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Fundamental Investigations of Fretting Fatigue*

(Part 3, Some Phenomena and Mechanisms
of Surface Cracks)

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It has been known that the fatigue strength related to fretting is significantly reduced and that non-propagating fatigue cracks are often observed in the superficial layer of fretted area.

In order to clarify the causes of such phenomena, the initiation of fatigue cracks is investigated in relation to the contact stresses caused by fretting.

The main results obtained are as follows.

(1) The reduction of fatigue strength is mainly attributed to the stress concentration caused by the frictional force due to fretting. Fatigue cracks are located at the stress concentrated area.

(2) The fatigue cracks show inclinations to the surface, and the direction can also be explained by the contact stresses.

1. Introduction

Fretting corrosion can occur in a variety of materials and in very diversified circumstances. An example of machine components where fretting is most frequently found is a press-fitted shaft assembly.

Fatigue cracks are often found within fretted regions and many service fatigue fractures are also initiated at these regions. Therefore, it has been considered that fretting corrosion possibly causes premature fatigue failures, so that fretted regions are sensitive to the occurrence of fatigue cracks.

A few works have been carried out on the phenomenon of fretting fatigue which may be defined as a fatigue combined with fretting actions. A

survey of their published literatures indicates that the causes for the reduction in fatigue strength due to fretting are (1) pits, which are formed by fretting, acting as stress raisers, (2) effect of corrosion and (3) effect of contact stresses.

Waterhouse⁽¹⁾ carried out some fatigue tests and concluded that certain cavities caused by fretting could be initiators of fatigue cracks, since a rough calculation showed that the stress at the bottom of the cavity would be approximately four times the nominal tensile stress. Thum and Wunderlich⁽²⁾ carried out fretting fatigue tests of spring-steel specimens in oil and in air. Because the fatigue limit obtained in oil was only slightly higher than in air, they concluded that the roughening of surface caused by the fretting was a main factor of lowering fatigue strength and that the effect of corrosion would be secondary.

Cornelius and Bollenrath⁽³⁾ performed a series of fatigue tests in which flat specimens were clamped

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between pads. As the result, the fatigue strength was found to decrease linearly with the increase of clamping pressure, and they stated that the reduction in fatigue strength due to fretting corrosion could be ignored comparing with the effect of clamping stresses.

The studies cited above, however, investigated the causes of the reduction in fatigue strength only qualitatively. They could not explain quantitatively the causes which, under some conditions of fretting, reduced the fatigue limit only to one-third^{(4)~(6)} or one seventh of ordinary fatigue strength⁽⁷⁾. Moreover, the experiments carried out so far were only with respect to the fracture of specimens. As Horger found out with large press-fitted axles, fatigue cracks under fretting initiate at very low stresses well below the fatigue limit of plain specimens and do not propagate in some cases⁽⁸⁾.

The non-propagating fatigue cracks which are considered as one of the features of fretting fatigue can also occur in small size specimens as stated in the previous paper⁽⁷⁾. None of the studies has investigated in detail these superficial fine cracks caused by fretting fatigue.

In the present paper, using the fretting fatigue testing machine described in the previous paper⁽⁷⁾, results of extensive investigation of the superficial fine cracks are reported, and the effects of the stresses at fretted regions on the occurrence of surface cracks are discussed.

2. Experimental procedure

The testing machine and the dimensions and shape of specimens are exactly the same as those described in the previous paper⁽⁷⁾. They are stated only briefly as follows.

A cantilever type specimen as shown in Fig. 1 is subjected to an alternating plane bending stress.

The surface of specimen is clamped with a pair of fretting shoes which have cylindrical surfaces, the radius of which is 15mm as shown in Fig. 2. Fretting action is performed between these contact surfaces. The load is applied as shown in Fig. 3.

The contact surfaces are carefully cleaned with acetone before tests, and tests are carried out in air with no lubrication. The contact force for a unit width of specimen is kept constant at 12 kg/mm.

