Tribo-electrification mechanism for self-mated metals in dry severe wear process
Part I. pure hard metals
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Abstract
The tribo-electrification and wear behavior are investigated for self-mated pure hard metal pairs of Pt, Fe, Mo, Ti and W in dry severe wear process. Results show that the tribo-electrification of pin specimen appears to have much higher possibility of positive charge with higher wear loss at pin specimen by using Pt/Pt, Fe/Fe, and Mo/Mo pairs, but it becomes to have much higher possibility of negative charge with higher wear loss at plate specimen by using Ti/Ti and W/W pairs. It is found from the SEM observations on the wear surface and wear particle that the wear for those hard metal pairs is mainly caused by the asperity removal with small wear particle. According to these results, a model for tribo-electrification mechanism is proposed. Generally, the material transfer for the self-mated hard metals mainly causes the tribo-electrification. When the material transfers from pin specimen to plate specimen, the polarity of tribo-electrification for pin specimen becomes positive, and vice versa.

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1. Introduction
When the opposing bearing surfaces slide against each other under a normal load, they generally exhibit the charge transfer between them. This phenomenon is called the frictional electrification or the tribo-electrification. The direction of the charge transfer determines the polarity of the contact surfaces. The tribo-electrification is generally associated with the electric conductivity of the material, so that the tribo-electrification has been classified into three groups: metal-metal, metal-insulator, and insulator-insulator [1].

With regard to the study of the insulator-insulator contacts, Sasaki [2] found that the tribo-electrification accelerated the adhesion and lodging of wear particles on the friction interfacial surface, which resulted in wear-decreasing effect for ceramics. Nakayama and Hashimoto [3–5] investigated the tribo-emission mechanism of charged particle from insulating ceramic materials in various gas atmospheres. It was found that the gas pressure and the gas type influenced the emission intensity of charged particles, but they did not affect the friction coefficient. They also thought that the polymer-like deposits stuck strongly to the surface and reduced the friction and wear of aluminum oxide ball at the n-butane gas pressure [6].

With regard to the study of metal-insulator contacts, Nakayama and co-workers [7–9] investigated the tribo-emission phenomenon of charged particles for various materials during the frictional damage. Results showed that emission intensity increased with increasing the electric resistivity of the materials. Hence, the emission intensity for the metal–metal contacts should approach to zero. Negatively charged particles were emitted much more intensively in conductor, while both negatively and positively charged particles were emitted in insulator. The friction coefficient was dependent on the tribo-emission intensity. Cunningham [10] found that the amount of charge generated increases with increasing slip ratio and belt tension. He thought the frictional heating between the bell and the roller caused this amount of charge. Ohara and co-workers [11,12] investigated the effect of thin film deposited by various methods on the frictional electrification. They found that the molecular orientation in surfaces and the number of molecules per unit area determine the polarity and magnitude of the frictional electrification charges. Peterson [13,14] studied the contact charging between insulator and metals. He thought that the contact charging depends only upon the nature and surface conductivity of the materials in contact.
Wagner [15] found that the insulator has a higher effective work function than metal, so it accepts electrons from them when put into contact. Therefore, the tribo-electrification for insulator-insulator contacts or metal-insulator contacts includes frictional electrification, contact electrification, and emission of charged particles. The tribo-electrification phenomenon is quite complex.

With sliding contact between the metal and the metal, the frictional heat generated on the surfaces would give rise to the difference of temperature between the surfaces. This would generate a Seebeck potential across the surfaces. This is called the charging by a Seebeck effect. When the surfaces are separated, some of the charge generated leaks back by tunnel effect so that the charge is partially self-neutralized, but some of the charge remains. This tunnel effect leakage fades out at a certain critical separation [16]. This charging is called the separating charging. Harper [16] thought that whether the sliding is smooth sliding or adherent sliding, the material transfer always occurs. This material transfer also may cause the charging. It has been known that the contact between two metals can be approximated as a single contact and the multiple contacts [17]. Generally, for the softer metal sliding upon itself, contact of two very smooth surfaces may be approximated as a single contact at a certain load. For the self-mated harder metals under low contact-stress conditions, multi-asperity contacts occur. The average size of adherent fragments formed during sliding for the self-mated hard metals is smaller than that for the self-mated soft metals [18]. Moreover, since the oxide formation significantly influences the transition between mild and severe wear [19], the surface reactivity of the specimen significantly influences the mechanism of tribo-charging in the process of mild wear.

