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Friction and wear of a rubber coating in fretting

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Abstract

The friction characteristic of a rubber coating undergoing fretting-like oscillatory motion against a steel slider is experimentally investigated. The variation of friction coefficient and rubber coating life as a function of load, velocity and displacement amplitude are investigated. Results of experiments on the effect of load, velocity and displacement amplitude on the coating life are presented.

Keywords: Rubber; Rubber coating; Fretting; Oscillatory motion

1. Introduction

Fretting describes a type of contact failure in systems that undergo very small vibration amplitudes. This type of a failure is often associated with a combination of oxidation corrosion and abrasive wear between two contacting metallic bodies. Fretting is commonly found between the riveted joints of an airplane, tools of a pressing machine, in the contact of electrical switches, and so on. The oscillatory sliding motion causes not only interfacial heat generation but also stress concentration on the mating surfaces. The generation of heat contributes to oxidation corrosion while stress concentration leads to the formation of surface cracks and wear. As a result, a component undergoing fretting motion ultimately fails to perform its intended task.

Fretting research works have been devoted to different objectives ranging from the fundamental understanding of its mechanisms [1,2] to establish relationships between fretting and fatigue [3–5] to assess cyclic variation of the friction coefficient [6,7]. While these factors are intimately related, it is generally believed that the increase in the cyclic variation of friction is a major driving force behind the rapid growth in the contact stress, fatigue and wear.

Research aiming to combat fretting failure by means of application of a suitable coating to reduce friction are the subject of several published papers [8,9]. Rubber coating is an example of a useful material often utilized to prevent direct contact between surfaces, to reduce leakage, to reduce stress concentration and to provide resistance to fretting by minimizing the vibration amplitude. Rivin has looked at the use of thin layers of rubber to accommodate relative displacements between the surfaces of meshing gears [10]. However, rubber tends to easily wear out and has a finite life. As a result, its protection of surfaces is limited.

A literature survey of research works dealing with wear and friction characteristics of rubber reveals that the majority of the open publications are limited to applications involving tires and belts. In these applications, the interest lies in the bulk properties of rubber undergoing continuous sliding motion [11–19,22,23]. The tribological behavior of a thin rubber coating as a means of protecting the metal substrate has thus far received little attention in the open literature.

In this paper, we provide the results of experiments devoted to the understanding of the friction and wear characteristics of a relatively thin rubber coating stamped on steel plates. The experiments were performed under different loads, oscillating velocities and displacement amplitudes.

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Furthermore, a series of laboratory tests were also performed to determine the coating life as a function of load, displacement amplitude and velocity.

2. Experimental procedure

The apparatus used for measurement of friction and wear was a universal microtribometer equipped with a computerized data acquisition system. A crank mechanism produced the necessary oscillatory motion. It was designed to accommodate changing the displacement amplitude. A variable-speed servomotor provided sinusoidal reciprocating motion. The schematic of the device is shown in Fig. 1. A piezo-force sensor was used to measure the normal force and tangential force. The resolution of the force sensor was 0.01 N. The load axis is controlled within 1 μm by the servomotor and the load error is within 0.2 N. The displacement and the rotating revolution per minute are controlled within 1 μm and 0.02 rpm by the servomotor, respectively.

The type of rubber was fluoropolymer. The typical properties of this material based on 1.90 mm thick slab were: shore hardness (HSA) of 66 MPa and tensile strength of 5.17 MPa. A screen-printing technique was used to have the coatings on the flat metal sheets (0.5 mm thickness). The screen was a wire mesh with only the designed area being open to allow the flow of coating. Once the sheets were coated, an oven cured the coatings.

All tests reported in this paper were performed using a stainless steel ball that was of the same material as the plates. Its diameter and surface roughness (Ra) were 10 mm and 0.02 μm, respectively.

The normal force, the velocity and the displacement amplitude were varied to investigate the friction and wear of rubber coatings. All experimental tests were conducted under ambient conditions with a constant temperature of 20 °C and a relative humidity of 40–50%.