Fig. 1 Specimen used for fretting fatigue tests

Fig. 2 Fretting shoe

Fig. 3 Illustration of the load application in tests

Table 1 Chemical properties of materials tested

Materials	Carbon %	Silicon %	Manganese %	Phosphorous %	Sulphur %	Nickel %	Chromium %
Carbon steel	0.33	0.18	0.49	0.043	0.036	--	--
Nickel-Chromium steel	0.35	0.26	0.51	0.013	0.011	3.20	0.83
Nickel steel	0.33	0.29	0.66	--	--	3.34	0.05

Table 2 Mechanical properties of materials tested

Materials	Heat treatment	Yield stress kg/mm ²	Tensile strength kg/mm ²	Elongation %	Reduction of area %	Vickers hardness
Carbon steel	Annealed*	39.7	53.8	37.0	61.4	**
Nickel-Chromium steel	Quenched and tempered	103.0	133.6	15.0	--	H _V 313
Nickel steel	Quenched and tempered	72.8	82.6	25.0	--	H _V 250

* This material is employed for the tests after induction hardening.

** The surface hardness of specimens is about H_V 500.

The materials used in this experiments are made of nickel steel, nickel-chromium steel and carbon steel which were used in the previous paper. Their chemical compositions and mechanical properties are listed in Tables 1 and 2, respectively. Specimens made of carbon steel are induction-hardened, and specimens made of alloy steel are quenched and tempered. These three materials are chosen to know how the hardness level of material affects the fretting fatigue strength. The material of fretting shoe is the same high carbon steel as mentioned in the previous paper⁽⁷⁾.

3. Experimental results

3.1 Frictional force, relative slip and bending stress

Frictional force at the contact surface was measured through a wire strain gage attached to a lever to which the fretting shoe is mounted. On the other hand, the relative slip between the specimen and the fretting shoe was measured through a displacement detector, the detail of which was des-

Fig. 4 Variation of frictional force of fretting during one cycle of reversed bending stress

Fig. 5 Variation of relative slip during one cycle of reversed bending stress

cribed in the previous paper⁽⁷⁾.

The variations of the frictional force and the relative slip during one cycle of reversed bending are shown in Figs. 4 and 5. Both of them show the hysteresis loop with the change of bending stress. The variations of the coefficient of friction and the double amplitude of relative slip are shown in Fig. 6 for an induction-hardened carbon steel specimen. In Fig. 6, the number of bending stress cycles is chosen as an abscissa. In the very early stage of test, the coefficient of friction increases steadily and the relative slip decreases with the increase of number of cycles. After 100 cycles, both of them reach constant values asymptotically. Similar tendency is observed with specimens of the other materials. Variation of the amplitude of bending stress in the neighbourhood of fretted region, which is measured with a wire strain gage, is also shown in Fig. 6. The fact that the bending stress increases slightly with the number of cycles is attributed to the variation of frictional force.

Since these factors reach constant values after 100 cycles and the variations before 100 cycles are presumed to scarcely affect the results of experiments, these constant values will be used in the following discussions. The nominal bending stress at the center of contact region is extrapolated by the stress measured by a wire strain gage.

3.2 Correlation between the relative slip and the coefficient of friction

The variation of the coefficient of friction in relation to the relative slip for 0.33% carbon steel specimens is plotted in Fig. 7. It is seen that the coefficient of friction increases gradually with the increase of relative slip, but reaches to a constant value of 0.67 beyond the relative slip of about 10 microns.

3.3 Variation of fretted width

The fretted width on the surface of specimen increases gradually owing to the wear of contact

Fig. 6 A typical example of variations of the coefficient of friction and double amplitude of relative slip with the number of cycles of fretting

surface caused by fretting. Figure 8 shows an example of the increase of contact width for an induction-hardened carbon steel specimen, but, in these measurements, correct rearrangement of contact between specimen and shoe was not always easy. Therefore, all other measurements were made after 10^7 cycles without stop of test.

For various magnitudes of relative slip ampli-

Fig. 7 Relation between the coefficient of friction and relative slip

Fig. 8 Variation of the width of fretted area with number of cycles

tudes, the fretted width at 10^7 cycles under continuous fretting is shown in Fig. 9. It is seen that the fretted width increases linearly as the relative slip increases.

3.4 Superficial minute cracks

After 10^7 cycles of fretting, many dishlike pits of about ten microns in diameter occurred near both ends of fretted area where the contact pressure is rather low. A small number of pits of about 100 microns in diameter were found at the central portion of fretted region where contact pressure was the highest.

