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Fretting Corrosion Behavior of Lubricated Electrical Contacts at Various Temperatures

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ABSTRACT

Fretting tests on electrical contacts were conducted to evaluate the effect of a lubricant on the lifetimes of tin-plated copper contacts. A series of fretting tests was conducted at 323K, 348K, and 373K with the lubricant. During the fretting tests, it was observed that the electrical contact resistance continuously increased and fluctuated with the fretting cycles due to oxide debris generated on the tin-plated copper contact. The fretting lifetimes of the electrical contacts increase as the fretting displacement amplitude and testing temperature decrease. Lubrication of the tin-plated copper contact was found to enhance the fretting lifetime of the contact, regardless of the testing temperature or displacement amplitude. SEM observations of fretting-damaged surfaces confirm that there was less oxide debris on the fretting-damaged surfaces when a lubricant was used, compared to the surfaces of samples tested without a lubricant

Key words: Electrical contact, Fretting corrosion, Electrical contact resistance, Fretting lifetime, Conductive lubricant

INTRODUCTION

In recent years, the application of advanced electronic control devices has been rapidly increasing in order to reduce harmful emissions and improve safety and convenience [1]. In the electronic control systems installed in automobiles, problems mainly occur at connector terminals rather than in the wiring. Mechanical vibration and thermal expansion and contraction cause micro-displacements between contact surface pairs in automobile connector terminals. When the contact surfaces have oscillatory displacement at a small sliding amplitude level, electrical insulating oxidation products are continuously generated at the contact surfaces and cause fretting corrosion [2]. In such a situation, distortion of the signal data values output from various electronic control sensors may occur. Contact failures in such a connector can sabotage the safe operation of a vehicle.

In recent years, products have been introduced and partially applied to extend the lifetimes of connectors by applying a conductive lubricant to automotive electrical connector terminals. However, few studies have examined whether the performance capabilities of these electrical contacts are improved by these the lubricants [3-7]. For example, Mottine and Reagor investigated the effects of lubrication on fretting corrosion at dissimilar metal interfaces in a socketed IC device [3]. They reported that the lubrication of metal contacts reduced or eliminated fretting corrosion in various contact configurations. They observed that lubrication effectively reduced both the amount and rate of fretting corrosion, while also dispersing the oxide debris that formed. Joule heating caused by electric current accelerates surface oxidation when electric current is applied in cases of low-frequency fretting on automotive electrical connector terminals, also leading to the electrical breakdown of oxide films [4]. In addition, lubricating the contact points ultimately improves the contact performance due to the retardation of the formation process of a corrosion film, reduced wear and improved debris dispersal away from the contact interface [4]. Narayanan et al. [5] reported that using a lubricant on tin-plated connectors was very effective and that the contact resistance was very stable at room temperature. At ambient temperatures, fretting wear was delayed in the initial stages while oxidation and the accumulation of wear debris and oxidation products were delayed in later stages, improving the performance of the contact. They observed only a marginal improvement in the performance at elevated temperatures. At elevated temperatures, the tin coating wore out more rapidly due to the decreased hardness and because the lubricant prevented oxidation, the accumulation of wear debris, and mitigated the formation of oxidation products in the contact zone. However, there are relatively few studies of quantitative performance improvements in terms of longer electrical contact lifetimes when a conductive lubricant is applied to connector contacts.

Therefore, in this study, we investigate the effect of a lubricant on the fretting corrosion behavior by applying a conductive lubricant to determine whether it improves the performance and extends the lifetimes of electrical connector terminals in the automobile field. For this purpose, the fretting corrosion processes of electrical contacts with and without a lubricant at various temperatures were investigated. The effects of the fretting displacement amplitude on the contact resistance behavior under various temperatures were also investigated. The goal of these investigations is to evaluate quantitatively any improvements in the fretting lifetimes of electrical contacts when a conductive lubricant is applied.

