Research on coating method of thermal conduction silicone grease for spacecraft equipment based on stencil printing

Tao Guo¹,²,³, Dongmei Wang¹,², Zhanping Guo¹, Xing Fan¹ and Zhilong Zhang¹

¹Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China
²Beijing Engineering Research Center of the Intelligent Assembly Technology and Equipment for Aerospace Product, Beijing 100094, China
³E-mail: guotao102@163.com

Abstract. Thermal conduction silicone grease coating is one of the most important methods for passive temperature control of spacecraft equipment. It is difficult to have quantitative control over coating thickness and coating uniformity by manual coating method. This paper introduces the application, coating method and heat transfer mechanism of thermal conduction silicone grease, and proposes a thermal conduction silicone grease coating method for spacecraft equipment based on stencil printing. Also, this paper proves that the method is feasible with pull-off test, thermal vacuum test and thermal conduction test. The test results found that the contact rate of thermal conduction silicone grease with stencil coating is higher than that with manual coating; stencil coating does not cause abnormal overflow of thermal conduction silicone grease; the thermal conduction with stencil coating is nearly the same as that with manual coating.

1. Introduction

The spacecraft thermal control technology is mainly used to ensure that the structural components and instruments of the spacecraft are in a suitable temperature range in a harsh space environment, and can maintain normal operation [1], and is generally divided into active thermal control technology and passive thermal control technology. Spacecraft equipment and its components will release a lot of heat in operation. Therefore, poor heat passages will cause local temperatures to be too high, affecting the functions and even life of equipment [2]. Studies found that the reliability of power equipments are closely related to operating temperature. According to the Arrhenius model, the degradation rate of the power equipment chip changes exponentially with temperature, and its reliability decreases by 10% for every 2°C increase in temperature [3, 4]. Therefore, heat dissipation performance has become a key factor limiting the service life of power equipments. For the thermal design of spacecraft equipment, the most common and simplest way is to apply thermal conduction silicone grease between the surface of the equipment and its structural mounting surface. Thermal conduction silicone grease is a paste-like thermal interface conduction material with good thermal conduction and is widely used in aerospace, computer, automotive and other fields [5]. The factors affecting the thermal conduction after the thermal conduction silicone grease is coated include: the physical properties, the coating thickness, and the coating uniformity of the thermal conduction silicone grease. As the environment for the spacecraft is special, there are strict requirements on the material properties of the thermal conduction silicone grease. Generally, the total mass loss rate of the thermal conduction silicone grease in the space environment is required to be within 1.0%, and the condensable volatile
matter is required to be within 0.1%. The thickness of the thermal conduction silicone grease coating is closely related to the flatness of the equipment and its mounting surface. Generally, the thickness is required to be as thin as possible, under the premise of ensuring the filling of the gap between the two, for too much coating may cause the spacecraft to have oil climbing in the process of the thermal vacuum test, and then cause pollution.

The main coating method for spacecraft equipment to be coated with thermal conduction silicone grease is scraper coating: placing a proper amount of thermal conduction silicone grease in the center of the coating surface, and using the scraper to rotate the thermal conduction silicone grease in a clockwise, counterclockwise or horizontally or vertically to fill the entire mounting surface, and the filling should be as uniform as possible. The effect of thermal conduction silicone grease with scraper coating is completely dependent on the skill of the operator, making it difficult to have quantitative control over the coating thickness and coating uniformity of thermal conduction silicone grease. Nonetheless, the stencil printing method is a coating method which can realize quantitative control and uniformity control and is widely used in small products such as IGBT [6].

In this paper, the heat transfer mechanism of thermal conduction silicone grease coating is introduced. Also, the coating method of thermal conduction silicone grease for spacecraft equipment based on stencil printing is introduced. Moreover, the method is verified to be feasible with pull-off test, thermal vacuum test and thermal conduction test.

2. Heat transfer mechanism

When two very smooth planes are in contact with each other, the contact interface is microscopically irregular and defective. In fact, only a few discrete points are actually contacted [7], as shown in Figure 1. Only the contact area can have heat transfer by means of "heat conduction", and the effective heat transfer area is small, resulting in a large heat transfer resistance. The results show that at the microscopic level, the actual contact area between most planes is less than 2% of the total surface area. After being applied, the thermal conduction silicone grease will effectively fill the non-contact areas between the two planes and become the medium for heat transfer between the interfaces. Tests have shown that the contact heat transfer coefficient is larger with aluminum-aluminum interfaces coated by thermal conduction silicone grease than that without aluminum-aluminum interfaces coated by thermal conduction silicone grease by at least one order of magnitude [1].