Figure 10 shows an appearance of fretted surface on a nickel chromium steel specimen after 10^7 cycles of fretting under the condition of the relative slip being 11.2 microns and the alternating stress 16.1 kg/mm^2 . As seen from the photograph, many minute fatigue cracks which seem to be non-propagating cracks can be observed with a magnification of $50\times$. The number of minute cracks, the length of which is larger than 10 microns, is counted in Fig. 11 for each increment, 0.05 mm, of the distance from the center of contact region. Two extreme values of frequency exist at both sides of the center of fretted width. The distance between these two positions is nearly consistent with the initial contact width $2a_0$.

Figure 12 shows the cross section of the specimen at the position denoted with arrow in Fig. 10.

Fig. 9 Relation between the width of fretted area and the magnitudes of relative slips

Fig. 10 Photograph showing surface appearance of fretted region obtained by a nickel chromium steel specimen

As shown in the photograph, minute cracks have developed from the surface with an angle and have propagated to the center of contact area, and plastic flow is also observed near the surface.

3.5 Surface pits

No fatigue cracks can be observed in the neighbourhood of small pits which occur at the region where contact pressure is rather low, as shown in Fig. 13.

In order to investigate the effect of these small pits as the stress raiser on the initiation of fatigue cracks, tests were conducted with specimens, which had an indentation of micro Vickers hardness on the fretted area. Induction-hardened carbon steel specimens were employed and the cross diameter of indentation was about 30 microns. The appearance of the fretted surface after 3.7×10^6 cycles, under the test conditions of alternating stress being 15.5 kg/mm² and the relative slip being 15.8 microns, is shown in Fig. 14. Accumulated wear particles are recognized in the indentation as shown in the lower dark part of the photograph. A surface crack is also observed in the photograph, but initiation of crack from the indentation is not observed.

The indentation, though it might have work-hardened, must be a high stress raiser in view of the sharpness of the bottom, and thus it could be considered an initiator of fatigue crack. However, as seen in Fig. 14, the indentation was not the initiator of fatigue crack. This fact implies that such a small pit as seen in fretted area can hardly be an initiator of fatigue crack under fretting condition in spite of the stress concentration.

Fig. 11 Frequency distribution of the number of fatigue cracks in the longitudinal direction of the surface of specimen

Fig. 12 Photograph showing the cross section of a cracked specimen

Very rarely, relatively large pits are produced near the center of fretted area. Figure 15 is an example of surface appearance of the large pit which occurred on a nickel steel specimen. Similar large pits occurred on specimens of other steels. The cross section of the pit shown in Fig. 15 is shown in Figs. 16 and 17 with two different magnifications. As seen in these photographs, a plastic flow and also the process of formation of a large pit through the growth of cracks are observed. Since the pit

Fig. 13 Many small pits occurred near the end of the fretted area

Fig. 14 Photograph showing surface micro cracks and an indentation made by micro Vickers hardness diamond pyramid

Fig. 15 Occurrence of a large pits on the fretted surface

mentioned above is relatively larger than those which occur near the end of the fretted region where contact pressure is lower, possible initiation of fatigue crack from those large pits is considered owing to their stress concentration. Though it is a very rare case, fatigue cracks can be observed at the bottom of pits, a typical example being shown in Fig. 18.

As a whole, the majority of micro cracks have initiated with no relation to pits as have been shown in Fig. 10, and the frequency distributions of cracks at each location of surface are similar to the ones shown in Fig. 11.

4. Mechanism of fretting fatigue

The mechanism of the initiation of fatigue cracks under fretting condition will be discussed in the following by taking the stress state in the fretted region into consideration.

4.1 Stress states in the fretted region

Fretting fatigue tests in the present investigation are made under the condition as shown in Fig.

Fig. 16 A cross sectional view of the pit shown in Fig. 15

Fig. 17 Photograph showing the formation of pit through the development of cracks

Fig. 18 An example of a crack formed at the bottom of a large pit

3. Namely, a steel cylinder is pressed onto a plate specimen at a contact load P , and subjected to an alternating tangential load T . In the present tests, the thickness of the plate specimen is large enough to assume that the stress state of contact area can be approximated by the stress state between a cylinder and a half plane as far as the minute cracks within the contact surface are concerned. Therefore, the contact stresses can be obtained by a model as illustrated in Fig. 19.

