Numerical Investigation on Crack Detection Technique for Electric Connector with Joule Heating Effect

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Abstract: Using the electro-thermo-structural coupled-field finite element analysis, the crack detection technique with the Joule heating effect for the electric connector is studied and discussed. The physical behavior of the electric connector with an edge crack is investigated numerically. The electric current density, Joule heating temperature and structural deformation are obtained. As a result, the electric current concentration and Joule heating effect can induce a local hot spot or hot band region around the crack tip. Furthermore, the crack tip location can be determined according to the temperature distribution. For the accurate crack detection, two better electric loading conditions are found as follows: (a) shorter electric operating time (t_p), (b) larger electric current (I_0). The optimal condition, $I_0 = 100$ A and $t_p = 0.001$ s, is found for this crack detection research.

Keywords: Electric connector, Electro-thermo-structural, Joule heating, Crack detection, Finite element,

1. Introduction

The electric connector as shown in Fig. 1 is widely used in electronic products such as mobile phones, cameras and laptop computers. When the connector touches the electrode, the electric current or signal can be transferred through the contact surface. The electric connector is usually designed as an elastic spring to keep the electric contact on the connector/electrode interface. Under the working condition, the connector is subjected to the electro-thermo-structural coupling loads.

The strength and reliability of the electric connector are very important so that the existence of the crack or defect must be avoided or controlled. The cracks may exist in the electric connector after long working period. If a crack is found, the unstable crack growth must be avoided. The cracked electric connector must be replaced by a new one to keep a good working condition.

The crack detection technique is an important issue for the structural health and strength of the electric connector. The Joule heating method [1]~[3] is one of the crack detection technique and can be applied on the electric connector. Many researches have reported that the Joule heating effect can induce the local hot spot at the crack tip [1]~[5]. As shown in Fig. 2, when the crack tip is subjected to the electric load, the electric current density field concentrates at the crack tip. Due to the Joule heating, the electric concentration causes the hot spot at the crack tip zone. The crack tip location can be determined according to the hot spot, and the crack detection is achieved.

In this paper, the physical behavior of the electric con-

Figure 1: Typical electric connector.

Figure 2: Hot spot at crack tip.

connector with an edge crack is investigated using the electro-thermo-structural coupled-field finite element analysis. The electric current density, Joule heating temperature and structural deformation are obtained. Especially, the temperature field and hot region around the crack tip are discussed. Furthermore, the crack detection technique with the Joule heating effect is numerically investigated.

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Figure 3: Case study of this research.

Figure 4: Geometry of this research.

(a) Full model

(b) Local mesh around crack

Figure 5: Finite element model.

Table 1: Material data of UNS C17000 beryllium copper [6].

density	8260 kg/m ³
thermal conductivity	118 W/m-K @ 20 °C
	145 W/m-K @ 200 °C
specific heat	420 J/kg-K
resistivity	1* 10 ⁻⁷ Ω-m
coefficient of thermal expansion	1.67* 10 ⁻⁵ 1/°C @ 20~100 °C
	1.70* 10 ⁻⁵ 1/°C @ 200 °C
	1.78* 10 ⁻⁵ 1/°C @ 300 °C
Young's modulus	115 GPa
Poisson's ratio	0.3
Yielding strength	190 MPa
tangent modulus	11.5 GPa
melting point	865-980 °C

2. Problem Definition and Finite Element Analysis

In Fig. 3 and Fig. 4, it shows the sample geometry, boundary condition and electric load of this research. The crack length is denoted as a . The sample is subjected to a direct current (DC) I_0 . The material type of the sample is the UNS C17000 beryllium copper. In Table 1, it lists the material data [6].

The following conditions are considered in this study:

- (1) Three-dimensional analysis
- (2) Electro-thermo-structural coupled-field
- (3) Transient heat transfer
- (4) Convection on air/sample interface
- (5) Steady electric current (DC current)
- (6) Temperature-dependent material data
- (7) With electric/thermal/mechanical contact condition on crack surface

In this research, the finite element equation of the electro-thermo-structural coupled-field analysis is listed as the following matrix-form [7]:

$$\begin{bmatrix} M & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{U} \\ \dot{T} \\ \dot{V} \end{bmatrix} + \begin{bmatrix} C & 0 & 0 \\ C^{tu} & C^t & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} U \\ T \\ V \end{bmatrix} + \begin{bmatrix} K & K^{ut} & 0 \\ 0 & K^t & 0 \\ 0 & 0 & K^v \end{bmatrix} \begin{bmatrix} U \\ T \\ V \end{bmatrix} = \begin{bmatrix} F \\ Q \\ I \end{bmatrix} \quad (1)$$

where U , T , V , F , Q and I are the vector forms of the displacement, temperature, electric potential, force, heat flow rate and electric current, respectively. The material constant matrices M , C , C^t , C^{tu} , K , K^t , K^{ut} and K^v are the structural mass, structural damping, thermal specific heat, thermo-structural damping, structural stiffness, thermal conductivity, thermo-structural stiffness and electric conductivity, respectively. The coupled heat flow matrix Q contains the effects of the thermal loading and electrical Joule heating. C^{tu} and K^{ut} are thermo-structural coupled terms. Eq. 1 is a directly coupled nonlinear equation which is solved using the Newton-Raphson iterative method.

