Influence of the Rotational Micro Sliding on the Reliability of the Tin-Plated Electrical Contact

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ABSTRACT As a result of the rotational sliding test by applying a fretting corrosion tester on a tin-plated mock contact, the electrical resistance is stable at a low level at the beginning but then is increasing slowly to a high level. It is found out that the smaller the contact force is and the larger the rotation angle is, the earlier the resistance will increase. Investigating the causes of the increase of the resistance by observing the fretting trace, it is expected that the resistance increases because the whole contact surface is covered with oxide particles.

1. INTRODUCTION

In automotive connectors, the electrical connection is established by engaging a male terminal and a female terminal. In general, tin-plating is applied to the surface of these terminals for the purpose of corrosion protection. The increase of contact resistance is observed after the repeated sliding on a micro distance in the order of tens of μm. This phenomenon is widely known as "fretting"[1]. Number of terminals has been increasing for automotive connectors and the contact force per terminal tends to decrease for easier working conditions of operators in engaging these connectors. However, the smaller the contact force is, the easier the increase of resistance due to micro sliding is. Therefore, it is important to understand the phenomenon in order to eliminate the increase of the resistance. It has been already reported[1), 2), 3), 4)] ,based on a linear reciprocated sliding test, that the increase of the resistance caused by a micro sliding depended on the contact force, the sliding distance, the shape of contact, the press oil, the type of plating and the thickness of the plating. A rotational mode[5] exists in addition to the linear one in the sliding mode and we have reported before that the influence of the rotational sliding on the reliability of the tin-plated contact[6]. Further, we have reported the difference from the linear sliding and the estimated volume of wear particles after improving the displacement between the center of the rotation and that of the contact[7), 8)]. Here, we report the results of the observation and the analysis of the changed resistance and the deteriorated condition of contact in the rotational micro sliding under the condition of improved displacement, and furthermore the analysis of the influence of the contact force and the rotation angle and its comparison to the linear micro sliding.

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2. METHOD OF EXPERIMENT

2.1 Sample Material and Test Pieces

Cut out a test piece of 20 mm in height, 20 mm in width and 0.25 mm in thickness from a tin-plated copper alloy strip and emboss a hemisphere-like projection of R 2.0 mm near the center of it as a mock of the contact which exists inside a female terminal to simulate an embossed test piece. And cut out a test piece of 10 mm in height, 40 mm in width and 0.30 mm in thickness and fold it into a rectangular shape as a mock of tab of a male terminal to use as a flat test piece. Further, a sketch of the embossed test piece and that of the flat test piece are shown in (i) and (ii) of Figure 1 respectively. Put the embossed test pieces and the flat test pieces in acetone under ultrasonic cleaning for 5 minutes to remove contaminants, such as oil, to use as test pieces for the fretting corrosion test.

Furthermore, the sample material for the embossed test piece is a Cu-Ni-Si alloy strip (FAS-680 made by Furukawa Electric) which is high in strength and superior in stress relaxation property. This alloy strip is successively electrically plated with Ni and Cu and then coated with matted Sn in reflow process. And, the sample material for a flat test piece is a brass strip and this alloy strip is successively electrically plated with Cu and then coated with matted Sn in reflow process.

The composition of these sample material alloys is shown in Table 1. And, the thickness of the plating on these sample material is shown in Table 2. Further, the thickness of the plating of the Sn layer and the Cu-Sn intermetallic compound shown below is measured by the electrolytic stripping method and that of the Ni layer is measured by fluorescent X-ray analysis.