The coefficient of friction approaches a constant value for the magnitude of relative slip larger than about ten microns as stated previously (Fig. 7). Let the constant value of coefficient of friction be designated as μ .

The analysis will be made of the case where the coefficient of friction is constant, i.e. the tangential force T is larger than or equals to μP . When T is larger than μP , the whole contact surface between fretting shoe and specimen slides relatively. Thus, the force which acts on the contact surface is equal to μP . Moreover, contact pressure $p(x)$ is assumed to be distributed in Hertzian fashion even in the presence of a tangential load $T^{(9)}$.

$p(x)$ is, then, expressed as

$$p(x) = p_0 \sqrt{1 - (x/a)^2} \quad \dots\dots\dots (1)$$

The distribution of tangential force, $q(x)$, is assumed to be equal to $\mu p(x)^{(10)}$,

$$q(x) = \mu p_0 \sqrt{1 - (x/a)^2} \quad \dots\dots\dots (2)$$

In Eqs. (1) and (2), p_0 denotes the maximum contact pressure, and $2a$ the contact width, and they are obtained from the equations,

$$p_0 = 2P/\pi a, \quad \dots\dots\dots (3)$$

$$2a = \sqrt{8RP(1-\nu^2)/\pi E}, \quad \dots\dots\dots (4)$$

in which P is the normal load per unit length in the y direction. The symbols ν and E are the poisson's ratio and the modulus of elasticity.

When the normal force and the tangential force are distributed along a portion, $|x| \leq a$, on the boundary of the half plane, as given in Eq. (1) and Eq. (2), respectively, the stresses on the contact surface can be calculated in the following equations which have been obtained by Poritsky⁽¹¹⁾ or Smith and Liu⁽¹²⁾.

$$\sigma_x/p_0 = -2\mu(x/a) - \sqrt{1 - (x/a)^2}, \quad \dots (5)$$

$$\sigma_z/p_0 = -\sqrt{1 - (x/a)^2}, \quad \dots (6)$$

Fig. 19 An illustrative model for the stress analysis

$$\tau_{xz}/p_0 = -\mu\sqrt{1-(x/a)^2} \dots\dots\dots (7)$$

In the present investigations, when the alternating bending stress, σ_a , is positive, the tangential force, T , acts also in the positive direction of x axis, and vice versa. Therefore, the maximum and minimum stresses of σ_x during one cycle of test, result in the following equation referring to Eq. (5)*,

$$\sigma_{x\max}/p_0 = \sigma_a/p_0 - 2\mu(x/a) - \sqrt{1-(x/a)^2} \dots\dots\dots (8)$$

$$\sigma_{x\min}/p_0 = -\sigma_a/p_0 + 2\mu(x/a) - \sqrt{1-(x/a)^2} \dots\dots\dots (9)$$

The range of alternating normal stress, σ_R , in one cycle of test can be obtained from Eqs. (8) and (9) as follows,

$$\sigma_R/p_0 = (\sigma_{x\max} - \sigma_{x\min})/p_0 = -4\mu(x/a) + 2(\sigma_a/p_0). \dots\dots\dots (10)$$

The mean value of σ_R becomes

$$\sigma_m/p_0 = -\sqrt{1-(x/a)^2}, \dots\dots\dots (11)$$

which is always less than or equal to zero over the whole contact surface.

4.2 Mechanism of fretting fatigue

Let the ratio of σ_R to the range of alternating nominal bending stress, $2\sigma_a$, be defined as a stress concentration factor K_t . Then, from Eq. (10), K_t can be expressed as

$$K_t = \left| \frac{\sigma_R}{2\sigma_a} \right| = \left| 1 - 2\mu \left(\frac{x}{a} \right) \left(\frac{p_0}{\sigma_a} \right) \right|. \dots\dots\dots (12)$$

Substituting Eq. (3) into Eq. (12), K_t is also given by

$$K_t = |1 - 4\mu(x/a)(P/\pi a \sigma_a)|. \dots\dots\dots (13)$$

In the present investigation the load P and the amplitude of alternating stress σ_a are kept constant. However, the contact width increases due to wear as the number of cycles of fretting increases (see Fig. 8). Assuming that the pattern of pressure distribution $p(x)$ in Eq. (1) is not affected by the increase of contact width $2a$, the maximum contact

Fig. 20 Calculated stress concentration factors on the fretted surface

* The stress σ_x was taken as the most important stress because the change in magnitude of σ_x is the maximum of the normal stresses on any other fixed planes through a fixed point on the surface or beneath the surface⁽¹²⁾, and further because the alternating range of stress is of great importance for fatigue phenomenon.

pressure, p_0 , decreases with the number of cycles, N , as shown in Fig. 8. Therefore, the stress concentration factor K_t given in Eq. (13) gradually decreases with the increase of N .

