# *The sensitivity of using tribo-electrification responses for monitoring the tribological properties between a thin film of tin*

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***Abstract*—The traditional method of using the continuous variation of the friction coefficient with sliding distance to monitor the tribological properties between the contacts of soft metal films is generally low in sensitivity. This paper proposed the novel method of using instead the continuous variation of tribo-electrification voltage. This method was investigated experimentally for the dry friction sliding of iron on copper coated with a thin film of tin and was shown to be much superior to the traditional method in terms of sensitivity. The method has the added advantage of the ability to assess the solid to film lubrication of the soft metal film. Finally, a continuous model to represent the wear mechanisms for iron sliding against copper coated with a thin film of tin was proposed.**

***Keywords- tribo-electrification, sensitivity, tin film, surface slip***

## I. INTRODUCTION

One of the most efficient means of resisting wear or reducing friction during contact is surface coating. The type of coating material and its range of applications are vast. Amongst them is hard metal coating [1], which essentially means replacing the original surface with a new more durable one, and soft metal coating [2], which reduces the friction coefficient on the contacting surface albeit having a low tear resistance. Most surface coating researches focused on investigating the coating techniques and analyzing the wear-resistance or friction coefficient of the coated surface. Amongst them, however, reports on simultaneously studying the surface coating and the dynamic film lubrication was scarce [3]. Other relevant studies [4] proposed continuous measuring and recording of the friction force during a wear test. This not only provided numerical values for the friction coefficient, but also allowed any changes in the sliding behavior to be monitored.

However, the author observes that in many continuous friction tests, changes in the friction coefficient become increasingly less distinct. In view of this, it is necessary to introduce more improved physical measurements other than the friction coefficient to monitor the film lubrication characteristics in sliding metal contact. Since the authors had experimentally studied the tribo-electrification mechanisms in-depth [5-7], the knowledge is applied and adapted to the study of using tribo-electrification responses for monitoring the tribological properties of the thin tin film contact in this paper. Therefore, the objective of this paper is to develop a novel method with high sensitivity for the continuous monitoring of the tribological properties between the soft metal film contacts.

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## II. EXPERIMENTAL APPARATUS AND PROCEDURES

### *A. Experimental apparatus*

The experiments were to assess the feasibility of the proposed method, and to clarify the responses of tribo-electrification and friction coefficient during the film-breakdown period. The experiments were conducted on a reciprocating friction tester using the crank-slider mechanism with a measuring system as shown in Fig. 1.

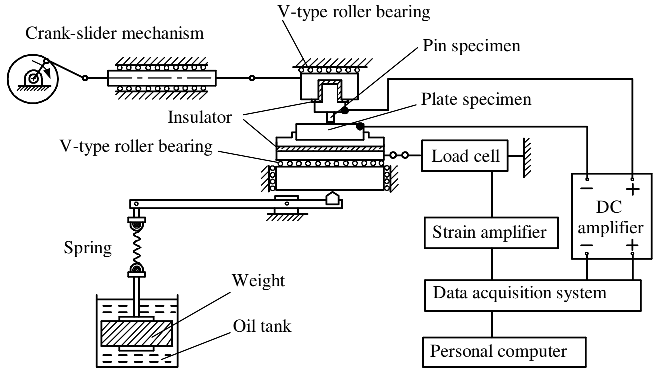



Figure 1. The friction tester with a measuring system

### *B. Test specimens*

The thickness of the coating was about 10 μm. Fe was selected as the material for the pin. The pin and plate specimens are shown in Fig. 2. The Fe/Sn pair is incompatible and the Sn/Cu pair is partially compatible. Therefore, the energy of adhesion for the Sn/Cu pair is distinctively larger than that for the Fe/Sn pair. The iron pin was sequentially polished by emery papers to a surface roughness, Ra, in the range 0.05–0.1 μm before each test.

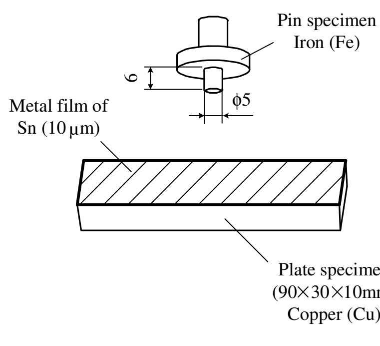


Figure 2. Size and shape of the specimens

*C. Experimental procedures*

Prior to each friction test the specimens were cleaned with acetone in an ultrasonic cleaner and securely locked in position in the tester. When the crank rotated clockwise at a set speed of 150cpm, a normal load was applied to the interface of the specimens. In this study, the stroke of the crank-slider mechanism was set as 7 mm. The normal load was varied from 20 N to 100 N at an increment of 20 N.