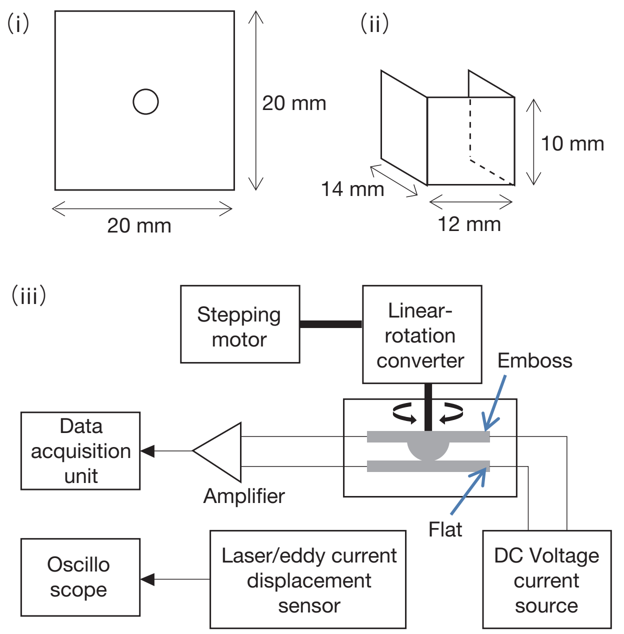

Figure 1 (i) Embossed test piece, (ii) Flat test piece, (iii) Schematic diagram of the rotational fretting corrosion tester.

Table 1 Composition of the alloy for the embossed test pieces and the flat test pieces (mass %).

	Ni	Si	Zn	Sn	Mg	Cu
Emboss test piece	2.0-2.8	0.45- 0.6	0.4-0.55	0.1-0.25	0.05-0.2	Bal.
Flat test piece	—	—	28.5-31.5	—	—	Bal.

Table 2 Structure and thickness (μm) of plating for the embossed test pieces and the flat test pieces.

	Sn	Cu-Sn	Ni
Emboss test piece	0.3	0.5	0.5
Flat test piece	0.6	0.6	—

2.2 Test Method

A schematic diagram of the rotational fretting corrosion tester is shown in (iii) of Figure 1. This tester is designed to make contact between an embossed test piece and a flat test piece with an optional contact force and give them the relative rotational movement at an optional rotation angle. In this research, the test was carried out in an environment of an atmospheric room temperature. The contact resistance was measured by the four-terminal method with the loading of a constant current of 5 mA. The test conditions of the contact force and the rotation angle applied in this research are shown in Table 3.

Table 3 Test conditions of the rotational micro sliding (rotational angle and contact force).

Rotational Angle (degree)	2, 6 and 10
Contact Force (N)	1 and 6

2.3 Evaluation Method

The surface and FIB (Focused Ion Beam) cross section of the fretting traces on the flat test pieces were observed by applying SEM (Scanning Electron Microscope), SIM (Scanning Ion Microscope) and EDS (Energy Dispersive X-ray Spectrometer) Element Mapping.

3. RESULTS AND INQUIRY

3.1 Influence of the Number of Slidings on the Contact Resistance

The results of the observation of the change of the contact resistance during the repeated rotation at the rotation angle of 6 degree are shown in Figure 2. The resistance was stable and staying at a low level until the 10^2th turn under the contact force of 1 N but then was increasing slowly. Under the contact force of 6 N, it stayed at a low level until the 10^4th turn but then was increasing slowly. Such behavior was observed under any of the 6 conditions shown in Table 3 as the resistance continued to increase without any decrease after it had once increased. This was different from earlier behavior[3] as the resistance decreased after it had once increased, which was observed under the condition of a sliding distance of 30 μm in the linear sliding test.

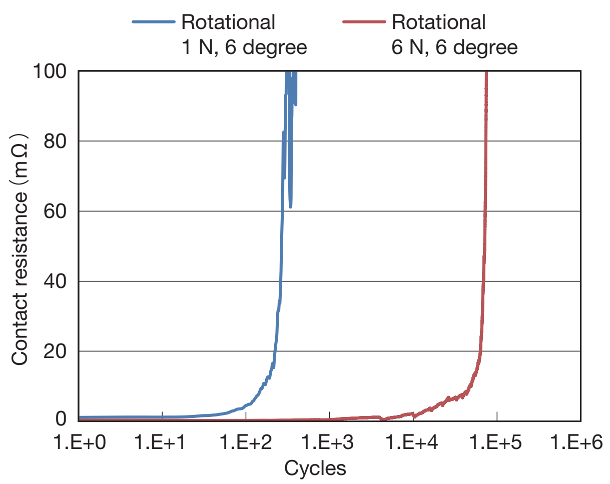

Figure 2 Relation of the contact resistance profile against the number of rotational slidings.

