Effects of Stress Ratio and Fretting Fatigue Cycles on the Accumulation of Fretting Fatigue Damage to Carbon Steel S45C

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Fretting fatigue damage formation in carbon steel S45C has been examined by using an interrupted fretting fatigue testing method, which consists of two-stage fatigue loading. The first stage is fatigue loading with fretting under one of the stress ratios \( R = -1, 0, 0.33 \) and \( 0.5 \), and the second stage is fatigue loading without fretting under \( R = 0.5 \). The minimum number of cycles, \( N_r \), in the first stage which caused a break in the second stage was \( 7.5 \times 10^4 \) and was independent of \( R \). The damage layer at \( N_r \) was about one grain size, and was hardened due to the formation of fine cell structures. It was concluded that the fretting fatigue damage is accumulated in the early cycles of fretting, and does not depend on \( R \).

Key words: Fatigue, Fretting Fatigue, Fatigue Damage, Stress Ratio, Microbeam X-ray Diffraction, Carbon Steel

1. Introduction

Fatigue life in fretting fatigue is much shorter than that in normal fatigue without fretting, because a fretting fatigue crack initiates at the early stage of stress cycles and crack propagation rate is high. The effect of fretting on crack initiation and propagation, however, is limited to the surface layer under fretted surface. It was shown experimentally that the number of stress cycles to a break changed, even though the fretting shoes were removed after a certain number of stress cycles. This kind of experiment was called an interrupted fretting fatigue test.

The fretting fatigue limit was defined by Watson et al. as a lower limit of the number cycles in the fretting stage to cause a failure of the specimen within a given total number of cycles (usually 10⁶ cycles). Authors denote this limit as \( N_s \), i.e. \( N_s \approx N_r \), where \( N_r \) is the number of fretting fatigue cycles before interruption, \( N_r \) is the total number of cycles to a break, or the sum of \( N_s \), and \( N_r \) (the number of cycles to a break after removal of the fretting shoes) and \( N_r \) is the number of cycles to a break in full fretting fatigue tests.

In this paper, the effects of mean stress and number of fretting stress cycles, \( N_s \), have been examined by using interrupted fretting fatigue tests under four levels of stress ratios \( R = \) minimum stress / maximum stress. The fretting fatigue damage accumulated by \( N_s \) has been investigated by surface roughness tests, micro Vickers hardness tests, and microbeam X-ray diffraction tests.

2. Experimental Procedures

2.1 Materials

A commercial carbon steel S45C was used for the specimens and fretting shoes. The chemical compositions are listed in Table 1. The materials were normalized at 850°C for an hour and air-cooled. The mechanical properties of the specimen are listed in Table 2. Both the specimen and fretting shoes were machined to the dimensions shown in Fig.1. Their contact surfaces were finally polished with #1000 emery paper.

| Table 1. Chemical compositions of specimen and fretting shoe. (wt.%) |
|---|---|---|---|---|---|---|
| Specimen | C | Si | Mn | P | S | Fe |
| 0.43 | 0.20 | 0.75 | 0.019 | 0.012 | Bal. |
| Shoe | 0.45 | 0.26 | 0.72 | 0.021 | 0.020 | Bal. |

| Table 2. Mechanical properties of specimen. |
|---|---|---|---|---|
| L.V.P. \( \sigma_y \) MPa | U.T.S. \( \sigma_u \) MPa | Elong. | R.A. \( \phi \) % | V.H.N Hv |
| 500 | 725 | 18 | 51 | 201 |
2.2 Interrupted fretting fatigue tests

All the fatigue tests were conducted by using a servo hydraulic fatigue machine. The fretting fatigue tests were performed on the specimen with the fretting shoes clamped by a loading ring, made of S45C, as shown in Fig. 2. The clamping force, or contact pressure was measured by strain gages.

