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OVERVIEW OF FRETTING CORROSION IN ELECTRICAL CONNECTORS

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ABSTRACT−Fretting corrosion widely known as a degradation mechanism refers to the combination of fretting wear and corrosion such as oxidation. This paper critically reviews the works published previously on fretting corrosion of electrical connectors. Various experimental approaches such as testing machines, material selection, testing environments, acceleration testing techniques and preventing methods are addressed. Future research prospects are suggested.

KEY WORDS : Fretting corrosion, Contact resistance, Electrical contact

1. INTRODUCTION

Electrical contacts are commonly found in many places such as a household television set, a computer, a motor car, power connections in industry, and many more devices. Especially, the electrical contact problem in automotive application is the most important issue as automobiles experience severe operating conditions such as the engine vibration, operating temperature and outdoor environmental conditions. Since the performance of electrical devices depends on the reliability of electrical contacts, a thorough understanding of failure in electrical contacts assumes significance.

Fretting corrosion is the combination phenomenon of fretting wear and environmental corrosion such as oxidation, in other words, a complex problem involving combined action of mechanical motion and chemical reaction. Fretting corrosion occurs at the contact surface and both fretting wear and environmental corrosion complements each other.

In electrical contacts, the fretting corrosion causes increase in electrical contact resistance. Especially, in view of the trend of low power consumption, miniaturization, weight reduction and computerization of mechanical systems, there are many circuits that operate with low level electrical signals for communication with electronic control system. These systems are quite sensitive to the change in electrical signal and often lead to malfunction due to the increase in the contact resistance (Kim *et al.*, 2004). Furthermore, the electrical connectors in automotive industry are exposed to harsh environment (vibration, temperature, humidity, corrosive gas).

This paper critically reviews the works published previously on fretting corrosion of electrical connectors. Various experimental approaches such as a testing machine, material selection, testing environments, acceleration testing techniques and preventing methods are addressed. Future research prospects are suggested.

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2. MATERIAL SYSTEMS

Most of terminal material parts used in the electrical connector are electro-plated with tin, gold, silver or other noble metals (Baumann *et al.*, 1983; Whitlaw, 1986; Abbott *et al.*, 1993; Braunovic *et al.*, 1994). Copper-base alloys such as, brass and bronze, are widely used as the base metal because of good electrical conductivity and strength. Among the various coatings used tin or tin-lead coatings are widespreadly used because of the oxidation protection of base alloy and the economical efficiency. On special cases, noble metals such as platinum, silver (Rudolph and Jacobson, 1996) and gold (Peel, 2004) are plated on the base metal. At the latest, shape memory alloy (SMA) is also developed for electrical connector to prevent fretting corrosion (Kulisic *et al.*, 2000; Yurick *et al.*, 2001).

Tin is a very soft metal and rapidly forms a thin and brittle oxide layer, which is easily disrupted and pressed into the surface of soft and ductile tin, when the connecter is assembled. The contact surface has the oxidized tin debris, intermetallic compounds which are accumulated and cause a high electrical resistance some time later at apparently still good looking contacts (Denial and Mucklich, 2004; Malucci, 1999 TCPT).

Antler *et al.* (1982 IEEE) showed that fretting motion could degrade the materials such as a palladium due to catalytic behavior causing the formation of frictional polymers on the surface. Whitelaw (1986) studied the effects of fretting on palladium nickel, where both frictional polymers and nickel oxides caused contact degradation. The survey indicated that even noble metals can be degraded due to fretting. Braunovic (1990) studied the effect of fretting on aluminum conductors coated with various contact materials. It was observed that as fretting corrosion progresses the degradation characteristics such as melting/arcing, abrasion, adhesion and delamination wear occur in aluminum power applications using a variety of contact materials, both fretting amplitude and contact force affect the rate of fretting degradation, and the larger amplitudes produce greater degradation rates while the larger forces produce the lower rates.

3. FRETTING CORROSION TESTS

There are various experimental approaches for the fretting corrosion in electrical contacts. They are classified into contact point, fretting source, corrosion environments and so on.

3.1. Single and Multiple Contacts

The displacement of fretting motion is in micro-scale. There are two kinds of testing methods on the contact specimen design. One is a single contact point test. Whereas, the other is a multiple contact point test using the connector product itself.

3.1.1. Single contact tests

To make a simplified contact point model for fundamental fretting studies, most of experimental investigations deal with the single contact point method (Glossbrenner, 1993). The experimental specimen composes of a rider and a flat specimen with the same material, as shown in Figure 1. The contact point area depends on the shape of the rider specimen such as hemisphere, wedge.

