Effect of Dust Contamination on Electrical Contact Failure

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I. Introduction

Dust can cause serious contact failure

The complexity of dust effect

Dust comprise many different materials with different properties, composition change with local conditions

The effect of dust on electric contacts depends on the nature of materials in dust related to:

- the inherent characteristics of the materials
- the application conditions
- the environment

Simple test do not fully simulate dust effect.
Research on dust effect is becoming more important and urgent for developing countries, such as China, due to,
- A growing huge market
- Dust contamination is one of the major problem
- A global manufacture base

Dust contamination is caused by the contact surface exposure in air.

Evidences of contact failure
- High contact resistance in relay due to organic particles
- High porosity on Au plating caused by dust
- Accumulation of particles in contact area leading to high resistance that causes failure in high-frequency telecommunications and mobile phones.
Fig. 1. Accumulated particles on contact surface caused a mobile phone failed in 3 months. Si is found in all three testing areas.
Research Laboratory of Electric Contacts

Our studies are based on,
the inspection and analysis of failed contacts
after field operation
the studies of the characteristics of dust particles and
effect of dust on contact performance

This paper summarizes:
– the composition of materials in dust
– the mechanical, electrical, chemical characteristics of
dust particles
– the manner of the deposition of dust particles
– their adhesion and attachment to the surface
– micro motion at the contact interfaces
– the creation of high resistance
– testing methods
II. Materials involved in the dust

A. The environment in China

Desert and sandy regions are about 1.74 million km$^2$, 18.2% of the area of China extending into 18 provinces. Few obstacles for the wind blows. Ground materials are driven into the air over a large region and even cause frequent dust storm which reaches the northern part of China. Large amount of fine particles received in coastal cities such as Shanghai.
B. Collection of the dust particles

Beijing was chosen as a typical city for dust collection.
- the capital of China with almost 15 million populations
- on the wind-path from the desert
- a great deal of city construction using concrete
- more than 2.7 millions of automobiles
- a moderately dusty city in China

Dust particles were collected indoor on the university campus.
C. Identification of the materials in dust

1) Inorganic compounds
   - By means of XRPD, EPMA, and TEM
   - Inorganic material is about 70% of the dust particles by weight.

Table 1. Composition of inorganic materials in fine dust particles (size < 10 micron). Compared with that of all dust (by weight)

<table>
<thead>
<tr>
<th>Materials</th>
<th>quartz</th>
<th>feldspar</th>
<th>calcite</th>
<th>gypsum</th>
<th>mica</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine particles</td>
<td>1</td>
<td>0.8</td>
<td>1.91</td>
<td>0.72</td>
<td>2.24</td>
</tr>
<tr>
<td>All dust</td>
<td>1</td>
<td>0.77</td>
<td>0.48</td>
<td>0.05</td>
<td>0.41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials</th>
<th>dolomite</th>
<th>kaolinite</th>
<th>lime</th>
<th>illite</th>
<th>hornblende</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine particles</td>
<td>0.10</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>All dust</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
2) Organic materials
   – Identified by infrared spectrometry, GC/MS, thermo gravimetric analysis
   – Main constituents:
     A series of alkanes (C$_7$ – C$_{40+}$)
     Some ortho-benzendicarboxylic acid esters
   – Properties:
     At room temperature,
     C$_7$ – C$_{16}$ are liquid. Those greater than C$_{16}$ are solid.
     ortho-benzendicarboxylic acid esters are oily liquid.
     non conductive materials.
     soft and often sticky, temperature dependent.
     Carbon black $< 15\%$.
     Organic materials $> 9\%$ of the dust.
3) Water soluble salt
   – Positive ions tested by ICP. Negative ions tested by IC

Table 2. Fractional weight percentage of elements for ions in dust solution (mg/g)

