Role of Surface Micro-Texturing in Acceleration of Initial Running-in during Lubricated Fretting

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Surface texturing is considered to be an effective means of enhancing the properties of a tribological contact not only in a normal uni-directional sliding condition but also in fretting under lubricated conditions. Well-regulated “micro dimples” were formed on a flat surface using the method of micro fabrication. In this study, a bearing steel (HV760) was used for the specimens with ball-on-flat configuration. The frictional force and relative movement between the specimens were measured simultaneously during fretting with a frequency 7.35 Hz, for fretting up to $2 \times 10^5$ cycles under a lubricated condition of 350 neutral oil (typically used for grease lubricated contacts). The normal load, and fretting stroke were varied in the range of 4.9 N to 22.1 N, 12 µm to 215 µm respectively. The initial running-in process (namely, the phenomenon of a significant reduction in the coefficient of friction seen in the early stages of fretting) was the main focus of the study, with comparisons being made between specimens with flat surfaces. The main findings were that a micro texturing surface resulted in a reduced number of cycles to complete the running-in process (when compared to the flat surface), but that the wear scar was wider in the micro texturing surface. It is proposed that the micro texturing surface provides a less stiff contact than the flat surface and that the lubricant can become entrapped in the dimples in the contact, and thus provide enhanced entrainment of the lubricant into the contact.

**Keywords:** fretting, surface texturing, micro texturing surface, micro fabrication, lubricated condition, micro pool, dimple pattern

1. Introduction

Under fretting conditions, it is well known that the lubrication of the contacting surfaces is difficult, since the small stroke does not readily entrain lubricant into the contact. In this study, the effect of surface texturing on fretting under lubricated conditions is investigated. In the past, a few studies have addressed the effect of surface texturing on fretting under lubricated condition1-5). However, questions still exist as to the mechanisms by which the tribology of the contact is changed by fretting.

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between specimens with flat surfaces and those with micro texturing surfaces. It is hypothesized that the micro texturing surface is able to more readily provide lubricant into the contact between the two surfaces. Well-regulated “micro dimples” were formed on the surface using the method of micro fabrication in order to consider the effect of micro texturing, and the micro texturing surface was compared with that of flat surface. The influence of normal load $W$ and fretting stroke $\Delta r_e$ was investigated. In addition, these results were discussed in light of the results of a numerical analysis of the contact stiffness of these surfaces.

2. Experimental

2.1. Apparatus

Figure 1 shows a schematic diagram of the apparatus used for the micro texturing. This apparatus consists mainly of X-Y-Z automatic stage, diamond indenter, dead weight, and vibration-free table. The feeding pitch is 2 µm in the X-Y direction, and 1 µm in the Z direction. A finished (mirror finish) flat specimen is set on the stage, and then well-regulated indentations using diamond indenter, dead weight, and the automatic positioning stages are performed.

Figure 2 shows a schematic diagram of the fretting rig, which was partially modified from an apparatus previously reported. The driven specimen is attached to a cantilever, which is horizontally oscillated by a motor through a crank mechanism. A fixed specimen is attached to an upper holder and loaded against the driven specimen. The frictional force is measured by four strain gauges mounted on two leaf springs which form part of the upper holder. The relative stroke, $\Delta r_e$, between both specimens, (defined as the peak-to-peak amplitude of the tangential displacement between the upper and lower specimens) is measured by an eddy current pickup. The frictional force, and relative stroke between the specimens were measured simultaneously during fretting.

2.2. Specimens and experimental condition

Specimens used for the fretting test were a bearing steel ball (HV760), 9.525 mm in diameter, and a bearing steel flat (HV760). Prior to texturing, the surface roughness of flat and ball specimen was both $R_y = 0.1$ µm. The surface texture pattern formed on the flat specimen is shown in Fig. 3. Table 1 shows the details of the specimens and the experimental conditions used for the fretting test.

3. Results

3.1. Change in coefficient of friction $\mu$

Figure 4 shows the change in coefficient of friction $\mu$, for both the mirror-finished surface and the micro texturing surface. The case of the mirror-finished surface (Figure 4(a)), $\mu$ starts to increase after around 100
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fretting cycle irrespective of the load, reaching a value of 0.6 to 0.9. For the two lower loads ($W = 4.9$ N and $W = 14.7$ N), the frictional force is then seen to drop sharply after a certain number of cycles, reaching a constant value of around 0.2. This rapid reduction of friction coefficient to a value which is then maintained for significant numbers of fretting cycles is termed the end of the running-in process. For the higher load of $W = 19.6$ N, the process of running-in was not completed by the end of the test (i.e. by 200,000 cycles) with $\mu$ being maintained at 0.6. There is a tendency that the smaller load results in a shorter running-in process. In the case of the micro texturing surface (Fig. 4(b)), the process of running-in was seen to be completed at all loads, with the running-in period completed at smaller numbers of cycles for the micro texturing surfaces when compared to the mirror-finished surfaces.