Whitley and Bock (1974) presented one of the first papers on the fretting corrosion in electrical contacts. Data on a variety of materials such as tin, tin alloys, nickel, silver and gold were provided. In addition, the experiments included similar and dissimilar metal contact configurations. The results clearly showed that at a certain fretting cycle, when contact member was tin, tin alloy or nickel, fretting degradation occurred in the unlubricated cases. Moreover, lubricated contacts generally exhibited little or no degradation under the same test conditions (Wang and Lee, 1987). The time to failure had some dependence on the contact force and the voltage (Lee and Mamrick, 1986). Generally the test objectives were to evaluate the performance of various material systems by using the flat to rounded mating technique as mentioned above.

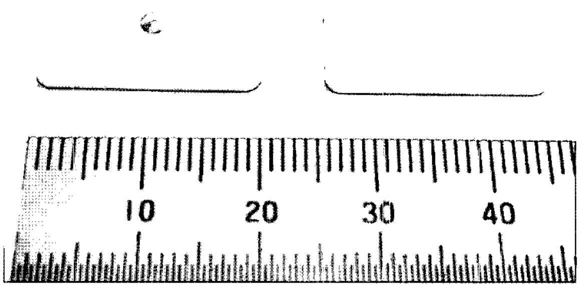

Figure 1. A rider and a flat specimen for single contact tests.

3.1.2. Multi-contact tests

These kinds of test are close to the field test rather than fundamental approach. These experimental investigations have a multi-contact point tester using the separable edge card connectors (Hooyer and Peekstock, 1987; Flowers *et al.*, 2004). This method is also used in the industry to evaluate the performance of the commercial product. It is an advantage that insertion or push down force; i.e. normal load in the connector is actualized on the contact surface realistically.

Malucci *et al.* (1995; 1999; 2001) performed a number of efforts to understand the fundamentals of fretting corrosion and to relate to real world field conditions. To make realistic fretting motion in the assembled specimen, they have used electro-dynamic shaker or vibrator. Swingler *et al.* (2002) also used the multi-contact connector terminals and proposed a multi-contact (M-C) model, which was used to evaluate the reliability function of a population of terminals with "*n*" number of contact interfaces on each terminal. The function explains the influence of multi-contact interfaces in commercially available terminals compared to a single interface often studied in fretting tests.

3.2. Fretting Motion

The fretting is characterized by micro-movements. When the two surface of the contact come together they move relatively each other along the surface. Even when contacts are firmly fitted together, these movements can still occur. Usually, fretting displacements in electrical contact parts are reported to be below 70 μm (Hannel *et al.*, 2001). Fretting is also a problem producing the debris and aiding oxidation and corrosion processes as the coated surface, wears out.

There are various fretting source in the fretting test in the electrical contact. To make a fretting motion, researchers use various source such as an external vibrator, an electro-dynamic shaker, a stepping motor and thermal expansion. Each fretting source in the tester has its particular frequency and amplitude.

3.2.1. Frequency

Antler (1985) showed that the rate of fretting motion affects degradation rates, in the case of Cu-Cu contacts. The fretting frequency is one of the important controlling factors in fretting corrosion test because corrosion is function of time. The fretting frequency used in many investigations can be classified as three ranges; high, medium and low fretting frequency.

The high fretting frequency was operated by the electro-dynamic shaker, solenoid vibrator and excitation machine with 20–120 Hz (Tristani *et al.*, 2001; Hannel *et al.*, 2000; 2001). Usually, the multi-contact test with the real connector is operated at 30–80 Hz (Flowers *et al.*, 2004).

The medium fretting frequency was operated by the stepping motor with using the attached micrometer screw (Antler, 1982 ASTM) and also electro-dynamic shaker with 5–20 Hz. Most of single contact investigation used at these frequencies.

The low fretting frequency was operated by the heating and cooling metal bar. These samples are also composed of a flat and a rider as a single contact. Swingler (1994; 2000 PIME) used 3 MHz considering temperature change condition.

3.2.2. Displacement

Fretting displacement is one of an important factor of the single contact tests. Actually, the fretting displacement in the real field conditions is not reported.

Castel *et al.* (1984) studied the increase of amplitude increases degradation rate, the cycle rate has little or no effect below 20 Hz, and little or no degradation occurs below amplitudes of 3 μm. In addition, Antler (1985) showed that contacts exhibit greater resistance near the ends of the fretting path, displacement amplitude affects degradation rates, a rapid increase in resistance occurs when the cyclic motions are less than 130 μm. Hannel *et al.* (2000; 2001) also showed that resistance of small fretting contact area made by partial slip is lower than that of large fretting contact area made by gross slip.

