Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Particle contamination, the disruption of electronic connectors in the signal transmission system*

ZHANG Ji-gao

(*Research Lab of Electric Contacts, Beijing University of Posts & Telecommunications, Beijing 100876, China*)

E-mail: jgzh@public2.bta.net.cn

Received Dec. 19, 2006; revision accepted Jan. 5, 2007

Abstract: Particle pollution in air, also sometimes known as fine dust contamination, may cause electric contact failure. Recent research further proved that the fine particle is becoming a major disruption of the electronic connectors in signal transmission system. This paper specifies the connector contact in mobile phone application. To study the contact failure of mobile phone, a series of inspections and analytical research methods are introduced. Special features that cause the contact failure are summarized. Particle accumulation is the main problem; organic material such as lactates from sweat of the human body may act as adhesives to stick the separate particles together and make them adhere on the contact surface; chemical properties of dust cause serious local corrosion. The corrosion products may trap the particles and firmly attach on the contact surface; micro motion frequently occurs at the contact interface. Hard particle can be embedded into the surface, and soft particle could be squeezed and inserted into the contact; silicon compounds in dust play the most important role in forming high resistance regions that lead to failure; deposition of particles depends on the amount of materials, static electricity attracting force and gravity force applied on the particles. Current dust test can hardly reflect the serious contact failure. It is difficult to simulate the complexity of contact failure caused by particle contamination. Thus alternative ways of simulation experiment and improvement of contact reliability are proposed.

Key words: Dust, Particle contamination, Micro motion, Corrosion
doi:10.1631/jzus.2007.A0361 **Document code:** A **CLC number:** TB114.3; O224; O211.6

INTRODUCTION

Electrical and electronic products in China have been developed rapidly. Taking telecommunication products as examples, by the end of 2005, the number of mobile phone users has reached 400 million, and optical telecommunication customers have exceeded 300 million. These are important sources that support the rapid economic growth of this country. However, numerous unpleasant complaints related to the unreliable mobile phones have been reported to the Consumer Association. They are listed as the top complaints beyond all others over the past consecutive years. At the same time, the returning of the failed mobile phones to the companies for repair has been increased unexpectedly. The error code rates of optical telecommunications have seriously affected the quality of message exchange. Even though great effort has been made to replace the suspected connectors, and clean up the contacts, the error code rates would turn up again eventually. Thorough studies and research on the failure revealed that a large number of failures are caused by unreliable electrical contacts. As it is known, electronic connectors are widely used in telecommunication and electric control systems; their function is to link the electronic signal through various transmission lines. Unreliable connection directly affects the reliability of the system. Since the connector contact is the unique electronic component that is exposed in air, the contact will be undoubtedly greatly affected by the ambient environment. Result of tests on the failed connector contacts used in mobile phones collected from various cities in China

* Project (No. 50277002) supported by the National Natural Science Foundation of China

revealed that the contacts were contaminated by various materials of different sizes accumulated in them. Fig.1 illustrates a typical failed contact of a mobile phone whose life is only 3 months. At the testing points 1, 2, 3, certain amount of Si which is one of the main elements in dust, was found in the contaminant of the contact.

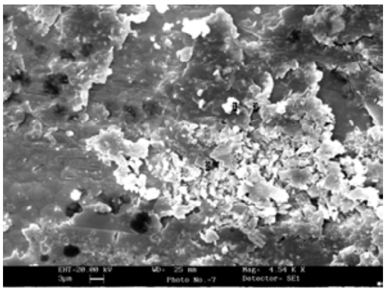
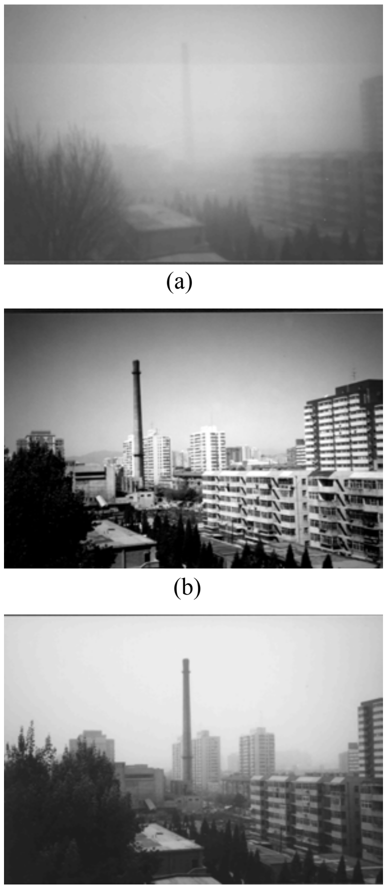