FRETTING TEST METHOD AND SPECIMENS

The electrical contact specimens used in the fretting tests were composed of copper alloy (Ni: 1.82%, Si: 0,75%, Zn: 0.01%, Sn: 0.37%, Cu: balance) of the type-widely used as connectors for signal transmission. The specimen thickness is 0.3 mm. The thickness of the tin plating layer is 10 μm. In order to realize a single contact point, the upper specimen was convex specimen and the lower specimen consisted of a flat plate. In order to make the radius of curvature of the convex specimen 1 mm, a ball bearing with a diameter of 2 mm was used as an indenter and 1 mm of displacement was applied vertically using a lower mold with a hole with a diameter of 2 mm.

In this study, we designed and built the system used for the fretting test. The experimental setup is shown in Fig. 1. The system is composed of a displacement generation system, a normal force measuring system, a system for transferring dead weight to the test specimen, and holders to fix the specimens. The constant current - resistance measurement method was used to measure the contact resistance of the specimen. In order to observe changes in the resistance during the fretting test, as shown in Fig. 2, constant current of 0.1 amps was applied to both ends of the connector, and in the diagonal direction, the voltage drop was measured using a multimeter, with Ohm's law applied. A detailed description of a test apparatus similar to that used here can be found in the literature [8].

Fretting tests were conducted at 323K, 348K and 373K while changing the fretting displacement amplitudes to 30 μm, 50 μm, and 77 μm under a constant contact load of 0.85 N. The sliding speed of the test specimen was very slow, on average 0.02 μm /s during the fretting test. The lubricant used in the test was the NyoGel 760G type created by Nye Lubricant, a synthetic type of hydrocarbon grease with medium viscosity typically used to improve the service lifetime and performance of electrical connectors. The fretting test was performed until the contact resistance reached a maximum of 0.1Ω. The fretted surfaces of the specimens tested with various conditions were observed by SEM. The surfaces damaged by fretting were analyzed by energy spectroscopy (EDS) installed on the SEM.

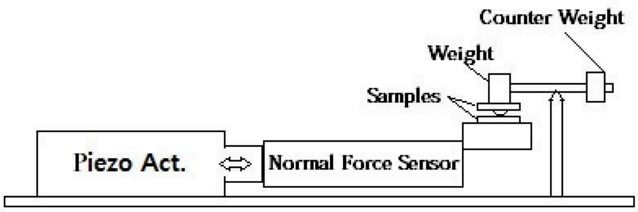


Fig. 1 Fretting test system

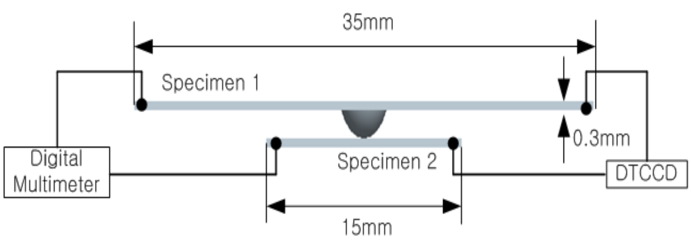


Fig. 2 Schematic of the contact resistance measurement method

RESULTS AND DISCUSSION

Changes in contact electrical resistance

Figs. 3(a), (b) and (c) show the changes in the electrical resistance per cycle at corresponding fretting amplitudes of 30 μm, 50 μm, and 77 μm at a temperature of 323K and under a contact load of 0.85 N. From Fig. 3(a), the contact resistance gradually increases to approximately 1600 cycles, after which, it increases sharply, increasing sharply again later. The contact resistance reaches a resistance level of 0.01Ω near 1850 cycles, after which, it increases sharply again after a slightly stable period. In Fig. 3(b), corresponding to a fretting amplitude of 50 mm, the contact resistance gradually increases to about 300 cycles. Past this, the resistance increases very quickly, reaching 0.01Ω near 310 cycles, and the contact resistance becomes very unstable after that. On the other hand, from Fig. 3(c), corresponding to a fretting amplitude of 77 µm, the contact resistance gradually increases to 140 cycles, similar to the fretting amplitude of 30 µm, and then slightly increases to 0.01Ω close to 190 cycles. After 200 cycles, it increases more rapidly and becomes unstable.

