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Failure analysis of a kind of low power connector

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Abstract: A kind of low power connector used e.g. in household appliances was partly burned in routine experiment. The heat sources were four paralleled contacts constructed by springs (Sn/CuSn-alloy) in socket and a plug sheet (Ni/Steel) while mating. The contact interfaces were detected by scanning electronic microscope (SEM) and X-ray energy dispersive spectroscopy (XEDS), obvious wear tracks and various contaminants, including element Si, Al, Na, K, S, Cl, O, etc., were found. The contamination degrees on the four paralleled contacts were different, so that the ratio of average contact resistance on the four contacts was about 5:8:3:1. The maximum contact resistance on contacts of the plug sheet reached 28 Ω. The main failure reasons were fretting and contamination between the contact interfaces. Fretting simulation showed that connection resistance of connectors was raised up, even to ohms level. When the current increased to 5 A, the socket housing was heated and decomposed. By the thermal analysis, it was estimated that the connector would be burned under the lower current if the current was not evenly distributed on the four paralleled contacts caused by uneven contamination. Improvement methods for connector failure are also discussed.

Key words: Connector, Thermal failure, Fretting, Contamination
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INTRODUCTION

When connectors work in a vibration field, it is hardly avoidable for the contacts to meet fretting corrosion, especially for those coated by the non-noble metals, such as tin, aluminum, nickel and copper (Antler and Drozdowicz, 1981-1982; Antler, 1995; Lee and Mamrick, 1987; Braunovic, 1991). And environment contamination causes tarnished films to be formed on contacts, which aggravates the degradation of contacts under fretting (Neufeld and Rieder, 2005; Zhou *et al*., 2000a; 2000b).

Usually one connector adopts the structure of paralleled multiple-contact to improve the contact stability and reliability. Multiple-contact can averagely divided the input current to reduce the total contact resistance since the total contact resistance, the connection resistance, must be lower than the contact resistance of any paralleled contact pair. But if one or more contacts failed, the input current would flow into other paralleled contacts, which could make them over loaded and easily destroyed.

In this paper, a kind of failed low power connector used in a household appliance was investigated. The plastic housing of this socket was partly burned in a routine experiment of the appliance. Surface analysis and study of the contacts revealed the possible failure reasons of the failed connector. Proper experimental simulations and theoretical calculation were carried out to verify the failure mechanisms and find the failure conditions. Improvement in methods for joining connectors will be also discussed.

EXPERIMENTAL APPROACHES

The approaches of failure analysis are divided into the three following steps:

(1) The possible failure reasons were studied.

By observing the burned phenomena of the socket housing, the locations of heat sources were pinpointed and the burned degrees of the contacts were compared. The deformation of the springs in the burned sockets was tested to consider the residual normal force on the contacts. The morphology and element compositions on the contacts were detected by SEM and XEDS respectively. The contact resistance of the contacts on the plug sheet was measured and compared.

(2) The effects of fretting on the connector failure were investigated.

The reliability and stability of connectors under fretting were studied. The effects of various current (1~6 A) on the contacts under fretting were also compared.

(3) Thermal analysis of contacts was carried out.

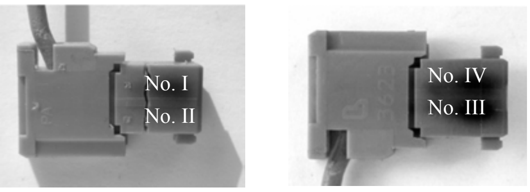
The thermal failure condition was studied by calculating the Joule heat produced on contacts under various currents. The effect of contamination on thermal failure of connectors was estimated roughly.