The stress concentration factor K_t given in Eq. (13) is illustrated schematically in Fig. 20. In the figure, K_{t1} is a stress concentration factor corresponding to $K_{t1} = \sigma_{w1}/\sigma_a$, where σ_{w1} is designated as the minimum stress to initiate fatigue cracks. The straight line (1) shows K_t before the start of test and the contact width $2a$ is, therefore, the initial value of $2a_0$. As the number of cycles increases, K_t declines gradually as shown by the lines (2) and (3).

Since K_t is larger than K_{t1} in the range, $\alpha \leq x \leq \beta$, until the distribution of K_t is shown by the line (2), there is a possibility of initiating fatigue cracks. When K_t decreases to the line (3) owing to further increase of contact width, there is no possibility of the initiation of fatigue cracks. In this case, only the damage due to fretting corrosion is observed in the contact surface.

Accordingly, it may be concluded that the initiation of fatigue cracks at much lower alternating stress under fretting condition may be due to the high stress concentration at the contact surface caused by the frictional force of fretting.

In order to verify the mechanism about the initiation of fatigue cracks, a calculated result of stress concentration factor is compared with a test result where micro fatigue cracks are observed on the fretted surface. The comparison are shown in Fig. 21, in which the test results are taken from the specimen in Fig. 15 of the previous paper (Part 2). On the other hand, K_t is calculated from the test condition of P , σ_a and the relative slip being 12.0 kg/mm, 9.3 kg/mm² and 18.5×10^{-3} mm, respectively. Moreover, 0.67 is taken as the coefficient of

Fig. 21 The locations of cracks formed and the calculated stress concentration factors on the fretted surface

friction from Fig. 7.

As shown in Fig. 21, fatigue cracks are concentrated in the neighbourhood of $x = +a$ or $-a$ where K_t takes its extreme values. Thus it is concluded that the mechanism stated above is reasonable for the crack initiation of fretting fatigue. Since the similar result was also observed in Fig. 11 showing the frequency of number of fatigue cracks for nickel chromium steel specimens, the occurrence of cracks seems to depend on the stress state but not on materials.

Comparing the depth of fatigue cracks shown in Fig. 21 with the distribution of stress σ_x inside the specimen which is shown in Fig. 22, it is seen that the larger the stress inside the specimen is, the deeper the cracks grow.

5. Discussion

5.1 The direction of the growth of fatigue cracks

If the mechanism of the initiation of fatigue cracks under fretting condition depends substantially on the state of stresses as mentioned above, the direction of the growth of fatigue cracks should be related to that of principal stresses. The direction of principal stresses might be inclined to the surface owing to the frictional force of fretting, so that cracks should propagate from the surface with an angle provided that cracks will propagate in perpendicular to the maximum principal stress.

Let an angle between the directions perpendicular to σ_x and to the maximum principle stress be θ . Then, θ can be expressed by the following equation.

Fig. 22 Distribution of contact stress, σ_x , when the coefficient of friction is 0.67

$$\theta = \frac{1}{2} \tan^{-1} \left\{ \frac{2\tau_{xz}}{\sigma_x - \sigma_z} \right\} \dots \dots \dots (14)$$

Substituting Eqs. (5), (6) and (7) into Eq. (14), θ becomes as follows,

$$\theta = \frac{1}{2} \tan^{-1} \left\{ \frac{\sqrt{1 - (x/a)^2}}{(x/a) - (\sigma_a/2\mu p_0)} \right\} \dots \dots \dots (15)$$

Equation (15) is derived for the case when the tangential load T acts towards positive x axis. In the opposite direction of T , μ in Eq. (15) becomes negative. However, as σ_a becomes also negative, Eq. (15) is satisfied in both directions of T .