The virgin SEM topography of the Sn-film on Cu surface is shown in Fig. 3. As the generated electric potential between the specimens during the reciprocating friction process was in the order of μV, two DC isolated amplifiers in series were used at a high gain of 50,000. All tests were carried out under dry friction condition. The room temperature for the test was 25 ± 2 °C, and the relative humidity was 65 ± 5%.

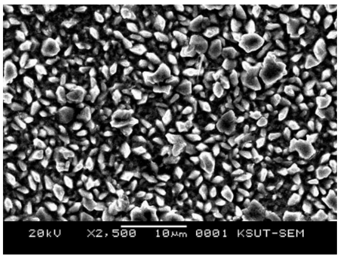



Figure 3. The SEM topography of Sn-film on Cu surface

## III. RESULTS AND DISCUSSIONS

### 3.1 Responses of tribo-electrification and friction coefficient for the pure metal pairs

Figures 4-6 show the typical responses of Fe/Sn, Sn/Cu and Fe/Cu, respectively, under a normal load of 20 N.

It is seen from Fig. 4 that the tribo-electrification is nearly zero at initial contact, but increases due to friction with sliding distance. Beyond a sliding distance of 50 mm, this voltage approaches a saturated negative value of –8 μV. The friction coefficient is relatively small. Moreover, both variations appear to be stable. One plausible explanation is the incompatibility of the Fe/Sn pair.

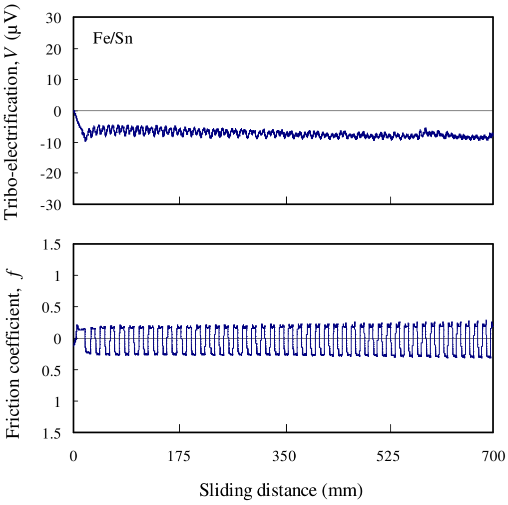



Figure 4. The responses of tribo-electrification voltage and friction coefficient for the Fe/Sn pair

In the case of the Sn/Cu pair shown in Fig. 5, the tribo-electrification increases from zero to a saturated negative value with slightly higher oscillation amplitude that is deemed unstable. The saturated tribo-electrification is very small at about –1μV and the corresponding friction coefficient is unstable and slightly higher than the previous case. The nature of the response could be attributed to the partial compatibility of the Sn/Cu pair.

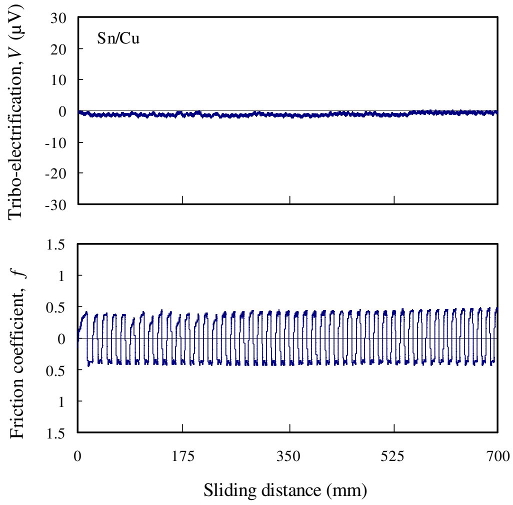



Figure 5. The responses of tribo-electrification voltage and friction coefficient for the Sn/Cu pair

In the case of the Fe/Cu shown in Fig. 6, the tribo-electrification increases from zero to a saturated positive value of between +2 ~ +7 μV with the largest oscillation amplitude. The corresponding friction coefficient is also large with amplitudes of between 0.55 and 0.8. The response is described as an unstable periodic function for both the tribo-electrification and friction coefficient variations, due possibly by the partial compatibility of the Fe/Cu pair.