Fig.1 Accumulated particles on failed contact surface (covered with thin Au)

Another example is the surface of failed coaxial connector contacts used in optical telecommunication system is covered with elements of gypsum, sulfates of copper and nickel. Gypsum is one of the major components in dust and is soft and easy to be squeezed into the contact interface. The water solution of gypsum containing certain concentration of SO_4^{2-}, in a humid environment, may cause corrosion on contact surface.

China has a huge market for electrical and telecommunication products, and is becoming the base of global manufacturers. Therefore contact failure is not only a domestic problem but also a global one that has to be solved.

A series research was carried out in western countries and great efforts have been made to reduce electrical contact failure since the 1960's (Reagor and Russel, 1985; Williamson *et al.*, 1956; Mano, 1981; Robbins, 1973). At present, contact problem is not as serious in western countries. The main target in the west is to reduce the effect of corrosive gases in the air such as SO_2, H_2S, Cl_2, NO_2, etc. Purification of work area air is also an important strategy to reduce dust contamination. Unfortunately this is not the case in China where air pollution has become very serious. High concentration of SO_2 gas remains in the air, and a great amount of fine particles is floating all over. Dust storm hits the northern part of China almost every year. Fig.2a illustrates dust storm in Beijing. Fig.2b shows the same area after rain shower. Fig.2c shows the same area under normal condition with low visibility. Even in southern coastal cities such as Shanghai, high amount of fine particles in the air have also been found.



(a) (b) (c)

Fig.2 (a) Dust storm in Beijing; (b) Photo taken after rain shower; (c) The usual air pollution in Beijing

For further studying the air pollution effect on gold plated samples, a series of sheets were placed indoor in Shanghai for monitoring the changes on the surface.

Fig.3a shows the corrosion stain on gold plated sample after 22 months of exposure indoor in Shanghai (taken by optical microscope). Fig.3b shows the morphology of a corrosion stain (taken by scanning electron microscope (SEM)). In the stain, where a core is located at the center, surrounding by several rings. Fig.3c shows the ring formed by numerous islands (Zhang *et al.*, 2000).

X-ray energy spectroscopy (XES) reveals the composition of these islands consisted mainly of ele-

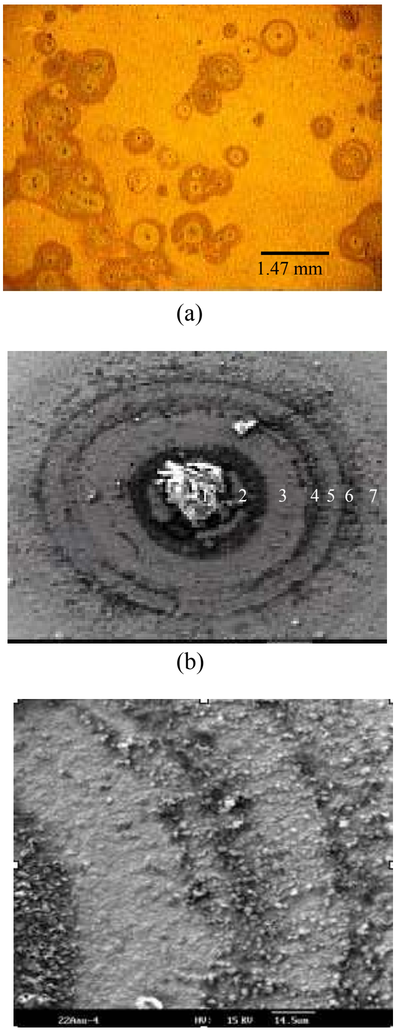


Fig.3 (a) Gold plated sample after 22 months of exposure; (b) Morphology of a stain (SEM); (c) Corrosion ring formed by numerous islands (SEM)

ments of Ni, Cu, S, O, and Cl. By further studying under electron spectroscopy for chemical analysis (ESCA), the compounds were identified as sulfates, chlorides and oxides of nickel and copper. The result shows that Si and Ca are elements commonly found in dust.

