Investigation on failure mechanism of electrical connectors under repetitive mechanical insertion and withdrawal operations

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Abstract. Electrical connector is an essential accessory component for electrical and electronic interconnection circuit. In order to investigate the degradation behavior of electrical connector, a series of repetitive mechanical insertion and withdrawal operations of electrical connector have been carried out. The results indicate that there is an increasing trend in insertion/extraction force in the initial stage. Afterwards, it becomes a gradually decreasing trend attributed to the mechanical wear of the contact components. In addition, the oxidative wear of substrate copper alloy material causes the fluctuation phenomenon of contact resistance. The relevant mathematic models for insertion/extraction force and contact resistance calculation are presented to research the dynamic insertion/extraction process. Finally, the degradation behavior and associated physical mechanisms are proposed by analysing the laser confocal photographs and parameter waveforms comparison.

Keywords: Electrical connector, insertion force, contact resistance, degradation behavior.

1. Introduction

Electrical connectors are indispensable components in modern industrial and domestic application. Mechanical failure and electrical contact failure often occur in electrical connectors in field application. Field data have shown that connector degradations and failures contribute to 30~60% of the failure cases of electronic components in the system [1].

Mechanical insertion and withdrawal operations, which realizes the function of electrical connection and disconnection, is the most fundamental working mode of electrical connector. The unsuitable insertion/extraction force could result in many failure cases, such as inconvenient insertion, loose contact, instantaneous even permanent disconnection [2, 3]. The mechanical structure, shape and size of connector are considered as the key factors of the insertion/extraction force [4, 5]. Rong [6] stated that the material, dimension and assembly of contact pair could affect the insertion and extraction force and the fatigue life of connector.

Contact resistance is a significant parameter for reliability and service life of electrical connector. Reliable electrical contacts mainly demand low and stable contact resistance in a long term [7]. The gradual increases, irregular increases, periodic variations and instantaneous increases of contact
resistance are the main criteria for electrical contact failure of electrical connector [8, 9]. Relevant studies have proved that repetitive insertion and withdrawal operations, fretting wear result in the destruction of surface coating material [10, 11]. It not only increases the friction coefficient and leads to the increase of insertion force, but also results in the exposure of the substrate metal and the formation of oxide film, which reduces the electrical contact performance and causes the failure of connector. The dynamic process can reflect the final running state of the connector. However, the research on the degradation law of dynamic waveforms of force and contact resistance and its influence on failure phenomenon is little known.

In this paper, a test rig specially designed for simulating the insertion/extraction operation and collecting the dynamic data of force and contact resistance in-situ in real time is described. The insertion/extraction physical model is presented to research the dynamic process of insertion/extraction operation. Under the repetitive mechanical insertion and withdrawal experiments, the parameter degradation law and associated physical mechanism are studied by analyzing the laser confocal photographs and dynamic waveforms of connector.

2. Experimental details

2.1. Description of the test rig

The test rig consists of three main modules, including mechanical modules (Actuation structure and spatial position adjusting unit, as shown in Fig.1), electrical measurement and control module and programmed PC software. The horizontal actuation of the moving plug is obtained by means of the electric slide table (RCA2-TWA4NA, IAI, Japan). And the motion velocity could be setting from 2mm/s to 100mm/s easily. The relative position of plug and socket could be realized by 2 three-dimensional linear translation stages (3D LTS). In addition, the plug is connected with the force sensor (FA404-5kg, FIBOS, China), which could measure the transient force during the insertion/extraction process. A low friction pulley, installed above a 3D LTS, is used to support the transmitting rod of the plug, and thus excludes the undesired disturbance from the transmitting rod. The electrical connector and its subsidiary mechanism are installed in the constant temperature and humidity chamber (HTC-100D-I, SANTN, China), which could control the temperature and humidity environment during the whole experiment accurately.

The contact resistance is measured by using four-wire method (as shown in Fig.2) to eliminate the connection resistance of lead and soldered joints. During the test, the force and contact resistance of the whole insertion/extraction process are collected and uploaded to the PC simultaneously with the help of data acquisition card (PCI-1706U, Advantech, China). The data acquisition and logging process are controlled by the PC with the help of LabVIEW software specifically programmed for this purpose.