The relation between θ and x/a calculated from Eq. (15) is represented in Fig. 23, taking $(\sigma_a/2\mu p_0)$ as parameter. The variation of θ with different values of parameter $(\sigma_a/2\mu p_0)$ is not so large, but it goes continuously from zero at the end to a rather large value at the center of contact area. The angle θ is considered to specify the crack direction from the criterion considered herein.

In order to compare the experimental results of growth of cracks with the calculated values of the directions of principal stress, the test results of an induction-hardened carbon steel specimen are shown again in Table 3 which has already been reported in the previous paper. The locations where micro cracks initiated at contact surface and the directions of propagation of cracks are listed in Table 3.

The magnitudes of σ_a , p_0 and μ are substituted in Eq. (15), and the calculated results are illustrated in Fig. 24 by taking the contact width $2a$ as parameter. At the same time, the test results in Table

Fig. 23 Direction of the maximum principal stress on the fretted surface

Table 3 The location where cracks initiated and the direction of crack propagation

Location x mm	0.20	0.17	0.14	0.12	-0.12	-0.145	-0.175	-0.185
Direction θ°	35°	30°	40°	45°	-33°	-27°	-24°	-24°

3 are also plotted by circles.

It is seen from this figure that the test results are situated on the calculated curves of $a=0.3 \sim 0.4$ mm. Therefore, it is presumed that the fatigue cracks have already originated before the contact width $2a$ becomes $0.6 \sim 0.8$ mm. In other words, it seems, from the relation between the number of cycles of fretting and the contact width, that cracks originate before the number of cycles is $5 \times 10^4 \sim 10^5$. The fact is fully consistent with the test results stated in the previous paper.

As stated above, it has been clarified that the direction of the growth of fatigue cracks is well associated with the state of stress in the contact area. This may be one of the reasons for the rationality of the proposed mechanism.

5.2 Non-propagating fatigue cracks

Surface cracks which do not propagate to fracture sometimes occur depending upon test condition as stated previously. These surface cracks had also been observed in the fretted regions of press-fitted axle assemblies⁽⁷⁾. The existence of such nonpropagating fatigue cracks is one of the features peculiar to fretting fatigue, and will be discussed in the following.

The initiation of fatigue cracks under fretting condition depends mainly on the stress state in the surface layer. The stress state is calculated from the contact pressure and frictional force during fretting, and the induced stress is restricted to a very thin surface layer of specimen. Figure 25 represents the distribution of contact stress, σ_x , in relation to the depth from the surface, z/a . The upper curve shows the stress σ_x when load T acts in positive direction of x axis, and the lower curve shows it when T is reversed. It is noted that the

stress σ_x decreased rapidly with the increase of depth from the surface. In the present tests, since specimens are subjected to an alternating bending stress σ_a , the resultant stress is the σ_x shown in Fig. 25 superimposed by σ_a . Therefore, the resultant re-

Fig. 25 The distribution of contact stress, σ_x , in relation to the depth from the surface, z/a , when μ is taken as 0.67

Fig. 24 Comparison between the direction perpendicular to the direction of maximum principal stress and that of crack propagation in the fretted surface

Fig. 26 Distribution of reversed stress which is the resultant of contact stress σ_x and alternating bending stress σ_a

versed stress which actually acts on the specimen is such as shown in Fig. 26. The upper and the lower curves in Fig. 26 show the distributions of the maximum and minimum stresses in the longitudinal direction of specimen during the test.

As shown in the figure, the alternating range of resultant stress decreases rapidly with the depth from the surface about $z/a=1$.

Even if the fatigue cracks originate at the contact surface due to the higher reversed stress and develop into the specimen, they soon come into the region of lower stress as shown in Fig. 26. This is the significant difference of the fretting fatigue from the ordinary fatigue. Thus it is considered that retardation of the propagation of cracks is much easier in fretting fatigue than in ordinary fatigue.

It may be concluded that fretting fatigue is an phenomenon of initiating shallow cracks owing to large reversed stress combined with contact stresses in the fretted area, and after the initiation, the dominating phenomenon is a fatigue of ordinary plain specimens containing such surface cracks as caused by fretting fatigue.