Table 1 shows the number of corrosion stains and number of dust particles (only those larger than 4 μm are counted) on gold plated samples after 22 months of indoor air exposure in Shanghai. The table shows that when gold plating is as thin as 0.48 μm, the number of corrosion stain reaches to 132 cm^{-2} and that of dust particles exceeds 920 cm^{-2} after 3 months of exposure.

Table 1 Number of stains and particles (>4 μm) vs exposure time (month)

Month	Number of stain (cm^{-2})		Number of particles (cm^{-2})
	Au 0.48 μm	Au 1.55 μm	
3	132	41	920
8	139	51	1220
15	139	75	–
22	180	80	–

Periodically sliding the above corroded sample and testing contact resistance (normal force 50 g, sliding distance 30 μm) with a micro motion apparatus, contact resistance was kept at a very low rate. This fact shows that the corrosion products are crashed and worn out as debris but that metallic contact was still made. However, when the rider passes across the ring after certain number of cycles, contact resistance became a very high value as shown in Fig.4a. SEM/XES inspection on the surface, a silicon particle (probably quartz) with about 5 μm is embedded on the surface that causes high resistance as illustrated in Fig.4b.

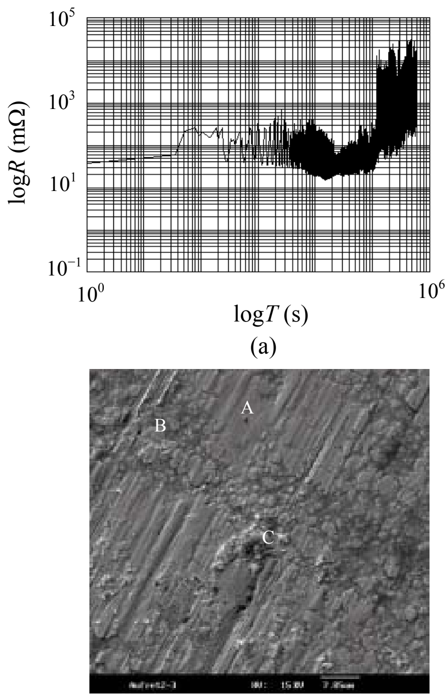


Fig.4 (a) Micro motion on corroded sample. Vertical scale illustrates contact resistance (mΩ, in log), horizontal scale shows time (s, in log; 300 s per sliding cycle); (b) Spot C is the embedded particle. Spots A and B are corrosion products

For studying the contact reliability of connector used in telecommunication and electrical control systems, we tested and analyzed the failed mobile phones collected in China. The result can be used to estimate the reliability of connectors applied in various other electrical and telecommunication products since the problems would be similar.

TESTING METHOD

Identifying of the connector failure

Mobile phone connectors mainly consist of a spring with spherical head as a rider contacting a printed circuit board surface. During sliding or micro motion, the surface plating of the spherical contact is mostly worn out. Contaminants including wear debris are usually accumulated on the plane surface tend to form a tiny region with high resistance. To find out the problem, three testing processes were carried out:

(1) Based on the failure symptom provided by the service center, the suspected connectors are picked out. Important connectors such as power, SIM card, antenna and display screen are the main items for testing.

(2) Replace the suspected connector by a new one, if the symptom disappeared, then this particular connector has great failure probability.

(3) Find out the high resistance region at the suspected contact. If one or more tiny regions with high resistance are found, they are identified as a high-risk contact which can cause contact failure. Different electronic systems install different connectors, so the rate of high resistance can be different. However, the analytic methods of finding out the problems are similar.