The interrupted fretting fatigue tests were carried out to determine the accumulation of fretting damage. As shown in Fig.3, the tests consist of two-stage fatigue loading, i.e. the first stage is fatigue loading with fretting under one of the stress ratios $R_1=-1$, 0, 0.33 and 0.5, and the second stage is fatigue loading without fretting under $R=0.5$. A stress amplitude of $\sigma_0=120$ MPa and a contact pressure of $p=80$ MPa were applied. The stress amplitude was lower than the fatigue limits of normal fatigue for all the stress ratios.

The full-fretting fatigue tests, in which fretting was applied to the specimen at each test, were carried out for four levels of $R$. As $N_r$ for $R=0.5$ was $2.3\times10^6$ as shown in Fig.4, the interrupted fretting fatigue tests for all $R$ were stopped at the number of cycles $N_r=3\times10^6$ which is about ten times $N_r=2.3\times10^6$, because it could be verified that the fretting fatigue damage had never accumulated in the first stage of fatigue loading.

2.3 Measurements of fatigue damage

The fretted surface on the specimen was examined by a SEM and a surface roughness tester. The fretting fatigue damage in the surface layer was analyzed by using microbeam X-ray technique as follows:

For microbeam X-ray diffraction, 10x10x5 mm³ pieces, containing a contact area were cut from the fretted specimen. The microbeam X-ray diffraction was carried out after descaling the fretted surface for surface damage information. Then the piece was electro-polished by 15 to 20 µm from the surface for subsurface damage information. The X-ray diffraction conditions are listed in Table 3, and all the X-ray diffraction tests were carried out with all of 12 samples for 4 levels of $R$ and 3 levels of $N_r$. The half value breadth $\Delta(2\theta)$ measured for the information on surface damage, and the microbeam X-ray parameters (total misorientation $\delta$, micro lattice strain $\Delta d/d$, subgrain diameter $t$ and excess dislocation density $D_e$) were analyzed from diffraction patterns of fretted surfaces.

3. Results

3.1 Number of fretting fatigue cycles to a fracture

Figure 4 shows the results of the full-fretting fatigue tests (solid marks) and the interrupted fretting fatigue tests (semi-solid marks). In this figure, the marks with arrow show that the specimen did not break at $N_r=3\times10^6$ cycles. Although $N_r$ in the full-fretting fatigue tests decreased with $R$, the minimum number of fretting cycles to a break of the specimen in the interrupted fretting fatigue tests was $N_r=7.5\times10^4$ independently of $R$. This result shows that the fatigue damage accumulated in the fretting cycles $N_r=7.5\times10^4$ will cause a break of the specimen in the following fatigue.
loading of \( R=0.5 \) without fretting. In this paper, \( N_f=7.5\times10^4 \) was named the critical number of fretting fatigue cycles, \( N_{cr} \).

3.2 Damage to the fretted surface and subsurface

3.2.1 Fretting wear

Figure 5 shows an appearance of the contact surfaces. The contact surface could be divided into three regions, i.e., two slip (wear) regions and one non-slip (adhesion) region. The width of slip regions increased with \( N_f \).

Figure 6 shows the surface roughness of the contact surfaces. The surface roughness was small at \( N_f=5\times10^4 \) but it was large at \( N_f=7.5x \) and \( 10x10^4 \) where \( N_f \) exceeded \( N_{cr} \). This figure is an example of \( R=1 \), and it has been found that the wear progress with \( N_f \) does not depend on \( R \).