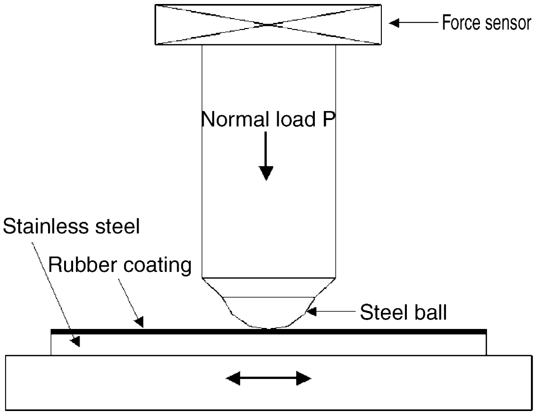


Fig. 1. Experimental apparatus.

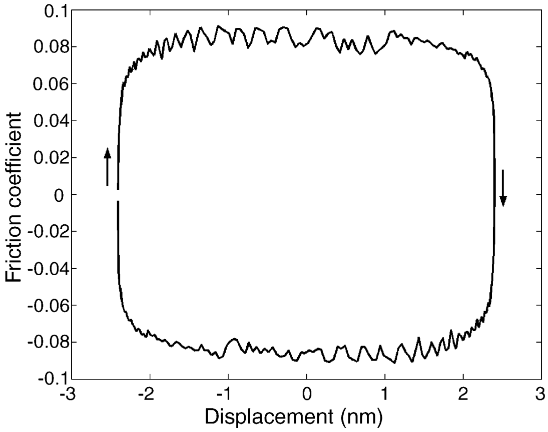


Fig. 2. Variation of friction coefficient with displacement under a normal load of 2 N.

3. Results and discussion

In this section, we report a series of experiments conducted to measure the friction coefficient of a rubber coating in contact with a stainless steel ball in reciprocating motion. The normal loads were 2, 4, 10, 16 and 25 N. The displacement amplitude was 4.8 mm and the maximum velocity in the middle of the stroke was 0.6 mm/s.

3.1. Friction exposed to oscillatory motion

In a sinusoidally oscillatory motion, the velocity changes continuously from nil at each end of the stroke to a maximum at the middle of the stroke. Therefore, the friction coefficient changes continuously with velocity [11]. An example of experiments with fresh rubber is shown in Fig. 2. When the velocity is nil, the friction coefficient is small but finite. The maximum coefficient is seen to occur in the middle of the stroke and falls into its lowest value at the both ends of the stroke. This figure reveals that the friction coefficient is drastically affected by changes in the velocity as it oscillates.

The friction coefficient of the fresh rubber coating as a function of load is shown in Fig. 3. These results correspond

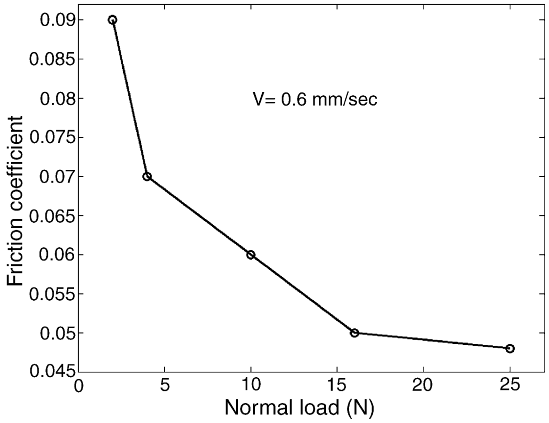


Fig. 3. Friction coefficient of fresh rubber as a function of load.

