Fundamental Investigations of Fretting Fatigue*
(Part 2, Fretting Fatigue Testing Machine and Some Test Results)

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In the present paper, the construction and features of a fretting fatigue testing machine designed by the authors are explained, and the experimental results obtained by using the testing machine are stated concerning mainly the relative slip which is considered to be one of the most significant factors affecting the fretting fatigue strength.

The following are known from this investigation.

In fretting fatigue, many shallow micro-cracks which seem not to propagate to a complete fracture are formed and develop somewhat obliquely from the surface of specimen because of the effect of frictional force due to fretting.

Fatigue strength is reduced significantly by the effect of fretting, and the strength reduction factors, concerning both nucleation of fatigue cracks and fatigue fracture, are greatly influenced by the magnitudes of relative slips. The fatigue strength is most significantly reduced when the relative slips are about 0.015~0.020 mm, and reduced to less than 1/5 of its strength without fretting, and if the relative slips could be kept less than 0.005 mm, a marked improvement would be expected.

1. Introduction

In 1911, Eden et al. stated firstly the fact that fatigue test specimens had been fractured in the grips of their machine, associated with the phenomenon of fretting corrosion. Some years later, in 1924, Gillet and Mack reported the same phenomenon, which had occurred even at very low stress levels independent of the tensile strength of the specimen. After a decade, the role of fretting corrosion in the fatigue failure of the press-fitted portion of railway axles was investigated by Künnel. Since then, many investigations have been continued on the fatigue strength of press-fitted axles, and it has been found that the fatigue failure of press-fitted axles occurred usually slightly inside the hub in the press-fitted portion at stresses far below the usual fatigue limit. Such a greatly reduced fatigue strength of the press-fitted axles were considered to be attributable partially to the stress concentration caused by the shape near the ends of the press-fit but also to be affected mainly by fretting corrosion which occurs near the end of the press-fit. A quantitative evaluation of the fatigue strength of materials with fretting corrosion received considerable attention, and the investigations to clarify the phenomenon called fretting fatigue have been commenced.

The majority of investigations on fretting fatigue so far have been done mainly in relation to the machine components such as the bolted or riveted joint and the press-fitted assembly, so that the fatigue specimens used have been similar in shape and combination of parts to those components.

However, several fundamental investigations have been done under fretting which occurred in the grips of fatigue testing machine or under fretting due to the relative surface movement between the specimen and the shoe, which are pressed on each other. It has been known from these fundamental investigations that the fatigue strength is significantly lowered because of the existence of fretting, and the reduced fatigue strength seems to be independent of the tensile strength of material, although the reduction rate varies with the test condition. Furthermore, materials which show distinct fatigue limits in ordinary fatigue tests for plain specimens, hardly show distinct fatigue limit in fretting fatigue tests, or if they show distinct fatigue limit, the magnitude is very small. Thus,

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it is commonly stated that the fretting fatigue is somewhat analogous to corrosion fatigue. On the other hand, it has been reported that, when subjected to fretting in atmosphere of inert gas, the occurrence of fretting corrosion is reduced but the reduction of fatigue strength is almost the same as that in air where the fretting corrosion is considerable. This fact implies that there is no relation between the rate of occurrence of fretting corrosion and the reduction of fatigue strength.

Any method to prevent effectively the significant reductions of fatigue strength under fretting conditions has not yet been known because very little investigations have been done and also because the effect of fretting on the fatigue strength of materials depends significantly on test conditions. Speaking more in detail, many factors which influence the fretting fatigue strength such as contact pressure, relative slip amplitude, environment conditions, materials, size and shape of specimen have been incompletely examined, and a systematic study concerning these important factors has not yet been made.

In the above mentioned tests which utilize the grips of fatigue testing machine, for instance, the relative slip amplitude decreases inevitably with increasing clamping pressures and it increases with increasing alternating stresses under a constant clamping pressure. Therefore, in order to know the influence of each factor as well as the mechanisms of fretting fatigue, it is necessary to make tests where each factor is independently varied.

The authors have designed and constructed a fretting fatigue testing machine suitable for studying the effect of these factors, and a series of work is now in progress to obtain fundamental knowledge on fretting fatigue. In the present paper, the outline of the testing machine and several test results obtained so far are presented.

2. Fretting fatigue testing machine

The fretting fatigue testing machine designed and constructed by the authors are shown schemati-
ed to the ring. The frictional force between shoe and specimen can be obtained by measuring the axial force of lever \( \oplus \) by means of a wire strain gage.