ANALYSIS AND TESTING OF THE FAILED CONNECTOR

Observation of the burning phenomena of the failed connector

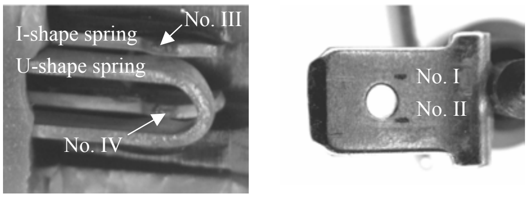
The face and backside of the burned socket are shown in Figs.1a and 1b respectively. The U-shape and I-shape springs in the socket and its mating plug sheet are shown in Figs.2a and 2b respectively. Four pairs of contacts are formed when the springs in the socket mate with the plug sheet, labeled by Nos. I, II, III, and IV respectively. The material of socket housing was plastic; its thermal decomposition temperature was 310 °C. The substrate material of the springs in the socket was CuSn-alloy, the surface finish was tin; the substrate material of the plug sheet has steel, the surface finish was nickel.

There were obvious burned tracks on the socket housing, as shown in Fig.1. The dark color of the housing indicates that the temperature on the housing reached the thermal decomposition point (310 °C) at least. The surfaces of springs in the socket and the plug sheet are tarnished, as shown in Fig.2. The positions of burned tracks on the housing are consistent with the four contacts, comparing Fig.1 with Fig.2, so that the housing is burned by the heat produced on contacts. It is clear that the color of the two burned tracks at the backside of the housing is similar, shown in Fig.1b. However, the color of No. I burned track is lighter and the No. II is the lightest at the face of the housing, shown in Fig.1a. The burned tracks with different degrees at the housing indicate that the heat produced on the four contacts is not equal.



(a) (b)

Fig.1 Outside observation of the burned socket housing. (a) The face of the housing; (b) The backside of the housing



(a) (b)

Fig.2 Observation of the contact pairs. (a) The springs in the socket; (b) The face of the mating plug sheet

Deformation of the springs in the socket

The deformation vertical to the contact surfaces will influence the normal force between the contacts. The contact zones on the springs in the sockets are a plane shown in Fig.3. According to the design drawings, the two contact planes should be parallel, the length (*l*) was 0.5 mm, and the interval (*a*=*b*) between two springs was 0.59 mm.

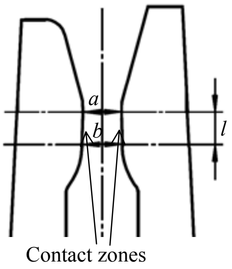


Fig.3 Schematic drawing of springs in the socket

The deformation of the springs in the burned socket was measured by optical microscope. The sizes of the springs in a new socket were also measured for comparison. The average values of 3 tested results are listed in Table 1.

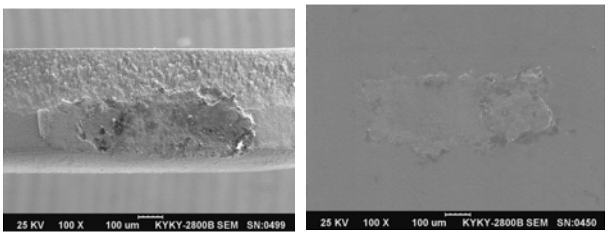
Table 1 The deformation of the springs in sockets

Sockets	Deformation of the springs (mm)		
	a	*b*	*l*
New socket	0.58	0.62	0.58
Burned socket	0.79	0.82	0.78

The sizes of the springs in the new socket basically meet the design requirement. However, both the size *a* and *b* of the springs in burned socket are 0.2 mm larger than those in the new socket, which may be caused by the relaxation of springs under high temperature. The increase of the interval between two springs reduces the normal force between the contacts, which leads to increase of contact resistance. The length (*l*) of the springs in the burned socket also increased by 0.2 mm, which has relation with the wear and melting on contact zones in the burned socket.