### Table 3. Conditions of microbeam X-ray technique and photography.

<table>
<thead>
<tr>
<th>Characteristic X-ray</th>
<th>Fe-Kα</th>
<th>α-Fe(220)</th>
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<tbody>
<tr>
<td>Diffraction plane</td>
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</tr>
<tr>
<td>Bragg's angle deg</td>
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<td></td>
</tr>
<tr>
<td>Double pin-hole of slit ( \mu )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irradiated area ( \mu )</td>
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<tr>
<td>Divergence angle rad</td>
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</tr>
<tr>
<td>Resolving power ( \mu )</td>
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<td>Tube voltage kV</td>
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</tr>
<tr>
<td>Tube current mA</td>
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</tr>
<tr>
<td>Distance from specimen to film mm</td>
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</tr>
<tr>
<td>Ratio of diffraction image mm</td>
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<td></td>
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<tr>
<td>X-ray film</td>
<td>Fuji $150$</td>
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</tr>
<tr>
<td>Exposure time h</td>
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</tr>
</tbody>
</table>

![Fig. 5. Appearance of fretting wear of specimens.](image)

\( N_f=5\times10^4 \)

\( N_f=7.5\times10^4 \)

\( N_f=1\times10^4 \)

![Fig. 6. Surface roughness on fretted surface of specimens (\( R=1 \)).](image)

3.2.2 Variation of hardness from surface to interior

Figure 7 shows the results of micro Vickers hardness tests at the slip region for \( N_f=0, 5x, 7.5x, \) and \( 10x10^4 \) at \( R=1 \). The surface of the slip region had hardened. The hardness decreased with an increasing depth from the surface, but it became a constant value at the deep region more than 150 \( \mu \)m and agreed with the hardness at the zone not affected by fretting. The same results had been reported by Endo et al. The hardness at \( N_f=7.5x \) and \( 10x10^4 \) was higher than at \( N_f=5\times10^4 \), and the hardness of the slip region was saturated at \( N_{cr} \).

The hardness of the non-slip region was lower than that of the slip region.

![Fig. 7. Variation of micro Vickers hardness from the fretted surface to interior (\( R=1 \)).](image)
3.3 Results of microbeam X-ray diffraction

3.3.1 Results of the surface in the slip region

The diffraction patterns of the fretted surfaces were a continuous ring as shown in Fig. 8(a). This indicates that the surface has been deformed and roughened heavily by fretting, resulting in fine crystallization and strained lattice. Figure 9 shows the half value breadth $d(26)$, which is a parameter of degree of deformation, obtained from the density of the diffraction ring. $d(26)$ tends to increase with $N_f$ and $R$, indicating that a more plastic flow in the slip region takes place with an increasing $N_f$ and $R$. But, $d(26)$ has a tendency to saturate at $N_f$ in the same manner as hardness.

3.3.2 Results of subsurface in the slip region

The diffraction patterns obtained from the subsurface were spotty for all $R$ as shown in Fig. 8(b). Figure 10 shows the microbeam X-ray parameters (subgrain size $t$, excess dislocation density $D_e$, total misorientation $\beta$, and micro lattice strain $d_\delta/d$) obtained from the diffraction pattern. The values of $t$ and $D_e$ changed into an increase of $N_f$ from $5 \times 10^4$ to $7.5 \times 10^4$, but were constant at $N_f = 10 \times 10^4$. The same results were obtained for $\beta$ and $d_\delta/d$. These results indicate that the subsurface in the slip region formed fine subgrain structures which were strained and had high dislocation density. As mentioned above, the fretting fatigue damage, which caused a break of the specimen in the following fatigue loading, is accumulated at the critical number of $N_f = 7.5 \times 10^4$, and it is independent of the stress ratio $R$. Figure 10 explains the results in Fig. 4 from a standpoint of microscopic level while Fig. 7 does so macroscopically.

Fig. 9. Variations of half value breadth $d(26)$ with number of fretting fatigue cycles $N_f$ and stress ratio $R$.  