Investigating surface contaminants

Since contaminant at the contact surface is extremely small, it is very difficult to be taken out for identification by various instruments. An important method to roughly estimate the compounds is to test the elements involved in the contaminant by XES. The test compares the elements of compounds within the real dust collected indoor a building. Inorganic materials in dust which are more than 76% by weight, are mainly silicon compounds such as mica, quartz, feldspar and calcium compounds such as calcite, gypsum, lime, etc. (Liang *et al.*, 1997). Certain amount of dust may include oxides of iron, copper, aluminum, titanium, zirconium. Water soluble salts such as NaCl, NH_4SO_4 are usually attached to the solid particles. Both positive ions and negative ions of the dusty water solution collected from Beijing and Shanghai are listed in Table 2 (Wan *et al.*, 1999).

Identification of the corrosion products is rather simple. As it is known that the substrate metal is copper alloy, plated with Ni and thin Au on top, the corrosion products are limited to mainly sulfates and chlorides of nickel and copper.

Organic compounds involved in dust (except fiber) are a series of alkanes (C_7~C_{40+}) and two ortho-benzendicarboxylic acid esters (Zhang *et al.*, 1998). At room temperature, alkanes of C_7~C_{16} and the two esters are in oil state, only C_{17}~C_{40+} are in wax state. When temperature is below 100 °C, most of the organics are in oil state. Organic materials are more than 9% by weight.

TESTING RESULT — SPECIAL RELATED FEATURES OF FAILED CONTACTS

Mixture of various materials with different sizes of particles

XES inspection reveals that the contaminants include a mixture of dust particles, wear debris of corrosion products as well as wear particles of nickel and copper and their oxides (Feng *et al.*, 2005). Many of these contaminants are accumulated at the end of wear tracks or the vicinity areas as illustrated in Fig.5. In Fig.5, both Si and Ca are found at 3 testing spots.

Table 2 Test result of both positive and negative ions in dust solution

City	Positive ions (mg/g)				Negative ions (mg/g)			
	Ca^{2+}	Na^{+}	Mg^{2+}	K^{+}	SO_4^{2-}	NO_3^{-}	Cl^{-}	F^{-}
Beijing	20.55	2.11	1.85	1.50	21.1	4.6	2.1	0.6
Shanghai	27.54	3.75	2.09	1.77	45.3	5.1	8.5	2.1

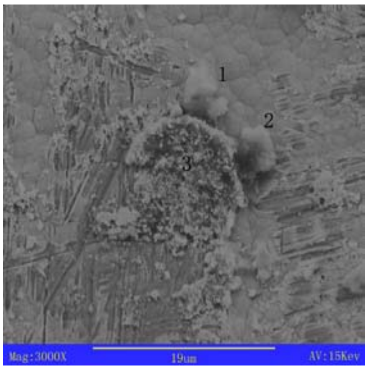
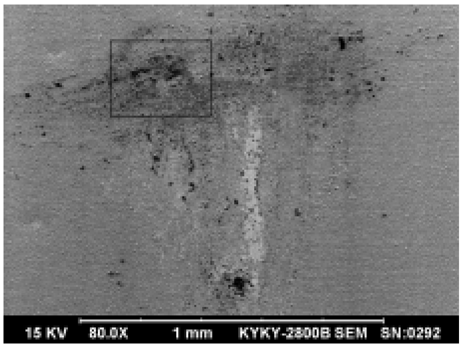


Fig.5 Accumulated particles located at the end or beside the sliding track. Grey color indicates Ni plating and bright color indicates Au plating

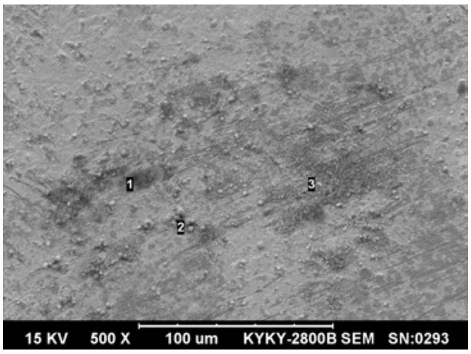
Organic adhesives found in the accumulated particles