3.2 Wearing Process at the Contact Force of 1 N and the Rotation Angle of 6 Degree

The results of the observation of the surface of fretting trace on the flat test piece by SEM and EDS after stopping the sliding at the 100^{th} turn (the resistance = 9 mΩ) under the condition of the contact force of 1 N and the rotation angle of 6 degree are shown in Figure 3. The fretting trace appears to be a circle of 180 μm in diameter. O is detected at anywhere on the fretting trace. And the intensity of the Sn has decreased on the one hand and that of the Cu has increased on the other. No Zn is detected. It is explained based on the above mentioned facts that the thickness of the tin plating has decreased or the Sn is oxidized by wearing but that the wearing has not yet reached the base material.

The results of the observation of the surface by SIM are shown in Figure 4. Based on this figure, it is found out that the surface before sliding (a) is flat but there exist a comparatively flat part (b1) and a part (b2) with a circular projection while the surfaces of fretting traces (b1 and b2) are rougher. Further, the results of the observation of the SIM image of FIB cross section on the neighborhood of (a), (b1) and (b2) in Figure 4 are shown in Figure 5. In a part before sliding (a), a Sn layer exists on the Cu-Sn intermetallic compound and the solidified structure with grains of approximately 1 μm in diameter, which is particular to the reflow plating, is observed. There exists the Cu-Sn intermetallic compound in either the fretting trace (b1) or (b2) but their conditions are different from that of the part before sliding (a). It is explained that (b1) is one part filled up with the wear particles and (b2) is another part filled up with no particles.

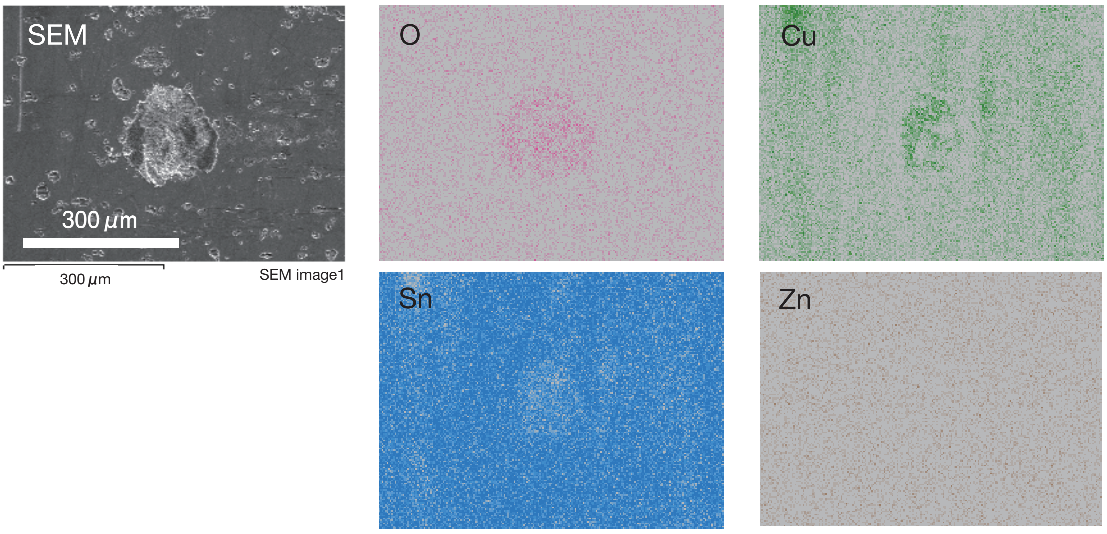

Figure 3 A SEM image of the surface of the flat test pieces and their EDS mapping images. (Rotated under condition of 1 N, 6 degree and 100 turns.)

