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Mechanical behavior and fatigue life estimation on fretting wear for micro-rectangular electrical connector

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ABSTRACT

With the increasing demand to miniaturize electrical connectors and maintaining its high reliability, micro-rectangular electrical connectors are now widely used. Fretting is generally recognized as an essential failure mechanism for an electrical contact. Considerable work has been carried out to understand fretting of connectors and contact metals, by experiments and simulation methods based on a simplified "hemispheric-flat" model. It is difficult to simulate the contact interfaces between a twist pin and a socket for a micro-rectangular electrical connector. Hence, we develop a 3-D finite contact model. In the present investigation, before the fretting process caused by vibration, an additional insertion step was conducted, in order to obtain the initial state of the contact pair at mated contact surfaces when fretting occurs. We validate consistent behavior for the strand component of the twist pin during the insertion and fretting processes in the simulation. A slight stress release was observed during insertion when the bumped part of twist pin was completely inserted into the socket. The performance of the twist pin, including displacement, contact force, contact area and stress state, during the fretting process was periodically changing due to the vibration of the socket.

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1. Introduction

Electrical connectors have been extensively used as the primary mechanical and electrical connecting component in various electronic products or electronic systems. The performance of the electrical connector will directly influence the performance of an entire system. According to a statistical study, 28% of system malfunctions are caused by the failure of electrical connectors [1]. The pioneering work of Bock and Whitley [2] demonstrated that fretting was essential for the degradation of electrical contacts in 1974. Comprehensive surveys on the topic were conducted in 1980s by Drozdowicz [3] and Antler [4].

The micro-rectangular electrical connector is ideal for applications with extreme miniaturization, reduced weight, space saving and high reliability, due to its high pin density, small size, lightweight body and reliable contact. To miniaturize electrical connectors, a reduction in contact force is desirable [5]. Therefore, fretting corrosion is a challenge in miniature connectors.

Fretting refers to a contact motion between two contacting surfaces with a small amplitude, ranging from several to a hundred micrometers. Such tiny relative motion can be influenced by external vibrations, changing temperature or a combination of this two factors [4]. It is generally acknowledged that fretting is one of the major failure mechanisms for electrical connectors.

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The stability of low-contact resistance between contact-containing components is critical to maintain proper operation of the electrical connector. W. H. Abbott [6] noted that the slight increase in contact resistance (milliohm) is a significant factor in the failure processes for connectors during low amplitude motion. Therefore, it is necessary to understand the complex processes related to degradation of electrical connector, in order to optimize electrical connector design and to minimize the effects of conditions for reliable performance. Significant experimental studies [7–12] on contact fretting for contact materials or electronic connectors have been published. However, because it is difficult to conduct such experimental tests, simulation-based methods have been widely used in investigations on fretting.

As early as 1996, Villeneuve [13] simulated the terminal crimping process of electronic connectors in vehicles using the finite element analysis (FEA) method. Flowers [14,15], Malucci [16], Monnier [17], Angadi [18], Ishimaru [19], Park [20] and other researchers [21,22] have validated the convenience and accuracy of finite element modeling and analysis in solving dynamics problems of electrical connectors related to fretting damage. In those previous investigations on fretting, including experimental work and modeling simulations, the general object was simplified as the hemispheric-plane contact pair model, such as the dimple-flat [20], the micro-spherical contact [19,22] and the u-bend cantilever beam to flat beam [14] and [15]. However, fretting on a twist-socket contact of a micro-rectangular electrical connector, which is considerably different from those "sphere vs. plane" contact models, has rarely been reported. Because the size of the micro-

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rectangular electrical connector is very small, and its structure is notably complicated, it is difficult to measure the contact force and the contact area of the twist-pin in real time by means of theoretical modeling or experiment; these quantities must be determined using a simulation method. Consequently, there is considerable interest in seeking simulation of vibration-induced fretting between the twist-pin and socket contact pair.

Fretting occurs at a mated electrical connector, causing metal transfer, wear and oxidation of the contact surface. One challenging aspect of fretting simulation is to make the stiffness value and the mated state of the twist pin as close as possible to its value in the real situation. Chen [23] mentioned that a mating step was created in the modeling simulation, while in numerous research studies on fretting, a force or stress was loaded directly on the contact body. Their simulations focused on the fretting wear process of contact pairs and ignored the previous insertion process. However, it is noted that the insertion process can produce the initial stress for contact pairs; in fact, studying the fretting wear is based on considering a certain stress caused by the insertion process. Therefore, this paper proposes a new 3D finite element (FE) model of a twist pin-socket contact pair for a micro-rectangular electrical connector. The fretting process caused by vibration can be understood through numerical simulations. The dynamic characteristics and fretting behavior of the twist pin-socket contact pair are analyzed while considering the effects of the initial stress during insertion process. After we determine the relationship among contact force, contact resistance and contact area, the fretting fatigue life can be effectively evaluated.