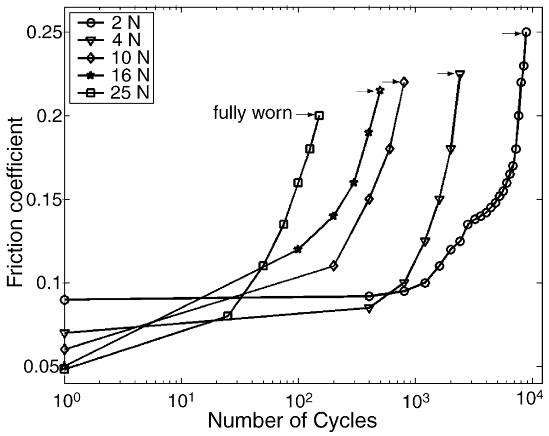


Fig. 4. Friction coefficient of rubber as a function of number of cycles.

to the friction at the middle of the stroke. It is shown that the friction coefficient of fresh rubber decreases in a non-linear fashion as the load increases.

3.2. *Effect of load on friction coefficient and its relationship to coating life*

A series of experiments was continued until the rubber coating was fully worn off and the friction coefficient was measured under each one of the load values. The experiments were conducted in reciprocating motion, and so one cycle means one passage on the contact area. The results for coating life as a function of number of cycles are shown in Figs. 4 and 5. The friction coefficient of the rubber coating is seen to increase with the number of cycles as the rubber wears out. For example, the friction coefficient with 2 N starts from 0.09 and reaches 0.15 after about 3600 cycles as shown in Fig. 4. When the load is higher, the friction coefficient varies much more rapidly. For example, the friction coefficient with 25 N is roughly 0.05 at the beginning but reaches 0.15 just after 100 cycles as shown in Fig. 4. The end cycle where the rubber coating is fully worn out is marked in the figure. At the beginning, the friction coefficient of fresh rubber decreases as load increases as mentioned earlier, and it also decreases as load increases when rubber is fully worn out. When the load is large the rubber quickly tears off and the friction coefficient sharply increases. As shown in Fig. 5, the higher the load, the shorter is the rubber coating life.

It has been reported that the wear volume of bulk rubber in continuous sliding increases as the normal load increases [12,13], which agrees with the results of our research with oscillatory motion. However, contrary to these results, Barquins [14] reported that the friction coefficient decreased as the number of cycles increased. In his research, the load and the sliding velocity were 20 mN and 500 μm/s, respectively. This disparity can be attributed to the lighter loading condition and the use of a glass ball in Barquins' experiments which resulted in a much less rubber wear.

3.3. *Effect of velocity on friction coefficient and its relationship to coating life*

A series of experiments was performed to measure the friction coefficient of rubber under various oscillating velocities and was continued until the rubber coating was fully worn off. The imposed load was 10 N and the other operating parameters were maintained as the same as the previous test in Sections 3.1 and 3.2. The results of the friction coefficient reported in this section correspond to the middle of the stroke where the maximum friction coefficient occurs. The friction coefficient of the rubber coating is found to increase as the sliding velocity is faster as shown in Fig. 6. It increases by four-fold from 0.03 at 0.025 mm/s to 0.12 at 100 mm/s.

Fig. 7 shows how long the rubber coating lasts at different operating velocities. The coating life is measured in terms of the number of cycles before it is worn out. It is interesting to note that although the friction coefficient increases with increasing oscillating velocities, the coating life tends to be short at low velocity. As shown in Fig. 7, the rubber coating life is strongly dependent upon the velocity. Coating life is very short at very low oscillatory velocities, typically it lasts only 250 cycles at 0.025 mm/s. As the velocity is increased

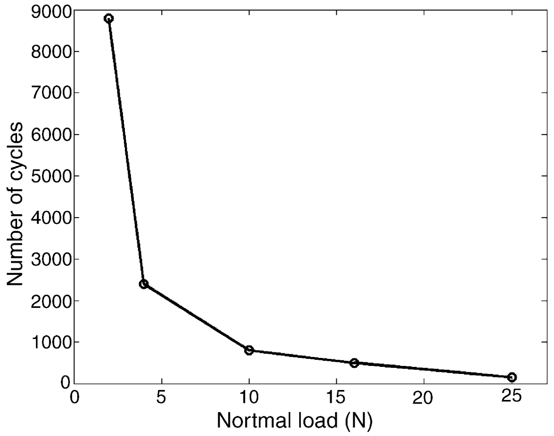


Fig. 5. Rubber coating life as a function of load.