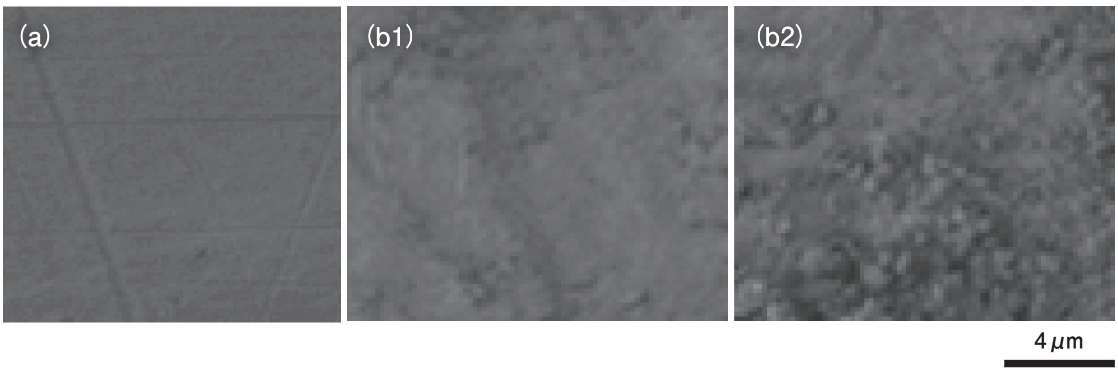

Figure 4 SIM images of the surface of the flat test pieces.
(a) Before rotational sliding.
(b1) and (b2) Fretting trace after rotational sliding.
(Rotated under condition of 1 N, 6 degree and 100 turns.)

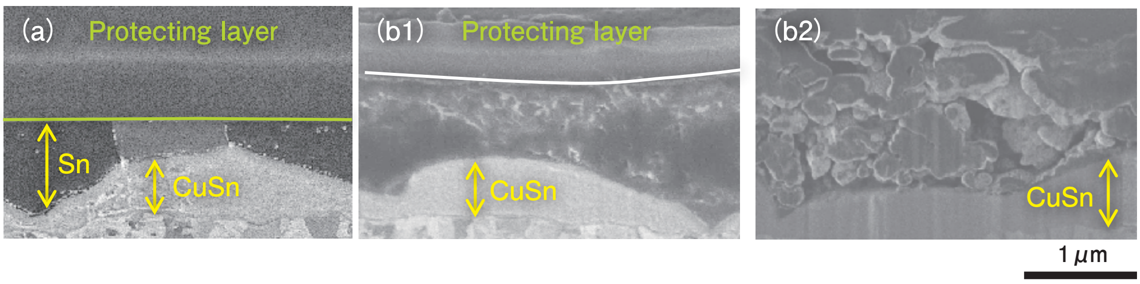

Figure 5 SIM images of the FIB cross section of the flat test pieces.
(a) Before rotational sliding.
(b1) and (b2) Fretting trace after rotational sliding.
(Rotated under condition of 1 N, 6 degree and 100 turns.)

The results of the observation of the FIB cross section by SEM and EDS are shown in Figure 6. O is hardly detected in the Sn layer of the part before sliding (a). On the other hand, O and Sn are detected in the layers above the Cu-Sn intermetallic compound but no Cu in the fretting trace (b1). Based on the above mentioned facts, it is explained that there exist oxide Sn in the layers above the Cu-Sn intermetallic compound and metallic Sn partly in the cross section of the fretting trace.