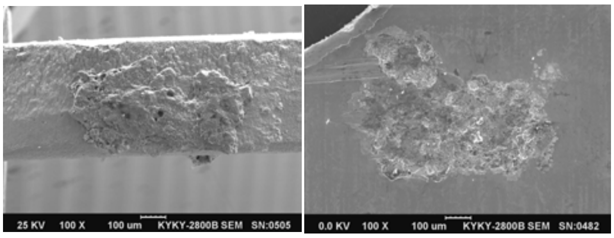
Morphology and element compositions on the contacts

SEM photos of two pairs of contacts, Nos. II and III, are shown in Figs.4 and 5, respectively. No. II contact is formed by the U-shape spring in the socket and the face of the plug sheet, the adjacent housing is burned most lightly. No. III contact is formed by the I-shape spring in the socket and the backside of the plug sheet, the adjacent housing is burned heavily.



(a) (b)

Fig.4 No. II contact pair in the burned connector. (a) The contact on the U-shape spring in the socket; (b) The contact on the face of the plug sheet



(a) (b)

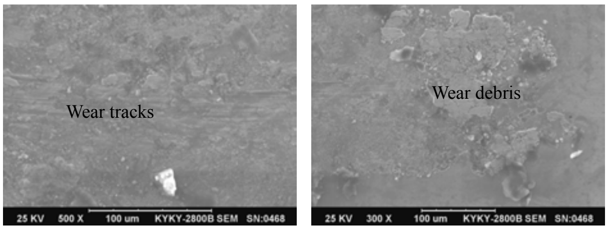
Fig.5 No. III contact pair in the burned connector. (a) The contact on the I-shape spring in the socket; (b) The contact on the backside of the plug sheet

1. Morphology of contacts

The morphology of the two contacts (Nos. I and II) on the face of the plug sheet was similar. The length was about 700 μm, and the width was about 250 μm. The morphology of the other two contacts (Nos. III and IV) on the backside of the plug sheet was similar. The length was about 750 μm, and the width was about 300 μm, larger than the contacts on the face of plug sheet since the contacts on the backside were molten more heavily.

2. Wear on the contacts

There were obvious wear tracks on the contacts on both the springs in the socket and the plug sheet, shown in Figs.4 and 5. The center of No. I contact on plug sheet is magnified in Fig.6a. The wear tracks appeared to be along the insertion direction of the plug sheet. Wear debris was accumulated on the end of wear tracks, as shown in Fig.6b.



(a) (b)

Fig.6 Obvious wear tracks on No. I contact on the plug sheet. (a) Center of the contact; (b) Right part of the contact

The element compositions in the center of wear tracks on the plug sheet were mainly Ni, Fe and a little Sn, Cu, as well as Si, Al. The wear debris was mainly Sn, Cu, O and C. It can be deduced that fretting occurred on the contacts. During fretting, both Sn and Cu transferred from the springs to the plug sheet, and were oxidized and pushed away to accumulate at the ends of the wear tracks. Ni and Fe on the plug sheet were also worn.

3. Molten phenomena on contacts

Molten materials could be found on the border of the contact zones on the plug sheet. It could be deduced that the materials of connectors were molten under high temperature, but that the fretting between the contact interfaces occured at the same time. Therefore the molten phenomena in the center of contacts were covered by the wear tracks, but remained on the border of contact zones, as shown in Fig.7. The main compositions on molten zones are the materials of contacts, Fe, Ni, Cu, Sn and O, C. Obvious molten zones were not found on the No. I and No. II contact pairs.

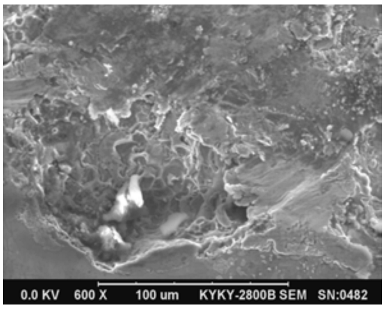


Fig.7 The molten zone on the border of No. III contact in Fig.5b

4. Contamination on contacts

Contamination exists on all the contacts. Since most of the contaminants are insulative, space charges are produced on contaminants under SEM, shown in Fig.8. The element atomic percentage of the contaminants is about C (70.5%), O (25.1%), Na (1.3%), K (0.5%), Si (0.2%), S (0.3%), Cl (1.2%) and Ni (1%). Both morphology and compositions of such kind of contaminants are similar to the galvanic corrosion of contacts in natural environment (Zhou *et al*., 2000b). The contaminants distribute on the border of contacts, which could also be pushed and accumulated by fretting.