3.2. Influence of normal load $W$

Figure 5 shows the relation between the cycles for completion of the running-in process ($Nr$) and the normal load $W$. The cycles for completion of the running-in process ($Nr$) of micro texturing surface is generally shorter than that of mirror finished surface, especially at higher loads, although there is a little acceleration or even deceleration at 10 N and 12.3 N. This means that the effect of micro texturing in promoting running-in is more significant at these higher loads. For the micro texturing surface, an increase in load will result in an enlarging of the contact area, and thus the number of micro pool where lubricant could be entrapped within the contact is increased. As such, the lubricating oil existing in these dimples may contribute to the completion of the running-in process. These influences are discussed in detail later in the paper.

3.3. Influence of fretting stroke $\Delta re$

Figure 6 shows the relationship between the number of cycles for completion of the running-in process ($Nr$) and the fretting stroke $\Delta re$. It can be seen that the cycles for running-in are similar for the dimple and mirror finished surface when the fretting stroke is under $\Delta re = 120 \mu m$. However, the effect of the micro texturing surface is very clear at the larger fretting stroke of $\Delta re = 250 \mu m$. The theoretical Hertzian contact width under this condition is 159 µm. When these two surface types were compared at $Nr = 1000$ cycles, the wear scar width for running-in is around two thirds of 2b for the dimple pattern.

3.4. Observation of fretted wear scar

The size of the wear scar, and the wear depth after fretting testing was measured by a laser-scanning microscope. Fig. 7 shows a comparison between wear scars from the mirror-finished and the micro texturing contacts following wear under the same conditions ($\Delta re$
It is clear that the micro texturing surface results in a significantly wider wear scar than that associated with the mirror-finished surface (197 µm compared to 143 µm). As such, it is postulated that as the nominal stiffness of the micro texturing surface decreases and thus the contact width increases, then completion of the running-in becomes easier. From the results of profile “A-A”, the wear depths lay between 1.8–3.0 µm for both flat and ball specimens irrespective of the surface texturing ones, 3–6 µm for both flat and ball specimens of the mirror finished ones. Wear depth of mirror finished surface was larger than that of micro texturing one.

4. Discussions

4.1. Contacting stiffness of micro texturing surface

From the results shown in Fig. 7, the width of the wear of the micro texturing surface was greater than that

\[ \Delta \text{re} = 36–39 \, \mu\text{m}, \; W = 12.3 \, \text{N} \]

Series 1

(a) \( p = 22 \, \mu\text{m} \) \( (d = 4.4 \, \mu\text{m}) \)  
(b) \( p = 46 \, \mu\text{m} \) \( (d = 9.3 \, \mu\text{m}) \)  
(c) \( p = 68 \, \mu\text{m} \) \( (d = 13.7 \, \mu\text{m}) \)

Series 2

(d) \( p = 46 \, \mu\text{m} \) \( (d = 9.3 \, \mu\text{m}) \)  
(e) \( p = 68 \, \mu\text{m} \) \( (d = 13.7 \, \mu\text{m}) \)  
(f) \( p = 86 \, \mu\text{m} \) \( (d = 17.4 \, \mu\text{m}) \)

Fig. 8 Patterns of micro texturing surface
of mirror finished surface, and also the running-in process was shorter. It is clear that there is a change in contact stiffness for the micro texturing surface. In addition, in the case of dimple pattern, it is necessary to clarify whether the lubricating oil existing in the dimples could bear a partial load or not in the contact. For this reason, stiffness of the micro texturing surface was measured by use of a Young’s modulus measuring system developed by some of the authors and reported in previous work. On this system, the Young’s modulus is obtained from the relationship between the relative approach during indentation of a spherical indenter onto a surface, utilizing the equations governing the elastic contact deformation of a sphere and a flat.

From Hertzian theory, the relative approach between a sphere and a flat $\delta$ is,

$$\delta = kP^{\frac{3}{5}}, \quad k = \left(\frac{9}{4E' R}\right)^{\frac{3}{5}} \quad (1)$$

If normal load $P$ and $\delta$ are measured simultaneously, the proportionality constant $K$ can be calculated, and thus the equivalent Young’s modulus $E'$ is obtained. As such, the Young’s modulus of flat $E_f$ is given by,

$$E_f = \left(\frac{1-\nu_s^2}{2/E' - (1-\nu_s^2)/E_s}\right)^{-1} \quad (2)$$

Here $E_i$ is the Young’s modulus of sphere, $\nu_s$ is the Poisson’s ratio of sphere, $\nu_f$ is the Poisson’s ratio of flat, and $E'$ is given by,

$$E' = \left[\frac{1-\nu_s^2}{E_s} + \frac{1-\nu_f^2}{E_f}\right] \cdot \frac{1}{2} \quad (3)$$

The sphere used for the indentation was Si$_3$N$_4$ with a diameter of 9.525 mm ($E_s = 300$ GPa, $\nu_s = 0.28$). The properties used in the calculations for the steel were $E_i = 208$ GPa and $\nu_i = 0.30$.