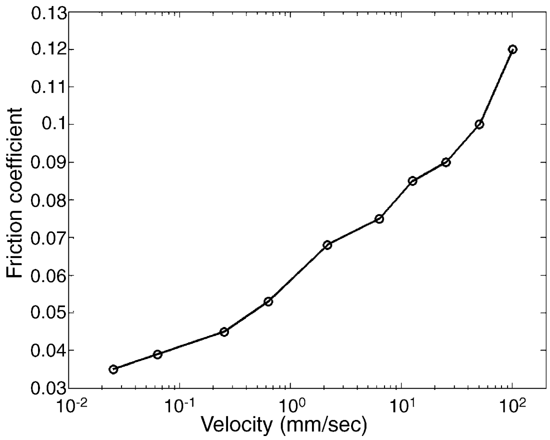


Fig. 6. Friction coefficient vs. velocity.

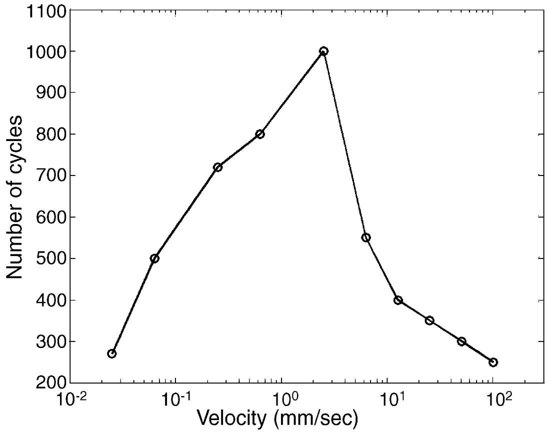


Fig. 7. Rubber coating life vs. velocity.

up to 2.5 mm/s, more cycles are needed for the rubber to completely wear off. At higher velocities, the coating life begins to deteriorate with increasing velocity. Further discussion on the effect of velocity on wear is given in Section 4.

3.4. Effect of displacement amplitude on coefficient of friction and its relationship to coating life

The displacement amplitude of the reciprocating motion was varied from 0.076 to 4.8 mm, while the load was maintained at 10 N. The results of the friction coefficient obtained in the middle of the stroke with various velocities are presented in Fig. 8. As shown, the friction coefficient does not change much on varying the displacement amplitude.

The rubber coating life lasts longer when the displacement amplitude is shorter as shown in Fig. 9. Wear of rubber is a strong function of the displacement amplitude in oscillatory motion. The trend of life in the small displacement amplitude is similar to that in the big amplitude. That is to say, the coating life is short at low sliding velocities and at high velocities, in terms of the number of cycles necessary for the rubber to completely wear off.

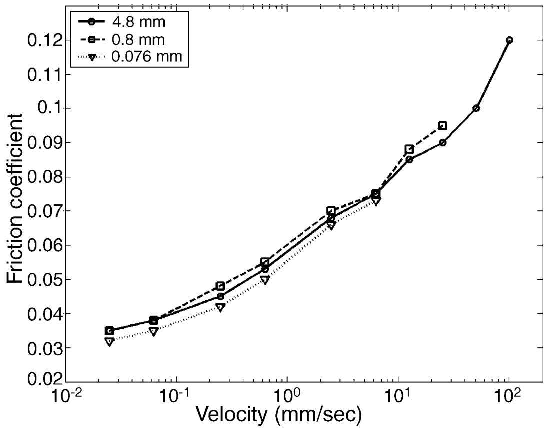


Fig. 8. Friction coefficient vs. velocity for various displacement amplitudes.

4. Discussion

Rubber is a viscoelastic material and its friction behavior is governed by viscoelastic material properties. In addition, rubber friction force depends on the operating speed and temperature. Further, viscoelastic losses and dependence on frequency can affect the tribological behavior of rubber.