Three hundred sixty three spots were tested by XES on 29 failed contact surfaces. Among them, 252 spots approximately 70% of total testing points showed very high carbon concentration beyond 30 of atomic percentage (at.%). As we inspected, the ratio between Si and C was around 1:2.4 (by at.%) in the dust. Commonly, concentration of Si was less than 5 at.% in the dust, thus concentration of C is not more than 15 at.%. If C is found to be higher than 15 at.%, the organic materials must be from the other sources. Observation on both natural dust particles and accumulated particles from failed contact, apparent differences were found between them as shown in Table 3.

In order to identify the organic materials covered on the contacts, the contaminants of 8 failed contact surfaces are taken and studied under precision infrared spectrometry. The result shows that 6 of them are lactates that are mainly sodium lactate mixed with calcium lactate and perhaps amino acid (Zhang *et al.*, 2006). The signals received from the other two samples were rather weak, but seem to be the same as that of the majority of samples. Fig.6 shows contaminants on the failed contact surface taken by SEM. High concentration of C was tested under XES.



(a)



(b)

Fig.6 (a) Contaminant 80×; (b) Contaminant in the square, 500×

Fig.7 illustrates a comparison of infrared spectrum of tested sample with standard sodium lactate. It shows that the specific peaks of both spectra were highly overlapped.

The formula for sodium lactate is, $CH_3CH(OH)COONa$. It can be formed by lactic acid $CH_3CH(OH)COOH$ reacted partially with sodium chloride NaCl. Actually lactic acid, lactates, amino acid and NaCl water solution are materials from human sweat. It is reasonably deduced that lactic acid vapor gets into the mobile phone and reacts with salty solution (from dust particles) to form lactates. Recent experimental result shows the appearance of lactates by the above processes. Sodium lactate is in solid state (wax) at lower temperature and in liquid state (oil) at room temperature. At certain temperature

Table 3 Differences between natural dust and accumulated particles

Type	Adhesion on contact surface	C concentration	Edges on particle surfaces	Corrosion products of Ni, Cu
Natural dust	Poor	Very low	Sharp	No
Accumulated particles	Strong	Very high	Round and smooth	Involve

range, it can be very sticky and act as adhesive. Sodium lactate with low water content, at appropriate temperature may perform higher resistivity and higher adhesive capability. Since lactates are not good insulator, high contact resistance usually happened at the piled contaminants with thickness nearly 1~2 microns.

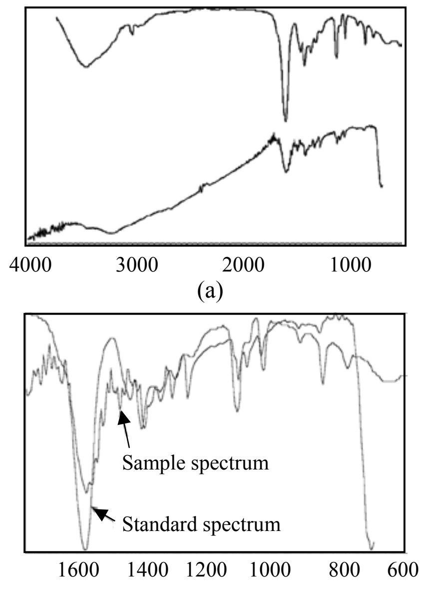


Fig.7 (a) Full spectrum, upper is standard sodium lactate, lower is testing sample; (b) Specific spectrum, upper is standard sodium lactate, lower one is testing sample.

Dust corrosion and the trapping effect of corrosion products in dust particles

XES analysis shows that, the major elements in dust (Si, Ca) are frequently accompanied by the major elements of corrosion products (Cl, S, O, Ni and Cu). The study has proven that 68% of the testing spots on 9 failed contacts have the above combination of elements (Lin and Zhang, 2004). Since water soluble salts are attached on the surface (Zhang *et al.*, 2006) of dust particles, they dissolve in water to form electrolyte and cause local corrosion in wet environment. Evidently, the corrosion product may trap the dust particles and keep them tightly on the surface. Recent simulation experiment has proven the above deduction. From the testing result, it seems with a short term failure within 3 months of life, more dust elements are found at the contaminants, but for a long term failure, more elements of corrosion products are shown. For the latter, the corrosion is probably caused by both the dust and gases in the air. Table 4 illustrates the special facts of dust corrosion and gases corrosion respectively.