3.3. Normal Load

Zero insertion forced design is essential with easy assemble concept for a multiple terminal connectors. The increase of the force reduces resistance (Castel *et al.*, 1984), but connector terminal needs the low normal load. Even though low normal load condition is regarded as a prevention of wear and abrasion, it makes small contact point and raises the adhesion problem. Fretting corrosion develops in the terminals without difficulty because of the higher fretting displacement and small contact point.

The stress relaxation of the electrical terminal plate is also another problem of decreasing the normal load. The design and materials of the terminal plates, time, external vibration and temperature are the important variables of the stress relaxation (Swingler and McBride, 1998; Tristani *et al.*, 2001; Dijk and Meijl, 1999).

3.4. Corrosion Environments

All metals and alloys inevitably undergo corrosion in the earth. One of the representative corrosion phenomenon in fretting corrosion is atmospheric oxidation. One of the widely used plating materials, tin always has the surface with oxide film. The debris of plating and base metal from the fretting wear oxidized at or by the sliding contact points. The volume of the oxide is higher than that of the tin debris. The oxidation and corrosion increase at the automotive environments such as variation of the temperature, humidity and exposed to the contamination of the exhaust gas.

3.4.1. Temperature

The automotive electrical connectors on the power and signal circuit are exposed under the high temperature as in the engine compartment. The thermal cycling is also an important phenomenon in automotive field condition (Malucci, 1996). This environment brings about the change of the traditional connector designs because at lower contact force, higher temperature, lower circuit voltage and unlubricated base metal such as tin are susceptible to corrosion due to oxidation and surface film growth.

Lee and Mamrick (1988) showed that both current heating and ambient temperature affect fretting degradation rates in a complex manner that involves oxidation rate and the effects of the softening temperature of tin. Malucci (1999 TCPT) considered the length of fretting motion (ΔR) via the temperature swing (ΔT) in the cycle and the number of fretting cycles (C) to arrive at the following equation:

$$\Delta R = k(\Delta T)^P C^m \quad (1)$$

Oxidation and stress relaxation effects were introduced with new parameters, r and W, respectively, yielding a final equation:

$$\Delta R = kr^n(\Delta T)^P C^m W^s \quad (2)$$

where k is a product specific parameter and the other parameters are all applications or material related.

3.4.2. Humidity and atmospheric gas

Table 1. Various environmental factors.

Environmental factor	Characteristic	Ref.
Temperature	Oxidation rate	Lee and Mamrick, 1986; 1987; 1988 Swingler, 2000 IEEE
	Stress relaxation effects	Malucci, 1999 TCPT
	Thermal cycling	Malucci, 1996
	Softening temperature of tin	Bryant, 1994; 1994 Holm
Humidity	Galvanic cell formation	Swingler, 2000 IEEE
	Tribological factor	Saka *et al.*, 1984
Atmospheric gas	Various corrosion product	Swingler, 2000 IEEE
Vibration	External vibration	Malucci, 2004
Cycle	High frequency : electro-dynamic shaker, solenoid vibrator	Tristani *et al.*, 2001 Hannel *et al.*, 2000; 2001
	Medium frequency : stepping motor	Antler, 1982 ASTM
	Low frequency : thermal expansion	Swingler, 1994; 2000
Displacement	Fretting amplitude	Castel *et al.*, 1984 Dijk and Meijl *et al.*, 1999 Hannel *et al.*, 2000; 2001

The corrosion and oxidation processes are accelerated with high humidity because ionized hydrogen in the condensed moisture produces the formation of the galvanic cell easily (Swingler, 2000 IEEE). Humidity is also an important tribological factor in the contact area at fretting wear motion (Saka *et al.*, 1984).

Besides the oxygen, the automotive connector also exposes to the contamination of the corrosive exhaust gas such as SO_2, NO_2, Cl_2 and H_2S (Swingler, 2000 IEEE), and hydrocarbon contaminants cause the most significant increase in the connector electrical contact resistance (Kim *et al.*, 2004).

As discussed above, there are various environmental factors that influence the fretting corrosion of the electrical contact. The environmental factors and their characteristics are arranged in Table 1.