<table>
<thead>
<tr>
<th>i) Positive ions</th>
<th>Dust solution (Beijing)</th>
<th>Dust solution (Shanghai)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>2.11</td>
<td>3.75</td>
</tr>
<tr>
<td>K</td>
<td>1.50</td>
<td>1.77</td>
</tr>
<tr>
<td>Ca</td>
<td>20.55</td>
<td>27.54</td>
</tr>
<tr>
<td>Mg</td>
<td>1.85</td>
<td>2.09</td>
</tr>
<tr>
<td>Zn</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Fe</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Cu</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Mn</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>Si</td>
<td>-</td>
<td>0.18</td>
</tr>
<tr>
<td>ii) Negative ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>6.34</td>
<td>17.35</td>
</tr>
<tr>
<td>( \text{SO}_4^2 )</td>
<td>18.90</td>
<td>32.25</td>
</tr>
<tr>
<td>F</td>
<td>0.58</td>
<td>2.30</td>
</tr>
<tr>
<td>( \text{NO}_3 )</td>
<td>3.86</td>
<td>5.22</td>
</tr>
</tbody>
</table>
III. Characteristics of dust particles

A. Mechanical behavior

Hardness of materials in dust and related metals are listed in appendix using Moh’s scale.
A Moh’s hardness above 6 compare to gold is hard.
Moh’s hardness below 2 is considered as soft.
Three interacting conditions between dust and contacts
- Hard particles on a soft surface (common)
- Hard particles on a hard surface
- Soft particles on a hard surface
1). For stationary contacts

Fig.2. Model with a particle embedded at the contact interface

Fig.3. Electric current passes through the peak to peak connection
Fig. 4. Pits on gold plated contact surface where the particles are located
Fig. 5a. A hard particle is inserted at the interface.
Fig. 5b. Particle is fully buried under force
Fig. 5c. A curve of the critical radius of particle with force at an symmetric contact. Below the size, particle will be fully buried.
Below critical radius, the particle is fully embedded. No contact failure is happened. Beyond critical radius, part of the particle body exposed. High resistance or even infinity may occurred.

If surface roughness is considered, value of critical size should be added with twice of an average micro peak height.
2). For dynamic contacts

Upper limit of the particle, beyond the limit, particle can be pushed away. Below the limit particle may stay.

\[ r > R \left( 1 - \cos \theta \right) / \left( 1 + \cos \theta \right) \]

\( \theta \), frictional self locking angle,
\( r \), hazardous radius of particle,
\( R \), radius of the probe

Fig. 6. Model of spherical probe in contact with a particle that is located on a plane sheet. Beyond the size, particle will be pushed away.
Example

Fig. 7a, Spot C is dust particle, size 5-7um, composed of Si element. Spot A and B are corrosion products.

Fig. 7b, Micro motion across a dust particle.
B. Electrical behavior

1) Measurement of the electric charge

Fig. 8. Electric charge carried by dust particle
Particles carry similar amounts of positive charge and negative charge. In DC electric field, the amount of fine particles deposited on a negative polarity surface and on a positive polarity surface are closely similar.

A sequence of materials is listed below with typical amounts of electric charge from high to low: Organic materials, TiO$_2$, gypsum, mica, quartz, feldspar, calcite, Al$_2$O$_3$, solid particle with salt coverage.

Humidity will reduce the electric charge carried by particles.
Humidity effect

Fig. 9. Electric charge carried by the particle in different humid conditions
2). Electrostatic attracting force on the particle

1. No external electric field

\[ F_e = - \frac{Q^2}{16 \pi \varepsilon_0 d_0^2} \]

- Example 1, high porosity on Au plating by dust contamination.
- Example 2, wax lubricant with high permittivity can powerfully attract dust particles.

\[ F_e = - \frac{Q^2}{4\pi \varepsilon_0} \left[ 2d_0 + 2 \left( \frac{\varepsilon_0}{\varepsilon_1} \right) d_1 \right]^2 \]
2. With external DC electric field
\[ F = QE \]

Table 3. Voltage vs particle density (number of particles / mm²)

<table>
<thead>
<tr>
<th>Voltage</th>
<th>1 um</th>
<th>1 - 2.5 um</th>
<th>2.5 – 5 um</th>
<th>5 - 10 um</th>
<th>&gt;10 um</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 v</td>
<td>58</td>
<td>22</td>
<td>14</td>
<td>2</td>
<td>1</td>
<td>96</td>
</tr>
<tr>
<td>30 v</td>
<td>222</td>
<td>50</td>
<td>26</td>
<td>14</td>
<td>9</td>
<td>321</td>
</tr>
<tr>
<td>90 v</td>
<td>193</td>
<td>83</td>
<td>46</td>
<td>16</td>
<td>10</td>
<td>348</td>
</tr>
</tbody>
</table>

Dust deposition is highly selective
C. Chemical behavior

Dust solution collected from Beijing & Shanghai caused serious corrosion.