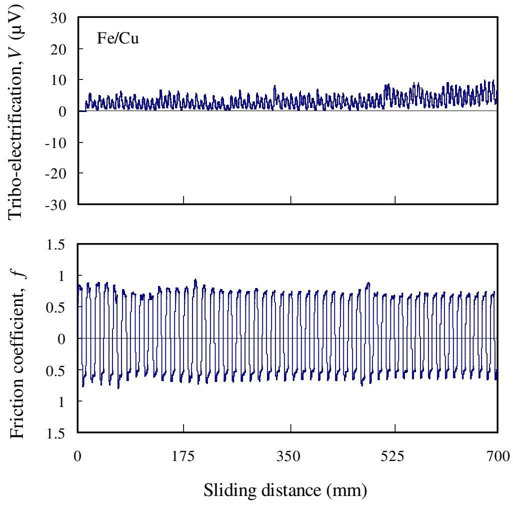
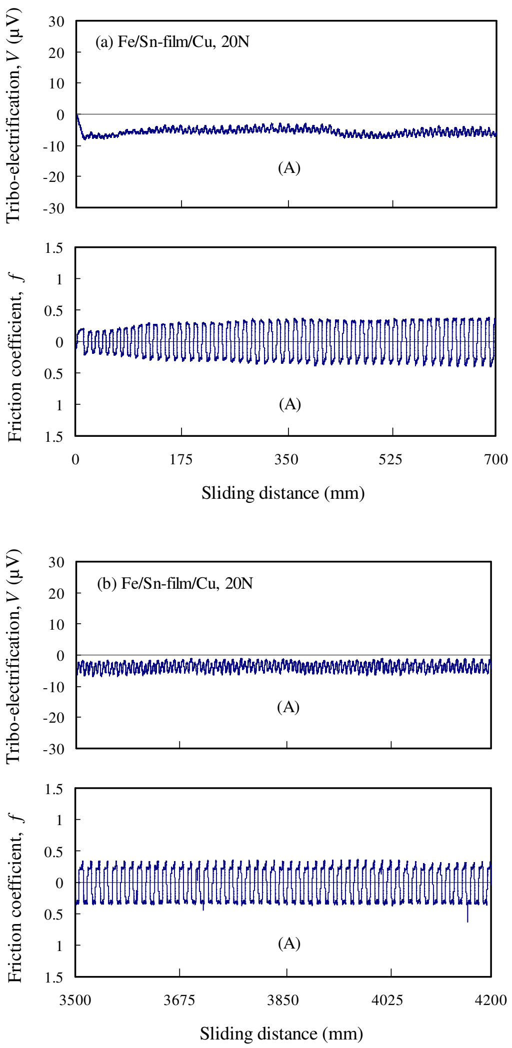



Figure 6. The responses of tribo-electrification voltage and friction coefficient for the Fe/Cu pair

### 3.2 Responses of tribo-electrification and friction coefficient for monitoring the tribological properties between the tin film

Typical variations of the tribo-electrification and the friction coefficient with sliding distance produced by the Fe/Cu pair with a 10μm film of tin metal (abbreviated as Fe/Sn-film/Cu) under 20 N are shown in Fig. 7(a)-(d). It is seen from this figure that the variations of tribo-electrification can be classified into three regions: Region A with negative polarity, Region B, the transitional region with random polarity and Region C with positive polarity. The range of the variations, however are different in each case as is the sliding distance range. While the variation in friction coefficient between the metals is comparatively high at the running-in period, the variation stabilizes thereafter and eventually oscillates with small amplitudes during the initial friction cycles. This can be reasonable explained by the solid-film lubrication mechanism as proposed [4]. It is also evident that in all cases, the variations of friction coefficient only increase slightly with increasing sliding distance during the initial friction cycles, making it very difficult to distinguish the above three regions.



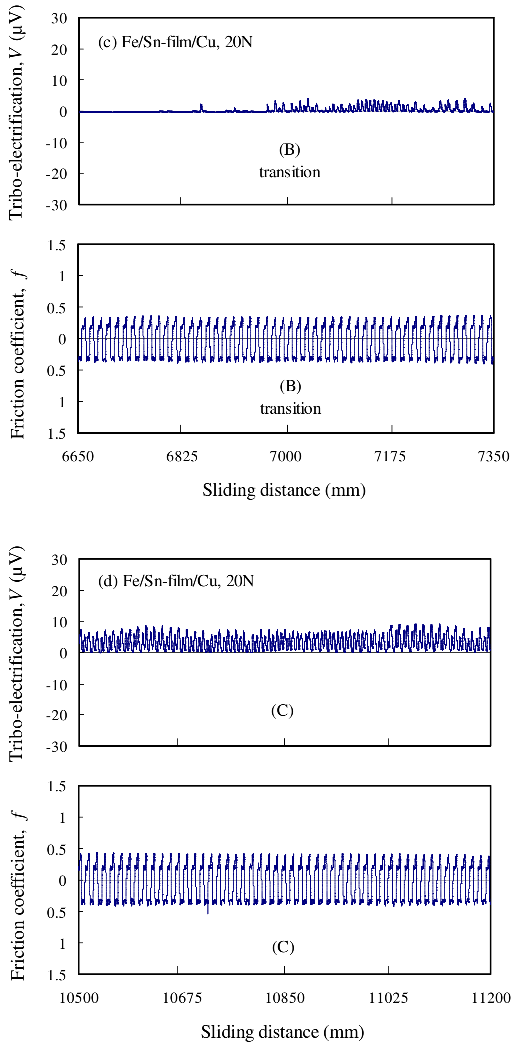




Figure 7. The responses of tribo-electrification voltage and friction coefficient for Fe/Sn-film/Cu during (a) 0-700mm, (b) 3500-4200mm, (c) 6650-7350mm, (d) 10500-11200mm.

