Fretting Fatigue Strength of Several Materials Combinations*

By Kichiro ENDO**, Hozumi Goto***, and Takuo NAKAMURA****

Fretting fatigue tests are carried out with various materials combinations, and the reduction rates of fatigue strength by fretting are obtained with an observation on the behaviors of frictional force. Stress analyses on the contacting surfaces are conducted elastically by using the maximum stress due to friction together with repeated stress applied on specimens, and the results are compared with the experimental results. The fatigue strength is reduced more remarkably by fretting under bending than under twisting and the damage is greater to materials combination with higher tangential stress. These results agree fairly well with the consideration where the fatigue cracks are initiated under the maximum repeated shearing stress calculated from the combination of bending or twisting stress and frictional stress. The strength reduction rate is, however, greater than the analytical one for specimens of aluminum alloy and for lower cycle frequencies. Although further studies should be made on the behaviors in fretting fatigue which are similar to those in corrosion fatigue, it may be concluded that the initiation of fretting fatigue cracks is due to the maximum repeated shearing stress.

1. Introduction

It is well known that severe damage of fretting wear† occurs when metals forming an alloy with each other are mated and when the hardness of materials is low under combination of similar metals. However, it is not fully clear how the fatigue strength reduction due to fretting is correlated to the fretting wear. The reduction of fatigue strength due to fretting seems more remarkable as the tensile strength of materials is higher and/or the fatigue strength of a smooth specimen without fretting in air is greater, and the hardness of fretting pad is higher\(^{(4)}\)\(^{(5)}\). A report\(^{(6)}\) says, however, that the number of cycles where the fretting fatigue damage arises becomes larger with an increase in the hardness of fretting pad. It is also reported\(^{(3)}\) that the fatigue strength of a press-fit assembly is greater when a cast iron disk is used on a steel shaft than when a steel disk is used on it. Thus, the effect of materials combination on fretting fatigue has not been well known.

In the previous paper, the fretting fatigue tests of a carbon steel were carried out at a comparatively large amplitude of relative slip, and the fretting fatigue strength was found smaller under lower cycle frequency\(^{(6)}\). The reason was considered as follows. The damaged layer due to fretting fatigue is formed in early period of the total life, and from it fine fatigue cracks are initiated. The fretting fatigue damage is caused by the combination of frictional stresses and repeated stresses. The frictional stresses, however, depend on the frequency because the conditions of fretting friction are affected remarkably by chemical action, and this is a main cause of the frequency effect. Consequently, the variations of frictional force and the stress conditions with progress of stress cycles are noteworthy under fretting of various materials combinations, since these may be important causes of the various reduction rates of fatigue strength by fretting.

In the present paper fretting fatigue tests are carried out with several materials combinations, and the reduction rates of fatigue strength by fretting are obtained together with observations on the behaviors of the frictional force acting on contacting surfaces. The stress analyses on contacting surfaces are conducted elastically, and the analytical results are compared with the experimental results by calculating the maximum shearing stress and the maximum tangential stress due to friction. Discussions are made to examine the possibility to explain the fretting fatigue phenomena with mechanical factors.

2. Experimental procedures

The testing apparatus and the experimental procedures are almost the same as those in the previous

\(†\) Although the surface damage due to fretting is generally called fretting corrosion, it is called in the present paper fretting wear because of the secondary role of corrosion in fretting.
paper, and are briefly described here. The dimensions of specimens and fretting pads are illustrated in Fig. 1. Flat fretting pads are clamped on specimens of 3 mm radius for twisting tests and fretting pads of 3 mm radius are clamped on flat specimens for bending tests in order to simulate the geometrical conditions of contact in twisting and bending.

The chemical compositions of materials used are given in Table 1, and the static mechanical properties after heat treatments in Table 2. The material (a) is a 0.34% C carbon steel for twisting tests, and the material (b) is a 0.53% C carbon steel for bending. Both the materials were normalized at 870°C for one hour before machining. After the final surface finishing, they were annealed in vacuum at 650°C for one hour. The material (c) is a 7075 aluminum alloy for bending tests, solution heat-treated at 480°C and aged.