Barquins [15,16] obtained the following "master curve" formula with the functional form of $\mu = f(\log a_t v)$ to describe the dependence of friction coefficient on velocity, v and temperature:

$$\log a_t = -\frac{8.86(T - T_0)}{101.5 + T - T_0} \tag{1}$$

where T represents the operating temperature and T_0 is a reference temperature. Barquins et al. [17] reported that friction force increased as the velocity increased but their experiments were conducted with a low velocity from 0.01 to 3.4 mm/s. Persson [18] reported that friction force decreased as the velocity increased in the high velocity range depending on the nature of the substrate surface roughness and on the mechanical properties of rubber. Persson's attention was focused on examining the behavior of bulk rubber undergoing continuous motion.

In our research, the temperature is constant and the velocity is sinusoidal, where in each stroke the rider undergoes an acceleration and deceleration. As shown in Fig. 2, the friction coefficient of the rubber coating increases in each stroke as the velocity increases. The maximum friction coefficient in the middle of the stroke increases as the velocity increases as shown in Fig. 8. The interaction between the varying velocity as well as acceleration/declaration within a stroke and the viscoelastic nature of rubber is quite complex and much worth an additional detailed study.

Barquins and Courtel [15] and Barquins [16] studies revealed that Schallamach waves depend on temperature and the radius of the glass slider. In their studies, the bulk rubber and the glass slider were exposed to a relatively low load from 0 to 50 mN. The behavior of a rubber when used as a coating to avoid fretting, or when used for avoiding leakage, is also

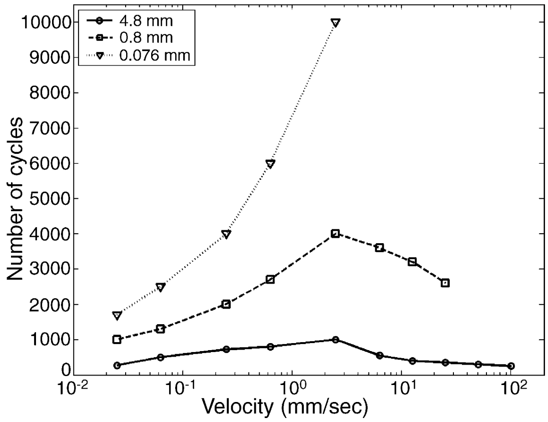


Fig. 9. Rubber coating life vs. velocity for various displacement amplitudes.

affected by the velocity and surface roughness of the slider [18]. All of the tests that detected a Schllamach's wave were conducted with a unidirectional and constant speed slider. In the experiments reported in the present paper, no such waves were observed probably because of the oscillatory nature of the sliding motion, the high loads and the surface roughness. The Scallamach wave has been studied for an understanding of the friction mechanism of rubber [15,16]. However, the relation, if any, between the Schallamach wave and rubber wear is still not clearly understood.

From a mechanical point of view, either a sphere on a plane or a cylinder on a plane is used in fretting studies. Theoretical analyses [20,3] and experimental observations [4] reveal that gross slip occurs at the end of the contact region between a ball (or a cylinder) and a plane. The maximum tensile stress is also found at the contact end [20,3]. Given that the magnitude of the friction coefficient in metallic contact is inversely proportional to the sliding velocity [21], in tests involving reciprocating motion, the maximum friction is registered at the end of the stroke. These are the locations where fretting failure is likely to initiate. On the other hand, the friction coefficient of rubber is proportional to the velocity in oscillatory motion and varies from nil in the end of the stroke to the maximum at the middle of the stroke.

In the absence of coating protection, increasing the load on two contacting metals that undergo fretting, tends to slightly reduce the coefficient of friction [21]. Introduction of a suitable rubber coating would be useful since increasing the normal load reduces the coefficient of friction as shown in Fig. 3. A rubber coating can reduce the friction force on the whole contact path, especially at the extreme ends of oscillation amplitudes, where fretting fatigue is likely to initiate (see Fig. 2).