![Figure 1. Schematic diagram of the test rig.](image-url)
2.2. Experiment methods

Weipu WS16-2 type connector is selected as the experimental sample as shown in Fig.3. This connector contains 2 contact pairs and its rated current is 10A. The internal pins and jacks are made of gold-plated copper alloy. As shown in Fig.3 (d), there is a constricted structure at the front part of the jack to provide the contact force to the pin under the insertion condition. The details of experimental conditions are listed in Table 1.

![Figure 3. Appearance and structural schematic diagram of the connector.](image)

| Parameter                      | Value   |
|--------------------------------|---------|
| Temperature                    | 25℃     |
| Humidity                       | 65%RH   |
| Insertion/Extraction Velocity  | 100mm/s |
| Insertion/Extraction Cycle     | 12s     |
| Supply Voltage                 | 6V      |
| Current Load                   | 100mA   |
| Load Resistance                | 60Ω     |
| Sampling Rate                  | 25kHz   |
3. Results and analysis

3.1. Degradation of insertion/extraction force and contact resistance

The maximum values of the force during the insertion/extraction process are defined as the insertion force $F_i$ and the extraction force $F_e$, respectively. Fig.4 shows the variations of the insertion force $F_i$, extraction force $F_e$, and stable contact resistance $R_1$ and $R_2$ for two contact pairs as functions of operation cycles. It is found that the insertion force increases rapidly from 10.5N to 27.4N initially, and the extraction force increases sharply from 9.8N to 31.4N below 300 cycles. However, the contact resistance of contact pairs is low and stable during the initial stage. There is a decrease trend after 300 cycles in insertion force and extraction force, and the reduction speed also decreases gradually. After 15000 cycles, the extraction force reduces to 4.1N, which is less than 50% of the initial value. According to the EIA standard EIA-364-13C, 5N is the lifetime limit of electrical connector with 2 contact pairs, and the extraction force could not be lower than this value. Therefore, the mechanical failure occurred in the electrical connector after 15000 cycles. In addition, there is an obvious increase trend in contact resistance after 15000 cycles, which increases to above 10mΩ. After that, a severe fluctuation in contact resistance of contact pairs is observed. According to the standard GJB 101A-97, 10mΩ is defined as the lifetime limit of electrical connector with copper alloy contact pair. So electrical contact failure occurred in the electrical connector after 15000 cycles. The electrical contact failure rate is also increasing with the increase of operation cycles.

![Figure 4](image-url)
3.2. Typical insertion and extraction process

The typical waveforms of the insertion/extraction force and contact resistance are shown in Fig. 5. At the beginning of plug insertion stage, the insertion force increases sharply to the maximum value of 12N, and the contact resistance decreases to the stable value (the contact resistance of first contact pair is 2mΩ, and the second pair is 1.3mΩ) attributed to the increase of contact force. Then, the insertion force decreases to the stable value of 8N gradually, while the contact resistance keeps relatively stable with the increase of insertion depth.

The insertion force reduces to 0 rapidly at the beginning of the withdrawal process. And the force remains at 0 in a short period of time from 475ms to 500ms due to the matching gaps between various components of the connector, such as pin/jack and insulator, insulator and shell. After that, the extraction force sharply increases to about 9.5N, while the contact resistance keeps stable attributed to the negligible change of expansion of the jack. The extraction force decreases to 0 and the contact resistance increases rapidly due to the decreasing in expansion of the jack at 535ms, when the pin separates from jack.

![Figure 5. Typical experimental waveforms of force and contact resistance.](image)

The insertion/extraction physical model of contact pair is shown in Fig. 6. The center line of pin is taken as the horizontal axis, which is coincide with the center line of jack. The insertion process of pin could be divided into three stages: the mechanical contact between the cambered surface of pin and jack (Stage A), the expansion of jack (Stage B), and the insertion on straight part of pin (Stage C).
According to Reference [5], the theoretical calculation formulas of insertion force $F_i$ and extraction force $F_e$ of single contact pair could be obtained as follows

$$ F_i = \begin{cases} 
2k\delta \frac{\mu \cos \alpha + \sin \alpha}{\cos \alpha - \mu \sin \alpha}, & (0 < s \leq l_1) \\
2\mu k\delta_{\text{max}}, & (s > l_1) 
\end{cases} $$  \hspace{2cm} (1)$$

$$ F_e = \begin{cases} 
2k\delta \frac{\mu \cos \alpha - \sin \alpha}{\cos \alpha + \mu \sin \alpha}, & (0 < s \leq l_1) \\
2\mu k\delta_{\text{max}}, & (s > l_1) 
\end{cases} $$  \hspace{2cm} (2)$$