![Figure 1 Dimensions of test specimens and fretting pads](image)

**Table 1 Chemical compositions of test specimens (%)**

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<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
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<td>(c)</td>
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<td></td>
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<tr>
<td>(d)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(e)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

**Table 2 Mechanical properties of test specimens**

<table>
<thead>
<tr>
<th></th>
<th>Yield point $\sigma_s$ or $\sigma_{0.2}$ kg/mm²</th>
<th>Ultimate tensile strength $\sigma_B$ kg/mm²</th>
<th>Elongation $\varphi$ %</th>
<th>Hardness $H_V$</th>
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</thead>
<tbody>
<tr>
<td>(a)</td>
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<td>34</td>
<td>135</td>
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<tr>
<td>(b)</td>
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<td>64</td>
<td>24</td>
<td>160</td>
</tr>
<tr>
<td>(c)</td>
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<td>190</td>
</tr>
<tr>
<td>(d)</td>
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<tr>
<td>(e)</td>
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<td>67</td>
<td>10</td>
<td>210</td>
</tr>
</tbody>
</table>

![Figure 2 Fretting apparatus](image)

**Fig. 1 Dimensions of test specimens and fretting pads**

- (a) For twisting test
  - 1 Strain gage
  - 2 Specimen for twisting test
  - 3 Fretting pad

- (b) For bending test
  - 1 Thin plate
  - 2 Strain gage
  - 3 Specimen for bending test

**Fig. 2 Fretting apparatus**

- (a) for twisting test
  - 1 Strain gage
  - 2 Specimen for twisting test
  - 3 Fretting pad

- (b) for twisting test
  - 1 Thin plate
  - 2 Strain gage

- (c) for bending test
  - 1 Fretting pad
  - 2 Thin plate
  - 3 Strain gage
at 120°C for 24 hours, which is called T6 treatment, before machining. Its final finish is polishing. The material (d) is a pure copper for bending tests, which is annealed in vacuum at 350°C for one hour after surface finishing. The material (e) is a 7075-T6 aluminum alloy heat-treated by the producer and is used for twisting tests. All the final surface finishes of specimens and fretting pads are made with emery paper #600.

The fatigue testing machine used is of constant deformation type and its cycle frequency is varied from 170 to 3000 c/min. Figure 2 shows the fretting apparatus attached to the fatigue testing machine. In this apparatus the twisting deformation or the bending deflection causes a reversed relative slip between specimen and fretting pads which is synchronized with the repeated stress. The amplitude of slip is, therefore, nearly proportional to that of repeated stress except under an extremely small stress amplitude.

Under small amplitudes of relative slip the fretting fatigue strength is affected remarkably by the slip amplitude, decreasing with an increase of slip amplitude up to the amplitude of about 10μm. Further increase of slip brings little additional reduction of fatigue strength. In the present test conditions, the slip amplitude is about 80μm at the steady state of fretting when carbon steel specimens are subjected to repeated twisting stress of τb = 14.0 kg/mm². The value of slip amplitudes in the bending tests of carbon steel is not measured, but the extents of fretting wear scars are almost the same as those in the twisting tests. The slip amplitude is, therefore, considered to be in the same order as in twisting because of the similar geometrical conditions of contact in twisting and bending. The slip amplitudes used in both the tests are found to be in the range where the effect of slip on fatigue strength is saturated, and a small change of slip amplitude may be ignored.

Since the slip amplitudes in the twisting tests of aluminum alloy are large due to the lower rigidity of specimens, they are adjusted to the same order as in twisting tests of carbon steel by fixing the fretting apparatus on the thin plates (1) in Fig. 2 (b), so that the fretting apparatus is able to rotate around the centre of specimen in accordance with the rigidity of the thin plates. In the bending tests of aluminum alloy and pure copper the slip amplitudes are adjusted by changing the thickness of the thin plates (2) shown in Fig. 2 (c) according to the ratio of rigidity of carbon steel specimen to aluminum alloy or to pure copper.

As a linear relation is found between the tangential force due to friction and the strain of gage (1) for twisting tests or of gage (2) for bending in Fig. 2, the frictional force acting on contacting surfaces is measured dynamically by using an oscillograph. The maximum value of frictional force during one cycle is obtained from oscillograms and its changes with progress of fretting cycles are shown hereafter.