Corrosion products include sulfates & chlorides of Ni & Cu, elements of salts, Ca, K, Na, Mg.

Dust particles are associated with corrosion.

Difference between dust corrosion and gas corrosion.

– Whether positive ions and solid particles are around,
– Whether corrosion products are locally and unevenly distributed.
– Gas corrosion needs longer time than dust corrosion.
IV. Required conditions to cause electric contact failure

A. Micro movement

Fig. 11a. Wear tracks due to micro motion.

Fig. 11b. Particles piled at the end of the track.
Effect of micro motion

Producing wear debris from plated metals and corrosion products. Embedding hard particles (quartz). Squeezing laminate particles (mica), and soft particles (gypsum). Collecting and accumulating contaminants to form high resistance regions. Contact probe climbs on the surface of high resistance region, contact failure may occur.
Fig. 12. Contaminants at the failed contacts showing tiny (dark) regions of high resistance

7 places showed 100-300mΩ, 3 showed 0.3-3Ω
5 places contain Si and Ca compounds (calcite or clay)
The distribution of dust in the depth of accumulated particles
Tested according to Anderson and Hasler equation

\[ R(x) = \frac{0.64}{\rho} \left( E_{0}^{1.68} - E_{c}^{1.68} \right) \]

Table 4. Elements at different x-ray penetration depth (represented by \( E_{0} \))

<table>
<thead>
<tr>
<th>( E_{0} ) (Kev)</th>
<th>C</th>
<th>O</th>
<th>Na</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>Cl</th>
<th>K</th>
<th>Ca</th>
<th>Ni</th>
<th>Cu</th>
<th>Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>81</td>
<td>13.6</td>
<td>0.4</td>
<td>0.1</td>
<td>1.3</td>
<td>0.5</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>72.3</td>
<td>15.3</td>
<td>1.9</td>
<td>0.1</td>
<td>0.4</td>
<td>1.1</td>
<td>0.8</td>
<td>4.3</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>40</td>
<td>18.8</td>
<td>12</td>
<td>0.7</td>
<td>1.0</td>
<td>3.9</td>
<td>1.3</td>
<td>0.5</td>
<td>10.5</td>
<td>10.6</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>10.3</td>
<td>15.8</td>
<td>7.8</td>
<td>1.5</td>
<td>1.6</td>
<td>10.1</td>
<td>2</td>
<td>0.5</td>
<td>25.7</td>
<td>22</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

Mica is deeply inside the contaminant.
Gypsum, feldspar, salts and corrosion products are spread throughout the contaminant.
B. Deposition of dust particles

Particle deposition depends on electrostatic attracting force, gravity force (related to surface orientation and roughness) and the amount of materials in dust.

C. Adhesion among particles and between particles and contact surface

For failed contacts of mobile phone, high concentration of carbon is found by XES. Infrared spectrometry shows the carbon is a component of lactates. Lactates are part of the sweat of human body. At certain temp. range and water content, it may act as adhesives to stick the particles together and attach them on the surface.
Identification of sodium lactate

Fig. 13a Contaminated area with high C atomic %

Fig. 13b. Upper curve is standard spectrum of sodium lactate. Lower is the spectrum of testing sample.
Some other possibilities for the particles to adhere on the contact surface:

1. Electric static field attraction may catch the particles.

2. Water film may hydrate the clay and silicates and keep them on contact surface.

3. Corrosion products may trap the dust particles and hold them together.
V. Conclusion

• The purpose of this paper is to rouse attention to this urgent and serious problem.
• Lab simulation of the field failure is of great importance.
• Further research both theoretical & experimental is needed.
• Research areas for improving reliability at this stage are suggested as follows:
  – To reduce the micro movement at the contact interface
  – To reduce residual materials
  – To purify the air in local working area.
  – To improve packaging design and the design of connectors
Thank you