Figure 5 shows the finite element model of ANSYS. It is modeled by the SOLID226 element, i.e. the 20-node isoparametric solid element associated with the electro-thermo-structural analysis. The crack tip region is modeled by the quarter-point elements for expressing the $r^{-1/2}$ singularity of the electric current density field.

The electric/thermal/mechanical contact condition on the crack surfaces is considered in the simulation. The approximate method proposed in [8][9] is adopted in this study. The ANSYS contact element types: TARGE170 and CONTA174 are utilized to express the electric/thermal/me-

Figure 6: Temperature distribution (units: °C).

Figure 8: Electric current density field (units: A/m²).

Figure 7: Hot band region in front to crack tip.

Figure 9: Electric concentration around crack tip.

chanical contact condition along the crack surfaces.

3. Results and Discussions

3.1 Hot Region near Crack Tip In this research, the geometric parameters are as follows:

- (1) $l = 3.8$ mm, $h = 2.42$ mm
- (2) $R_1 = R_2 = 0.5$ mm, $R_3 = 0.3$ mm
- (3) $e = 0.1$ mm, $w = 1$ mm
- (4) $a = 0.5$ mm, $b = 1$ mm

In addition, the heat transfer parameters for the heat transfer are as follows:

- (1) $T_0 = T_\infty = 26$ °C
- (2) Convection coefficient: $h_c = 21$ W/m² - K

As a result, Fig. 6~Fig. 9 show the temperature field and electric current density under $I_0 = 20$ A at 0.25 s. It can be seen that the Joule heating effect causes a high temperature area (local hot band region) in front to the crack tip. Also, there is a local concentration of the electric current density near the crack tip. Similar to the elastic stress field, the electric current density also has the $r^{-1/2}$ singularity at the crack tip [2].

Figure 10: Temperature distribution without crack (units: °C).

3.2 Effect of Crack Figure 10 shows the temperature distribution without the crack. There is no local hot region in this case. However, in Fig. 7, it proves that the local hot region can be used to determine the crack tip location. This concept can be applied to the crack/defect detection by the use of the thermal camera and image.

3.3 Effect of Electric Operating Time In this section, the condition $I_0 = 20$ A is used. Referring to Fig. 7, the temperature distribution along the path LCM is discussed. For the discussion, the temperature ratio T/T_L is defined,

Figure 11: Distribution of T/T_L under different t_p . Figure 12: Distribution of T/T_L under different I_0 .

where T_L is the edge temperature at the point L . The larger value of T/T_L at the crack tip implies the larger temperature difference between the crack tip and environment. Above situation is better for the crack detection.

In Fig. 11, it shows the distribution of T/T_L along the path LCM under different operating times (t_p). The values of T/T_L almost keep constant along the position 0.5~1 mm, *i.e.* the path CM. As a result, the crack tip location (point C) can be determined by the Fig. 11. When the electric operating time t_p is shorter, T/T_L at the crack tip is larger. The shorter electric operating time is better for the crack detection.

3.4 Effect of Electric Current In this section, the condition $t_p = 0.25$ s is used. In Fig. 12, it shows T/T_L distribution under different I_0 . The curves are similar to Fig. 11. When the electric current I_0 is larger, T/T_L at the crack tip is larger. Larger electric current is better for the crack detection.

3.5 Optimal Condition for Crack Detection According to previous sections, two better loading conditions

Figure 13: Distribution of T/T_L of three cases.

(a) Case-1

(b) Case-3

Figure 14: Temperature contours.

for the crack detection are found as follows: (a) shorter electric operating time, (b) larger electric current. Based on above conclusions, the following three cases are adopted for the further analysis:

- (1) Case-1: $I_0 = 30$ A, $t_p = 0.15$ s
- (2) Case-2: $I_0 = 70$ A, $t_p = 0.03$ s
- (3) Case-3: $I_0 = 100$ A, $t_p = 0.001$ s

In Fig. 13, it shows the distribution of T/T_L of three cases. Obviously, a peak value of T/T_L occurs at the crack tip in Case-3. Also, this case has larger values of T/T_L than

other two cases. It implies that the loading condition of Case-3 is optimal case in this analysis.

From the temperature contours in Fig. 14, it shows the advantage of the Case-3 condition. In Case-3, a local hot spot occurs at the crack tip and it can be used to determine the crack tip location precisely. However, in Case-1, a hot band region in front to crack tip is observed. For the crack detection, the band region is not as good as the hot spot.

4. Conclusion

The crack detection technique with the Joule heating effect is numerically investigated in this paper. For the accurate crack detection, two better electric loading conditions are found as follows: (a) shorter electric operating time (t_p), (b) larger electric current (I_0). The optimal condition, $I_0 = 100$ A and $t_p = 0.001$ s, is found for this crack detection research.

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