In these three cases, the period of the region where the contact resistance increases steadily shortens with an increment of the fretting displacement amplitude. Also, it can be seen that the number of cycles reaching 0.01Ω decreases as the fretting displacement amplitude increases. Figs. 3(a), (b) and (c) show that the initial electrical resistance of approximately 0.002Ω suddenly drops after a few cycles. This phenomenon appears to be due to the fracturing of the initial tin oxide layer. If the oxide layer existed at the initial phase of the fretting test, the electrical resistance will increase to a value corresponding to that of the tin oxide layer. Moreover, metal-to-metal contact points will form when the oxide layer is fractured due to fretting, reducing the contact resistance, as described in another study [9].

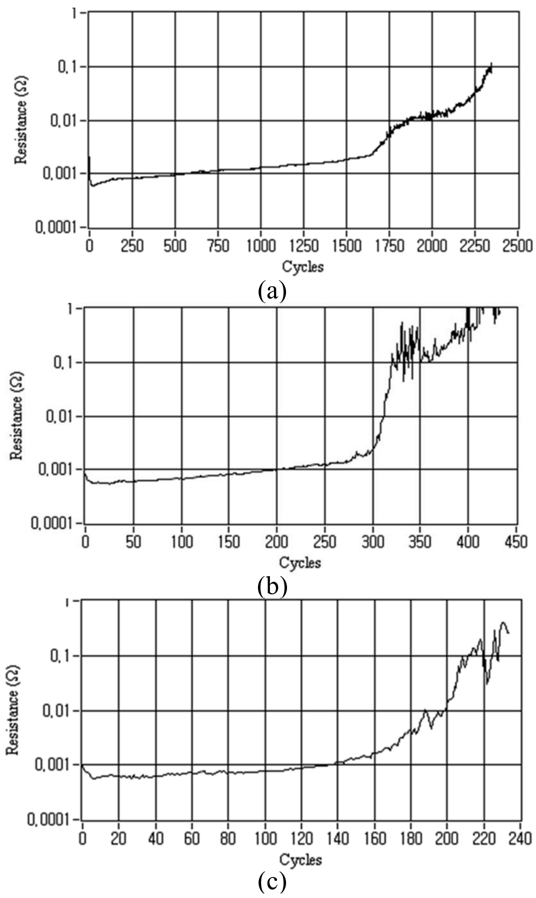
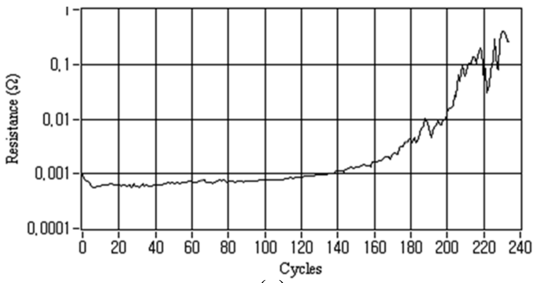
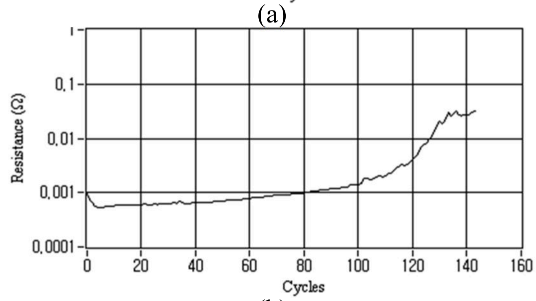


Fig. 3 Variation of the contact resistance with the fretting cycles at displacement amplitudes of (a) 30 µm, (b) 50 µm, and (c) 77 µm at 323K

