatigue limit specimens of variable amplitude fretting fatigue tests were heat tinted after fatigue test and opened to observe cracks. The optical microphotographs are shown in Fig. 8(b) and (c). Fig. (b) and (c) correspond to the data points designated as (b) and (c) in Fig. (a). Non-propagating cracks were observed on the fracture surfaces of both specimens. The application of σ_1 formed a non-propagating crack. Although this crack was non-propagating under σ_1, it propagated under σ_2 with high mean stress. This non-propagating crack acted as a pre-crack for σ_2 and caused a decrease of fatigue limit for σ_2 in case of variable amplitude.

Fatigue limit diagrams of constant amplitude fretting fatigue, variable amplitude fretting fatigue and constant amplitude pre-cracked fatigue are over-plotted in Fig. 9. The variable amplitude fretting fatigue was far lower than the constant amplitude fretting and was almost the same as that of pre-cracked specimen. This suggests that the characteristic of variable amplitude fretting fatigue is originated from the characteristic of short crack.

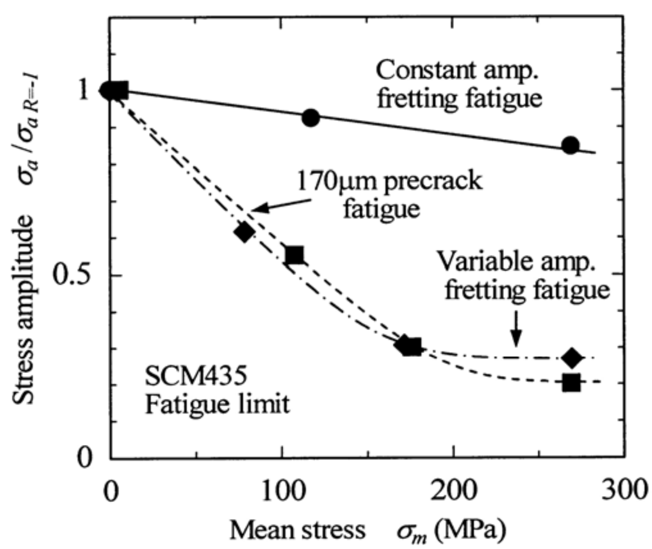
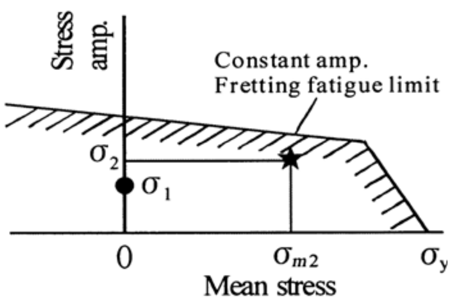


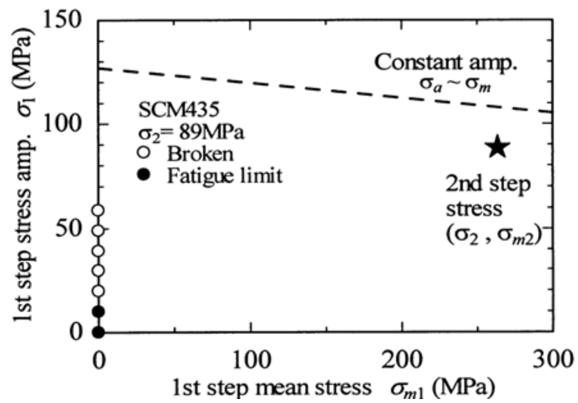
FIGURE 9. Fatigue limit diagrams of varying fretting condition A and pre-crack fatigue.

4.2 Test result for pattern B

The 2nd step stress (σ_{m2} , σ_2) was set just below the constant amplitude fatigue limit and the 1st step stress σ_1 was changed as shown in Fig.10(a). This was to examine the fatigue limit of σ_1 in regard to the formation of non-propagating crack that could function as a trigger for crack growth under sufficiently high σ Figure 10(b) shows the test result. Fatigue failure did occur even when σ_1 was well below the fatigue limit. A σ_1 higher than 10 MPa, which was surprisingly



(a) Loading condition B



(b) Fatigue limit diagram

FIGURE 10. Fretting fatigue limit diagram of varying loading condition B.

low compared with the constant amplitude fatigue limit (127 MPa), gave a damaging effect. This result suggests that stress repetition of σ_1=20 MPa, which was about 15% of the constant amplitude fretting fatigue limit, served to form a non-propagating crack. In order to verify that the stress repetition of σ_1=20 MPa really forms a non-propagating crack, only the 1st step stress of σ_1=20 MPa with zero mean stress was applied for 10^7 cycles. The crack inspection result is shown in Fig.11. It was surprising that a non-propagating crack was formed even at such a low stress. It was verified that such low stress amplitude with zero mean stress could be detrimental through the formation of non-propagating cracks.