3. Stencil printing method

Stencil printing is to open a small number of holes in a rigid metal plate, and place the stencil on the coating surface, and then place an appropriate amount of thermal conduction silicone grease in the center of the stencil, and use a scraper to spread evenly. Thermal conduction silicone grease will be retained on the coated surface through small holes in the stencil.
The flatness of the installation surface of the spacecraft equipment is better than 0.1mm/400mm, and the size of the equipment is generally not more than 400mm. Therefore, the coating thickness of the thermal conduction silicone grease should be the same as the flatness. It is recommended that the coating thickness be no more than 100μm.

For the application conditions of the spacecraft equipment coated with thermal conduction silicone grease, the stencil production process is as follows:

1. Measure the mounting surface of the equipment that coats thermal conduction silicone grease to obtain the length a and width b of the coating surface, the size of steel plate trepanning area is A and B, A and B should be larger than a and b, as shown in Figure 2;

2. After determining the size of steel plate trepanning area, design the trepanning ratio C, C is equal to the ratio of the black open area to A*B;

3. The coating thickness of thermal conduction silicone grease is h, and the thickness of the metal plate is H=h/C;

4. After determining A, B, C and h, select the metal plate with thickness H to complete the processing of the stencil, and then fix the stencil to a rectangular box of appropriate size to complete the final processing. The rectangular box secures the stencil for it to maintain a good flatness.

The trepanning rate and thickness of the stencil are known and the thickness is uniform. The stencil coating method can realize the quantitative control of the coating thickness and uniformity of the thermal conduction silicone grease.

![Figure 2. Stencil production design.](image-url)

4. Process test

After coating thermal conduction silicone grease with stencil, there is no thermal conduction silicone grease in the non-trepanning area. After being installed, the equipment will be moved forward and backward, left and right, to ensure that the thermal conductive silicone grease is filled into the non-trepanning area. However, there is no test and data support in terms of if there is air left in the thermal conduction silicone grease and whether the air left will affect the thermal conduction performance and if oil climbing will be caused during the thermal vacuum test. This section conducts relevant verification by pull-off test, thermal conduction test, and thermal vacuum test.

4.1. Pull-off test

The pull-off test is mainly to verify the influence of stencil coating and manual coating on the contact rate of thermal conduction silicone grease, and the higher the pull-off force, the higher the contact rate of thermal conduction silicone grease, and vice versa. The pull-off test is divided into two parts: 1, the lateral pull-off test (the pull force sensor is used to push the equipment along the parallel direction of the equipment mounting surface, and the maximum thrust of the relative displacement of the equipment against the simulation plate is recorded); 2, the vertical pull-off test (the tension sensor is used to pull the equipment vertically along the mounting surface of the equipment, and the maximum pull force is recorded when the equipment is disconnected from the simulation plate).
In order to ensure the consistency of the total amount of thermal conduction silicone grease coated with stencil between that coated manually. Manual coating procedure is as follows: firstly, stencil coating is conducted before scraper is used to gather thermal conduction silicone grease in the center of the equipment, and at last, the coating is made even manually. Each method is applied 10 times.

Each coating starts between 9:00 and 10:00 in the morning. After being coated, the coated equipment is mounted on the simulation board, and fasteners are installed, and the fasteners are tightened to a force of M5:4.5Nm. The pull-off test of the equipment is carried out from 8:30 to 9:00 the next day. This solution ensures that the time from the coating to the pull-off test is equal and thus the time period inconsistency affecting the test results is eliminated.

The thermal conduction silicone grease after the pull-off test is shown in Figure 3. The contact rate of the thermal conduction silicone grease coated with stencil is 100%, and that of the thermal conduction silicone grease coated manually is slightly lower. The pull-off test results are shown in Table 1. As shown by Table 1, the mean values of the vertical pull-out force and the horizontal pull-off force of the stencil coating are larger than that of the manual coating, indicating that the thickness uniformity of the stencil coating is better than that of the manual coating.