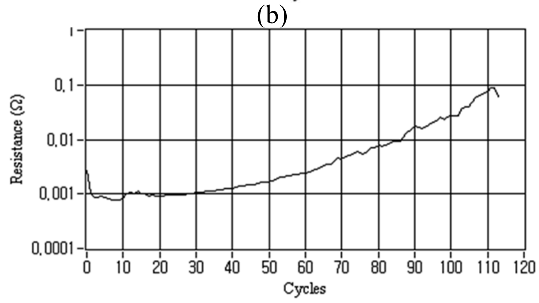
Figs. 4(a), (b) and (c) show the results at fretting amplitude of 77 µm for testing temperatures of 323K, 348K and 373K, respectively. The contact resistance behavior of tin-plated specimens tested without lubricant exhibits three characteristic steps of resistances, a first step with a relatively low and stable contact resistance value, a second step with a continuously increasing contact resistance value, and a third step with very unstable intermittently contact resistance [9]. From Figs. 4(a), (b), and (c), it can be seen that the contact resistance continued to increase as the number of fretting cycles increased without a distinction between the first, second, or third steps regardless of the temperature at a fretting displacement amplitude of 30 µm. It can also be seen that as the temperature increases, the contact resistance increment per cycle increases, with the number of cycles run before reaching 0.01Ω reduced. This phenomenon stems from the suppressed formation of the oxide film on the contact surfaces due to the lubricant, and the suppressed electrical shielding of parts of the contact surfaces on which the oxide particles accumulated while being repeatedly fractured. In addition, the contact surfaces increase somewhat due to the conductive lubricant.



(a)



(b)



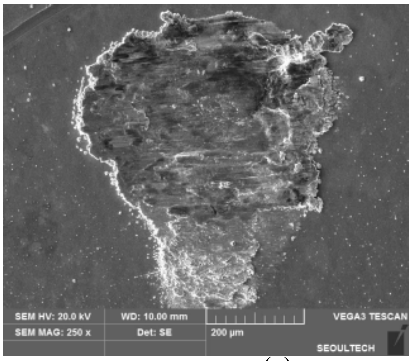
(c)

Fig. 4 Changes in the contact resistance of connectors across the contact zone as a function of the number of fretting cycles with a displacement amplitude of 77 µm at (a) 323K, (b) 348K and (c) 373K

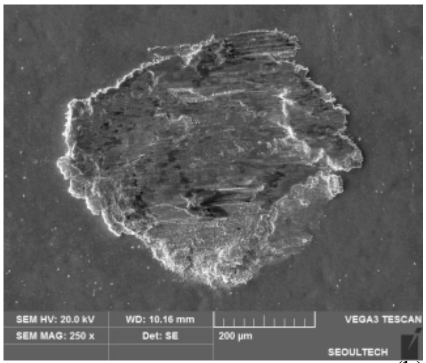
SEM observation and EDS analysis of the fretted surfaces

SEM was used to observe the fretting damaged contact surfaces of the flat sides tested with the lubricant at a fretting displacement amplitude of 77 µm. Figs. 5(a), (b), and (c) show the surface shapes of the fretting-corrosion samples tested at 323K, 348K and 373K, respectively. These photographs confirm that the damaged surfaces were generally very clean and without much oxide debris in their vicinity. This differs from the results of the fretting-damaged surfaces of tin-plated contacts without the lubricant, where the oxidized plating layer was peeled off and the oxide film was crushed to a size ranging from several µm to 100 µm and deposited after the fretting test [9]. It was also found that for the specimens with the lubricant, as the temperature increases, fewer oxide particles appear around the damaged surfaces, and the roughness of the damaged surfaces becomes smoother. In order to determine whether the debris around the damaged surfaces consists of oxides, the debris on the damaged surfaces was analyzed by means of the energy dispersive spectroscopy (EDS) device installed in the SEM.

