Modeling and Simulation of Multi-Material Soldering Performance for Spacecraft

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Abstract. In recent years, there have been several on-orbit failure cases of spacecraft thermistor circuit. Through the analysis of failure mode, it is confirmed that the failures are mostly caused by the failure of wire solder joint. In this paper, the finite element method (FEM) is used to simulate the effects of different soldering parameters on the stress-strain characteristics of spacecraft solder joints in cold-hot alternating environment.

1. Introduction

In recent years, some thermistors, which is used to measure the temperature of satellite during the in-orbit work in order to get the working temperature of the instruments or panels, outside the satellites lost their functions during the in-orbit work. It brought troubles for thermal control of the satellites. So analysis and experiment are carried to find the reasons to help us to improve the design and assembly of the thermistor circuit.

During the service of mechanical and electrical products, due to the change of ambient temperature, conductors and devices will produce thermal expansion and contraction behavior. Therefore, in the design of products, it is necessary to focus on how to improve the reliability of products under complex environment [1-2]. As the key link of the thermistor circuit cable connection, the multi-material soldering interface on spacecraft often fails when the on-orbit environment temperature changes dramatically. For printed circuit boards, people usually use higher experimental temperature and faster heating rate than the actual service environment to conduct accelerated thermal cycle test, in order to study the fatigue life of soldering interface. In the course of satellite service, cables outside cabins have high and low temperature cycling effect, so it is particularly important to analyze the reliability of cable solder joints. However, previous studies mostly focus on the package circuit board, and the research on the interface between pins and wires rarely involves [3-5]. In order to locate the failure point accurately, study was carried out to find out the failure reason and put forward improvement method.

Finite element analysis software ANSYS is used to analyze the thermal stress of wire soldering of dissimilar materials. The method of direct coupling temperature field and stress field is adopted, that is,
the thermo-stress coupling unit is selected, and the temperature freedom and displacement freedom are completely coupled together. A 20-node hexahedron coupling unit 226 is selected, and the analysis type is set to Structural-therma [6].

2. Finite element modeling
According to the actual structure size, a geometric model is established through reasonable simplification, the parameter setting is as follows: the pin diameter $D_1$, the wire diameter $D_2$, the solder diameter $D_3$, the corresponding radius dimension are respectively $R_1$, $R_2$ and $R_3$, and the distance between the wire and the pin is $H_1$, the solder tin thickness is $H_2$, the length of the wire is $L_1$, the length of the wire is $L_2$, the length of the solder $L_3$, as shown in Figure 1 and Figure 2.

![Modeling Diagram of Soldering Form](image1)

Figure 1. Modeling Diagram of Soldering Form

![Modeling Diagram of Soldering Dimension](image2)

Figure 2. Modeling Diagram of Soldering Dimension

According to the actual sizes of pins and wires, $D_1$ is 0.3 mm and $D_2$ is 0.37 mm. The length of pin is 15 mm, the length of wire is 10 mm, and the length of soldering tin is 5 mm. Different soldering tin diameters $D_3$ can be obtained by adjusting $H_1$ and $H_2$, $D_3 = D_1 + D_2 + H_1 + 2 \cdot H_2$. When modeling, set the solder tin center to be at the origin of coordinates, then the $Y$ axis coordinates of pin center $Y_1 = R_3 - H_2 - R_1$, the $Y$ axis coordinates of wire center $Y_2 = -(R_3 - H_2 - R_2)$. The values of $H_1$, $H_2$ and $D_3$ are shown in Table 1.

| No. | H1 (mm) | H2 (mm) | D3 (mm) |
|-----|---------|---------|---------|
| 1   | 0.1     | 0.15    | 1.07    |
| 2   | 0.15    | 0.15    | 1.12    |
| 3   | 0.15    | 0.2     | 1.22    |
| 4   | 0.2     | 0.15    | 1.17    |
| 5   | 0.2     | 0.2     | 1.27    |
| 6   | 0.2     | 0.25    | 1.37    |
Considering the calculation accuracy and time, the reasonable element size is set up, and the finite element model is established as shown in Figure 3.

Figure 3. Finite element model of the multi-material solder joint

3. Parameters setting
In this paper, the ideal elastic-plastic model of bilinear follow-up hardening is adopted. The material parameters required are elastic modulus, tangent modulus, yield strength, Poisson's ratio and linear expansion coefficient. The tangent modulus is 0.01% of the elastic modulus, which is conducive to the convergence of calculation. The material parameters are shown in Table 2. Fixed constraints in X, Y and Z directions are applied to pin and wire respectively, and then temperature loads are applied to all joints. The loading conditions are (+140°C) and (-150°C).

4. Simulation analysis
The soldering of pins and copper wires is accomplished by manual operation. The deviation of manual operation will inevitably lead to the difference of the distance between pins and copper wires \( H_1 \) and the thickness of soldering tin \( H_2 \), and the difference of these parameters may affect the performance of joints. In addition, the fixing position (restraint condition) of soldered joints is also an important factor affecting the performance. Therefore, the effects of wire spacing, solder tin thickness and constraints on the stress and strain of joints during cold and hot cycles are studied by means of finite element analysis.

