The Fretting Fatigue Limit Based on Local Stress at the Contact Edge

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ABSTRACT : *It is well known that fretting fatigue is affected by various factors such as contact pressure, relative slip, contact length, specimen size, loading type and so on. The reason why these factors affect fretting fatigue was investigated. The stress distribution near the contact edge was measured using a small stress concentration gage. It was shown that the stress concentration varied significantly depending on these factors. It was found that the S-N curve was expressed uniquely on the basis of the local stress at the contact edge. The meaning of the local stress in fretting fatigue was also studied based on the fracture mechanics. The crack analysis showed that the fatigue limit condition could be evaluated based on the threshold condition for short fatigue crack and the ΔK behavior of small fretting fatigue crack was uniquely determined by the local stress.*

INTRODUCTION

Fretting fatigue is one of phenomena that degrade the integrity of industrial machines after a long period of operation. The design practice requires a quantitatively unified evaluation methodology for fretting fatigue. However, the evaluation based on the nominal stress *S-N* curve depends on various conditions [1-2], which introduced complexities.

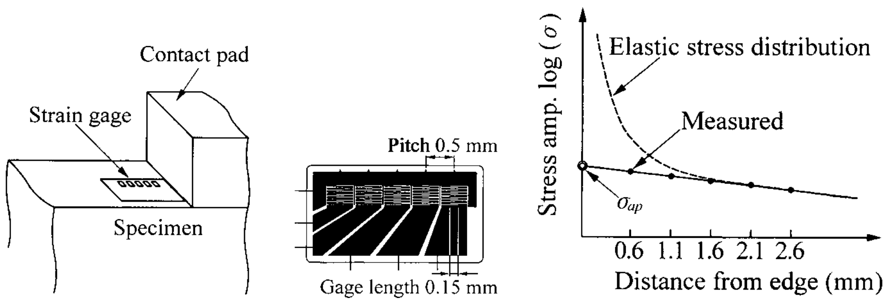
In the previous study [3], the author experimentally showed that the local stress at the contact edge could quantitatively evaluate the effects of contact pressure, relative slip range, contact length, specimen size and loading type on fretting fatigue limit.

In this report, finite element analysis was done to evaluate the stress intensity factor of a short crack under fretting fatigue condition to make clear the reason why the local stress can be the unifying parameter of the fretting fatigue limit.

EXPERIMENTAL STUDY ON THE LOCAL STRESS *S-N* CURVE

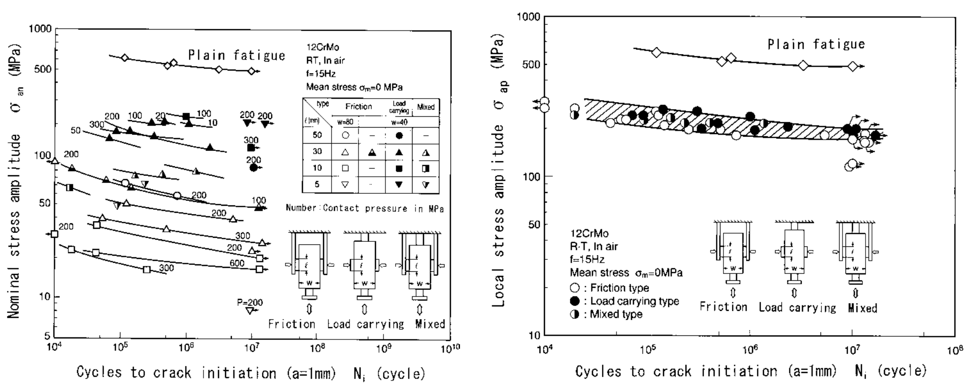
Summary of the Previous Study

The local stress amplitude σ_{ap} was defined based on the stress distribution



(a) Contact edge (b) Strain gage (c) Definition of σ_{ap}

Figure 1 Stress distribution measurement and the definition of local stress



(a) Nominal stress (b) Local stress

Figure 2 Fretting fatigue *S-N* curves

near the contact edge which was measured using a small multi-element stress concentration gage as shown in Fig.1.

Figure 2(a) shows the fretting fatigue *S-N* curves of 12CrMo steel ($\sigma_{0.2}$=640MPa, σ_B=810MPa) expressed on the basis of nominal stress. Since the stress concentration depends on the loading type and specimen size, *S-N* curves were substantially scattered. The load carrying type test gave higher *S-N* curves and the friction type test gave lower *S-N* curves. The mixed type test results were in the middle. Figure 2(b) shows the *S-N* curve on the basis of local stress amplitude σ_{ap} for the same data in Fig.2(a). All the data fell in a narrow band. It was experimentally shown that the local stress amplitude could successfully evaluate the effects of loading type, specimen size and contact pressure.