In the present apparatus, the repeated moment is measured by means of the strain induced in the torsion bar through which the specimen is fixed at its driven side. The moment is varied a little with the restriction of twisting or bending deformation of specimen due to frictional force. Accordingly the nominal repeated twisting stress τb or bending stress σb is modified with the change of moment after the clamping of fretting pads. Since both the fatigue tests are of constant deformation type, the rigidity of specimens, that is the moment induced in the torsion bar, decreases gradually, followed by a rapid decrease after about 20% reduction of the original value. The number of cycles to failure is determined by 20% reduction of the moment.

The specimen and fretting pads are cleaned with acetone and alcohol just before tests. The testing parts are housed in a box made of a vinyl chloride plate in order to keep off oil and dust. Fretting fatigue tests are carried out in an air whose temperature and humidity are not controlled.

3. Results of tests

3.1 S-N diagrams

S-N diagrams of fretting fatigue tests under completely reversed twisting and bending are shown in Fig. 3 and Fig. 4 respectively. Materials used are carbon steel vs. carbon steel, aluminum alloy vs. aluminum alloy and pure copper vs. pure copper. The contact load per unit length p is kept at 4 kg/mm and the stress cycle frequency is 1800 c/min. S-N curves of the usual fatigue tests in air without fretting are also shown in both the figures. The reduction rates of fatigue strength by fretting, that is, the differences of fatigue strengths under no fretting from those under fretting divided by the former are obtained from Fig. 3 and Fig.4, and

![Fig. 3 S-N diagram of fretting fatigue tests of the same materials combinations and usual fatigue tests under completely reversed bending](image-url)
are shown against the number of cycles to failure in Fig. 5. The strength reduction rate is the most remarkable for aluminum alloy, diminishing in order of carbon steel and pure copper. The reduction rate is more remarkable under bending than under twisting.

Figure 6 shows S-N curves under completely reversed twisting fatigue tests of 0.34% C carbon steel specimens fretted with pads made of the same material, aluminum alloy [the material shown in Table 1 (c)]] and pure copper. The fatigue strength of steel is found higher with copper pads than with steel pads, while it is almost equal between with steel pads and with aluminum alloy pads.

Figure 7 shows S-N curves under completely reversed twisting fatigue tests of 7075-T6 aluminum alloy specimens fretted with pads made of aluminum alloy which is almost similar to the specimen [the material shown in Table 1 (c)]] and with pads of 0.34% C carbon steel. Both the fatigue strengths are found nearly equal. Fenner et al. indicated in the pulsating axial fatigue tests that the fatigue strength of aluminum alloy specimens fretted with steel pads was lower than that fretted with pads of the same material as specimens. The reason for discrepancies with our results may be the test conditions, such as the geometrical conditions of contact, contact loads and testing stresses.

3.2 Behaviors of frictional force

Figure 8 shows some examples of the variation in frictional force per unit contact length against the number of fretting cycles measured in the bending fretting fatigue tests under the combinations of like materials.
In the initial period of fretting of steel vs. steel, the asperities of contacting surfaces yield under contact pressure, and the breakdown of natural oxide films due to fretting leads to an increase in the area of metal-to-metal contact, so that the frictional force increases. After the frictional force reaches the peak value, the lubricating action of loose oxidized debris accumulated between the contacting surfaces causes a decrease in the frictional force. In early stage of fretting between aluminum alloys the intermetallic adhesion also occurs as is observed in the fretting of steels. The oxidized debris which are very hard cause the abrasive action so that the frictional force continues to increase gradually. Since the hardness of oxide films of copper is almost the same as that of the bulk copper and the oxide films break down gradually, the frictional force increases comparatively slowly and its value is very small. Halliday found that intermetallic welding arose under all fretting conditions in combination of duralumin and aluminum, and that the oxide of copper exhibited protective qualities under mild frictional conditions. These coincide well with the present results.