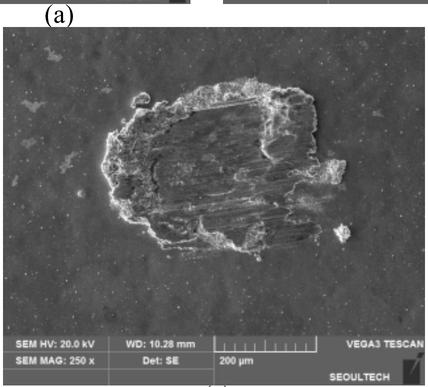
Fig. 6 shows the EDS results of the test specimen (Fig. 5(c)) at a temperature of 373K and with a fretting displacement amplitude of 77 µm. Fig. 6(b) indicates that the oxygen content is about 17% in the location where fretting damage is not observed (point 1). On the other hand, the content of oxygen is relatively high in the location where fretting damage occurred. The maximum content of oxygen is 71% at point 9. In addition, material containing 34% copper is detected at point 4, which corresponds to the center of the fretting-damaged surfaces. This finding suggests that the tin plating layer at the center of the contact area was mostly worn due to fretting, thus exposing the substrate alloy (brass). At point 3, which corresponds to the debris around the damaged area, material containing 32% oxygen is detected. The debris in this case is judged to consist of oxide particles. From these observation results, it was confirmed that tin oxide was generated on the damaged surfaces due to fretting corrosion.



(a)

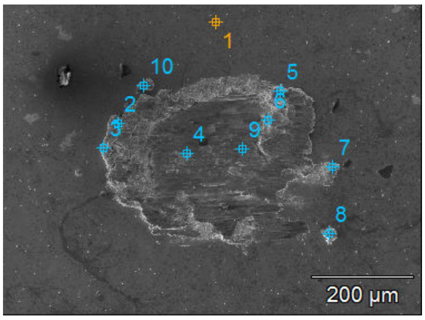


(b)



(c)

Fig. 5 SEM micrographs of the fretting wear surfaces of specimens at (a) 323K, (b) 348K and (c) 373K with a displacement amplitude of 77 µm.



(a)

Location	O (at. %)	Cu (at. %)	Sn (at. %)
1	16.91	-	83.09
2	52.48	-	47.52
3	32.82	-	67.18
4	32.98	33.98	33.03
5	19.23		80.77
6	65.58		34.42
7	34.81		65.19
8	16.73		83.27
9	71.28		28.72
10	28.64		71.36

(b)

Fig. 6(a) SEM micrographs of fretting-damaged surfaces and (b) EDS results at points 1~10 of the specimens at 373K with a fretting displacement amplitude of 77 µm.

Fretting lifetimes of electrical contacts

Several criteria have been used to determine the lifetime of electrical contacts. Whitley and Malucci suggested that failure of the electrical contact of a noble metal should be set to the time when the electrical resistance exceeds ten times the resistance value [10]. However, this criterion cannot be applied to connectors consisting of tin alloy due to the initial formation of an oxide layer. In this study, the electrical contact failure point was set to 0.01 Ω on the assumption that this tin-plated contact will be used for signal contacts. Table 1 summarizes the contact lifetime results under a constant contact load (= 0.85N) at 323K, 348K and 373K when the contact failure is assumed to occur at 0.01Ω. Experimental data [9] under identical conditions for tin-plated electrical contacts without a lubricant were added for comparison. Fig. 7 shows the number of cycles to failure as a function of the displacement amplitude with and without [9] the lubricant at test temperatures of 323K, 348K and 373K. This figure indicates that the contact failure lifetime generally tends to decrease with an increase in the fretting displacement amplitude and testing temperature. However, at temperatures of 323K and 348K, the trends of some temperature effects tend to reverse. The reason for this is unclear at present, and further research is thus warranted.

Fig. 8 shows a comparison of the lifetimes of the tin-plated connectors with and without the lubricant. In particular, when the fretting displacement amplitude is 30 μm at the temperature of 373K, the lifetime enhancement effect due to the application of the lubricant is found to exceed 20 times. Considering that the fretting displacement amplitude of the terminal of an automobile connector is less than 30 μm and the hood temperature is 373K or higher due to the operation of the engine, it is deemed that the application of a lubricant to these type of contact terminals would greatly extend their contact lifetimes.