Experimental Study on the Effect of Material Hardness

The effect of material hardness on the local stress *S-N* curve was experimentally studied.

Test Method

Test specimen is shown in Fig.3. Five steels with different hardness were chosen as shown in Table 1. The contact pad was made of the same material as the specimen. The contact condition was chosen as the full contact length of the pad. The mean contact pressure was set at 98MPa. The fatigue test was done at 28Hz under pure bending condition. The stress ratio was R= -1.

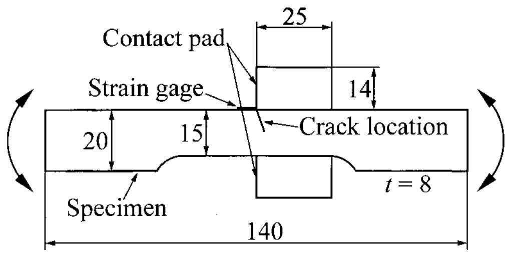


Figure 3 Test specimen

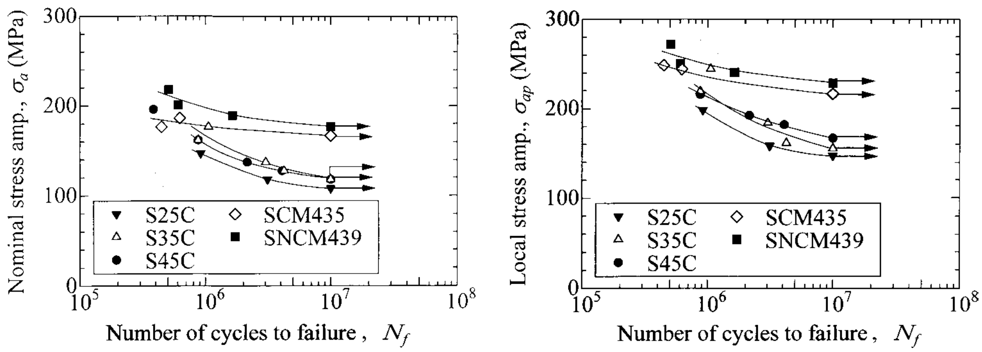
Table 1 Test materials

	Chemical composition (wt%)									Mechanical properties (MPa, %)				
Material	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	σ_y,$\sigma_{0.2}$	σ_B	δ	φ	HV
S25C	0.26	0.50	0.20	0.008	0.023	0.02	0.02	—	0.01	305	544	34.3	59.3	141
S35C	0.37	0.78	0.19	0.021	0.021	0.03	0.13	—	0.01	348	583	33.8	58.9	161
S45C	0.46	0.65	0.19	0.015	0.005	0.02	0.03	—	0.01	463	733	29.0	66.5	224
SCM435	0.35	0.75	0.19	0.022	0.014	0.02	1.09	0.19	0.02	870	989	22.4	65.4	305
SNCM439	0.38	0.75	0.26	0.016	0.017	1.78	0.78	0.16	0.13	1031	113	20.0	59.6	355

A small strain gage (KFR-015-120-D9-11N10C2™, KYOWA ELECTRONIC INSTRUMENTS) was used to measure the axial stress distribution near the contact edge. The gage length of each element was 0.15mm and five elements were arranged at a pitch of 0.5mm. The nearest measurement point was about 0.6mm away from the contact edge. The measured stresses were plotted on a semi-log graph and the local stressσ_{ap} was obtained by the linear extrapolation to the contact edge as shown in Fig.1.

Fatigue test result

Figure 4(a) and 4(b) show the S-N curves expressed on the basis of nominal stress and the local stress amplitude, respectively. The material hardness affected the S-N curve even when it is evaluated by the local stress. Harder material had higher fretting fatigue limit. The fatigue limits for each material are shown against Vickers hardness parameter (HV+120) in Fig.5. The fretting fatigue limit does not have a proportional dependency on the material hardness, which implies the characteristic of short crack [4]. A non-propagating crack was observed in the fatigue limit specimen as shown in Fig.6. It was about 120μm deep and almost two-dimensional crack.