Obvious dust elements were found on the contacts. Under 25 kV accelerating voltage, the atomic percentage of Al and O was about 46.9% and 27.2% respectively on the No. III contact shown in Fig.5a. Except Sn, Cu, Ni and Fe, the atomic percentage of various contaminants on the four contacts on the plug sheet are listed in Table 2. The contamination degrees of the contacts (Nos. I and II) on the face of the plug sheet are much more serious than those of contacts (Nos. III and IV) on the backside of the plug sheet. Contact No. II is the worst.

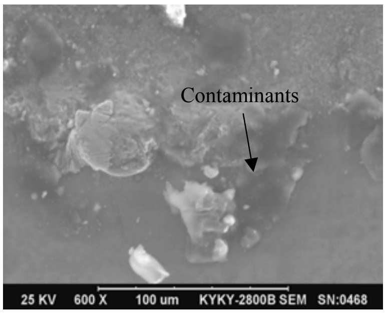


Fig.8 Contaminants on the bottom of No. I contact of the plug sheet

Table 2 Atomic percentage of contaminants on the four contacts on the plug sheet

Contacts	Center of contacts (%)	Ends of contacts (%)
No. I	41.8	41.0
No. II	48.0	71.4
No. III	10.8	15.3
No. IV	0	23.0

Contact resistance of the four paralleled contacts on the plug sheet

The contact resistance of the four contacts on the plug sheet was tested by four-point method. The constant current was set at 20 mA. The testing probe was a 1 mm diameter solid rod having a hemisphere end. Its substrate material was phosphor bronze, the underplating was nickel (2 μm), top finish was gold (0.9 μm). The normal force was set at 0.5 N. The contact resistance was tested on the crunodes of a rectangular lattice by using the self-made precise location resistance machine. The lattice was row 20 and column 6. The interval of two adjacent crunodes was 50 μm. The contact resistance on a new plug sheet was compared. The average, maximum and minimum contact resistances of four contacts on the plug sheet are listed in Table 3. The distribution of contact resistance value on the four contacts is shown in Fig.9.

It was clear that the contact resistance on No. II contact on the failed plug sheet was the highest and

Table 3 Contact resistance (mΩ) of four contacts on the failed plug sheet and a new one

Contacts	Contact resistance (mΩ)		
	Ave.	Max	Min
New coupon	15.2	52.0	4.7
No. I	487.7	4595.6	34.9
No. II	708.2	28086.7	15.2
No. III	247.0	14686.0	12.7
No. IV	91.9	1861.6	8.9

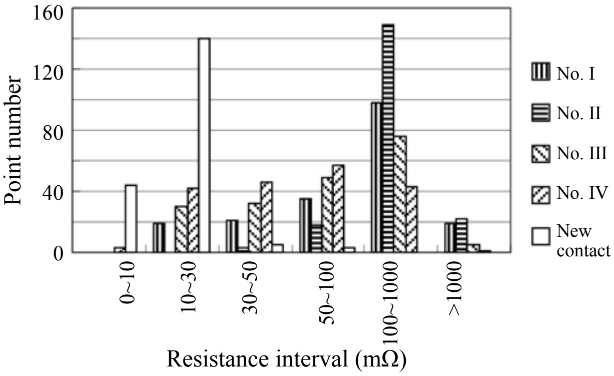


Fig.9 The distribution of contact resistance value of four contacts on the failed plug sheet and a new one

mainly concentrates in the 100~1000 mΩ range, with the maximum contact resistance reaching 28 Ω. The No. I contact was the second. The contact resistance on Nos. III and IV contacts was a little lower than them. The ratio of the average contact resistance on four contacts was about 5:8:3:1.

