In situ monitoring of friction surfaces and their sequence pattern analysis

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Friction occurs between solid surfaces, and even sometimes on lubricated surfaces. To understand tribological subjects, it is important to know the changes that occur in friction surfaces. In this study, a laser strobe technique is applied to a friction surface observation. The recorded surface images were analysed using pattern-matching methods and their correlations are discussed. A test using pin-on-plate methods with carbon steels was performed using a reciprocating motion speed of 10 Hz for 4.9 N. A pulsed laser light (Nd:YAG SHG = 532 nm, 5 ns per pulse) was irradiated onto the friction surface. It was induced using an optical microscope that was located just to the side of the pin. The laser pulse was synchronized with the plate motion, which was a trigger of the laser pulse. The surface image was stored for every cycle. These sequences were calculated and their correlations were analysed as a function of the surface pattern and the friction track size and shape. Analysis revealed that some groups were distinguishable as parameters of the damage size and shape.

Keywords: friction; surface; in situ monitoring; sequence pattern; laser strobe

1. Introduction

Assessment of friction surfaces is important to determine the start and progress of damage, along with its causes, extent, locations and processes. However, in situ monitoring of a friction surface is difficult owing to the friction that occurs between solid surfaces, and even sometimes on lubricated surfaces. To understand tribological subjects, it is important to determine changes of friction surfaces. In many cases, surfaces have been observed after tribological tests when test pieces are removed from the tribotester (Yahata et al. 1992). In some cases, transparency probes, such as X-ray, were used for surface observation of metals (Batchelor et al. 1998). Nevertheless, in such cases, the tribological conditions differ greatly from actual friction conditions. In other cases, metals have been used for tribological monitoring (Mishina & Kondoh 1999), but those test conditions included slow movement, light weight or only the initial friction stage. In these studies, the friction surfaces were monitored continuously using a CCD camera (Ando & Kato 1999), acoustic emission (Skare et al. 1998; Sun et al. 2005) and other means.

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In the present study, a laser strobe technique (Reeves et al. 1999; Carvalho et al. 2002) was applied for friction surface observations and recorded surface images were analysed by means of pattern-matching methods. Their correlation with friction damage was then examined.

2. Methodology

A test using pin-on-plate methods with carbon steel was conducted with reciprocating motion and rotating motion speeds of 10 Hz for 4.9 N. The 8 mm diameter pin was 1 inch (2.54 cm) high; the plates were 14×17×70 mm. A machine-based oil (25 μl) was coated onto the surface as a lubricant immediately before the tribotest. The pulsed laser light (Nd: YAG SHG =532 nm, 5 ns per pulse) was irradiated using an optical microscope located just to the side of the pin and irradiated onto the friction surface through an optical fibre. The laser pulse was synchronized with the plate motion, which served as a trigger for the laser pulse. This signal also triggered a CCD camera shutter to open at about 1 ms. During shutter opening, the laser pulse illuminated the friction surface; the reflected light was recorded by the CCD camera. The observation area on the friction surface was viewed using an objective lens on a 5–20 powered optical microscope at a working distance of 25–100 mm, and was recorded by CCD camera. Figure 1 shows the system set-up of the reciprocating tribotester, microscope, optical fibre, laser generator, pulse generator and the computer, which recorded the friction images. A surface image was recorded for every cycle as 560×640 pixels per image. These sequences were calculated and analysed for their correlations as a function of the surface pattern and the friction track size and shape.

Recorded images were compensated for their positions, which shifted owing to motor irregularity and mechanical vibration, compared with the first image or an averaged image, which was calculated using the first several images. Following this compensation, the optical unevenness was also compensated using the first
image or the averaged image. In these compensations, the better position and optical unevenness were determined to have a higher correlation coefficient than the others for the same image; their scores were plotted. The correlation coefficient was calculated using the following formula:

\[
    r_{xy} = \frac{S_{xy}}{S_{xx}S_{yy}}
\]

for \( \{X_i|i=0, 1, 2, \ldots, N-1\} \) and \( \{Y_i|i=0, 1, 2, \ldots, N-1\} \).

And here, \( S_x \) and \( S_y \) indicate dispersion of \( X_i \) and \( Y_i \). \( S_{xy} \) is the codisperse of \( X_i \) and \( Y_i \).

Therefore, \( S_x \), \( S_y \) and \( S_{xy} \) are represented as follows:

\[
    S_x = \sqrt{\frac{\sum_{i=0}^{N-1} (x_i - \bar{x})^2}{N}} \quad S_y = \sqrt{\frac{\sum_{i=0}^{N-1} (y_i - \bar{y})^2}{N}} \quad S_{xy} = \frac{\sum_{i=0}^{N-1} (x_i - \bar{x})(y_i - \bar{y})}{N}
\]

After compensation to estimate surface features from their surface patterns, some fracture shapes and sizes were inferred. We then determined where, when and at what frequency they appeared in the images. The calculated results were plotted as correlation coefficient scores as a function of time of tribological testing. Figure 2 shows the calculation procedure that was used for special shapes in the surface fracture images.