Figure 9 shows the variations of frictional force with fretting cycles measured in the twisting fatigue tests of 0.34% C carbon steel fretted with steel, aluminum alloy and pure copper. The frictional force of fretting of steel vs. steel reaches the peak value at about $2 \times 10^4$ cycles. On the other hand the number of cycles where the frictional force of fretting of steel vs. aluminum alloy or copper reaches the peak value is very small and in the order of $10^4$ cycles. This is considered due to variation of the fretting wear. The maximum depth of wear scars is measured by a Taly-surf profilometer as is shown in Fig. 10. For the combination of steel vs. steel the depth of wear scars of fretting pads is equal to that of the specimen and is smaller than that for other combinations of materials. When steel specimens are fretted with fretting pads of aluminum alloy or pure copper the depth of wear scars of fretting pads is greater than that of steel specimens, and increases rapidly in early stage. In this case an intimate contact is obtained earlier because of more fretting wear, and the frictional force increases more rapidly. After the early stage, a small quantity of iron oxide is observed in oxidized debris of aluminum or copper, and the frictional force becomes stable to the proper value under the above mentioned condition of friction.

Figure 11 shows an example of variations of frictional force measured in the twisting tests of aluminum alloy specimens fretted with aluminum alloy pads and carbon steel pads. The variations almost coincide in tendency with those in bending tests of aluminum alloy vs. aluminum alloy shown in Fig. 8 and those in twisting tests of carbon steel specimens vs. aluminum alloy pads shown in Fig. 9 respectively.

4. Stress conditions on contacting surface

The elastic stress conditions of specimens where the frictional force on contacting surfaces and the repre
ted stress applied on specimen are acting simultaneously are to be considered. The geometrical conditions of contact and the co-ordinates shown in Fig. 12. The following symbols are used in the analysis:

- \( p \): contact load per unit length kg/mm, \( p_0 \): maximum value of contact pressure kg/mm\(^2\), \( q_0 \): maximum value of tangential stress kg/mm\(^2\), \( \tau_0 \): amplitude of repeated twisting stress kg/mm\(^2\), \( \sigma_0 \): amplitude of repeated bending stress kg/mm\(^2\), \( \tau_{\text{max}} \): maximum repeated shearing stress kg/mm\(^2\), \( a \): half value of contact width mm, \( \mu \): coefficient of friction.

The following are assumed in analyzing the stress conditions on contacting surfaces.

1. Specimens and fretting pads come into contact with each other in a plane stress condition so that the stress distributions along the longitudinal direction of contact, that is, the direction of y axis shown in Fig. 12, are constant.

2. The contact pressure and the tangential stress are kept in elliptical distributions even if the form of contacting surfaces varies due to fretting wear.

3. The tangential stress is given by multiplying the contact pressure by the coefficient of friction.

4. The normal contact stress is ignored since it acts as a mean stress in the stress conditions and causes little effect on fretting fatigue damage.

In the co-ordinate of Fig. 12, the combined stress components on the surface of contact area \((x = 0, |x| \leq a)\) are

\[
\sigma_x = 2q_0(x/a) + \sigma_0, \quad \tau_x = q_0\sqrt{1-(x/a)^2} \quad (1)
\]

under bending, and

\[
\sigma_y = 2q_0(x/a), \quad \tau_y = q_0\sqrt{1-(x/a)^2} \quad (2)
\]

under twisting.

As the width of contacting surface varies with the fretting cycles, the value of \( q_0 \) also varies under the relation

\[
q_0 = \mu p_0 = 2\mu p/\pi a \quad \text{--------------------------(3)}
\]

from the assumptions (2) and (3).

The fine fatigue cracks due to fretting are considered to initiate with the maximum repeated shearing stress, which is calculated from Eqs. (1) and (2):

\[
\tau_{\text{max}} = \frac{1}{2}\sqrt{4q_0^2 + 4q_0(x/a)\sigma_0 + \sigma_0^2} \quad \text{--------------------------(4)}
\]

under bending, and

\[
\tau_{\text{max}} = \sqrt{q_0^2 + \tau_0^2} \quad \text{--------------------------(5)}
\]

under twisting. From Eqs. (4) and (5), the value of \( \tau_{\text{max}} \) under twisting is constant in the contact area. On the other hand, since \( \tau_{\text{max}} \) under bending takes a maximum value at the end of contact area \((x = a)\), the maximum value is used for the analysis. In the case of \( q_0 = 0 \), that is, without fretting,

\[
\tau_{\text{max}} = \tau_0/2 \quad \text{--------------------------(6)}
\]

is obtained. By using Eq. (6), Eqs. (4) and (5) can be rewritten as

\[
\tau_{\text{max}}^{\text{bend}} = \frac{1}{1+(q_0/\tau_0)} \quad \text{--------------------------(7)}
\]

and

\[
\tau_{\text{max}}^{\text{twist}} = \frac{1}{1+(q_0/\tau_0)^2} \quad \text{--------------------------(8)}
\]