Possible failure reasons of the burned connector

Analysis and testing of the burned connector revealed that the heat produced on contacts causes the thermal decomposition of the housing. Fretting, contamination and melting phenomenon occurred on contacts. The deformation of springs in the socket was over the design limitation. The contamination degrees on the four contacts were different, No. II contact was most severe, No. III and No. IV contacts were lighter. Correspondingly, the contact resistance on No. II contact was the highest, No. I contact was the second, the Nos. III and IV were a little lower than them.

The main failure reasons of the connector were deduced to be fretting and contamination on the contacts. Both fretting and contamination can degrade the contacts. However, the different contamination degrees on the four pairs of contacts cause the contact resistance on the severely contaminated contact to be higher than that of the others, where the current passes is less, less heat was produced too, where the contact burns were more light. Other paralleled contacts had to endure higher current, produce more Joule heat, and melt more severely. High temperature can make the stress relaxation of substrate material of springs so as to reduce the contact force and increase the contact resistance further. To confirm this estimation, fretting simulation and thermal analysis of contaminated contacts were carried out.

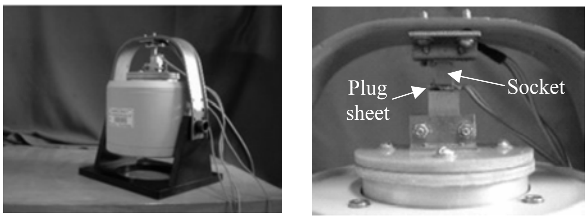
FRETTING SIMULATION

Fretting simulation by vibrator

The purpose of fretting simulation was to study the stability and reliability of connectors under fretting conditions.

1. Simulation method and conditions

The socket was clamped by a self-made fixture, the plug sheet was fixed on the vibration stage, shown in Fig.10. The amplitude of fretting was 200 μm, controlled by the signal generator. The frequency was 2 Hz. The D.C. current was set at 20 mA. The connection resistance, the total contact resistance of four paralleled contacts, was monitored, shown in Fig.11.



(a) (b)

Fig.10 The vibrator for fretting simulation. (a) The vibration stage; (b) The fixture of socket and the plug sheet

2. Fretting simulation under low current

Under 20 mA current, the connection resistance of the connector is shown in Fig.12. The connection resistance increases gradually from 3 mΩ to a balanced value 5 Ω, and fluctuates around this value. The maximum connection resistance reaches 23 Ω.

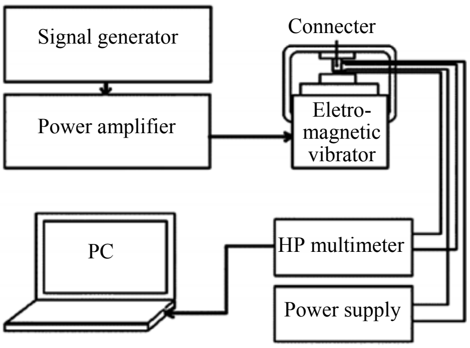


Fig.11 The sketch of vibrator system

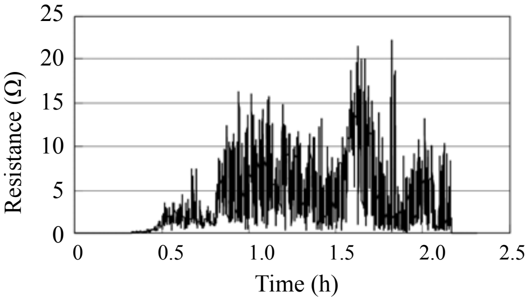
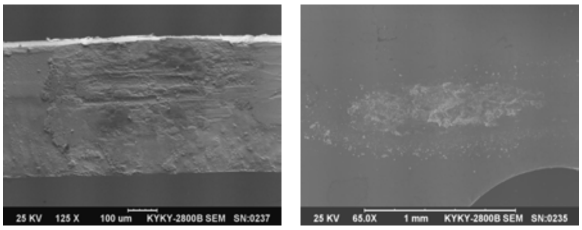