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3. Results and discussion

Images obtained from the reciprocating tribological test are shown in figure 3, which are selected first and around dramatically changed surfaces. Under these test conditions, the surface was changed drastically after 350 s. Figure 4 shows the calculated correlation coefficient scores and friction force obtained from the load cell. The time dependence of the correlation coefficient scores, which were calculated using obtained images, showed good agreement with the time dependence of the friction force.

This result confirms that the correlation coefficient scores are a remarkably good indicator of surface changes by friction. Nevertheless, this indicator was insufficient to elucidate the opportunity for surface damage. Accordingly, simple shapes were apparent on the friction surface images, e.g. rectangles or circles. The parameters of the focused shape were the size of the designated shape. A mask pattern of that shape and size was made using data from all images. Finally, frequency of that mask pattern on the images was measured and plotted. Figure 5 shows a calculated mask pattern (figure 5a) with a designated rectangle shape at 40×10 pixels; its appearance pattern (figure 5b) for each image and the time dependence of that feature (figure 5c) show how often it appeared in the images. The number under the appearance pattern shows the time of the image that was obtained. Dotted lines in figure 5b show drastic change times of the surface. These patterns show the designated shape and its size, along with when and where it appeared in the recorded images and how often they appeared in the images. Comparison of the appearance patterns and time dependence of the shape and size indicated surface damage groupings in the friction images.

Figure 3. Sequence photographs of a friction surface. (a) First image (0 s), (b) just before abrasive wear (350 s), (c) starting of abrasive wear (359 s) and (d) just after abrasive wear (360 s).

Figure 4. Calculation results from the images of (a) time dependence of the correlation coefficient (pick up every 10 images) and (b) obtained friction force from the tribotester.
Figure 6 shows the appearance patterns and the time dependence of the feature appearance frequency for several sizes of rectangular shapes. In this figure, dotted lines show a similar tendency and this group showed the surface fracture time. These results indicate that this shape and its size are indicative features for this tribological test.

The surface damage was analysed using surface observation images that were obtained at every friction. Special shapes and their size in these images were noted. This analysis revealed that surface modifications can be categorized into several groups that have similar time-dependent patterns in the sequence images. This grouping might be independent of tribological test conditions because the analytical result came from the recorded images. Generally, it was considered that a wear pattern was formed by surface scratching or adhesion of those resultant particles. The obtained images were recorded merely from these friction patterns. These observations explain why the surface changes occurred, but do not explain how the surface pattern forms. Several researchers (Kawaguchi et al. 1996; Williams 1999; Han & Lee 2002) have tried to understand friction behaviour by their original models and numerical analyses.

Next, we propose a simple model and explain how the friction surface pattern is formed. Fundamentally, the friction surface modification can be described by our unique method in presenting results, i.e. the friction surface was formed and categorized by the feature shape and its size, and how often it appeared in the image. In other words, the friction surface can be distinguished to calculate how often the special shape and size appeared during tribological test times under the test conditions. These parameters determine the friction force, material characteristics, loading force, friction speed and so on. In this model, the surface is divided into several
Figure 6. Appearance patterns and the time dependence of the feature appearance frequency for several sizes of rectangle shape. Same colour circles show similar time dependence. (a) 30×10 pixels (SH = 1), (b) 20×15 pixels (SH = 1) and (c) 10×20 pixels (SH = 1).
areas that have identical characteristics. The feature is simply a change of colour from white to black with a determined probability. For the relationships among areas, a condition restricts the areas, e.g. if a neighbouring area changes its colour, then the probability of a colour change increases. The areas are grouped into lines that correspond to wear tracks, with calculations performed along those lines.

Unfortunately, this model has not been calculated. After calculations in the near future, the frequency patterns of the special shapes that appeared will be compared with actual data.

4. Conclusions

To understand friction surface modification due to tribological testing, we proposed an in situ monitoring system using pulsed laser light synchronized to the tribological tester. By this monitoring system, friction surfaces were recorded for every friction at the same position until heavy damage occurred in the surface without the tester stopping, removing and resetting the test piece. From the recorded images of the friction surface, the surface damage was analysed by the images which were obtained at every friction and pursued special shape and its size in these images. As a result of this analysis, it was found that the surface modification could be categorized into several groups which had similar time dependence patterns to the feature in terms of how often they appear in the sequence images. This grouping might be independent of tribological test conditions owing to the analytical result obtained from recorded images.

References