5.3 Effect of surface pits formed by fretting

It has been clarified that one of the causes which significantly reduce the fatigue strength under fretting condition is the stress concentration caused by the tangential frictional force and that the direction of the propagation of cracks is clearly associated with the direction of contact stresses due to fretting. The effect of surface pits formed by fretting on the initiation of fatigue cracks will next be discussed.

As stated previously, small pits of 10~30 micron in diameter, or relatively large pits of 0.1~0.4 mm in diameter under certain circumstances are formed in the fretted area. The former is not necessarily the initiator of fatigue cracks as experimentally verified. An example where cracks were formed at the bottom of the latter pit has already been shown in Fig. 18. The majority of cracks, however, initiated with no relation to the pits as demonstrated in Fig. 10. It may be stated, therefore, that the occurrence of pits in the fretted area is not necessarily connected to the initiation of fatigue cracks under fretting conditions.

5.4 Prevention of fretting fatigue fracture

The maximum stress concentration K_t at the surface is, from Eq.(12), as follows.

$$K_t = 1 + 2\mu p_0 / \sigma_a \quad \dots\dots\dots (16)$$

Equation (16) shows that the reduction of fatigue strength by fretting can be alleviated by minimizing the value, μp_0 .

Moreover, since fretting induces a particular stress state only in the very thin layer of the sur-

face of specimen, one possible method of prevention is to increase the resistance to the initiation of fatigue cracks at the surface of specimens.

5.5 Variations of relative slip and frictional force

Frictional force increases in the early stage of fretting, and after 100 cycles it gradually approaches a constant value as stated before in Fig. 6. This fact is in good agreement with the test results obtained by fretting of steel ball and flat specimens by Tomlinson⁽¹³⁾.

Also as stated before, the amount of relative slip decreases gradually in the early stage of fretting and reaches a constant value corresponding to the stabilization of frictional force. This is the same tendency as the change of relative slips in the press-fitted axle assemblies⁽¹⁴⁾.

The variation of relative slips with number of cycles of fretting can be understood from the mechanism of fretting. In the early stages of fretting, cold weld and plastic flow in the contact surface occur. They increase the frictional force and accordingly decrease the relative slip. With further continuation of fretting, wear particles, are accumulated between the contact surfaces and the frictional force stabilizes.

6. Conclusions

In the present investigation, fretting fatigue tests are carried out for fretting between flat and cylindrical specimens. Since fretting can occur in various machine components under various circumstances, the distribution of contact pressure and tangential force may actually differ from those studied in the present investigations. However, it should be emphasized that the results obtained in the present investigations such as the effect of contact stresses can be applied in general.

The main results obtained are as follows.

(1) The variations of relative slip amplitude and frictional force show a hysteresis loop in one cycle, and it is seen that the mechanical energy is lost in the fretted area.

(2) The frictional force increases in the early stage of fretting, and after 100 cycles it becomes stable. The relative slip decreases at first and reaches a constant value corresponding to the stabilization of frictional force. This variation of relative slip shows the same tendency as observed in the press-fitted axle assemblies.

(3) Small pits of 10~30 micron of diameter, or under certain circumstances relatively large pits of 0.1~0.4 mm diameter, are formed in the fretted area. However, it is concluded that the occurrence of these pits does not play a significant role in

fretting fatigue.

(4) One of the causes to lower the fatigue strength under fretting condition is the stress concentration caused by the frictional force of fretting. And fatigue cracks are observed in the locations where the stress concentration is large.

(5) The initiation of fatigue cracks under fretting conditions depend mainly on the contact stresses superimposed on the alternating stress. And the fatigue cracks grow in the direction perpendicular to the maximum principal stress in the fretting area.

(6) The occurrence of non-propagating fatigue cracks under fretting conditions can be explained by the fact that the stress concentration caused by fretting is very similar to the sharply notched specimens, and that the effect of contact stresses extends only to a very shallow surface of specimens.

(7) Fretting fatigue is a phenomenon in the very shallow surface of specimen, and fretting fatigue strength is approximately the same as the ordinary fatigue strength of plain specimen containing micro cracks.

(8) The stress concentration caused by fretting increases as the maximum Hertz pressure p_0 and coefficient of friction increase. Therefore, the possible method of preventing the reduction of fatigue strength is to minimize μ and p_0 .

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