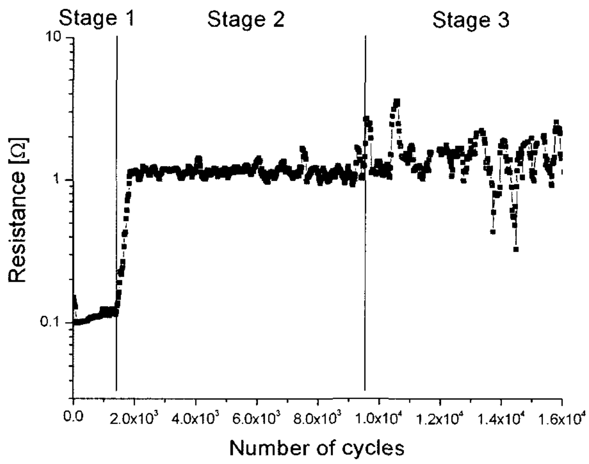

Figure 2. A periodical separation of the 3 stages on the variation of contact resistance during a test sequence.

4. DEGRADATION MECHANISM

Generally, degradation tendencies of the contact resistance are analyzed into three stages (Boyer and Tristani, 2000). A periodical separation of the 3 stages on the variation of the degradation during a test sequence is shown in Figure 2. At the first stage, initial contact resistance decrease, and then stable contact resistance is maintained. At the second stage, contact resistance increased gradually with small fluctuation. A continuous low resistance stage is observed where the contact interface is in a stable state under any condition. However, the final stage has an increase in contact resistance and repeats intermittent extinction and recovery to low contact resistance. This stage is denoted as an unstable state (Swingler and McBride, 2002). For contact stability, Abbott (1984) and Murrell *et al.* (1997) investigated contact stability as fretting progressed. It was observed that contact resistance threshold levels exist. In other cases, marinating the intermittent high contact resistance or

Table 2. Fretting corrosion mechanism.

Governing mechanism	Phenomena	Ref.
Electrical contact formation	Unoxidized fresh tin extrudes within the oxide crack	Slade, 1999
Surface Film Generation	Oxidizes and wiped films	Malucci, 1995; 1996; 1999 TCPT; 2001
Extinction	Intermittent extinction	Maul *et al.*, 2001 Swingler and McBride, 2002
	Stabilizing	Murrell *et al.*, 1997 Hannel *et al.*, 2000; 2001
	Recovery	Antler *et al.*, 1997

extinction is observed at the final stage (Murrell *et al.*, 1997).

The degradation mechanism can be summarized as below;

4.1. Electrical Contact Formation

The oxide film on the tin protects the tin and base material from the corrosive environment. As tin oxide film is more hard and brittle, the broken tin oxide is inserted to the tin matrix, which is relatively softer and ductile, during the connector assembling. In the contact area, unoxidized fresh tin extrudes within the oxide crack and meet together. Accordingly, there are insulation barriers formed by oxide and conduction areas formed by good electrical contact (Slade, 1999).

4.2. Surface Film Generation

Because fresh surfaces are generated and eliminated by fretting, the surfaces are covered with the wear debris. The brittle oxides are also made from the debris by the corrosion and oxidation. The exposed fresh tin and alloy by fretting wear is exposed to the corrosive atmosphere, too. The continuous fretting action wipes away this film, exposing fresh tin which subsequently oxidizes, forming a second film (Malucci, 1995; 1996). As these subsequent films are wiped away, further films are formed, generating more oxide (Malucci, 1999; Holm, 2001). During the long periods, various intermetaillc compounds are formed by base and plating elements, which also insulate electrical contact. In thermal cycling or high temperature conditions, the intermetaillc compound formation rate can be accelerated (Malucci, 1999 Holm). All of these insulators make the reduced total area of asperity metal-metal contact points, which increase the electrical contact resistance.

4.3. Intermittent Extinction

The slow increase in contact resistance rapidly changes in contact to large variation within fractions of a second, called intermittences or short duration discontinuities (Maul *et al.*, 2001). The various insulators are piled up at the contact surface and are taken into the sliding contact area. These insulators could combine together accidentally and read to electrical extinction. However, stabilized the wear scar (Murrell *et al.*, 1997) and gross-partial slip conditions which have slip stick domain (Hannel *et al.*, 2000; 2001) could the responsible for the recovery of electrical contact. In any case, the insulating layers form gradually on the contact area; the frequent repetition of intermittent extinction and recovery of contact resistance appears. The intermittence is related to the formation and wiping motion on the insulating layers and is originated from the area and thickness of the layer. As these subsequent films are wiped away, further films are formed, generating more oxide (Malucci, 1995). Finally, all this oxide builds up, forming an thick and electrically resistive junction (Bryant, 1994).