Based on the above mentioned results of observation, at the sliding with the contact force of 1N, the rotation angle of 6 degree and number of turns of 100, the base material and the Cu-Sn intermetallic compound layer seem not to be worn and their conditions before sliding are maintained. There exist some part filled up with the wear particles and the other part filled up with no wear particles. The wear particles are expected to be a mixture of oxide Sn and metallic Sn.

3.3 Influence of the Contact Force on the Change of Resistance and the Wearing Process

It is found out from Figure 2 that the number of turns for the contact resistance to reach 10 mΩ is more under the contact force of 6 N than that under the contact force of 1 N which is less than the former one. Based on the inquiry in the previous paragraph and Figure 3, the oxide particles seem to exist on the whole area of fretting trace at 100^{th} turn under the contact force of 1 N. On the other hand, SEM images of the surface of fretting traces under the contact force of 6 N and the rotation angle of 6 degree at the sliding turn at the 100^{th} (A), the 2000^{th} (B) and the 9700^{th} (C) are shown in Figure 7. As a result, no oxide particles seem to exist at the center under the contact force of 6 N until the 2000^{th} turn. This fact seems to show that the speed of increasing the resistance is slower under the contact force of 6 N. Further, the contact resistance is (A) 0.5 mΩ, (B) 0.9 mΩ and (C) 5.1 mΩ, respectively.

It is explained that the higher the contact force is, the wider is the area of no wear because the embossed test piece will move along with the flat test piece without any relative movement to generate no wear particles themselves. Or it is explained that the higher the contact force is, the less the air goes in. And it is explained that the wear particles generated from the sliding will not be easily oxidized and no oxide particles seem to be easily generated.

3.4 Influence of the Rotation Angle on the Change of Resistance

The influence of the rotation angle on the number of turns for the contact resistance to reach 10 mΩ is shown in Figure 8. Only in the test under the condition of the contact force of 6 N and the rotation angle of 2 degree, the contact resistance did not reach 10 mΩ even at the $200{,}000^{th}$ turn and the test was terminated. It is found out that the larger the rotation angle is and the smaller the contact force is, earlier the resistance will reach 10 mΩ. It is explained that larger the rotation angle is, the smaller the area is, in which the embossed test piece will move along with the flat test piece without any relative movement and more oxide particles are generated.