![Comparison of thermal conduction silicone grease forms after vertical pull-off tests.](image)

(a) Stencil coating  (b) Manual coating

**Figure 3.** Comparison of thermal conduction silicone grease forms after vertical pull-off tests.

| Times | Vertical Pull-off force (N) | Horizontal Pull-off force (N) | Vertical and Horizontal Pull-off force (N) |
|-------|-----------------------------|-------------------------------|------------------------------------------|
|       | Stencil coating | Manual coating | Stencil coating | Manual coating | Stencil coating | Manual coating |
| 1st   | 18.03           | 28.01             | 4.01           | 2.45           | 22.04           | 30.46           |
| 2nd   | 31.59           | 21.15             | 3.02           | 1.44           | 34.61           | 22.59           |
| 3rd   | 31.93           | 31.49             | 3.02           | 1.86           | 34.95           | 33.35           |
| 4th   | 19.07           | 21.08             | 2.96           | 1.50           | 22.03           | 22.58           |
| 5th   | 29.34           | 18.73             | 2.70           | 1.53           | 32.04           | 20.26           |
| 6th   | 30.70           | 24.56             | 2.50           | 3.22           | 33.20           | 27.78           |
| 7th   | 35.40           | 27.83             | 3.52           | 2.77           | 38.92           | 30.60           |
| 8th   | 24.85           | 21.19             | 4.35           | 2.55           | 29.20           | 23.74           |
| 9th   | 26.35           | 20.03             | 3.54           | 1.70           | 29.89           | 21.73           |
| 10th  | 35.54           | 29.36             | 2.54           | 2.40           | 38.08           | 31.76           |
| AVG   | 28.28           | 24.34             | 3.22           | 2.14           | 31.50           | 26.49           |
4.2. Thermal vacuum test
The thermal vacuum test is mainly to verify whether the stencil coating causes the coated thermal conduction silicone grease to overflow in a vacuum environment. The test environment is set as the ergodic environment for the thermal test of the spacecraft and the test results are shown in Figure 4. The coated thermal conduction silicone grease overflows whether it is stencil coating or manual coating, and there is no significant difference in the degree of overflow. Indicating that after the thermal vacuum test, the process of stencil coating does not overflow abnormally.

(a) Stencil coating - before thermal vacuum test  (b) Manual coating - before thermal vacuum test

(c) Stencil coating - after thermal vacuum test  (d) Manual coating - after thermal vacuum test

Figure 4. Thermal conduction silicone grease overflow comparison.

4.3. Thermal conduction test
The thermal conduction test is mainly to verify the effect of stencil coating and manual coating on thermal conduction performance. Two heating plates are attached (the single heating plate resistance is 10±0.2Ω) at the center of the lower surface of each equipment to form a heating circuit, and the 24V power supply is used to supply power to the heating circuit; the thermistor is pasted at the center of the upper surface of the equipment. The temperature data of the thermistor is recorded, and the results are shown in Table 2, Table 3 and Figure 5. As shown by Figure 5, the thermal conduction performance of the equipment with stencil coating is slightly better than that with manual coating, but the difference is not significant.

Table 2. Thermistor heating data of stencil coating.

| Time  | Equipment 1 | Equipment 2 | Equipment 3 | Equipment 4 | AVG    |
|-------|-------------|-------------|-------------|-------------|--------|
| 11:01 | 0.150       | 0.148       | 0.145       | 0.143       | 0.147  |
| 12:00 | 0.118       | 0.115       | 0.115       | 0.114       | 0.116  |
| 13:00 | 0.096       | 0.093       | 0.093       | 0.094       | 0.094  |
| 14:01 | 0.080       | 0.079       | 0.079       | 0.078       | 0.079  |
| 15:01 | 0.067       | 0.067       | 0.067       | 0.067       | 0.067  |
| 15:26 | 0.063       | 0.063       | 0.063       | 0.063       | 0.063  |
Table 3. Thermistor heating data of manual coating.

| Time   | Equipment 5 | Equipment 6 | Equipment 7 | Equipment 8 | AVG  |
|--------|-------------|-------------|-------------|-------------|------|
| 11:01  | 0.142       | 0.142       | 0.137       | 0.143       | 0.141|
| 12:00  | 0.113       | 0.113       | 0.109       | 0.116       | 0.113|
| 13:00  | 0.092       | 0.092       | 0.090       | 0.095       | 0.092|
| 14:01  | 0.078       | 0.077       | 0.074       | 0.079       | 0.077|
| 15:01  | 0.065       | 0.064       | 0.063       | 0.068       | 0.065|
| 15:26  | 0.061       | 0.060       | 0.060       | 0.063       | 0.061|

5. Conclusions

This paper proposes a coating method based on stencil printing for spacecraft equipment to be coated with thermal conduction silicone grease, which can realize quantitative control of coating thickness and uniformity of thermal conduction silicone grease. The pull-off test is used to indirectly prove that the contact rate of thermal conduction silicone grease with stencil coating is better than that with manual coating. The thermal vacuum test proves that the stencil coating does not cause the thermal conduction silicone grease to overflow abnormally. The thermal conduction performance of the equipment with stencil coating is slightly better than that with manual coating. Therefore, stencil printing can be used to coat thermal conduction silicone grease for spacecraft equipment.

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