As discussed above, three stages of the fretting corrosion mechanism for the electrical contact is arranged as Table 2.

5. ACCELERATED TESTING ON FRETTING CORROSION

Malucci (1999 TCPT) studied some of the major issues associated with accelerated testing of electrical connector contacts constructed with tin or tin-lead plated copper alloys. The analytical approach was taken by considering known failure mechanisms for these materials as related to expected aging process through time-varying materials properties. The accelerated tests were designed by estimating test parameters that produced the amount of aging expected in the field. Also, using the regression analysis technique, Yasushi *et al.* (1999) obtained expressions for the relationship between the environmental factors and the transition of the terminal state as time elapsed. And one of the accelerated life testing model is proposed as below (Elsayed, 1996).

$$\frac{L_0}{L_s} = \left(\frac{V_0}{V_s}\right)^{-n} \exp\left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_s}\right)\right] \quad (3)$$

where L is time to failure, S and O symbols mean the accelerated stress conditions and normal operating conditions, respectively. V is electrical voltage, T is the absolute temperature, E_a is the activation energy and k is a Boltzmann's constant. And a humidity dependence model is considered as below (Elsayed, 1996).

$$A_F = \frac{t_0}{t_s} = \frac{v_0}{v_s}\exp\left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_s}\right)\right]\exp\left[-\beta\left(\frac{1}{RH_0} - \frac{1}{RH_s}\right)\right] \quad (4)$$

where RH is the relative humidity and β is an experimental constant.

6. METHODS TO AVOID FRETTING CORROSION

One method of inhibiting the increase of contact resistance is the use of lubricants, which reduce friction and wear. To some extent they also shield the surface from air. The rate of oxide formation can be decreased by cutting down available oxygen combined with reducing mechanical deformation at the interfaces. The effectiveness of a lubricant to inhibit fretting corrosion depends on its composition, viscosity, long term stability and on its consumption at the surfaces (Antler *et al.*, 1997; Dijk and Meijl, 1999). Therefore, the effectiveness of lubrication is limited and is not a satisfactory solution to eliminate severe fretting corrosion. Swingler (2000) performed some fundamental fretting corrosion studies on four types of interface such as clean, lubricated, powered and powered lubricated interfaces, and the interface was considered as in a single contact interface. It is reported that electrical powering has effect on the fretting contact interfaces, because electric field across the contact system is sufficient for electrical breakdown oxide film. But, it has not so much effect than the use of lubricants.

The other possibility is to change to the electrical terminal with noble metal plating such as platinum, silver and gold, although, it is not economical. However, it is also reported that even gold plating could be oxidized at fretting corrosion (Peel, 2004). Development of special connector materials such as shape memory alloy (Kulisic *et al.*, 2000; Yurick *et al.*, 2001) is also one of the possible way.

As the better effective method of preventing fretting corrosion, Horn *et al.* (1995) suggested to avoid the relative motion in the contact region of mated connector parts by a special contact design. Applications of electronics in systems that are exposed to high vibratory and shock stresses require the use of fretting protected electrical connections. Recently, Daniel *et al.* (2003) developed periodic micro-/nano-patterns on electrical contacts for wear minimization using interfering beams of a high-power Nd:YAG-Laser.

7. FUTURE RESEARCH PROSPECTS

There is little doubt that the investigation of fretting corrosion of electrical contacts in various conditions will remain as an important area of research in the future. Particularly, identifying factors that govern the failure is necessary. The effects of environmental conditions such as vibration, temperature, fretting frequency, humidity, normal force, type of coating and base materials, etc. on the life should be studied systematically under the consideration of all environmental parameters. Furthermore, accurate information related to fretting corrosion of electrical terminal should be used in the condition of experimental. The fretting corrosion tester with the functions to control many important environmental conditions together should be developed.

The life estimation and the accelerated testing method of electric connector under actual fretting corrosion conditions should be studied. In commercial applications, there may be no kernel solution of the preventing method; therefore, continued efforts are needed to see if it is possible to predict fretting corrosion.

The design of electric connector to prevent the fretting is also a very important research subject. The development of better lubricants to prevent oxidation is still needed for further study.

8. SUMMARY

Many studies have been made in the field of fretting corrosion of electrical connectors during the past 30 years. In this overview, an attempt has been made to identify the previous research trends and to suggest future research prospects. There is a need to properly design the fretting test assembly that allows the variation of the salient variables parameters that are known to influence the fretting corrosion life of electrical connectors. Development of accelerated test methods, methods to prevent fretting corrosion and theoretical approach for life estimation are challenges for further research and development in this area.

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