Fig. 10. Variations of micro lattice strain $d_\delta/d$, total misorientation $\beta$, excess dislocation density $D_e$, and subgrain diameter $t$ with number of fretting fatigue cycles.
4. Discussions

4.1 Effect of fretting wear

The fretting fatigue damage is accumulated under the combined cyclic stress, contact pressure and frictional stress, the effects of the fretting wear, etc. The fretting wear affects the crack initiation and early propagation process due to wear of the incipient cracks. With respect to this point, the fretting fatigue fracture occurred at the site which was decided as the result of the concurring growth and wear of a crack. Generally, the fracture site shifts inward in the slip region with an increase in fretting cycles. Therefore, the fracture site was 50 to 100 µm from the contact edge in interrupted fretting fatigue tests, and was 300 to 500 µm in the full fretting fatigue tests. The fretting fatigue damage is accumulated in the early cycles where the fretting wear is not severe but the resultant stresses of cyclic stress, contact pressure and frictional stress do act effectively. With an increasing $N_e$, fretting wear at contact edges increases, hence, the concentration of the contact pressure and frictional stress at the edges decreases.122

4.2 Substructure of damaged layer

The substructure in a 0.08%C steel subjected to cyclic sliding friction was investigated with a TEM by Garbar et al.19 According to their result, the sub-surface layer is characterized as cellular structures which have fine diameter and are expanded in the direction of friction. The sub-structure, however, changes to coarse cells and equilateral cells with an increasing depth from the surface. Moreover, the important fact is that microcracks initiate at the cell boundaries normal to the frictional direction.

It is considered that the hardening as shown in Fig.7 and the fine crystallization as shown in Fig.10 result from the formation of fine cellular structures as revealed by Garbar's investigation. Therefore, the specimen at $N_e$ is likely to be in a state where the microcracks will be apt to initiate at the cell boundaries. Microcrack was not observed at $N_e$ and found at $N_e=10^{-4}$ under a microscope as shown in Fig.11.

4.3 Effect of stress ratio R on damage accumulation

The relation between the stress ratio $R$ and the damage depth at $N_e$ was examined by fatigue loading without fretting using the fretting fatigued specimen by removing the fretted surface by emery papers from 5 to 50 µm. The results are shown in Fig.12. The specimen with the surface removed by 20 µm did not break at $N_e=3\times10^6$ independently of $R$. That is, the depth of a damaged layer formed at $N_e=7.5\times10^4$ was about one crystal diameter and also corresponded to the hardened depth shown in Fig.7.

The fact that the results shown in Figs.4 to 8, 10 and 12 do not depend on $R$ agrees with the fact that the mean stress does not affect crack initiation, as elucidated by Nishioka et al.122 The damaged layer was limited to a small depth below the fretting surface because the applied stress amplitude of 120 MPa was low enough to cause the fretting fatigue fracture but was lower than the fatigue limit without fretting. Therefore, the diffraction pattern was still very spotty even under the highest stress ratio of $R=0.3$ as shown in Fig.8(d), i.e. the fine crystallization has not occurred.133

5. Conclusions

Fretting fatigue tests were conducted with S45C carbon steel by interrupted fretting fatigue method: the fretting fatigue test was done under one of the stress ratios $R=1$, 0, 0.33, and 0.5 in the first fatigue loading, and

![Fig.11. An example of fretting fatigue crack.](image)

![Fig.12. Depth of fretting fatigue damage.](image)
then normal fatigue test without fretting was done in the second fatigue loading under R=0.5. The following conclusions are obtained from the experimental results:

1. The lower limit of the number of fretting fatigue cycles, which causes the specimen to break in the following fatigue load without fretting, is named the critical fretting fatigue cycles, \( N_{cr} \), in this paper. \( N_{cr} \) is \( 7.5\times10^6 \) in these experimental conditions and is not affected by the stress ratio \( R \).

2. The hardness of the damaged layer is about 1.2 times that of the unaffected zone, and hardening is saturated at \( N_{cr} \).

3. Evaluating by microbeam X-ray parameter (\( \Delta d/d_0 \), \( \beta \), \( D_0 \) and \( t \)), the substructure in the damaged layer forms fine cells and the parameters are constant after \( N_{cr} \).

4. According to the results of microbeam X-ray parameters and hardness tests, the damage layer is found to be a well-developed cellular structure. The damage depth is about one grain size and is not affected by \( R \).

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References