When dust particle such as quartz is trapped by the corrosion product, it can easily be embedded into the surface and when certain normal force is applied may lead to high contact resistance. Simulation experiment was conducted and trapping effect has been repeatedly achieved.

Table 4 Comparison of dust corrosion with gas corrosion

Dust corrosion	Gas corrosion
High concentration of electrolyte can be formed in a short time	Concentration of corrosive gases in the air are in 10^{-6}, needs long time to cause corrosion
Elements of both negative & positive ions are found in corrosion products	Only elements of negative ions are found
Inside corrosion product, dust elements can be found	No dust is in the corrosion product
Serious corrosion occurred locally	Corrosion is more evenly distributed

Micro motion at the contact interface

Observation on electric contact surface of failed mobile phones, different kinds of micro motion occurred as follows: Regular linear motion with changeable sliding lengths, irregular motion and changeable distances, basically linear motion but changeable lateral movement and sliding distances, twisting, etc. Sliding wear tracks were evidently found on 40%~50% of the failed contact sheet surfaces. Although the rest of the sheets do not show clear wear tracks but accumulated particles were seen. Thus it is obvious that micro motion occurred at the contact interfaces. And the sliding distance was within 200 μm (He and Xu, 2005). The function of micro motion at the contacts could be summarized as: Producing wear debris both on corrosion products and plated metals; embedding the hard particles such as quartz into the plating surface; squeezing laminate particles such as mica, soft particles such as gypsum at the contact interface. Micro motion may also collect and accumulate particle contaminants and form tiny regions with high resistance. Once contact rider climbs on the surface of the region, contact failure may occur. When contact rider repeatedly passes over the high resistance region, the transmitted signal may perform abnormally. It also depends on the distribution of the resistance. This phenomenon is consistent with the failure symptom that is reported by the service center. There is a maximum size limit for the hard particle, beyond which the particle will be pushed away and not harm the contact. Calculation shows the diameter limit of this spherical shape of particle is about 70~80 μm. However, experimental result shows that most of the harmful particles are much smaller than this limit and are in the range lower than 5 μm. This is perhaps the large particles are difficult to get in the mobile phone and the amount of small particles are much more than the large particles in air. For larger equipment installed with larger connectors, external vibration probably is the major source of micro motion (Xu, 2003). But for the small mobile phones, continuous impact within a short distance may cause micro motion at the contact interface.

Silicon compounds in the dust, the most important constituent at contact surface to form high resistance

1. Definition of high resistance

At a force of 50 g, if contact resistance is much higher than 100 mΩ, usually that is considered as high resistance and 100 mΩ is the lowest dangerous limit. For mobile phone, different applications of the connectors may have their own limit.

At the failed contact surface more than one high resistance region can be found. At that region, elements of dust especially Si is tested. Fig.8 illustrates a failed contact surface with several accumulated contaminants. High resistance was found at 10 testing spots. One testing spot had a resistance value of more than 3 Ω. Table 5 shows the elements on several testing spots.

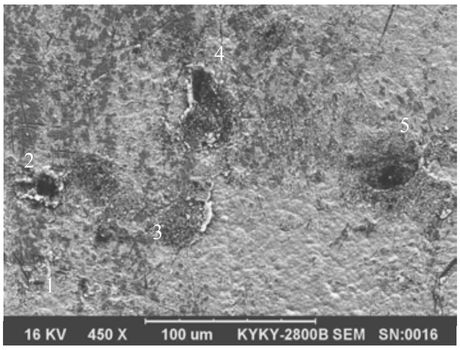


Fig.8 Contaminants on the failed contact surface

From Table 5, elements of Na, Al, Si, Ca are constituents of dust. Si was found at all spots. As it is known, the increase of the accelerated voltage of the XES, the X-ray penetration distance is deeper according to the equation derived by Andersen and Hasler (Goldstein and Yakowitz, 1975) as follows:

$$\rho R(x) = 0.064(E_0^{1.68} - E_c^{1.68}),$$

where ρ is the physical density of atom in g/cm^3, $R(x)$ is the X-ray penetration distance in μm, E_0 is the accelerated voltage in kV, E_c is the critical excitation voltage necessary to eject an electron from the inner K, L, or M shell, in kV. Table 6 lists the elements

Table 5 Elements on the contaminated surface tested at 5 spots atomic (%)

Testing spot	C	O	Na	Al	Si	Cl	Ca	Ni	Au
1	41.6	18.0	–	–	2.8	–	–	21.6	16.0
2	71.2	10.8	2.1	0.4	0.7	0.4	–	9.3	5.1
3	41.9	23.2	–	–	1.0	0.5	1.5	22.0	9.9
4	56.3	20.3	–	0.5	2.4	–	0.8	12.0	7.6
5	72.3	15.3	–	0.4	0.8	–	0.7	4.9	5.5

Table 6 Elements at the depth of contaminant at one testing spot

E_0	C	O	Si	S	Cl	K	Ca	Ni	Cu	Au
10	91.26	6.81	–	0.15	1.00	–	–	0.29	0.49	–
13	74.39	17.08	–	0.24	4.22	–	–	1.38	2.70	–
18	57.83	24.78	0.12	0.78	5.13	0.58	0.11	4.98	5.67	0.03
23	11.22	38.85	0.28	3.54	11.98	2.97	1.50	14.9	12.43	2.31

found by an increase of E_0 at a testing spot on the surface of accumulated particles. Apparently elements of Si, K, Ca are elements of dust particles, and they were trapped by organic materials, and mixed with corrosion products of nickel and Cu.

Deposition of dust particles is affected by the amount of materials in dust, electric field attraction and gravity force

With Milliken testing method, electric charge carried by a particle can be measured (Gao and Zhang, 2002). It was found that the amount of electric charge is greatly changed by the particle size and shape, materials and environmental conditions. The sequence of the amount of electric charge from high to low carried by particles of those important materials involved in dust is as follows: Organic materials (not water soluble), TiO_2, gypsum, mica, calcite, quartz, feldspar, Al_2O_3, solid particles attached by water soluble salt, etc.

Particles carrying larger amount of electric charge will have higher attractive electric force to be deposited on the contact surface. For instance, organic particles such as plastics that tend to deposit on the relay contact surface that causes failure (Chen and Witter, 2004).

The amount of electric charge carried by dust particles is greatly affected by the humidity. The amount of electric charge carried by particle with a radius of 1.5 micron at a humidity of 25% is about double of that in wet condition with 75% humidity.

When particles are in an external electric field, the attracting force is related to the electric field intensity and the amount of electric charge carried by the particles. As a fact, TiO_2 particles are rare material in dust, however, in the test many of them are deposited on the contact. It is because TiO_2 carry larger amount of electric charge than the other materials. This fact is also called "selective deposition" (Zhang *et al.*, 2005).

Fine particles may pass through tiny slots and holes of the mobile phone cabinet due to heat transfer of the air ventilation. As for the larger particles observed at the contacts, they seem to be produced inside by sliding wear, adhesion, attaching among various particles during the operation of the mobile phone or they are residual materials remaining at the contact surface during the manufacture and assembly processes.

CONCLUSION

As described above, contact failure initiated by the fine particles goes through a series of very complicated ordeal. Therefore the current dust test cannot precisely reflect the serious failure due to particle contamination. The main problems can be summarized as follows: The differences in composition and size of artificial dust particles, the ways of particle deposition, the adhesion among particles, the attachment of particles on contact surface, static and dynamic effect of particles of various materials on electric contact under load, micro motion at the contact interfaces, the external cause and simulation of micro motion, the formation of high resistance region, etc. At present, there is lack of lab test which can properly simulate the particle effect on electric contact failure. Therefore, it is of importance to establish a simulation test standard as well as a test equipment system. Clearly, to eliminate the dust contamination in China is a great task, which will take many years to get under control. However, to reduce the particle effect on electric contact should be an imminent task. Continuous study and further research not only are necessary but also have to be considered and supported.