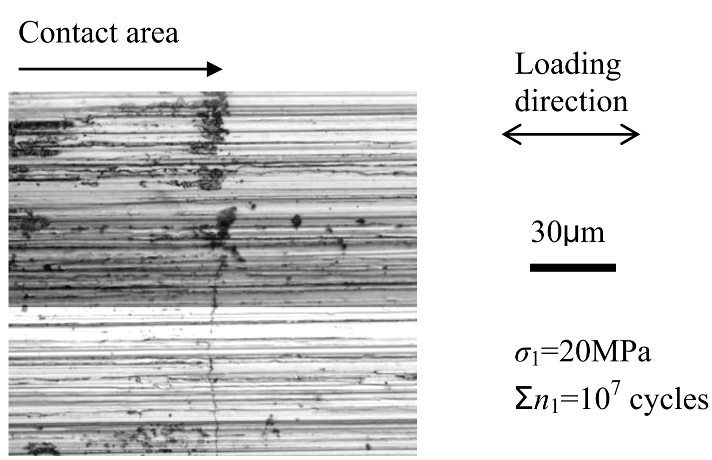


FIGURE 11. Surface observation of non-propagating crack formed only by the 1st step stress.

4.3 Allowable stress for multiple two-step loading

The allowable stress diagram for multiple two-step loading was established for σ_{m2}=270 MPa as shown in Fig.12. The chain line indicates the constant amplitude fatigue limit for σ_{m2}=270MPa and the broken line indicates that for σ_{m1}=0. The safe zone shown by the hatching is substantially reduced compared with both lines.

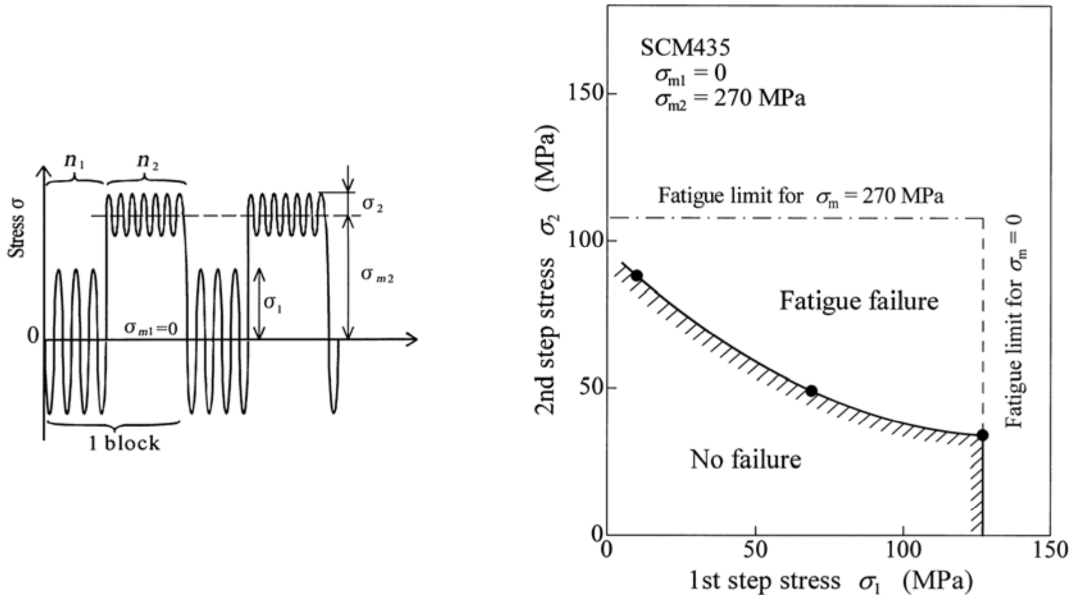


FIGURE 12. Allowable stress condition for varying loading fretting fatigue.

5. Conclusion

Fretting fatigue tests were done under varying loading in which every stress was below the fretting fatigue limit diagram. Obtained results are as follows.

(1) In case of constant amplitude loading, a non-propagating crack was formed only at low mean stress and non-propagating crack was not formed at positive mean stress.

(2) In case of multiple two-step loading, a non-propagating crack is formed by the application of 1st step stress σ_1 (R=-1) even below the fretting fatigue limit. The crack remains non-propagating and is harmless if constant stress amplitude is applied. However, thus formed non-propagating crack functioned as a pre-crack for the 2nd step stress σ_2 with high mean stress and it brought about the fatigue crack propagation in varying loading. The application of σ_1 acted as a trigger for the crack growth by σ_2. Consequently, fatigue failure did occur even when every stress was below the fretting fatigue limit diagram.

References

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