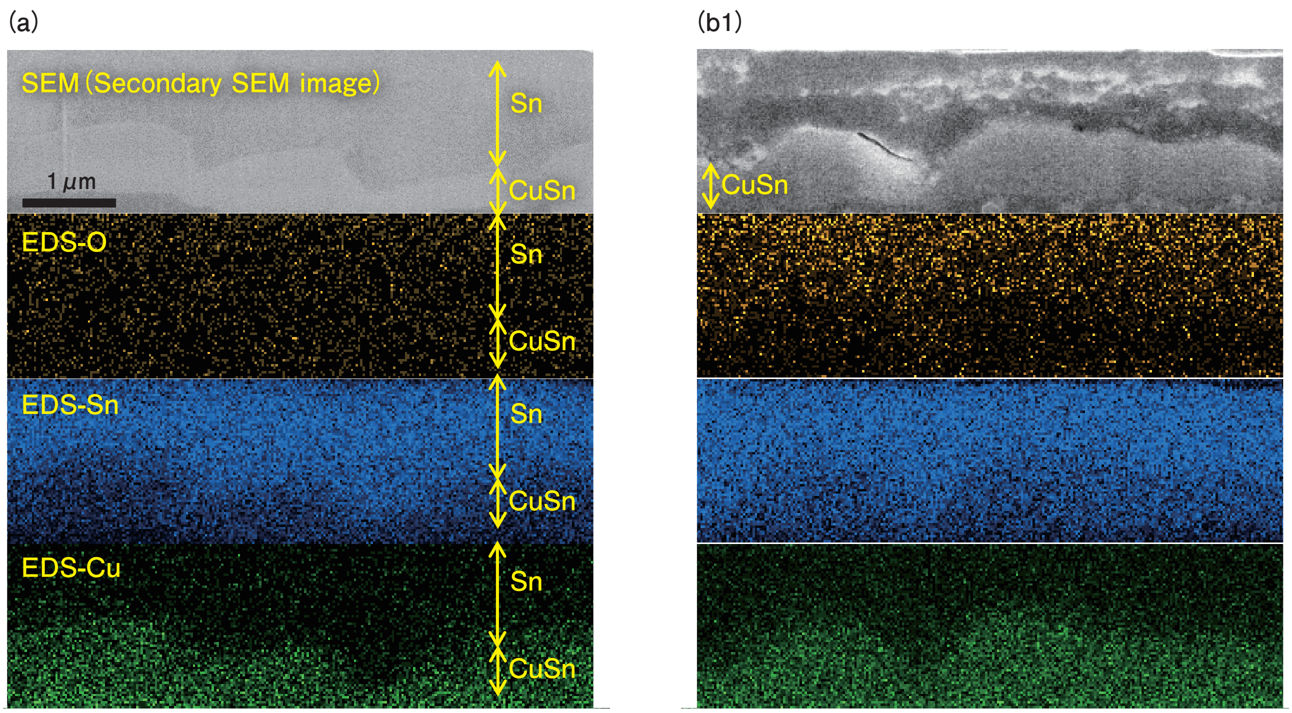

Figure 6 A SEM image of the FIB cross section of the flat test pieces and their EDS mapping images.
(a) Before rotational sliding.
(b1) Fretting trace after rotational sliding.
(Rotated under condition of 1 N, 6 degree and 100 turns.)

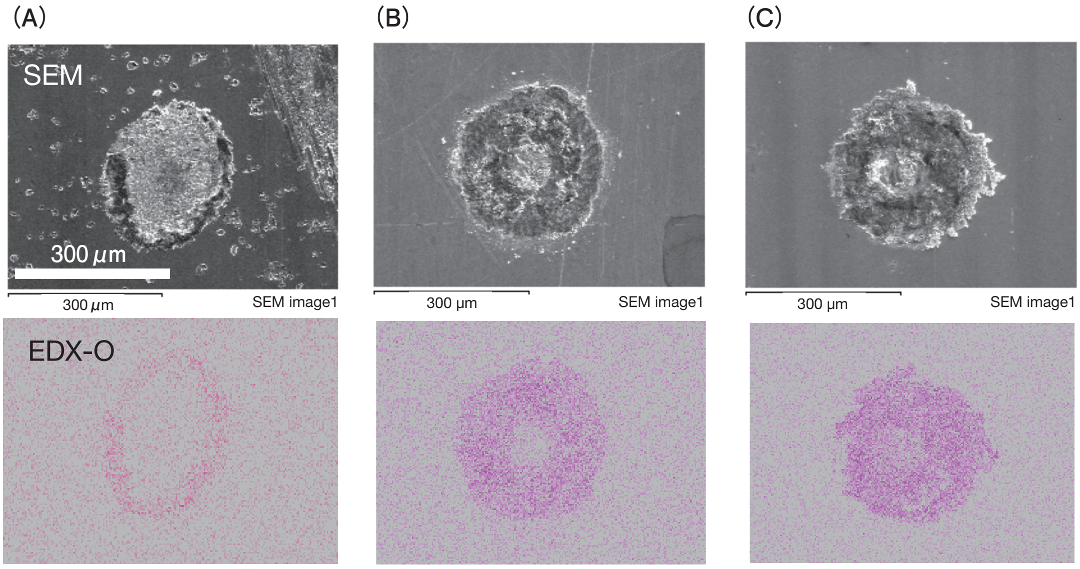

Figure 7 SEM images of the surface of fretting trace on the flat test pieces and their EDS mapping images.
(A) 100 turns
(B) 2000 turns
(C) 9700 turns
(Measured resistance showed (A) 0.5 mΩ, (B) 0.9 mΩ and (C) 5.1 mΩ.)