(a) Nominal stress (b) Local stress

Figure 4 *S-N* curves of materials with different hardness

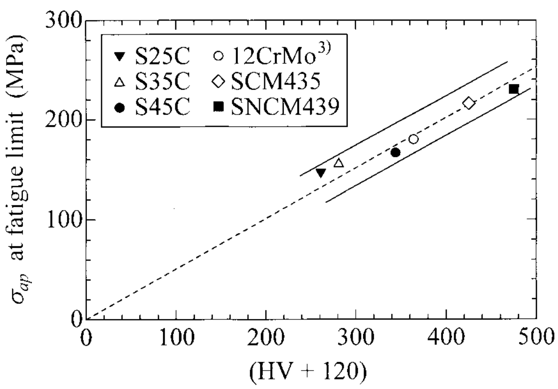


Figure 5 Local stress fretting fatigue limit and material hardness parameter

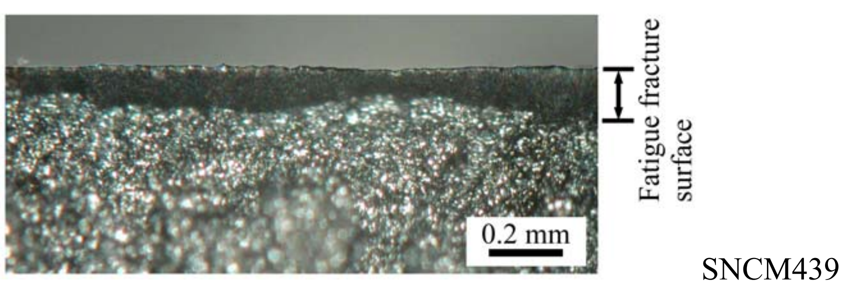
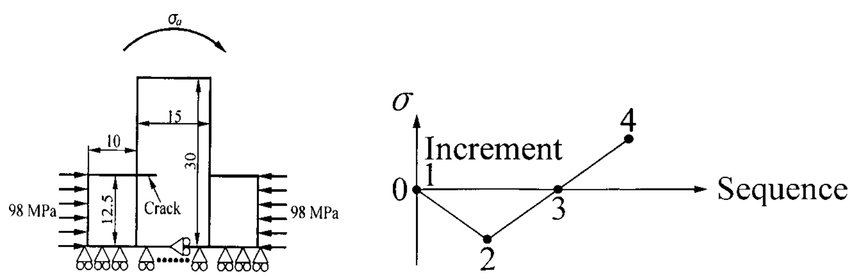


Figure 6 Non-propagating fretting fatigue crack in fatigue limit specimen

FEM ANALYSIS OF SHORT FRETTING FATIGUE CRACK

FEM model

The FEM model is shown in Fig.7(a). The code was MARC^{TM}(version K7.2). The analysis was done using two-dimensional 4 nodes plane stress element. The calculation step is shown in Fig.7(b). The contact pressure was applied in increment 1 and 3/4 cycle loading was applied in the following steps.



(a) FEM model (b) Calculation step

Figure 7 FEM model and increment of calculation step

The friction model was the modified Coulomb model in equation (1).

$$f_t \leq -\mu f_n \,(2/\pi)\arctan\,(V_r / C)\, t \qquad (1)$$

where f_t is the tangential force, f_n is the normal force, V_r is the relative slip velocity and t is the tangential direction vector to show the direction of relative velocity. The friction coefficient μ was set as 0.7 in this study. The parameter C was determined as follows.

A parametric survey changing C was done for the case without crack and the results were compared with the stress distribution measured in the fatigue test as shown in Fig.8. The survey indicated that C=0.0005mm/s was most appropriate.

Evaluation of Stress Intensity Factor for Bending Fretting Fatigue

A crack was introduced perpendicularly to the stress axis. The stress intensity factor was calculated by the COD method using mode I displacement at the increment 4. The stress intensity factor range ΔK was defined for the tension side only.