As mentioned above, the frictional electrification for the metal-metal contacts is a very complex phenomenon. The experiments are conducted for the self-mated pure metals under the complete contact conditions. Hence, the Seebeck effect for dissimilar metals and the charging due to the separation can be neglected in this study. Generally, high friction and severe wear are found when the two sliding surfaces consist of the same metal [18]. Under the severe wear condition, the effect of the surface film (such as oxide and nitride) on the tribo-electrification mechanism can be neglected due to the formation of the fresh surface in the process of severe wear. To clarify the effect of the wear mechanism on the tribo-electrification mechanism, only the process of severe wear is considered in this paper. Furthermore, the wear mechanism for the softer metal is different from the harder metal pairs. In this part, therefore, the harder metal pairs (larger than 1700 N/mm² of hardness) are prepared to investigate its effect on the tribo-electrification. According to the SEM observations on the wear particles and the worn surfaces, with the friction coefficient and the wear loss, the wear mechanism for the self-mated hard metals is investigated. The relationship between the tribo-electrification and the wear mechanism is also studied.

2. Experimental apparatus and procedures

2.1. Experimental apparatus

The experiments are conducted on a reciprocating friction tester with a measuring system shown in Fig. 1. A crank-slider mechanism is used in this reciprocating friction tester. The pin specimen is fixed to the carriage, which slides along a V type roller bearing. Hence, the pin specimen reciprocates and its stroke can be adjusted by the length of the crank. The stationary plate specimen is placed on a rest, which is supported by a V type roller bearing. This rest is connected with the load cell. Consequently, the friction coefficient between the pin and plate specimens can be measured easily. Moreover, in order to measure the tribo-electrification, the pin and plate specimens are also isolated respectively. Part of experimental setup is covered in a metal cage to avoid the interruption of external induced electricity. A normal load is applied to the pin specimen through

![Fig. 1. Schematic diagram of reciprocating friction tester with a measuring system.](image-url)
plate specimen by using the level rule. Furthermore, in order to avoid the impact effect and to remain the complete contact between the specimens during the friction process, a softer spring \((k = 0.17 \text{ N/mm})\) with an oil damper \((c = 1.04 \text{ Ns/m})\) is employed in the loading system [20,21].

In Fig. 1, the generated electric potential between the specimens during the reciprocating friction process is in the order of \(\mu\text{V}\). Hence, two dc isolation amplifiers in series are used to provide high gain (50,000). The response time is less than 1 ms with the accuracy of 0.1% full scale. Generally, the interference from the power supply is obvious at 60Hz, so an FFT algorithm with low-pass filter is used to filter the high-frequency noise. The frequency larger than 50Hz has been cut-off. During the reciprocating friction process, a load cell can measure the friction coefficient. The voltage signals of tribo-electrification and friction coefficient are input to the data acquisition system and fed to a personal computer for data analysis. Using the apparatus used to measure the contact resistance can monitor the contact condition.

2.2. Test specimens

Five pure metals are selected as the specimen materials, which are listed in the order of their surface hardness magnitude: platinum (Pt), ferrous (Fe), molybdenum (Mo), titanium (Ti), and tungsten (W). Material properties are given in Table 1. In this study, the materials should have hardness larger than 1700 N/mm². The size and the shape of the pin and plate specimens are shown in Fig. 2. However, since the platinum is very expensive, its size and shape are shown in Fig. 2b. Corner radii for all pin specimens are selected as 0.3 mm to avoid the effect of attack angle [22,23]. The pin and plate specimens are sequentially polished by 600, 800, and 1000 grade emery papers. The surface roughness, \(R_a\), is measured as 0.05–0.08 \(\mu\text{m}\) for the specimens before the friction test.

2.3. Experimental procedure

Before the test the specimens are cleaned with acetone in an ultrasonic cleaner. Then the specimens are placed and locked tightly in the tester. The location and tightness between the pin and plate interface must be adjusted accurately. When the crank rotates clockwise at a certain speed, the pin specimen reciprocates, and then a certain of normal load are applied to the pin and plate interface. In this study, the stroke of crank-slider mechanism is set to 7 mm, the normal load is 30 N, and the reciprocating speed is 120 cpn (or the maximum speed of the pin specimen \(V_{\text{max}} = 50 \text{ mm/s}\)). The friction test time is 20s. After friction test, the wear loss is measured by using the precision balance, and the wear surface with its wear particles is observed by using the SEM. Experiments were carried out under dry friction condition. The average room temperature for the test was about 25 °C, and the average relative humidity was about 72%.