The solid line in Fig. 13 shows the relation between \((\tau_{\text{max}}^{\text{bend}}/\tau_0)\) and \(q_0/\tau_0\) by Eqs. (7) and (8). The effect of slip amplitude is not considered in the above analysis, the reason for which is that the slip amplitudes in the present test conditions not being so large as to affect the fretting fatigue strength. At lower values of slip amplitude, \( q_0 \) should depend on it\(^{(7)} \).

5. Discussion

The fretting fatigue strength is closely related with the frictional force as is described in Chapter 3. The stress conditions are explained with stresses on contacting surfaces in Chapter 4. However, it may be necessary to pay attention to stresses within the layer in

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**Fig. 13** Relation between \((\tau_{\text{max}}^{\text{bend}}/\tau_0)\) and \(q_0/\tau_0\)

(The analytical results are shown with two curves, being compared with the experimental results)
which fine fatigue cracks are initiated as is mentioned hereafter.

The cracks which lead to fatigue failure of a smooth specimen without fretting are generally initiated at the latest stage of life, so that the crack propagation period is negligibly short. Consequently, the fatigue cracks due to fretting are considered to initiate when the value of \( \tau_{\text{max}} \) expressed by Eqs. (4) and (5) reaches the fatigue strength without fretting, provided that the fatigue cracks are generated by the maximum repeated shearing stress. Thus, when \( \tau_0 \) is defined as the fatigue strength accompanied by fretting, \((\tau_{\text{max}}-\tau_0)/\tau_{\text{max}} \) in Eqs. (7) and (8) will indicate the reduction rates of fatigue strength by fretting. Equations (7) and (8) are, however, based solely on the mechanical factor of fretting, and the chemical action, that is, the oxidation in the contacting surface layer, should be considered as is described later. Both the equations show that the reduction rate of fatigue strength is greater with a higher value of \( \tau_0 \) or with a lower value of \( \tau_0 \). Moreover, it is more remarkable under bending than under twisting as is shown with the solid lines in Fig. 13, which well agree with the experimental results in Fig. 5. Since, however, Eqs. (7) and (8) express the criteria for the initiation of fatigue cracks without due consideration for fatigue crack propagation, further study is expected to reveal more detail of the behaviors of the crack propagation during the fretting fatigue.

The effect of tangential stress is discussed as follows. Since the contact width \( a \) varies with the number of fretting cycles as is shown in Fig. 14 (a) as an example, the tangential stress \( \tau_0 \) is calculated from Eq. (3) as is shown in Fig. 14 (b) by using the curves shown in Fig. 9 and Fig. 14 (a). \( \tau_0 \) takes a high value at the beginning, and then decreases rapidly due to the initial increase in contact width. After \( 10^6 \) fretting cycles the rate of decrease of \( \tau_0 \) becomes small. The layer in which fatigue cracks are generated lies beneath the original contacting surface of specimen, since the contacting surface is worn out. It may be, therefore, more appropriate in discussion of the effect of tangential stress to use the value of tangential stress \( \tau_0 \) when it becomes almost steady after \( 10^6 \) cycles than to use the value at the beginning of fretting fatigue tests. The magnitude of \( \tau_0 \) can be obtained from Eq. (3) by using the value of the frictional force measured at \( 10^6 \) cycles, the width of wear scars being regarded as the width of contact.