The calculated results are shown in Fig.9. The solid lines in each figure show the scatter band of the threshold stress intensity factor range ΔK_{th} of a short crack for the reversed loading reported by Murakami [4] with the modification that it was divided by two to count for the tension side only. Solid symbols show the ΔK at fatigue limit and open symbols show the

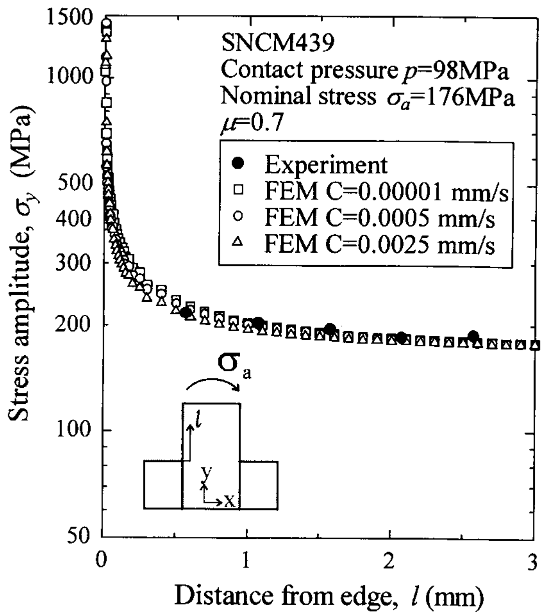


Figure 8 Comparison of measured and calculated stress distribution

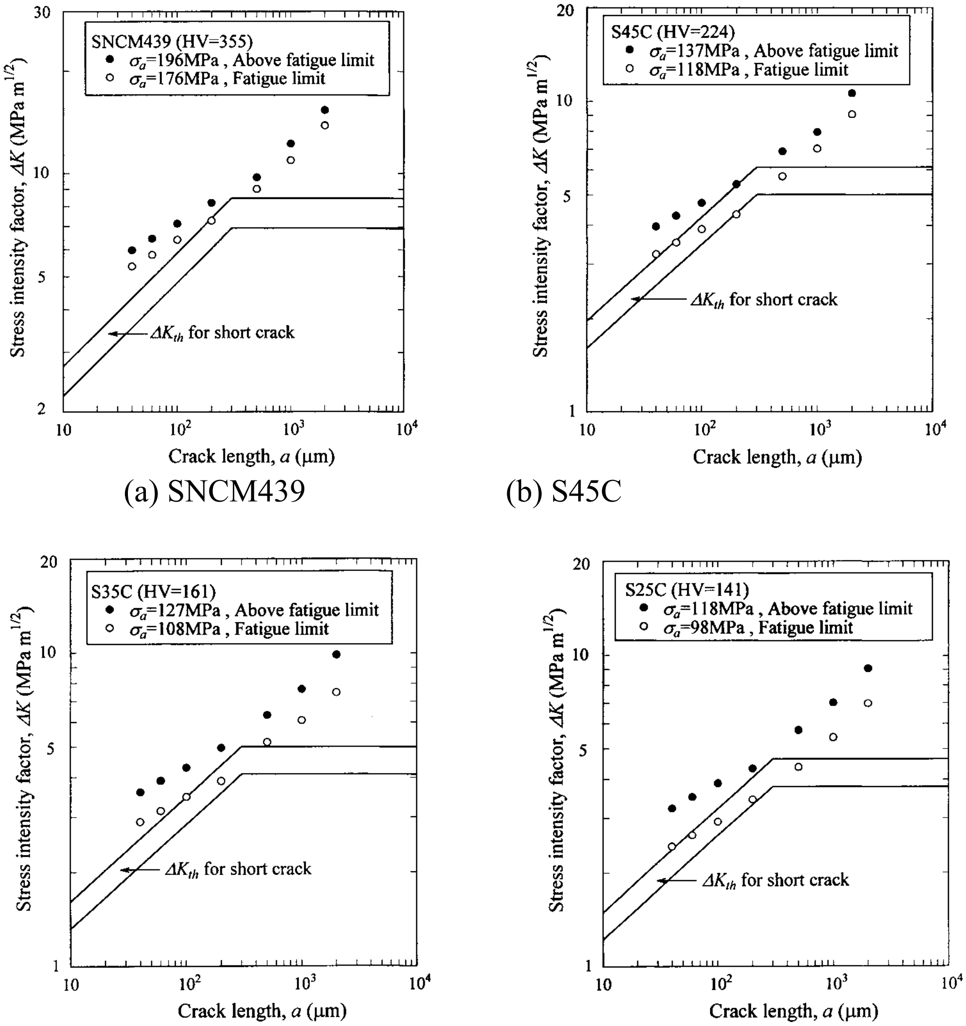
ΔK for the stress above the fatigue limit.