Since the relative slip between shoe and specimen is a resultant of the displacement of shoe, given by lever \( \oplus \) and the relative displacement due to the deflection of specimen, measurement of actual-slip magnitude is carried out in each test by the method as follows. A slip measuring apparatus is schematically shown in Fig. 3, the principle of which is exactly the same as already stated in the preceding paper\(^1\) (Part 1). The apparatus is attached to the neutral bending axis of specimen, and then the relative slip between this attached point and the end of shoe is measured.

Principal performances of the testing machine are as follows:
- Maximum contact load of shoe: 350 kg
- Maximum eccentricity of wheel (A): 24 mm
- Maximum eccentricity of wheel (B): 8 mm
- Frequency range of fretting and alternating stresses: 300 ~ 3000 rpm

3. Test specimens and shoes

The size and shape of specimens used in these fretting fatigue tests are shown in Fig. 4. The chemical compositions of material tested and the mechanical properties under normalized condition are shown in Table 1 and Table 2, respectively. Heat treatments for respective specimens employed in this experiment are as follows. A bar forged from 210 mm diameter stock was machined to the shape of specimen after normalizing followed by induction hardening and tempering at 230°C. Finally the surfaces were ground in the transverse direction to the required size of specimen. The specimen was tested as it was with no further polishing of the surface. Talysurf measurements showed that the maximum surface roughness was about 2.0 ~ 2.5 micro-meters across the direction of grinding.

The micro-Vickers hardness of the surface of specimen is about 500 H\(_v\). The distribution of hardness from surface of specimen to inside and a photomicrograph are shown in Figs. 5 and 6, respectively.

Shoes were made, as shown in Fig. 7, to a shape of cylindrical surface with 15 mm radius of curvature.

Table 1 Chemical composition of specimen used for fatigue test

<table>
<thead>
<tr>
<th>Element</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.33</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.18</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.49</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.043</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.036</td>
</tr>
<tr>
<td>Copper</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties of specimen

<table>
<thead>
<tr>
<th>Heat treatment</th>
<th>Normalizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield stress (kg/mm(^2))</td>
<td>39.7</td>
</tr>
<tr>
<td>Tensile strength (kg/mm(^2))</td>
<td>53.8</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>37.0</td>
</tr>
<tr>
<td>Reduction of area (%)</td>
<td>61.4</td>
</tr>
</tbody>
</table>

Fig. 5 The hardness distribution of specimen

Fig. 6 Micro-structure of specimen

Fig. 7 Fretting shoe
ture which contacts with the surface of specimen. They were made of high carbon steel for railway wheel, the chemical composition of which is shown in Table 3. Shoes were submitted to tests under normalized conditions. The maximum surface roughness is about 5 ~ 6 micrometers and the Rockwell hardness is about 106 HRC.

4. Test conditions

All of tests were carried out in air, and no special considerations have been given to humidity and temperature in the test room. Frequencies of alternating stress and relative slip are 1150 rpm, and the phase between the bending stress and the relative slip is completely coincident, so that the maximum bending stress occurs at the moment when the relative slip takes its maximum value. As the contact load of shoe is kept at a constant value and the contact portion of shoe to specimen is cylindrical with 15 mm radius of curvature, the contact may be regarded as that of plane and cylinder as illustrated in Fig. 8. When it is assumed that the Hertz theory is applicable even under the existence of a tangential force $T_{110}$, the contact pressure shows an elliptical distribution and becomes maximum at the center of contact area. The normal contact load for a unit width of specimen was taken 12 kg/mm through the tests, hence the maximum pressure, $p_{m}$ becomes 53.5 kg/mm² and the contact width, $2a$, becomes 0.286 mm.

Under the above contact conditions, tests were made with various combinations of bending stresses and relative slips.

5. Test results

5-1 The fretting wear of contact surfaces

As the number of reversals of fretting increases, the wear grows gradually on both surfaces of shoe and specimen, and reddish-brown iron oxide particles are observed to flow out from the fretted regions. With the progress of wear, the contact width increases also from the initial width of 0.286 mm calculated in the preceding chapter. A typical example of the increase of contact width with the number of reversals where the relative slip is $13.2 \times 10^{-3}$ mm and the reversed bending stress is 23.4 kg/mm², is shown in Fig. 9. Illustrative examples of the state of wear obtained by magnification using Talyssurf are shown in Figs. 10 and 11. The former shows a typical feature of wear for the relative slips smaller than about 20 microns, and the latter for those larger than 20 microns.

In Fig. 10, the two troughs near the center portion of worn profile are located approximately at both edges of initial contact surface. The cause of occurrence of these two troughs may be understood from the fact that the magnitude of relative slips at the end of contact surface is larger than that of central portion and the amount of wear increases with the increase of relative slips.