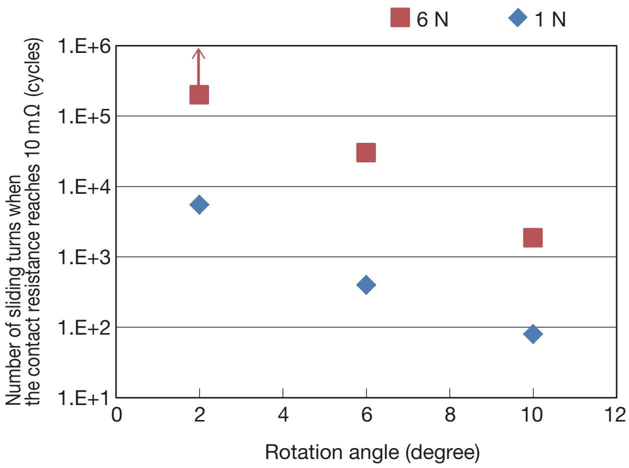

Figure 8 Influence of the rotation angle on the number of sliding turns when the contact resistance reaches 10 mΩ.

3.5 Comparison of the Rotational Sliding and the Linear Sliding

Considering the sliding distance in the rotational sliding shown in (i) of Figure 9, the radius of contact surface is estimated from Figure 7 to be 130 μm and the distance on the arc peripheral to be 14 μm in case of the contact force of 6 N and the rotation angle of 6 degree, and in the same way, the radius of contact surface is estimated from Figure 3 to be 90 μm and the sliding distance on the arc peripheral to be 9 μm in case of the contact force of 1 N and the rotation angle of 6 degree. And the changes of resistance in case of the linear sliding on the same distance as shown in (ii) of Figure 9 are shown in Figure 10 together with those by the above mentioned rotational sliding. The resistance has increased at the 1 x 10^2th turn in the rotational sliding under the contact force of 1 N but it has increased at the 2 x 10^3th turn in the linear sliding. The resistance has increased at the 1 x 10^4th turn in the rotational sliding under the contact force of 6 N but it has not increased even at the 250,000th turn in the linear sliding and it has kept being at 1.0 mΩ. It is found out that the resistance increases earlier in the rotational sliding either under the contact force of 1 N or 6 N.

The cause is interpreted as follows. The whole area of sliding surface is always contacting with the counter surface in the rotational sliding, but in the linear sliding, there is some period when the edge part of sliding surface of the flat test piece does not come into contact with the counter surface but is exposed to atmosphere even though the center of the sliding surface of the flat test piece is always in contact with the counter surface. That is to say, in the rotational sliding, no oxygen goes in easily and no oxidization occurs easily. However, the resistance increases earlier in the rotational sliding. So the cause cannot be attributed to the condition whether oxygen goes in easily or not.

It is interpreted that the sliding distance in the rotational sliding is shorter where the position is nearer to the center but on the other hand, the sliding distance in the linear sliding is constant for the whole area. So the volume of generated oxide particles is supposed to be less in the rotational sliding because the embossed test piece moves along with the flat test piece without any relative movement and the area free from wearing is wider. Therefore, the cause of earlier increase of the resistance in the rotational sliding cannot be explained by the condition whether the sliding distance is longer or not.