4.1. Effect of wire spacing on Stress during the hot-cold Cycling
When the solder tin thickness \( H_2 \) is 0.15 mm, and the wire spacing is equal to 0.1 mm, 0.15 mm and 0.2 mm respectively, the variation rule of the calculation results under 150°C is analyzed. Fig. 4 is the overall deformation displacement diagram. It can be found that three results have different degrees of deformation, of which 0.15-0.15 results are the most serious. The deformation of pin side is larger than that of wire side, and the maximum displacement occurs near the outer pin of solder. From Mises equivalent stress nephogram of solder, it can be clearly seen that the pin side solder stress is larger, reaching the yield stress of solder material (41 MPa). The maximum stress occurs in the solder between the pin and the wire, and is close to the end of the pin extension. The maximum total strain occurs at the connection between the pin and the pin, and the position is inclined to the inside of solder. The maximum plastic strain is slightly less than the maximum total strain, and the position is the same as the maximum total strain. According to the above analysis, due to the large difference of linear expansion coefficient between solder material and pin wire, serious inconsistency of deformation caused by heating leads to large thermal stress on the interface between solder and pin. Table 3 summarizes the stress and strain at different wire spacing. It shows that the change of wire spacing has some influence on the calculation results. With the increase of wire spacing, the maximum plastic strain of solder decreases gradually.

| material       | elastic modulus (GPa) | Tangent modulus (MPa) | yield strength (MPa) | Poisson's ratio | linear expansion coefficient × 10^6/°C |
|----------------|-----------------------|-----------------------|----------------------|----------------|--------------------------------------|
| pin            | 150                   | 15                    | 750                  | 0.3            | 6                                    |
| wire           | 130                   | 13                    | 150                  | 0.3            | 16                                   |
| solder tin     | 43                    | 4.3                   | 41                   | 0.36           | 24.5                                 |

Table 2. Values of material parameters
Table 3. Effect of Wire Spacing on Stress and Strain

| Wire spacing H1 (mm) | 0.1  | 0.15 | 0.2  |
|----------------------|------|------|------|
| Total maximum stress (MPa) | 690  | 770  | 658  |
| Maximum plastic strain of solder joint | 0.0664 | 0.0608 | 0.0594 |

4.2. Effect of Soldering Tin Thickness

When $H_1$ is 0.2 mm, $H_2$ is equal to 0.15 mm, 0.2 mm and 0.25 mm respectively, the variation law of calculation results under 150°C is analyzed. As shown in table 4, it can be seen that the change of solder thickness has no obvious effect on stress and strain, and the maximum plastic stress of solder will increase when the solder thickness reaches a certain level.

Table 4. Effect of Soldering Tin Thickness on Stress and Strain

| Soldering tin thickness $H_2$ (mm) | 0.1  | 0.15 | 0.2  |
|-----------------------------------|------|------|------|
| Total maximum stress (MPa)        | 658  | 760  | 664  |
| Maximum plastic strain of solder joint | 0.0594 | 0.0594 | 0.0984 |

4.3. Effect of Restraint Mode

When wire spacing $H_1$ is equal to 0.15 mm and solder tin thickness $H_2$ is equal to 0.2 mm, two sides (both sides of pin and wire) constraints and one side (pin or wire) constraints are applied to solder joint respectively, and the calculation results are analyzed. From the overall deformation displacement map, it can be found that the unilateral constraint reduces the deformation distortion obviously, and the maximum deformation displacement is one order of magnitude different from the two end constraints. The maximum stress of fixing both sides is 679 MPa. While the maximum stress of unilateral restraint occurs at the one end fixed restraint, the maximum stress value is about 150 MPa, which is significantly lower than that of two-side restraint, and the stress of pin-to-solder junction is smaller. Although unilateral restraint has reached the yield state, the yield area is smaller than that of bilateral restraint. That means one side restraint can significantly reduce the overall stress and the yield degree of solder. From the plastic strain nephogram of solder, it can be found that the plastic strain of solder under one side restraint decreases by about 50% compared with that under bilateral restraint. The specific data are shown in Table 5.

Table 5. Effect of Soldering Restraint Mode on Stress and Strain

| Fixing position | Both sides of pin and wire | pin | wire |
|-----------------|----------------------------|-----|------|
| Total maximum stress (MPa) | 679  | 149 | 150  |
| Maximum plastic strain of solder joint | 0.0805 | 0.0422 | 0.0422 |

5. Conclusion

In this paper, the finite element method is used to simulate the stress and strain of welded joints of various materials on spacecraft during cold-hot alternation. The main conclusions are as follows:

1) The maximum stress and strain of solder joint during cold and hot cycling are located at the interface between pin and solder. 2) Appropriate increase of wire spacing is beneficial to increase the cold and hot cycle life of solder joints. 3) Lowering the constraints at both ends of solder joints will have a positive impact on the cold and hot cycle life. 4) Increasing solder tin thickness is not helpful to improve the cold and hot cycle life of solder joints.

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