3. Experimental results and discussion

3.1. Variation of tribo-electrification and friction coefficient

When the reciprocating speed is adjusted to a certain of value, a certain value of normal load is applied to the pin and plate specimens interface, as shown in Fig. 1. The relative motion occurs between the pin and plate specimens, which results in the friction and wear with tribo-electrification generated from the friction surface. In this study, the variation of tribo-electrification can be obtained by measuring the electric potential difference between the specimens. Fig. 3 shows

<table>
<thead>
<tr>
<th>Properties of pure hard metals</th>
<th>Pt</th>
<th>Fe</th>
<th>Mo</th>
<th>Ti</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vicker’s surface hardness, (\rho) (N/mm²)</td>
<td>1700</td>
<td>2050</td>
<td>2600</td>
<td>3290</td>
<td>4350</td>
</tr>
<tr>
<td>Electric resistivity, (\rho) ((\mu\Omega\text{cm})</td>
<td>10.6</td>
<td>9.7</td>
<td>9</td>
<td>5</td>
<td>5.3</td>
</tr>
<tr>
<td>Surface energy, (\gamma) (erg/cm²)</td>
<td>1800</td>
<td>1500</td>
<td>1800</td>
<td>1200</td>
<td>2300</td>
</tr>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>71.1</td>
<td>74</td>
<td>142</td>
<td>17</td>
<td>166</td>
</tr>
<tr>
<td>Crystal structure</td>
<td>fcc</td>
<td>bcc</td>
<td>hcp</td>
<td>hcp</td>
<td>hcp</td>
</tr>
</tbody>
</table>

![Fig. 2. Size and shape of specimens: (a) hard metal pairs for Fe, Mo, Ti, and W; (b) noble metal pair for Pt.](image-url)
Fig. 3. Tribo-electrification voltage, friction coefficient, and contact resistance responses for Fe/Fe at the load of 30 N and the reciprocating speed of 120 cpm.

the typical changes of the voltage of tribo-electrification, the friction coefficient, and the contact resistance with sliding time produced by iron on iron pair under a normal load of 30 N and a reciprocating speed of 120 cpm. It is seen from this figure that at the first second, the contact resistance rapidly decreases to a certain value, the friction coefficient gradually increases, and the tribo-electrification is almost kept zero. This indicates that the pin specimen is ready to contact and to slide with plate specimen at the first second. After the first second, the voltage of tribo-electrification generated by friction is almost independent of the direction of the reciprocating motion, and it is not accumulated with sliding time. This voltage of tribo-electrification is not always positive, and sometimes it becomes negative repeatedly. This negative voltage is always very small, and less than the positive voltage. The amplitude of friction coefficient is in the range from 0.6 to 1.0. The rapid change of the friction coefficient with sliding time indicates the formation of wear debris [24]. Furthermore, the contact resistance is kept at a certain value. Hence, it is seen from Fig. 3 that the friction condition is at the running-in period, and the specimen is in contact with each other completely [19].

To clearly understand the voltage of tribo-electrification for five self-mated metals, the experiments are conducted under the same experimental conditions as Fig. 3. The typical results are shown in Figs. 4 and 5 for the voltage of tribo-electrification and the friction coefficient, respectively. In these two figures, the results are presented in the order of their surface hardness magnitude, i.e., platinum (Pt), ferrous (Fe), molybdenum (Mo), titanium (Ti), and tungsten (W). It is seen from Fig. 4 that although the voltage of tribo-electrification for various material pairs appears to have positive and negative values, their distributions on the negative value have significant difference. It is found that the possibility of positive voltage is much higher than that of negative voltage for Pt/Pt pair. The possibility of negative voltage gradually increases for Fe/Fe and Mo/Mo pairs. On the whole, the tribo-electrification of Pt/Pt, Fe/Fe, and Mo/Mo pairs appears to have more than 90% possibility of positive voltage, but the possibility of positive voltage for Ti/Ti pair is less than 50%. It is also found that it is hard to generate a positive voltage for W/W pair. Consequently, the possibility of negative voltage during the tribo-friction increases with increasing surface hardness or decreasing ductility. Especially for the brittle material of W/W pair, the voltage generated from the tribo-electrification is almost negative.