Many attempts have been made to find a relationship between the rate of abrasion loss and the physical and the mechanical properties of rubber [12,13,22,23]. Uchiyama [23] found the following relationship for determining the wear volume of rubber abrasion:

$$V = k_1 \frac{\mu P}{\sigma_{\mathrm{B}}} L \tag{2}$$

where V is the wear volume, μ represents the friction coefficient, P denotes the normal load, L the length of rubbing distance and k_1 is a constant. The parameter σ_{B} is expressed by the following equation:

$$\sigma_{\mathrm{B}} = \sigma N \tag{3}$$

where σ is maximum amplitude of tensile stress and N is the number of cycles. Fukahori [12] published the following relationship for the rate of abrasion with the mean strain amplitude, ε^* and the crack growth per cycle ($\mathrm{d}c/\mathrm{d}n$):

$$D = \frac{\mathrm{d}c(\varepsilon^*)}{\mathrm{d}n} \tag{4}$$

where $\varepsilon^* = \mu P/ES$, E is Young's modulus and S is the cross-sectional area. They proposed that abrasive wear of rubber is strongly influenced by the fracture resistance of the material undergoing repeated deformation as a result of two kinds of periodic motions: stick-slip oscillation and the microvibration generated during frictional sliding of rubber.

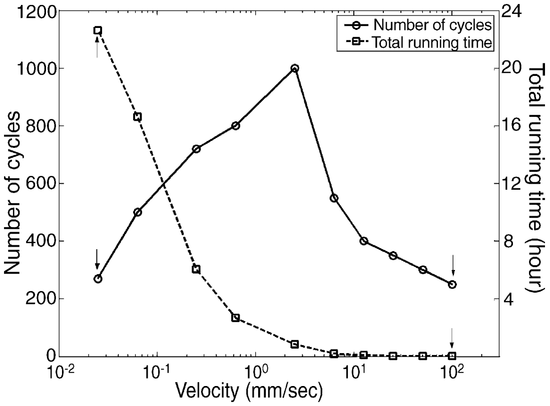
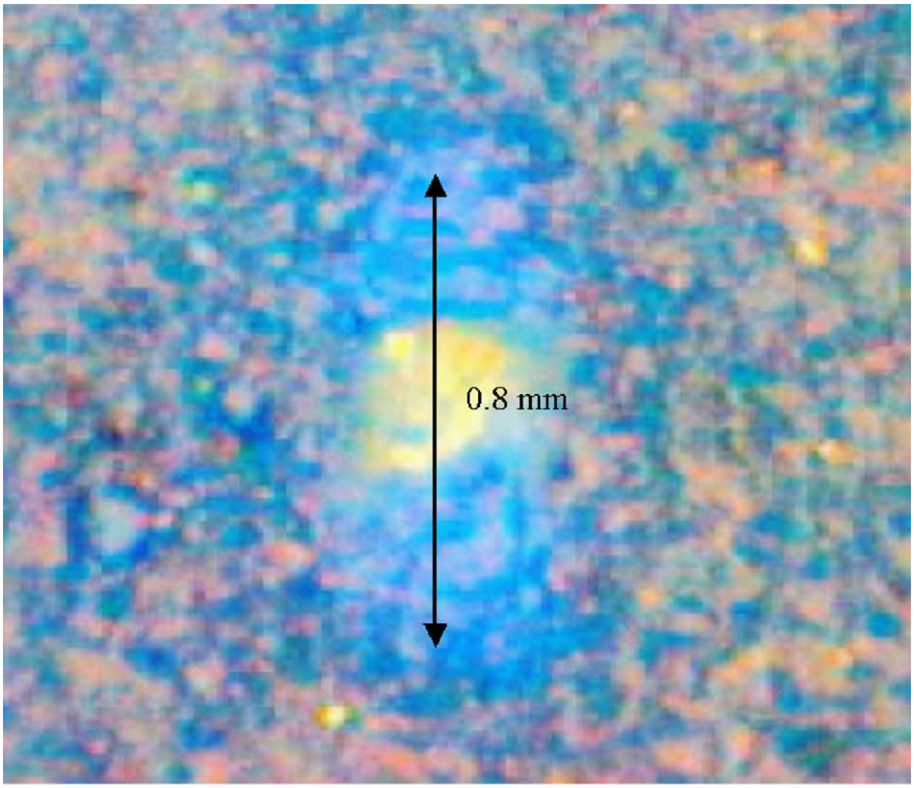


Fig. 10. Rubber coating life and total running time.