And the contact force $F_n$ could be written as

$$ F_n = \begin{cases} 
\frac{k\delta}{\cos \alpha - \mu \sin \alpha}, & (ds > 0) \\
\frac{k\delta}{\cos \alpha + \mu \sin \alpha}, & (ds < 0) 
\end{cases} $$  \hspace{2cm} (3)$$

where $ds > 0$ represents the insertion process, $ds < 0$ represents the extraction process, the angle $\alpha$ and the jack expansion $\delta$ could be expressed as

$$ \alpha = \arcsin \frac{l_1 - s}{r_1 + r_2}, \quad (0 < s \leq l_1) $$  \hspace{2cm} (4)$$

where $l_1$ and $l_2$ could be calculated by

$$ \begin{cases} 
l_1 = \sqrt{(r_1 + r_2)^2 - l_2^2} \\
l_2 = r_2 + \frac{\delta_0}{2}
\end{cases} $$  \hspace{2cm} (5)$$

where $s$ is the insertion depth of pin, $\mu$ is the friction coefficient between pin and jack, $k$ is the relevant stiffness of jack, $\delta_{\text{max}}$ is the maximum of the expansion, $\delta_0$ is the initial width of jack, $r_1$ is the curvature radius of the pin and $r_2$ is the curvature radius of the jack.

Fig. 7 shows the variations in insertion force and extraction force as functions of insertion depth of pin. It is noticed that there is a peak value of insertion force in the stage of jack expansion, which is attributed to the complex change of the angle $\alpha$ and the jack expansion $\delta$ (formula (4)).
Combining formula (3) with the empirical calculation formula of contact resistance

\[ R_j = K(0.102F_j)^{-m} \]  

The theoretical calculation formula of contact resistance is revised as

\[ R_j = \begin{cases} 
K(\frac{0.102k\delta}{\cos \alpha - \mu \sin \alpha})^{-m}, & (ds > 0) \\
K(\frac{k\delta}{\cos \alpha + \mu \sin \alpha})^{-m}, & (ds < 0) 
\end{cases} \]  

where \( K \) and \( m \) are the experimental value related to contact material and contact form.

According to formula (7), it is easy to explain that the contact force rises sharply to the maximum value due to the jack expansion, resulting in the rapid reduction of the contact resistance to the stable value in the jack expansion stage.

4. Possible failure mechanisms

Fig.8 shows the waveforms of insertion force, extraction force and contact resistance as functions of cycles of 1, 50, 30000, respectively. It is obviously observed that the force value of insertion and extraction process in the 50\textsuperscript{th} cycle increases to about 1.6 times compared with the first cycle. While the variation law of insertion/extraction force is consistent with that of the first cycle, and the contact resistance has no noticeable change.

The peak value of insertion force is disappeared after 30000 operation cycles and the insertion force increases with the increase of insertion depth. The maximum value of extraction force reduces from 11.64N to 4.4N. As shown in Fig.8 (c), the stable and reliable contact state between pin and jack could not maintain, which results in the obvious fluctuation of contact resistance during the insertion process. The stable value of contact resistance is related to the fluctuation state during the insertion process, so the contact resistance \( R_1 \) and \( R_2 \) show a strong fluctuation phenomenon after 30000 operation cycles.
Figure 8. Waveform comparison of insertion force, extraction force and contact resistance at 1, 50, 30000 cycles.

In order to better explain the degradation law of above parameters and associated physical mechanism of connector, the surface topologies of the pin before and after experiments are captured by the laser confocal microscopy. As shown in Fig.9, there is a serious wear on the surface resulting in an obvious inclined surface on the front of the pin due to the repetitive mechanical insertion and withdrawal wear. Combined with the insertion/extraction physical model and the comparison of dynamic waveforms at different stages mentioned above, it is speculated that the surface morphology of the contact pair changes as shown in Fig.10.

Figure 9. Surface topology of the pin.
At the beginning of the experiment, the wear of contact position leads to the increase of friction coefficient (as shown in Fig.10 (b)), resulting in a sharp increase trend on insertion force and extraction force (as shown in Fig.4 (a), (b) and the 50th waveforms in Fig.8 (a), (b)). However, there is no obvious change in contact resistance due to the slight wear on the surface of gold coating (as shown in the 50th waveform in Fig.8 (c)).