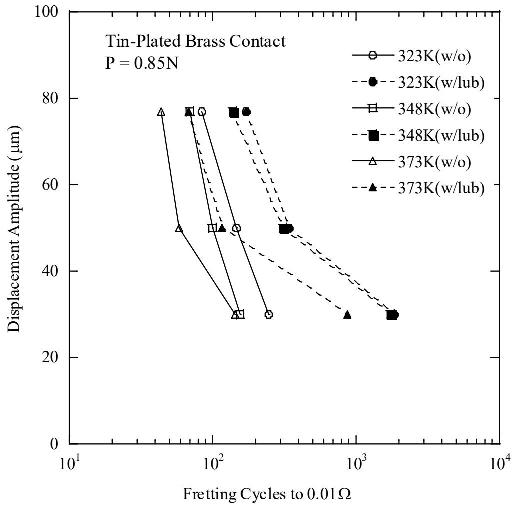


Fig. 7 Fretting cycles to 0.01Ω of tin-plated contacts as a function of the displacement amplitude with and without [9] a lubricant at different temperatures

Table 1 Summarized results of fretting cycles to 0.01Ω with and without [9] a lubricant

Fretting Disp. Amp.	**323K (cycles)**		**348K (cycles)**		**373K (cycles)**	
	with	**w/o**	**with**	**w/o**	**with**	**w/o**
30μm	1868	158	2111	155	1176	55
50μm	343	147	379	101	116	59
77μm	172	84	186	70	87	44

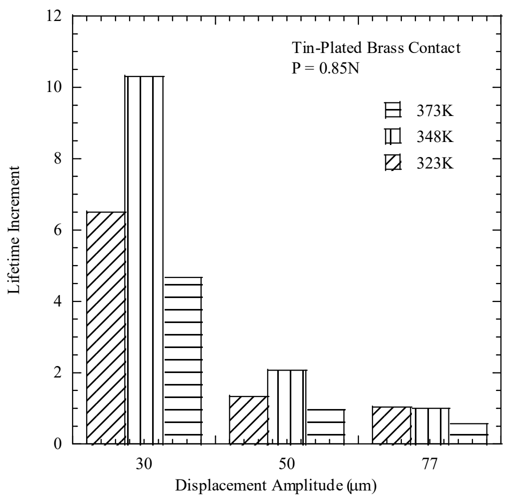


Fig. 8 Effect of a lubricant on the fretting lifetime to 0.01Ω of tin-plated contacts as a function of the fretting amplitude at different temperatures

CONCLUSION

In order to evaluate the effects of lubrication on the electrical contact lifetimes of tin-plated electrical connectors at 323K, 348K and 373K, a series of fretting tests was conducted at fretting displacement amplitudes of 30 µm, 50 µm, and 77 µm. The experimental results are as follows.

1. According to the results of the fretting test conducted at the testing temperatures of 323K, 348K, and 373K at a fretting displacement amplitude of 30 µm, the contact resistance continued to increase as the number of fretting cycles was increased without distinction between the first, second, and third steps. Application of the lubricant to the tin-plated electrical contacts had the effect of suppressing the formation of an oxide film on the contact surfaces and stabilizing the contact surface.
2. SEM observation of the specimen surfaces tested at a fretting displacement amplitude of 77 µm revealed almost no oxide debris around the fretting-damaged surfaces. However, it was found that as the temperature increases, the number of oxide particles increases slightly around the damaged surfaces.
3. For a contact specimen tested with the lubricant, the lubricant on the electrical contact is shown to significantly increase the lifetime of these contacts as the temperature increases and the fretting displacement amplitude decreases, compared to a specimen tested without the lubricant.
4. Considering that the fretting displacement amplitude of the terminal of an automobile connector is less than 30 µm and considering that the hood temperatures of 373K or higher are observed due to the operation of the engine, it is deemed that the application of a lubricant to these contact terminals would greatly extend their lifetimes.

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