An example of maximum depth of indentation of wear is approximately 0.03 mm as shown in Fig. 10, thus the depth is negligibly small in comparison with the thickness of specimen, 6 mm. Therefore the reduction of the section modulus of the specimen

![Figure 8: Distribution of contact pressure](image)

![Figure 9: Variation of contact width with number of reversals](image)

![Figure 10: Illustration of fretting wear](image)

![Figure 11: Illustration of fretting wear](image)
caused by wear can be neglected. Moreover, taking the shape of indentation into consideration, it is assumed that the indentation does not play the role of a notch.

5-2 Appearance of fretted surface

Figure 12 is a microphotograph of surface damage which appeared after $10^7$ cycles of fretting, where the alternating stress and the amplitude of fretting are kept constant at 9.3 kg/mm² and $8.5 \times 10^{-2}$ mm, respectively. Significant cold welds and large pits are found near the central part of the fretted area on which a larger contact pressure acts, and many dishlike pits of $10 \sim 20$ microns diameters as shown in Fig. 13 are found in the neighbourhood of the edge of contact area.

Figure 14 is a magnified appearance of the neighbourhood of the initial contact edge, which is located near the central part of the fretted portion in Fig. 12, after fretting of $10^7$ cycles. As shown in Fig. 14, many shallow hairline cracks are sometimes observed which do not propagate to a complete fracture after ten million of reversals of alternating stress. Since Fig. 14 is taken after polishing the fretted surface to make their existence of hairline cracks clear, it is hard to see hairline cracks in relation to pits. But in Fig. 15 which is taken after very slight polishing, it is rather clear that hairline cracks are often accompanied with pits.

As shown in Fig. 13, although many shallow dishlike pits occur, no cracks can be observed.

About the initiation of cracks, it is considered that crack might initiate in the very early stage of fretting, since micro surface cracks can be observed even at $10^4$ cycles.

Figure 16 is a cross-section of specimen, the fretted surface of which was already shown in Fig. 14. As shown in this figure, micro-cracks have propagated obliquely to the center of contact area, and the angle of inclination is larger for the crack which was produced near the center of the contact area. The fact that the inclination angle of crack varies depending on its location might be due to the shear force caused by fretting, as will be stated in the next paper.\(^{18}\)

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Fig. 12 Appearance of fretted area of specimen after $10^7$ cycles of fretting

Fig. 13 Appearance of surface pits caused by fretting

Fig. 14 Photograph showing surface micro-cracks

Fig. 15 Surface micro-cracks associated with pits

Fig. 16 Cross-section of specimen showing surface cracks
5-3 Effect of relative slip amplitude on fretting fatigue strength

For various combinations of the magnitude of alternating stress and relative slip, a number of fretting fatigue tests are carried out until ten million cycles, and the results are plotted in Fig. 17 with respect to the occurrence of surface pit and the initiation or growth of surface crack. In this figure, the abscissa indicates the range of the magnitude of relative slip motion.

As shown in Fig. 17, experimental results can be divided into the following five regions in accordance with combinations of the magnitude of alternating stress and relative slip.

Region (1) : In this region, fretting wear and small pits as shown in Fig. 13 occur, but no cracks can be observed.

Region (II) : In this region, minute cracks as well as small pits in Figs. 14 and 15 are produced, but the cracks do not propagate to a complete fracture even after $10^6$ cycles of fretting. In other words, this region indicates a range of combination of stress and slip where non-propagating fatigue cracks are produced.

Region (III) : In this region, the surface damage is similar to those shown in Figs. 14 and 15, but the alternating stress and the relative slip are larger than those in Region (II), and the minute cracks develop to a complete fracture of specimen. Figure 18 shows another micro-cracks observed near a crack which propagate to fracture.

Region (IV) : In this region, specimens are broken similarly to Region (III) but no micro-cracks are observed other than a crack which propagates to a fracture.

Region (V) : The appearance of surface damage in this region is somewhat similar to that in the Region (1), and no micro-cracks can be observed. However, the relative slips in this region are large, so that the amount of wear produced by fretting is considerable. Therefore, the boundary between Regions (1) and (V) is less clear than the others. The boundary is then tentatively taken at 20 microns of relative slip where wear becomes considerable.

6. Discussion

The authors have focused attention on the relative slip amplitude which is considered to have significant influence on fretting fatigue strength, and have carried out experiments to clarify the influence using the fretting fatigue testing machine mentioned above.

The results explained in the previous chapter will be discussed in the following.

6-1 The initiation and propagation of fatigue crack

In the Region (II) of Fig. 17, micro-cracks initiated but did not propagate to a complete fracture after $10^6$ cycles, and the fatigue cracks were already observed in the early stage of fretting. These results are considered to be coincident with the results obtained by Waterhouse and Fenner who pointed out that the fatigue strength was damaged only in the early stage of fretting.