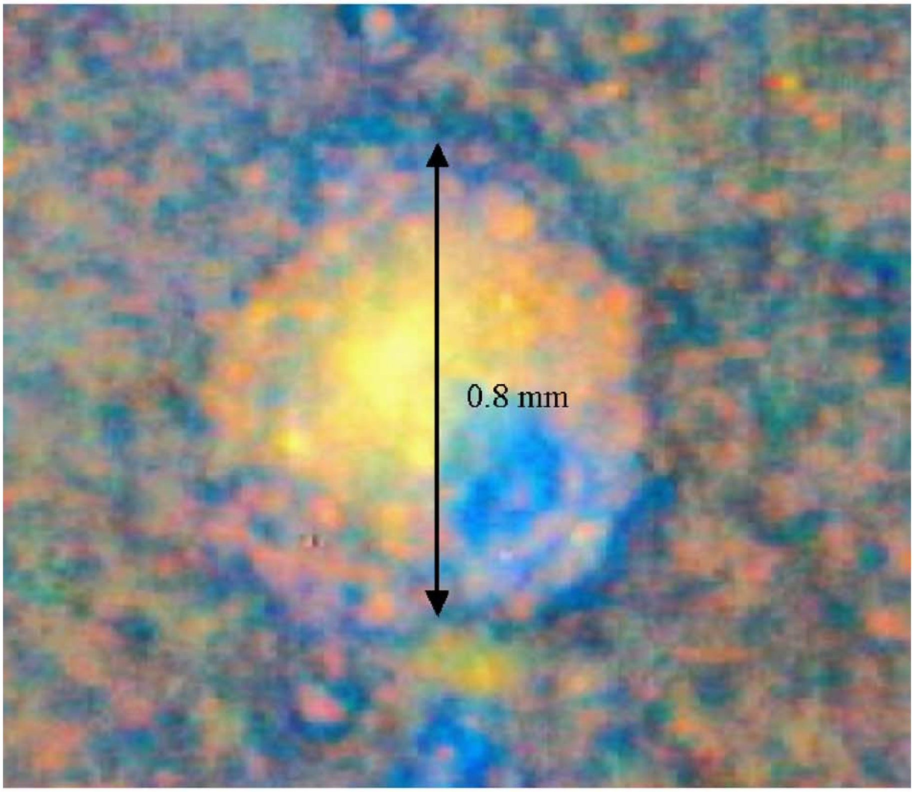
In our study, the rubber coating life is found to be short as the normal load increases as shown in Figs. 4 and 5, which is coincident with the prediction of Eqs. (2) and (4). But even though the friction coefficient at low velocity is very low as shown in Figs. 6 and 8 and other parameters are the same, coating life in low velocity is short as shown in Figs. 7 and 9. Even when rubber is exposed to a relatively low normal load, it is worn out after a small number of cycles at low velocity. Rubber wear seems to be also related to running time. Total running time is calculated from Fig. 7 and is shown in Fig. 10 with the coating life. As shown, the number of cycles in the positions marked by an arrow at low and high velocity are similar but the total running time at low velocity is very long. Rubber seems to be worn out easily in a small number of cycles under low frequency and long running time. It can be also concluded that rubber wear mechanism changes as sliding velocity changes.

Fig. 11 shows a picture of fully worn rubber in the displacement amplitude 0.8 mm, in which all experimental conditions were the same except the velocity. The fully worn region of rubber at the velocity, 21.27 mm/s occurred in the middle of the stroke as expected. The worn region is small and especially very narrow in the direction perpendicular to the velocity as shown in Fig. 11(a). The fully worn area of rubber when the velocity is 0.025 mm/s is large and very wide in the direction perpendicular to the velocity because the friction force is small and the total running time is very long. It is likely that the wear of rubber at low velocity oscillatory motion is related not to abrasion but to adhesion-type wear.