2. Finite element model

We use a typical twist-pin/socket to conduct a simulation on the fretting propensity in a micro-rectangular electrical connector. Pin contact of the male micro-rectangular is comprised of ten strands of copper-beryllium (Cu-Be) alloy held together, welded on both ends, and later bumped. The bumped area of the twist pin would be compressed during the insertion and the retention inside the mated socket. Therefore, seven electrical contact points are ensured with high reliability of the electrical connect.

A 3-dimensional geometry model of the twist pin and socket contact pair was built utilizing Pro/E software according to the actual dimensions of the contact interfaces. Normally, the convergence and accuracy of numerical model are depended on the element selection and meshing technology [24–26]. In this investigation, the twist pin structure is formed by copper wires twisted around, which is not suitable for using the incompatible element. Hence, the FE model adopts a three-dimensional hexahedral element with eight nodes and reduced integration, which is suitable for hourglass control and can get much more convergence in the stress and displacement analysis. Meanwhile, the structured and swept meshing technologies are applied for improving the accuracy, which are always used in the dynamic analysis. The socket movement was carried out under displacement load. Comparing to force load, the displacement load can get better convergence. The detailed section of the twist pin and socket is shown in Fig. 1. The FE model as presented in Fig.1 included 55,138 nodes, 34,457 linear hexahedral elements and 5946 quadratic tetrahedral elements. Because the FE model was considered as continuous elastic model, its constitutive equations based on the Generalized Hooke's Law [27] can be given by

$$e_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\sigma_{kk}\delta_{ij} \tag{1}$$

$$\sigma_{ij} = 2Ge_{ij} + \lambda e_{kk}\delta_{ij} \tag{2}$$

$$G = \frac{E}{2(1+\nu)} \tag{3}$$

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)} \tag{4}$$

where e_{ij}, e_{kk} are the strain tensors, σ_{ij}, σ_{kk} are the stress tensors, and δ_{ij} is called the Kronecker delta. ν is the Poisson's ratio, E is the Young's modulus, λ is called the Lamé constant, and G is the shear modulus.

The twist pin and socket were coaxially assembled, with the end of the pin being fixed and the socket moving as the load environment instead of exchanging the boundary conditions of the actual plugging process. The maximum diameter of the twist pin in the bumped area is 0.72 mm, whereas the socket has an inner diameter of 0.56 mm with a contact chamfer at the head. Namely, the radius ratio of the twist pin with ten strands and the socket is 0.36/0.28. Here, it should be pointed out that seven outer strands in the twist pin with ten strands are used to contact with the socket, while three inner strands are used to enhance the mechanical strength of the twist pin. The depth of the socket is 4 mm, and its outer diameter and inner diameter are 0.92 mm and 0.56 mm, respectively. In order to reduce the instantaneous impact and stress concentration caused by the twist pin insertion, the socket at the entrance is designed to be chamfering structure. Its chamfering radius is 0.42 mm. Moreover, the socket is the same alloy as the twist pin, which is also Cu-Be alloy.

The contact property of the twist pin and socket was a surface to surface contact between the external face of each twist pin strand and the inner socket face.

The material properties of each model part were established according to the real material properties as close as possible. The major properties, density, elastic and friction coefficient of each part of the system were matched as indicated in Table 1.

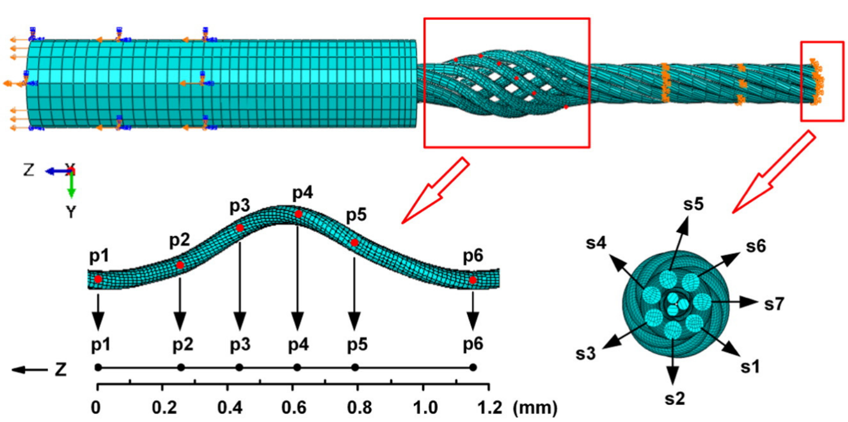

Fig. 1. 3-D finite element model of a twist-pin/socket contact system. The strands (s1 to s7) were clockwise distributed in a ring array. The nodes (p1 to p6) were selected along twist path on strand s5. The distance along the Z direction between these nodes can be determined by the ruler. Node p4 was the closest node to the center of the bumped area among these six nodes listed.

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