The damage curves of fretting fatigue of carbon steel and aluminum alloy are given in Fig. 15. These curves are obtained from the results of two stage testings from fretting fatigue to usual fatigue without fretting. The fretting damage is almost saturated in the first 25% of the total life cycles, and thereafter the total life remains constant irrespective of the fretting action. Since fine cracks are already recognized at the cycles where the fretting fatigue damage is saturated, the stage after the saturation of damage is known as the crack propagation period. Although the cycles of crack initiation are not examined, the fatigue

![Fig. 14](image1)

(a) Change of contact width

![Fig. 15](image2)

(b) Change of tangential stress

Fig. 14 Changes of contact width and tangential stress with progress of fretting cycles in twisting fatigue tests of carbon steel vs. carbon steel (\( \tau_0=14.0 \text{ kg/mm}^2, P=4 \text{ kg/mm}, 1800 \text{ c/min} \))

Fig. 15 Damage curves under twisting fretting fatigue of carbon steel and aluminum alloy of the same materials combinations
Table 3  Testing conditions in Fig. 13

<table>
<thead>
<tr>
<th>Test number</th>
<th>Material</th>
<th>Frequency ( \times )</th>
<th>Contact load ( \times )</th>
<th>Testing type</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Specimen</td>
<td>Load ( \times )</td>
<td>Load ( \times )</td>
<td>Type</td>
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<tr>
<td>1</td>
<td>Carbon steel</td>
<td>170</td>
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<tr>
<td>11</td>
<td>Al alloy</td>
<td>1800</td>
<td>4</td>
<td>bending</td>
</tr>
<tr>
<td>12</td>
<td>Pure copper</td>
<td>1800</td>
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<td>bending</td>
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</table>

Cracks after the saturation of damage are found to be so deep that they are able to propagate under only repeated stress applied on specimens. Consequently, the assumption is proper that the fretting damage is saturated in the first 25% of the total life cycles for all combinations of materials used. When \( \tau_e \) is used arbitrarily for the fretting fatigue strength at \( 10^6 \) cycles, it is known that fatigue cracks initiated in the surface layer have grown at \( 2.5 \times 10^6 \) cycles so deep that behaviors of crack propagation are not affected by fretting. The maximum shearing stress \( \tau_{max} \) repeated in this case must be equal to the one under which fatigue failure occurs at \( 2.5 \times 10^6 \) cycles without fretting. Its value is obtained from the \( S-N \) curves without fretting shown in Fig. 3 and Fig. 4.

Thus \( \tau_{max} \) and \( \tau_e \) are obtained from the experimental results and are plotted in Fig. 13. The results when the stress cycle frequency was varied in the previous paper\(^6\) are also shown in the figure. The number affixed to each point in the figure denotes the test number in Table 3. The curves obtained from the analysis agree well in tendency with the experimental values. Equations (7) and (8) may, therefore, give a criterion to estimate the failure in fretting fatigue.

Both the experimental values in bending and twisting lie a little above the analytical curves, and a greater reduction of fatigue strength is recognized than the one expected from the action of the tangential stress as shown in Fig. 13. In general the reduction of fatigue strength due to corrosive environments is more remarkable in the order of pure copper, carbon steel, aluminum alloy. Moreover it is well known that the frequency effect appears in corrosion fatigue. In Fig. 13, the data on aluminum alloy specimens show the greatest deviations from the analytical curve, and the data on carbon steel specimens show greater deviations under lower frequency than under higher frequency. These deviations show that the fretting fatigue is similar to the corrosion fatigue. Though there is something unknown on the crack propagation rates of various materials and also on the effect of electric potential of different materials combinations, it may be concluded from Fig. 13 that the stress level to initiate fretting fatigue cracks is estimated approximately from the maximum repeated shearing stress which is the combination of the frictional stress of fretting and the repeated stress applied.

6. Conclusions

Fretting fatigue tests are carried out with various materials combinations, and the reduction rates of fatigue strength by fretting are obtained with an observation on the behaviors of the frictional force. The stress analyses on contacting surfaces are conducted elastically by using the maximum tangential stress due to friction obtained from test results and the maximum repeated shearing stress. The following conclusions are obtained by considering the test results together with the analytical results.

1. The reduction of fatigue strength by fretting is greater under bending than under twisting, and is more remarkable with an increase of tangential stress due to friction.

2. The results mentioned in (1) agree well with the stress analysis in which fatigue cracks are considered to initiate with the maximum repeated shearing stress which is the combination of the repeated stress applied on the specimen and the frictional stress on contacting surfaces.

3. The reduction rates of fatigue strength of the materials found in the tests are greater than those obtained from the analysis. The deviations from analytical values are the greatest for aluminum alloy, and are greater under lower frequencies than under higher frequencies. The behaviors of fretting fatigue similar to those of corrosion fatigue are expected to be further studied.

References