Fretting of a metal is divided into three regimes related to slip motion. They are: partial slip, mixed slip and gross slip conditions according to the displacement amplitude of sliding [6,24]. Fouvry et al. [24] reported that the wear volume of metal in fretting increased as the displacement amplitude is increased. Liu and Zhou [6] showed that the friction coefficient and the depth of wear scar in dry sliding increased as the displacement amplitude increased. The present study



(a) V = 21.27 (mm/sec)



(b) V = 0.025 (mm/sec)

Fig. 11. Pictures of fully worn rubber (10 N): (a) $v = 21.27$ mm/s; (b) $v = 0.025$ mm/s.

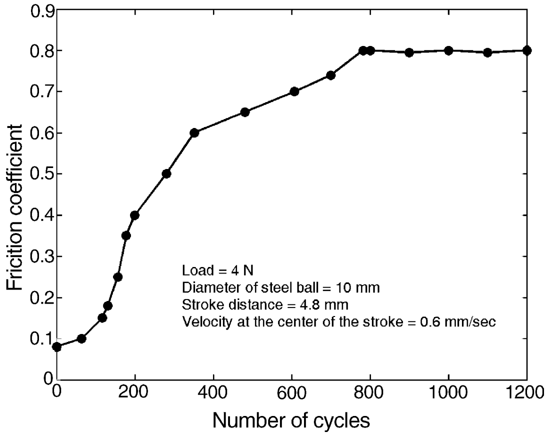


Fig. 12. Friction coefficient of a stainless steel plate against a stainless steel ball in reciprocating motion.

of rubber coating revealed a similar result: the coating life is shorter as the displacement amplitude is increased. The difference between their metallic and our rubber contact can be explained by noting that in [24], the fretting involved metallic contacts where the initiation of the wear scars started at the contact end points whereas rubber wear started at the center of the stroke as shown in Fig. 11. When a rubber coating is adopted in the contact, the region of the maximum friction force varies from the middle of the stroke to the end of the contact as the number of cycle increases because rubber contact occurs in the beginning and metallic contact occurs after the rubber coating is fully worn out. This relieves stress concentration on the contact.

The friction coefficient of the rubber coating is also less than the metallic contact as the number of cycles increases. An example of measured friction coefficient of metal against metal is shown in Fig. 12. The stainless steel ball slides on a stainless steel plate, and the friction coefficient increases rapidly as the number of cycles increases [4,9,13]. It reaches 0.8 after about 800 cycles in Fig. 12 but it reaches only 0.23 after 1200 cycles under the same operating condition as shown in Fig. 4. Therefore, it can be concluded that a rubber coating can protect the contact and prevent fretting failure.

5. Concluding remarks

The friction characteristics of a rubber coating were investigated, particularly as related to fretting. The focus of this paper was on the relationship between rubber friction and pertinent operating parameters such as the load, velocity and displacement amplitude. It was found that the friction coefficient of the rubber coating decreases as the load increases and increases as the velocity increases. However, the friction coefficient was found to be relatively insensitive to change of the displacement amplitude.

The rubber coating life is related to running conditions, i.e. the load, the velocity and the displacement amplitude. The humidity and temperature may also play a role, but these factors were not considered in the present study as they were held constant. It is found that the rubber coating life decreases significantly as load is increased and as the displacement amplitude is longer. However, the coating life was found to be very short when the system undergoes oscillatory motion in a low velocity regime. Even though the friction coefficient may be low, the wear of rubber seems to be related to the total running time at low velocity and to be related to associated adhesion.

The friction force of the rubber coating is less than that of the metallic contact and the maximum friction force of the rubber coating is in the middle of the stroke but that of metallic contact is at the contact end at the end of the stroke. This can protect the contact and increase the life of a machine when operating in an environment susceptible to fretting.

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