ACKNOWLEDGEMENT

The author thanks Dr. J.B.P. Williamson, Prof. K. Mano, and Prof. R.W. Vook for their encouragements and helpful comments.

References

Chen, Z.K, Witter, G.J., 2004. Contact Resistance Failure in Relay Assembly Process. 1st International Conference on Reliability of Electrical Products and Electrical Contacts, Suzhou, China, p.68-71.

Feng, C.F., Zhang, J.G., Luo, G.P., Halkola, V., 2005. Inspection of the Contaminants at Failed Connector Contacts. 51th IEEE Holm Conf. on Electric Contacts, Chicago, IL, USA.

Gao, J.C., Zhang, J.G., 2002. Measurement of Electric Charges Carried by Dust Particles. 48th IEEE Holm Conf. on Electric Contacts, Orlando, FL, USA.

Goldstein, J.I., Yakowitz, H., 1975. Practical Scanning Electron Microscopy. Plenum Press, p.83.

He, Z.P., Xu, L.J., 2005. Micro Motion at the Failed Contact Interfaces. 51th IEEE Holm Conf. on Electric Contacts,

Chicago, IL, USA.
Liang, Y.N., Zhang, J.G., Liu, J.J., 1997. Identification of Inorganic Compounds in Dust Collected in Beijing and Their Effects on Electric Contacts. 43rd IEEE Holm Conf. on Electric Contacts, Philadelphia, PA, USA, p.20-22, 315-327.
Lin, X.Y., Zhang, J.G., 2004. Dust Corrosion. 50th IEEE Holm Conf./ICEC, Seattle, USA, p.20-24.
Mano, K., 1981. Contact Failure by Dust Contamination. *In:* Reliability of Contact Components (3rd Ed.). General Electronics Publisher, Japan, p.92 (in Japanese).
Reagor, B.T., Russel, C.A., 1985. A Survey of Problems in Telecommunication Equipment Resulting from Chemical Contamination. Proc. 31th IEEE Holm Conference on Electrical Contacts, p.157.
Robbins, R.C., 1973. Economic Effects on Air Pollution on Electrical Contacts. Proc. Holm Seminar on Electric Contact, Phenomena, p.80-85.
Wan, J.W., Gao, J.C., Lin, X.Y., Zhang, J.G., 1999. Water Soluble Salts in Dust and Their Effects on Electric Contact Surfaces. ICECT, Nagoya, Japan, p.19-24.
Williamson, J.B.P., Greenwood, J.A., Harris, J., 1956. The influence of dust particles on contact of solids. *Proc. Royal Society of London*, **237**:560.
Xu, L.J., 2003. Dynamic influence on contact failure. *IEICE Trans. on Electronics*, **E86-C**(6): 963
Zhang, J.G., Liang, Y.N., Wan, J.W., Sun, B.S., 1998. Analysis of Organic Compounds in Airborne Dust Collected in Beijing. 44th IEEE Holm Conference on Electric Contacts, Arlington, VA, USA. p.26-28.
Zhang, J.G., Lin, X.Y., Zhou, Y.L., Williamson, J.B.P., 2000. Tidal Corrosion and Concentric Rings on Gold Plated Contacts. 20th International Conf. on Electrical Contacts, Stockholm, Sweden, p.303-308.
Zhang, J.G., Gao, J.C., Cui, F.F., 2005. The "Selective" Deposition of Particles on Electric Contact and Their Effects on Contact Failure. 51th IEEE Holm Conf. on Electric Contacts, Chicago, IL, USA.
Zhang, J.G., Gao, J.C., Cui, F.F., 2006. Adhesion and Attaching of Particles at the Failed Connector Contacts. 23nd ICEC'2006, Sendai, Japan.