Fig.12 The connection resistance between Sn/CuSn-alloy-Ni/Steel contact pair for about 2.2 h

The contacts on the spring in the socket and on the plug sheet after fretting are shown in Figs.13a and 13b respectively. The contact zone, about 700 μm×400 μm, was wider than the contacts in the burned socket, which means the wear by fretting is more severe than that in the burned socket. The surface finishes on both the spring contacts (Sn) and the plug sheets (Ni) were worn out, the substrate materials of contact pairs, Cu and Fe, were exposed. At last, the Sn, Ni, Cu and Fe were oxidized to increase the connection resistance. But there was no obvious molten track since the current was too low. Fretting simulations verified that the connection resistance of the connectors could increase to ohms level between the Sn/CuSn-alloy and Ni/Steel contact pairs.



(a) (b)

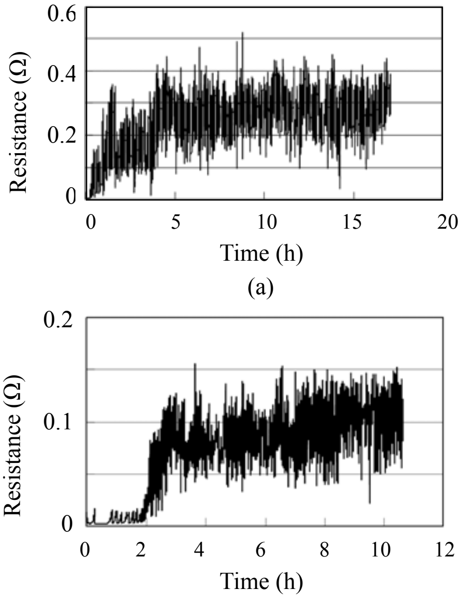
Fig.13 Morphology of a contact pair after fretting. (a) The contact on U-shape spring in the socket; (b) The contact on the plug sheet

Effects of currents on connection resistance of connectors under fretting

The rate current for the connector was 6 A (A.C.). If the high current passed through the contacts, the oxide film produced during fretting can be broken down. The effects of the current on the temperature of contacts under fretting conditions were studied under 1, 2, 3, 4, 5 and 6 A respectively.

1. Fretting simulation under high current

The curves of the connection resistance under 2 A and 6 A currents during fretting are shown in Figs.14a and 14b respectively. From the beginning, the connection resistance increased gradually, which is caused by the accumulated metal oxide produced on all of the four contacts under fretting. Then the connection resistance reached a balanced value and fluctuated around it. That is formed by the integrated effects of both fretting and current. The fretting causes contact resistance to increase, but the insulative oxide can be broken down to lower contact resistance when high current passes through the contacts. Then the oxide is formed continuously, contact resistance increased again cyclically. The balance was kept for more than 10 h.



(a)

(b)

Fig.14 The connection resistance during fretting. (a) 2 A current; (b) 6 A current

2. The effects of currents on connection resistance

Balanced connection resistance existed under various currents. The relation between balanced connection resistance and currents is shown in Fig.15. As the current increases from 1 A to 6 A, the balanced connection resistance reduces from 0.45 Ω to 0.1 Ω, but the reduced extent remained smaller. And the time to reach the balanced value was delayed from 50 min to 100 min (Fig.16). That proves the effect of the current on the reduction of contact resistance was stronger than that of oxide film formed by fretting on the increase of contact resistance.