Fig. 5 shows the variations of friction coefficient for the five kinds of metals under normal load of 30 N and reciprocating speed of 120 cpm with sliding time of 20 s. It is seen from this figure that the friction coefficient versus time is quite different for various material pairs. The amplitude of the friction coefficient is about 1.0–1.3 for Pt/Pt pair. For Fe/Fe and Mo/Mo pairs, the amplitude of the friction coefficient is in the range of 0.6–1.0. With increasing surface hardness, the amplitude of the friction coefficient decreases to a small value of about 0.3 for W/W pair. It is also seen from this figure that the friction coefficient appears to be gradual and stable for W/W pair, but it varies with time seriously for the other four material pairs. These results can be reasonably explanation by observing the SEM micrographs of wear surface and wear particle in Section 3.3.

In order to further understand the relationship between the tribo-electrification and the friction coefficient, the
amplitude of the tribo-electrification shown in Fig. 4 and the amplitude of the friction coefficient shown in Fig. 5 are plotted in Fig. 6. It is seen from this figure that the correlation between the voltage of tribo-electrification and the friction coefficient is not obvious. The electric resistivity, surface hardness, and surface energy of the material significantly influence this tribo-electrification. It is very obvious that the voltage of tribo-electrification for Ti/Ti pair is much higher than that of the other materials due to its higher electric resistivity. Under this higher electric resistivity, the charge is not easy to conduct out the conductor and then loses its charge. As a result, the electric potential of tribo-electrification is increased.

3.2. Wear loss

Fig. 7 shows the wear losses of the pin and plate specimens for the five kinds of metals under normal load of 30 N and reciprocating speed of 120 cpm with sliding time of 20 s. It is seen from this figure that the wear losses of the pin and plate specimens for Pt/Pt, Fe/Fe, and Mo/Mo pairs are much higher than those of Ti/Ti and W/W pairs due to the effect of surface hardness. Except the Mo/Mo pair, the wear loss decreases with increasing surface hardness of the material. This result can be reasonably explained by the Holm’s adhesive wear theory. It is also seen from this figure that the wear loss of pin specimen is larger than that of plate
specimen for Pt/Pt, Fe/Fe, and Mo/Mo pairs, but it is just opposite for Ti/Ti and W/W pairs.

3.3. SEM observation of wear surface and wear particle

As mentioned above, when the wear occurs on the surface of the pin and plate specimens, the tribo-electrification, the friction coefficient, and the wear loss are quite different for various self-mated material pairs. In order to explain this complex phenomenon, the types of wear surface and wear particle are observed by using the SEM, as shown in Fig. 8. It is seen from Fig. 8a that the wear surface for Pt/Pt pair appears a local projection with wear track. Consequently, large wear particles tend to be produced during the friction test. It is seen from Fig. 8b and c that a local projection is also observed on the wear surface of Fe/Fe and Mo/Mo pairs. Their size of wear particle is in the range from smaller than several millimetres to hundreds \( \mu \text{m} \). It is obvious that most of the wear particles belong to the small or powdery wear particles smaller than several \( \mu \text{m} \). It is believed that few large wear particles result from the junction growth, and the small or powdery wear particles are caused by the asperity removal during the friction test. However, the wear track for Fe/Fe pair is longer and straight, but for Mo/Mo pair is irregular. It is seen from Fig. 8d that the wear surface of Ti/Ti pair is quite flat with some small residual particles. The wear particle is in the range from tens \( \mu \text{m} \) to hundreds \( \mu \text{m} \). It is seen from Fig. 8e that the wear surface of W/W pair is very smooth with numerous powdery wear particles. Most of the wear particles are almost the powdery particle. In these two figures, it indicates that the large wear particles for Ti/Ti
As stated above, two principal modes of adhesive wear can be identified in this study as asperity removal and junction growth. For the junction growth, the real area of contact grows and the friction coefficient also increases steadily under the constant normal load, as shown in Fig. 5 for Pt/Pt and Ti/Ti pairs. The growth of contact area results in large wear particle. On the other hand, the asperity removal results in powdery wear particle with smaller friction coefficient for W/W pair.

### 3.4. Mechanism of tribo-electrification for hard metals

Over the past few decades, there have been many researches about material transfer between the two specimens of a sliding pair. Kerridge [25] studied severe wear of a radioactive annealed steel pin against a hardened steel ring. Results showed that wear debris particles were formed entirely from the transferred layer on the opposing specimen. Kayaba and Kato [26] investigated the adhesive transfer mechanism of self-mated steel pair by successive observation in the SEM. Results showed that two modes of adhesive transfer were identified: namely, the slip-tongue and the wedge. In those studies, it was found that the formation of wear particles or wear loss is correlated with the material transfer.