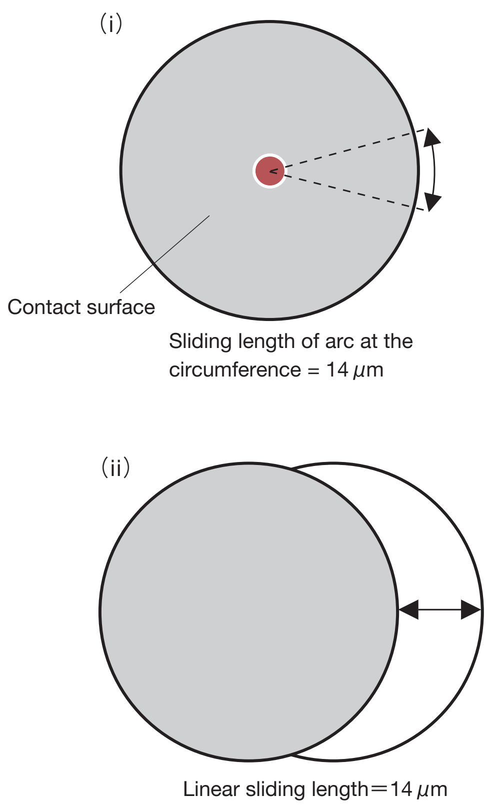

Figure 9 Schematic sketch of the sliding length on the contact surface.
(i) Rotational sliding length on the arc peripheral of the contact surface.
(ii) Linear sliding length equivalent to the rotational sliding length on the arc peripheral.

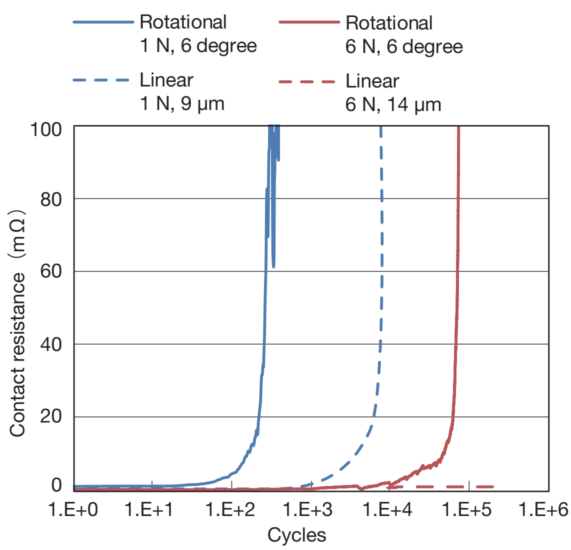

Figure 10 Relation of the contact resistance profile against the number of rotational slidings and linear slidings. (Under condition of 1 N and 6 N.)

Considering the ejection of the oxide particles, it is expected that there is almost no force working to move out the oxide particles in the radial direction in the rotational sliding. On the contrary in the linear sliding, it is thought that the generated oxide particles are ejected out to the edge based on the behavior[3] that the resistance decreases after it increases once in case the sliding distance is as long as 30 μm. In this way, it is explained that even in the short sliding distance of either 9 μm or 14 μm the ejection occurs as well. Based on what is mentioned above, it is explained that the resistance increases earlier in the rotational sliding because little amount of the oxide particles is ejected out and the number of sliding turns are less for the whole area of fretting trace to be covered with the oxide particles.

4. CONCLUSION

As the results of observation and analysis on the change of resistance and the deteriorated condition of the contact surface, the analysis of the influence of the contact force and the rotation angle, and the comparison with the linear sliding, the followings are found out;

(1) The resistance is stable at a low level at the beginning of sliding but then is increasing slowly. It is explained that the resistance increases to a high level because the whole contact surface is covered with the oxide particles.

(2) The higher the contact force is, the more the number of sliding turns increases, within which the resistance keeps stable at a low level. It seems that this is because the timing when the whole fretting trace is covered with the oxide particles is delayed. The cause of the delay of the timing is explained that the embossed test piece moves along with the flat test piece without a relative movement to widen the area free from wearing or no air goes in easily.

(3) The larger the rotation angle is, the earlier the resistance increases. It is explained that the embossed test piece doesn't move along with the flat test piece for some distance to make a relative movement and the area free from wearing is reduced.

(4) Assuming that the sliding distance of the arc peripheral is 14 μm in case when the rotation angle is 6 degree, the resistance in the rotation sliding increases earlier when comparing to the results between the linear sliding of 14 μm in distance and the rotation sliding of 6 degree in sliding angle. It is explained by the wear particles not being easily ejected in the rotational sliding.

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