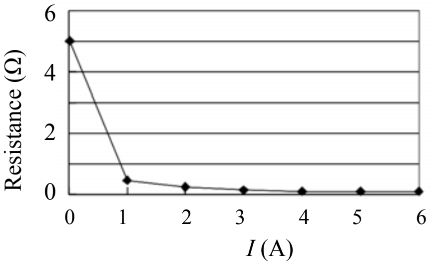


Fig.15 The relation between balanced connection resistance and various current

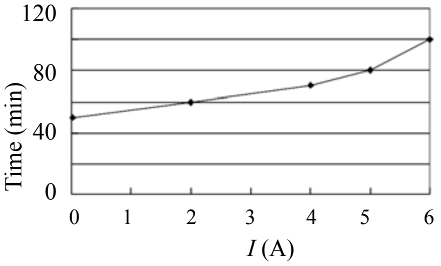


Fig.16 The time to arrive to the balanced connection resistance under various current

THERMAL ANALYSIS OF CONTACTS

Joule heat produced from contacts

Whether the connectors are burned or not depends on the Joule heat produced from the contacts. Although the connection resistance is reduced as the current increases, the Joule heat, I^2R, increases continuously, shown in Fig.17.

When the current reaches 5 A, obvious molten phenomenon begins to occur on the contacts and the adjacent plastic housing appears to be dark. One pair of contacts under 5 A current after fretting is shown in Figs.18a and 18b respectively. Under that condition, the balanced connection resistance of four paralleled contacts was about 0.11 Ω, the produced heat of the connector was 2.75 J in total, about 0.69 J for each contact pair averagely. The production of Joule heat is more than its dissipation in this mating structure of connector. That is the approximately critical failure condition.

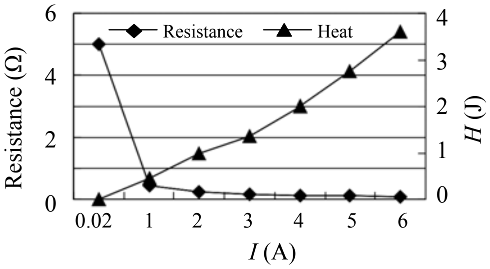
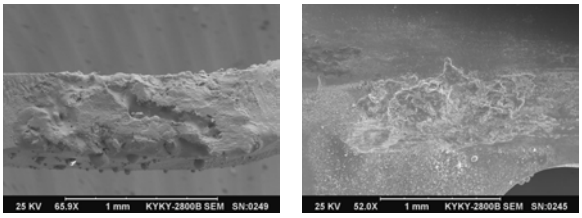


Fig.17 Joule heat increases with currents



(a) (b)

Fig.18 Obvious molten phenomena on one pair of contacts under 5 A current after fretting. (a) The contact on the U-shape spring; (b) The contact on the plug sheet

Effects of contamination on the heat produced on contacts

Since most of the contaminants are insulative, if the contacts were contaminated, the contact resistance would increase so as to produce more Joule heat. The different contamination degrees on contacts will change the current distribution among paralleled contacts. In the extreme case that one or two contacts do not work, current has to pass through the remaining contacts, which will cause some contacts to produce too much Joule heat, or even to melt.

According to the fretting simulation, the contacts have no obvious molten track when the current was 3 A during fretting. Under that condition, the balanced connection resistance was about 0.15 Ω, the integrated heat produced from the connector was 1.35 J, about 0.34 J for each contact pair. Suppose the connection resistance was not changed, if the four contacts were contaminated to different degrees, the ratio of contact resistance among the four contacts on the burned connector was 5:8:3:1. The corresponding current and contact resistances of every contact pairs in the connector are listed in Table 4 showing that the contact No. IV may be contaminated most lightly, the contact resistance was the least, 0.25 Ω, but the current was biggest, 1.8 A. Joule heat was 0.81 J, higher than the critical heat to melt a contact pair under 5 A current, 0.69 J. Therefore, this contact could be molten under lower current (3 A) and its adjacent housing could be burned.