As discussed above, the possibility of positive charge for pin specimen is higher by using Pt/Pt, Fe/Fe, and Mo/Mo pairs, because the wear loss of pin specimen is larger than that of plate specimen. This indicates that the material transfers from pin to plate. On the other hand, the possibility of negative charge for pin specimen is higher by using Ti/Ti, and W/W pairs, because the wear loss of pin specimen is less than that of plate specimen. This indicates that the material transfers from plate to pin specimens is obvious. To investigate the effect of the material transfer on the polarity of the tribo-electrification, an additional friction test is conducted under the same experimental conditions as Fig. 3 for the pure iron rubbing against the 0.7% C steel, as shown in Figs. 9 and 10. It is seen from Fig. 9 that the polarity of tribo-electrification for pin specimen is almost positive by using the iron pin against steel plate, but it becomes negative by using the steel pin against iron plate. It is also seen from Fig. 10 that the wear loss for iron is much larger than that for steel in spite of iron/steel or steel/iron pair. This indicates that the material transfers from iron to steel. Hence, the positive polarity of tribo-electrification for pin specimen is caused by the material transfer from iron pin to steel plate. Moreover, the negative polarity of tribo-electrification for pin specimen is also due to the material transfer from iron plate to steel pin. Consequently, the polarity of tribo-electrification for conductor/conductor pair can be used to identify the direction of material transfer. In addition, since both sliding surfaces are metallic in this study, the high electrical conductivity erases the effect of past charging [16]. However, the wear loss indicates the total amount during the sliding time. Consequently, it is hard to...
appear the correlation between the wear loss and the tribo-electrification. By combining the results shown above, a new model of tribo-electrification mechanism is proposed, as shown in Fig. 11. It is seen from this figure that when the asperity is broken off due to the strong adhesion, this wear debris will adhere to the opposing specimen. Since the free electrons are excited during the material transfer, the wear debris usually has negative electricity. As a result, when a specimen losses the wear debris, it would have positive electricity. Hence, it is seen from Fig. 11a that when the material transfers from pin to plate, the polarity of tribo-electrification for pin specimen becomes positive. This can be used to explain the results by using the friction tests of Pt/Pt, Fe/Fe, and Mo/Mo pairs. Similarly, it is seen from Fig. 11b that as the material transfers from plate to pin, the polarity of tribo-electrification for pin specimen is negative, something like the friction tests of Ti/Ti and W/W pairs. Moreover,
Fig. 9. Tribo-electrification voltage responses for pure iron rubbing against 0.7% C steel at the load of 30 N and the reciprocating speed of 120 cpm.

Fig. 10. Wear loss for pure iron rubbing against 0.7% C steel at the load of 30 N and the reciprocating speed of 120 cpm during friction test of 20 s.

when the asperity is removed, the contact point, which supports the normal load, moves to another asperity instantaneously. Hence, the variation of tribo-electrification with the sliding time appears to be very serious.

It is seen from Fig. 11 that the material transfer is the main source of charging. By using this model, the voltage of tribo-electrification shown in Fig. 4 can be used to explain the metal transfer. For example, the tribo-electrification is negative with very small amplitude at 1–2 s by using Pt/Pt pair. This indicates small amount of material transfers from plate to pin. At 4–6 s, this tribo-electrification becomes positive with larger amplitude, which indicates larger amount of material transfer from pin to plate.

4. Conclusions

In this study, the tribo-electrification and wear behavior are investigated for five kinds of self-mated pure metal pairs of Pt, Fe, Mo, Ti and W in dry severe wear process. The materials have hardness larger than 1700 N/mm² in this paper, hence called hard metals. From the experimental results of friction test with the SEM observations on the wear surface and wear particle, the following conclusions can be obtained:

1. The tribo-electrification appears to have much higher possibility of positive voltage with higher wear loss at pin specimen by using Pt/Pt, Fe/Fe, and Mo/Mo pairs. However, it becomes to have much higher possibility of negative voltage with higher wear loss at plate specimen by using Ti/Ti and W/W pairs.
2. The wear for all the self-mated metal pairs is mainly caused by the asperity removal with small wear particle.
3. A model for the tribo-electrification mechanism is proposed. The material transfer for the hard self-mated metals causes the tribo-electrification. When the material transfers from pin specimen to plate specimen, the polarity of tribo-electrification for pin specimen becomes positive, and vice versa.
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