The above results demonstrate the superior sensitivity properties of the tribo-electrification variations for monitoring the tribological properties between the soft metal films over the variations of friction coefficient. This is further verified from the SEM observations detailed in the following sections.

### 3.3 SEM observation of worn surface

To investigate the continuous wear mechanisms, the typical SEM micrographs on the boundary of the wear track of the Fe/Sn-film/Cu set-up under a friction test of 1000mm are shown in Fig. 8. It is evident from this figure that the tin film is not completely destroyed in the friction test and that surface slip is present at the surface of the tin film. This indicates that the strong adhesion between the tin film and the copper substrate has induced sliding to occur between the surface of the film and the slider. Moreover, the film surface appears to be flattened, as tin is relatively soft. In contrast, the typical wear track, shown in Fig. 8(b), does not show a completely flattened surface but regions of unworn tin particle residue, indicative that under this loading, the tin film provided low friction and solid lubrication.

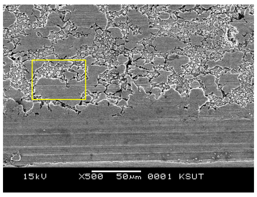
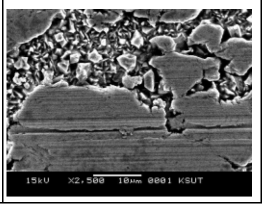
| 20N | (a) × 500 | (b) × 2500 |
|---|---|---|
| Wear track |  |  |

Figure 8. SEM micrographs on the boundary of wear track

### 3.4 Wear mechanisms with tin-film solid lubrication

A fact worth emphasising is that the above-mentioned Regions A, B and C are distinguished mainly from the variations of tribo-electrification voltage and not from the less distinctive variations in friction coefficient. It follows therefore that using the continuous variations of tribo-electrification voltage in real time to investigate the characteristics of film lubrication has great potential for development. The above results can also be used to analyze the effect of normal load on the tribological properties of iron sliding against copper coated by 10μm film of tin metal as shown in Fig. 9. The results can be used as a guideline in engineering design to estimate the lifespan of solid lubrication made of soft metal films. In the previous series of tests, only a film thickness of 10μm was considered but this may be an important factor affecting the lubrication characteristics between pure metal pairs. It is suggested that further work to be carried out to establish the relationships between the normal load and film thickness and the sliding distance.

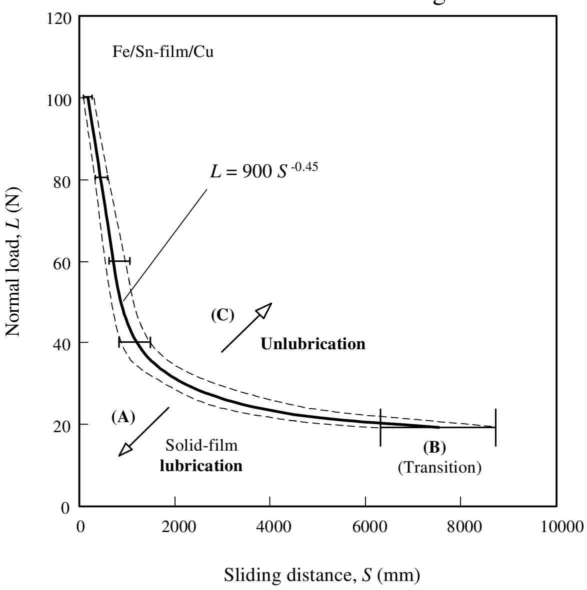



Figure 9. The lifespan of solid lubrication

*IV. Conclusions*

In this study, the feasibility of using continuous tribo-electrification variations for monitoring the tribological properties between the metal films was investigated in dry friction process. This study has proven that in terms of conductive metallic material, the sensitivity of the continuous variations of tribo-electrification voltage to the dynamic tribological properties of the thin films was superior to that of the friction coefficient and has therefore more potential for further development.

From the experimental results and the SEM observations on the worn surface of the copper specimen coated with a thin film of tin, the following conclusions were drawn:

1. Responses of the tribo-electrification voltage were successfully applied to monitor the tribological properties between soft metal films and for appraising the solid-film lubrication of the soft metal films.

2. The novel method of using continuous tribo-electrification variations for monitoring the tribological properties between the soft metal films is more sensitive than that by the continuous friction coefficient variations as usual.

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