With the increase of operation cycles, deformation occurs on the contact surface of pin and jack due to the repetitive mechanical insertion and withdrawal wear (as shown in Fig.9 (b)). And the accumulation of wear results in an obvious inclined surface on the front of the pin (as shown in Fig.10 (c)). Therefore, it is necessary to correct the insertion/extraction mathematical model established above. The theoretical calculation formulas of insertion and extraction force are still formula (1) and (2). However, the angle $\alpha$ changes from a function of the insertion depth to a constant value $\alpha_0$, and the expansion $\delta$ of jack changes from a complex function about the insertion depth $s$ to a positive proportion function

$$\delta = s \tan \alpha_0$$

The theoretical calculation formula of insertion and extraction force could be corrected as

$$F_i = 2ks \tan \alpha_0 \frac{\mu \cos \alpha_0 + \sin \alpha_0}{\cos \alpha_0 - \mu \sin \alpha_0}$$

$$F_e = 2ks \tan \alpha_0 \frac{\mu \cos \alpha_0 - \sin \alpha_0}{\cos \alpha_0 + \mu \sin \alpha_0}$$

Therefore, the insertion force is a positive proportion function of insertion depth $s$ in the last stage of the experiment theoretically, resulting in the peak value disappearance of insertion force and the increase of the insertion force with the increase of insertion depth, which reflects in the 30000th waveform of insertion force in Fig.8 (a). In addition, the fatigue and stress relaxation phenomenon, which is caused by the repetitive mechanical insertion and withdrawal operations, occurs on the jack resulting in the decrease of stiffness $k$ of jack. Combined with the formulas (9) and (10), this phenomenon aggravates the decrease of the insertion and extraction force of the connector.

The contact resistance of the connector keeps relatively stable in the initial stage of the experiment due to the inactivity chemical properties of the gold coating on the surface of the contact pair, which is difficult to form oxide film. The following four reasons leads to the increase and strong fluctuation of contact resistance in the last stage of the experiment. Firstly, the expansion $\delta$ of the jack decreases when the pin inserted due to the repetitive mechanical insertion and withdrawal wear, resulting in the decrease of the contact force $F_c$ between jack and pin. Furthermore, the fatigue and stress relaxation phenomenon, which is caused by the repetitive mechanical insertion and withdrawal behaviors, occurs on the jack resulting in the decrease of contact force $F_c$ by decreasing the stiffness $k$ of jack. These two reasons mentioned above induce an obvious reduction of the contact force $F_c$ provided by jack, which is unable to maintain the reliable contact state between the pin and the jack. And it would make the contact resistance increase and be unstable. Thirdly, the substrate metal is exposed to the environment and oxidized, which is caused by the destroyed gold plating due to the accumulation of wear. The oxide film adheres to the contact surface, resulting in the increase of contact resistance. The insertion and extraction behavior could destroy the formed oxide film continuously, and the substrate metal exposed to the environment and oxidized again. This physical process causes the increase and fluctuation phenomenon of the contact resistance in the last stage of the experiment. Finally, the

**Figure 10.** Schematic plot of the change of the surface morphology of contact pair.
insulation debris produced by insulator wear, oxide particles and metal particles adhere to the contact surface, reducing the real areas for current conduction and increasing the contact resistance. And these debris would displace with the repetitive insertion and withdrawal behaviors, resulting in the strong fluctuation of contact resistance value. These four physical processes mentioned above interact with each other and they would become more and more intense with the increase of operation cycles, resulting in the fluctuation phenomenon of contact resistance more and more frequent in the last stage of the experiment.

5. Conclusions
A test rig which allows for simulating the insertion and withdrawal behavior and collecting the dynamic data of force and contact resistance of electrical connector in-situ in real time under a controllable temperature and humidity environment is designed. The degradation behavior and associated physical mechanism of repetitive mechanical insertion and withdrawal experiments are investigated under 25℃ and 65%RH ambient stress. This study reveals that there is an obvious inclined surface on the front of the pin due to the accumulation of wear from repetitive insertion and withdrawal behaviors. Coupled with fatigue and stress relaxation phenomenon, the insertion force and extraction force are reduced and the mechanical failure occurs on connector. The reduction of contact force caused by wear and fatigue, the oxide film formed by oxidation of substrate metal and the debris produced by wear attached to the contact surface are the main factors for the increase and strong fluctuation of the contact resistance in the last stage of the experiment, which results in the electrical contact failure.

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