Table 4 The effect of different contamination degrees of paralleled contacts on produced Joule heat (I=3 A)

Conditions	Equal contact resistance among paralleled contacts			Different contamination degrees on paralleled contacts		
	I (A)	R (Ω)	Heat (J)	I (A)	R (Ω)	Heat (J)
Parallelled value	3.00	0.15	1.35	3.00	0.15	1.35
No. I	0.75	0.60	0.34	0.37	1.25	0.17
No. II	0.75	0.60	0.34	0.23	2.00	0.10
No. III	0.75	0.60	0.34	0.60	0.75	0.27
No. IV	0.75	0.60	0.34	1.80	0.25	0.81

DISCUSSION

Improvement methods for fretting failure of connectors

The materials of the springs in the socket and the plug sheet, Sn/CuSn-alloy and Ni/Steel, were non-noble metals, which are easily worn and oxidized during the fretting process to increase the contact resistance. To deal with the fretting failure of connectors, the structures of connectors can be redesigned, such as increase contact force, restrict the micro-motion between contacts, etc. The plating on contacts can be changed to postpone the fretting failure. Silver can be an alternative plating to replace tin plating on the spring contacts in the sockets to reduce the effects of fretting. The connection resistance between Ag/CuSn-alloy and Ni/Steel contact pairs during fretting under 6 A current is shown in Fig.19. Its connection resistance was about 0.03 Ω, much lower than that between Sn/CuSn-alloy and Ni/Steel contact pairs shown in Fig.14b. The reason is that Ag cannot be easily oxidized during fretting.

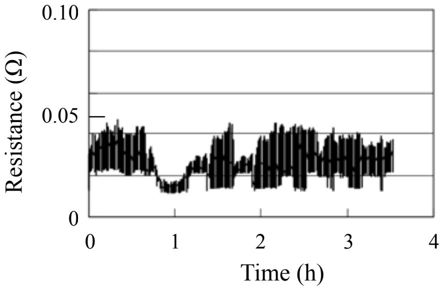


Fig.19 The connection resistance between Ag/CuSn-alloy and Ni/Steel contact pair during fretting under 6 A current

Effects of contamination on connector failure

The contacts are not molten and the plastic housing is not decomposed until the current increased to 5 A during fretting simulation. Comparing the sizes of wear zones in failed connector (Fig.5) and those in accelerated experiments (Fig.18), it is shown that the fretting simulation conditions are more rigorous than real working conditions. Therefore, it is not easy for the connectors to fail and burn only under fretting conditions in the applied field, but the fretting degrades the contacts indeed. The unevenly distributed contamination and the fretting on contacts are the main reasons for failure of the low power connectors.

Contamination on contacts in failed connector includes both dust particles and the products of galvanic corrosion. The distribution of contaminants on various contacts is different. The formation process and mechanism of the contamination on contacts in the connector is not clear yet. However, its existence and influences on the contacts are proven by the morphology and compositions detection, as well as the testing of the contact resistance. The content and distribution of contamination on contacts can severely influence the life of connectors with paralleled contacts.

CONCLUSION

(1) The main reasons for the failure of the connector are fretting and contamination on the contacts. Both fretting and contamination can degrade the contacts. The different contamination degrees on the four pairs of contacts make the current distribute unevenly. The paralleled contacts with lower resis-

tance have to endure higher current and produce more Joule heat, melt severely at last. High temperature can cause the stress relaxation of springs in the sockets to aggravate the failure further.

(2) Fretting simulations proved that the materials Sn/CuSn-alloy and Ni/Steel are not proper for fretting conditions under low current. When current increases to 5 A, the production of heat is more than its dissipation in the connector, so that the contacts are molten and the adjacent housing is decomposed. The critical Joule heat to cause failure of connectors is about 2.75 J, about 0.69 J for each contact pair averagely.

(3) There exists balanced connection resistance of connector under various currents during fretting, which is caused by the balance between fretting corrosion and effects of the current on breaking down the oxide film.

(4) As the current increases from 1 A to 6 A, the balanced connection resistance reduces from 0.45 Ω to 0.1 Ω, but the reduced extent considered to be smaller. And the time to reach the balanced value is delayed. That means the effect of current on reduction of contact resistance is stronger than that of oxide film formed by fretting on the increase of contact resistance.

(5) To deal with the fretting failure, the structure of the connector can be redesigned, such as increasing the contact force, restricting the micro-motion on contacts, etc. Silver can replace tin as the plating of springs in the sockets to postpone the fretting failure.

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