The phenomenon that cracks which had initiated in the early stage did not propagate further is rather similar to the behavior of fatigue crack in the specimen with a sharp notch. In other words, such cracks would be regarded as the well-known non-propagating fatigue crack.

When relative slips become larger than 25 microns as shown in Fig. 17, the critical alternating stress necessary for the initiation of fatigue crack becomes relatively high. The reason may be the fact that fretting wear is pronounced in these regions, and a
micro-crack once initiated will soon be worn out by fretting. This explanation is plausible, since the depth of micro-crack and the maximum wear depth are the same order of 0.01~0.04 mm as seen in Figs. 11 and 16. The region (V) in Fig. 17 might therefore be influenced by the susceptibility to wear of metals. As the resistance to wear of metal becomes smaller, the region (V) may be shifted to the left in Fig. 17.

Since the depth of micro-crack, which does not propagate to a fracture, in a broken specimen tested in the region (III) is the same order as that in the region (II), it is considered that only one crack among many cracks develops predominantly to a complete fracture and the others remain dormant. Therefore, when alternating bending stress is relatively large and wear is considerable, one predominant crack, which grows more rapidly than wear, develops to a fracture and the others are worn out. This is the explanation for the existence of region (V) in Fig. 17.

6.2 The effect of relative slip on fretting fatigue strength

An S-N curve of ordinary reversed bending fatigue tests carried out with specimens which were used in the fretting fatigue tests is shown in Fig. 19. When the result in Fig. 19 is compared with that of Fig. 17, it is clear that the fatigue strength in regard to the initiation of fatigue crack is significantly reduced by fretting, and that the fatigue strength reduction factor is greatly influenced by the magnitude of relative slip.

For instance, even though the alternating bending stress is kept constant at 20 kg/mm², different behaviors of fatigue cracks with the increase of relative slip are observed as follows. Until relative slip amplitude comes up to 5 microns, no fatigue crack can be observed, and between 5 and 20 microns micro-cracks which do not propagate to a fracture are observed. When the slip becomes more than 20 microns but less than about 50 microns, the crack grows to a fracture, and for a slip more than 50 microns the specimen is not broken because of severe wearing-out.

As mentioned above, if the relative slip is suppressed below 5 microns, the fatigue strength under fretting condition is relatively high but is gradually reduced to 1/7~1/8 of the fatigue strength of plain specimen with the increase of slip, and the critical alternating stress necessary for the growth of crack to a fracture is also reduced to 1/5 of that of plain specimen.

Fenner and Field[18] carried out experiments on the fatigue strength under fretting condition and reported concerning the effect of relative slip that fatigue strength of Al-alloy decreases progressively as the relative slip increases up to 10 microns.

Marsh[19] also referred to the effect of relative slip and stated that fatigue strength is most significantly reduced when relative slip is between 7 and 26 microns, and that possible improvement can be expected when slip is suppressed below 5 microns.

Although their experiments were conducted in relation only to the complete fracture but not to the initiation of cracks, good agreement is recognized with our results in the tendency of influence of slip.

When the relative slip amplitude is still larger than that employed in this experiment, the magnitude of relative slip becomes significant in comparison with the width of contact area. In the case, oxide powder of fretted debris peculiar to fretting cannot be accumulated in contact surface, and such a case cannot be considered fretting but a phenomenon of ordinary wear[19], then the experiment on such a case has not been carried out. It is, however, presumed that fatigue strength becomes relatively higher since the wear of specimen becomes remarkable and cracks will be worn out rapidly.

7. Conclusion

In the present paper, experimental results obtained by using a specially designed fretting fatigue testing machine are stated concerning mainly the effect of relative slip. The following are the main results obtained.

1) Micro shallow fatigue cracks, which are supposed to propagate to a complete fracture, i.e., non-propagating fatigue cracks, are observed under a certain condition of fretting.

2) These micro cracks remain dormant after a little growth to the direction obliquely from the surface. The reason of this development to oblique direction is considered to be the effect of frictional force of fretting.

3) Fatigue strength is reduced significantly by the effect of fretting, and the strength reduction factors concerning both initiation of cracks and its growth to a fracture are greatly influenced by the magnitudes of relative slip.

![Fig. 19 Fatigue strength of plain specimen used in the fretting fatigue tests](image_url)
Fatigue strength related both to initiation of crack and to fracture is reduced gradually as the relative slip increases reaching its minimum value when the relative slip is about 20 microns. Their minimum reduced fatigue strengths are about 1/7 and 1/5 the fatigue strength of plain specimen, respectively. For relative slip still larger than that, it becomes higher by the effect of wear.

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References