The crack was expected to grow in short crack region since the ΔK was higher than theΔK_{th} even at the fatigue limit condition. As the crack grows, theΔK_{th} increased and eventually the ΔK went into the ΔK_{th} band around about 100-200μm deep. The crack is expected to become a non-propagating crack and the fatigue limit is achieved. Thus obtained result is in good agreement with the experimentally observed non-propagating crack at the fatigue limit shown in Fig.6 for SNCM439.

On the other hand, the ΔK shown by open symbol for the stress above the fatigue limit was always higher than theΔK_{th} band. This means that the continuous crack growth occurs above the fatigue limit and eventually it leads to the final fracture. This behavior is commonly realized for every material with different hardness.

Effect of Loading Type and Specimen Size

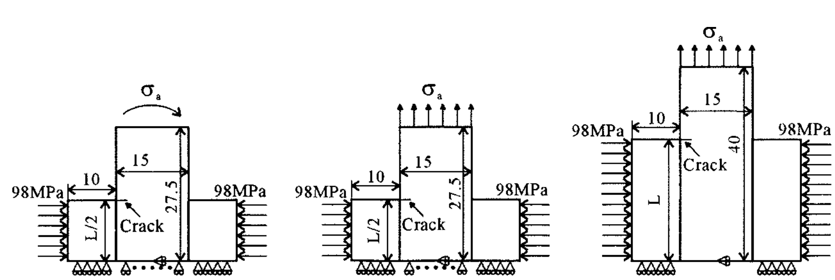
The effects of loading type and specimen size were evaluated. Other loading types are tension type and friction support type as shown in Fig.10. The calculated ΔK was divided by σ_{ap} for each specimen and shown in Fig.11. The $\Delta K/\sigma_{ap}$ fell in a band irrespective of loading type and specimen size. This means that the local stress amplitude at the contact edge σ_{ap} uniquely determines the variation of ΔK of fretting fatigue in short crack region.



(a) SNCM439 (b) S45C

(c) S35C (d) S25C

Figure 9 Variation of stress intensity factor due to crack growth



L=25,13 L=25,13 L=25,12.5

(a) Bending type (b) Load carrying type (c) Friction type

Figure 10 FEM models for other loading type and specimen size

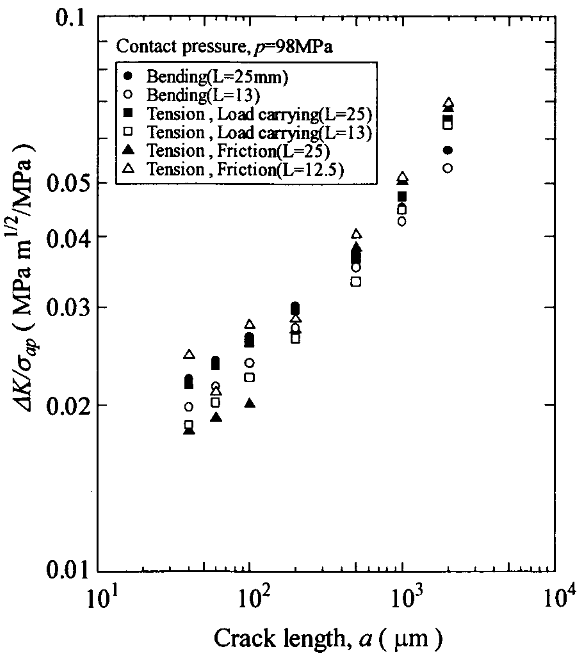


Figure 11 $\Delta K/\sigma_{ap}$ for different loading type and specimen size

Therefore, the local stress can be a unifying parameter to evaluate the condition of the fretting fatigue limit for the formation of macro-crack.

CONCLUSION

Experimental study showed that the fretting fatigue limits for various kinds of conditions could be successfully evaluated by the local stress σ_{ap} . The local stress accounts for the secondary stress caused by fretting in addition to the nominal stress. FEM analysis showed that the local stress had the function to determine the ΔK behavior of the short fretting fatigue crack irrespective of loading type and specimen size. This gives a background to use the local stress σ_{ap} as a unifying parameter for the evaluation of fretting fatigue.

REFERENCES

[1] Waterhouse,R.B. (1992) *Int.Materials Reviews*, **37**,77.

[2] Mutoh Y. (1995) *JSME Int. J. Ser.A*, **38**, 405.

[3] Kondo Y. (2001) *FFEMS*, **24**,791.

[4] Murakami Y. and Endo M. (1986) In *The Behavior of Short Fatigue Cracks*, pp.275-293, K.J.Miller and E.R.de los Rios (Eds.), Mech. Eng. Pub.