Figure 8 shows the details of two series of micro texturing patterns used for the stiffness measurements with the stiffness measurements being made with both dry surfaces and on surfaces immersed in lubricant (in the figure, “p” means pitch, and “d” means depth of the dimple); the measured contact stiffnesses under both test conditions are shown in Fig. 9. It can be observed that the contact stiffnesses of micro texturing surfaces decreases with increasing pitch, that is, increasing the size of the dimple, with all values of contact stiffness of the micro texturing surfaces being lower than that of the mirror-finished surface (nominal value of 208 GPa). Additionally, the contact stiffness under the lubricating oil was observed to be higher than that in dry conditions. This indicates that the lubricating oil existing in the
dimples bears a portion of the contact load.

When the Young’s modulus is obtained in Fig. 9, the relationship between the load and the approach of the two surfaces under load is also obtained. For instance, in the case of the pattern shown in Fig. 8(f), the approach at the load of 98 N was 4.17 μm, compared to that observed with a mirror-finished surface of 4.00 μm. These results were compared with the results of a numerical analysis. Using a method of analysis already reported\(^8\), the contact pressure distribution of the micro texturing surfaces was obtained, and then the contact radius and approach under load were obtained. In this analysis, a three dimensional elastic contact model was used. Fig. 10 shows a model used for the numerical analysis. As a model for the analysis, the patterns shown in Fig. 8(f) were applied, and the numerical analysis was conducted, discretizing into micro regions with a pitch of 4 μm. The contact pressure was set at zero in a dimple region (i.e. where there was no contact). The Young’s modulus of the sphere used for the calculation was 300 GPa (Si₃N₄, \(V_s = 0.28\)) or 208 GPa (SUJ2; wearing steel, \(V_s = 0.30\)) to allow comparison with both the experimental fretting results and that the experimental measurements of contact stiffness. From the model, the distribution of the contact pressure in the X direction at \(Y = 0\) is shown in Fig. 11. From this result, a pressure spike is seen at the boundary of the dimple and the contact face. It is seen that the radius of the contact of the micro texturing surface (\(r = 148 \mu m\)) is larger than that of the mirror finished surface (\(r = 136 \mu m\)). On the other hand, approach amount is 4.11 μm for the former, 3.95 μm for the latter, corresponding to the results obtained during the measurements of contact stiffness previously presented.

In order to assess the validity of the contact radius obtained from the numerical analysis, a LB (Langmuir-Blodgett) film was formed (accumulated total of 11 layers, with an estimated film thickness of 22 nm) on the micro texturing bearing steel surface, shown in Fig. 8(b), and on a mirror-finished surface, using a method described elsewhere\(^9\). The contact radius was measured by the identification of the contact region using the indentation of a silicon nitride sphere onto the surface. A result of such a test is shown in Fig. 12. The measured contact radius for the micro texturing surface was \(r = 152 \mu m\), and that for the mirror finished surface was \(r = 141 \mu m\), corresponding well to the results of the numerical analysis previously presented.

Both the experiments and the modeling work clearly indicate that the contact stiffness of the micro texturing pattern surface is lower than that of the mirror-finished surface. When present, the lubricating oil existing in the dimples bears a portion of the contact load. However, from the modeled result of the contact pressure distribution, the contact pressure around the dimples, i.e. the contact pressure in the plateau regions around the dimples is high, and it is still higher at the edge of the contact region than the maximum Hertzian contact pressure for the mirror finished surface at the center of the contact region. Moreover, the size of the contact region for the micro texturing surface is larger than that of mirror finished surface. In the next section, the influences of each of these characteristics of the micro texturing surface on the shortening of the running-in process are discussed.

4.2. Possible mechanism of the initial running-in process on lubricated fretting condition

The contact stiffness of the micro texturing surface is low compared to that of a mirror-finished surface. In addition, the micro texturing surface has the advantage to be preferentially worn away at the edge of the dimples, that is, in the plateau regions, since the contact pressures in these regions are high. It is considered that these characteristics could accelerate the completion of the running-in process. In addition, as Sugimura et al reported\(^10\), “The running-in process should be the advance process of the truncation”.

From the result of Fig. 4, it is found that there was no contribution of micro texturing for the coefficient of friction after the running-in period. Therefore, the effect of surface micro texturing appears only in the initial running-in process, and it is considered that it plays an important role of acceleration of its period.

In general, it is well known that it is difficult to retain the lubricating oil in the contact area under the fretting condition. Even if it exists between the contacting surfaces at the initial stage of fretting, it is gradually excluded by fretting action, and finally the boundary lubrication cannot be maintained. By applying surface texturing, (for example, a dimple pattern) “micro pools” of lubricant can be formed in the contact area, and the lubricating oil in these dimples can be provided to the friction surface around the dimples. This action would contribute to the earlier completion of the running-in period.
5. Conclusions

(1) The micro texturing surface has an effect to accelerate the initial running-in process compared with that of the mirror-finished one.

(2) The contact stiffness of the micro texturing surface is low compared to that of the mirror-finished one, and the contact region is larger. The lubricating oil existing in the dimples bears a portion of the contact load.

(3) The contact pressure around the dimples, that is, in the plateau regions, is high, and it is still higher at the edge of the contact region. These pressures are higher than the maximum Hertzian contact pressure for the mirror-finished surface at the center of the contact region.

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7. References


