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Research on Thermal Sealing Technology in Aerospace Manufacturing

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Abstract: *With the development of aerospace manufacturing technology, spacecraft need to withstand increasingly severe flight conditions. The enormous heat flow brought about by high-speed flight and its susceptibility to damage to the internal equipment and structural components of the aircraft. The thermal sealing structure of the gap between the outer thermal insulation layers of a spacecraft is a key component of the spacecraft's thermal protection capability. This article introduces the development status of thermal sealing technology, design methods of spacecraft thermal sealing mechanisms, and several typical thermal sealing structures in aerospace manufacturing.*

Keywords: *Heat sealing structure; Aerospace manufacturing; Spacecraft; Heat resistant structure*

1. Introduction

Nowadays, with the development of technology, the flight speed of spacecraft is getting faster and faster. During the flight operation of a spacecraft, the friction between itself and the atmosphere, aerodynamic loads, and thermal radiation generated by the power system can all cause a large amount of heat to be generated on the surface of the spacecraft, resulting in a significant temperature rise on the surface, which seriously restricts the testing indicators of the spacecraft. To solve the negative impact of surface temperature rise on aircraft, it is necessary to use high-performance and technologically advanced thermal protection systems and thermal sealing technology to protect the aircraft, in order to ensure that the flight indicators of the aircraft are not affected by the thermal environment to the greatest extent possible.[1]

Thermal sealing technology is the foundation of the aerospace design and manufacturing industry, and is a key design indicator for all components in extreme high-temperature environments. Therefore, whether it is a manned spacecraft or a gliding and cruising aircraft, the research on thermal sealing technology at positions such as cabin compartments, windows, and control surface gaps is a very important topic. [2]

2. Current Development Status of Thermal Sealing Technology

At present, there are two methods for aircraft thermal sealing technology. One is active thermal protection sealing, which uses the performance of the material itself and adopts active cooling to cool the surface of the aircraft, achieving a temperature controlled protection method. Then, the thermal sealing structure is downgraded to a universal sealing structure to reduce the severity of the sealing environment. Another type is passive thermal protection sealing, which uses insulation materials to cover the surface of the aircraft, playing a role in isolating heat sources. This type of thermal protection structure is generally a splicing structure, and there may be heat leakage in the splicing gaps, which requires strict thermal sealing protection.

2.1 Active thermal protection sealing

Among the active thermal protection sealing methods, the most commonly used method nowadays is sweating cooling, which has the highest cooling efficiency. [3-4] Spray cooling materials onto the surface of the aircraft through porous materials for extensive coverage, thereby reducing the surface temperature of the aircraft and optimizing the thermal environment during flight, so that the performance indicators of the sealing structure do not need to be very strict.

In recent years, the technology of active thermal protection sealing has gradually increased, and the main research direction for thermal protection materials is ceramic materials. For example, Remier et al. [5] conducted research using CMC materials, Forrest et al. [6] studied composite materials of Al_2O_3 and SiO_2.

Wu Yadong et al. [7] prepared porous metal materials by using an argon gas cylinder to provide high-pressure gas as a cooling and pressurizing power source, and used a quartz lamp for radiation heating. By adjusting the flow rate of cooling medium precipitated from porous materials, the effect of cooling medium flow rate on material surface temperature rise was experimentally studied. It was found that it is feasible to directly use metal materials as the outer wall of the aircraft without spraying heat-resistant materials through sweating cooling. By using sweating structures, the thermal environment of the aircraft can be greatly improved, thereby reducing the sealing structure requirements in the thermal environment, making the active thermal protection sealing method the best sealing method.

2.2 Passive thermal protection sealing

After decades of development, various high-temperature heat sealing components have been widely used in the aerospace field. Like HTV-2 In aircraft such as X-51 and X-37B, high-temperature sealing components are used to isolate the heat flux leaking from the gaps between insulation and protective materials.

Currently, there are three main types of passive thermal protection sealing methods in China: [8]:

1) Radiation method

Radiation method is a method of dissipating heat by radiating a large amount of heat to the surrounding area when the heating temperature rises. This method has the characteristic of not decaying with the consumption of heat-resistant layer materials and the extension of heating time, but its structure is complex. In general, this method is suitable for returning spacecraft with longer heating times, especially for space shuttles that have been used multiple times.

2) Heat sink method

The heat sink method is a passive thermal protection sealing method that uses the heat capacity of the structural material itself to absorb heat and achieve the purpose of heat protection. The anti heat sealing structure of this method is the simplest type of anti heat structure, but its efficiency is low, and the anti heat sealing is carried out at the cost of increasing the quality of the structure, and the heat absorption is relatively limited. It is generally only used in aircraft with small total heating and low Mach numbers.

3) Ablation method

The ablation method is a thermal protection method that exchanges material consumption for thermal protection. It has the characteristics of safety, reliability, and strong adaptability to flow field changes. Under high flow conditions, it is the only feasible thermal protection method, but only for one-time use. This method is the main thermal sealing method for spacecraft and missiles.

3. General design methods for thermal sealing structures of spacecraft

The thermal sealing structure design of spacecraft is a method of preventing external high-temperature gases and heat flows from infiltrating the interior of the spacecraft to the maximum extent through close contact. The mechanism of thermal sealing is to use the rebound characteristics of high-temperature sealing materials, apply pressure to fasteners and flange components to deform the high-temperature sealing materials and fill the gaps, and perform thermal sealing on the two contact surfaces. Fill the remaining gaps with high-temperature resistant sealant to block the possibility of other heat flows entering.

The design of spacecraft thermal sealing structures mainly revolves around the interface gaps in different parts of the spacecraft, including gaps between compartments, gaps at operating windows, and gaps between various moving components and the spacecraft. When designing a thermal sealing structure, it is necessary to first analyze the spacecraft's thermal environment, and then preliminarily determine the sealing form. Analyze and calculate the material parameters such as temperature resistance, thermal weight loss, and oxidation resistance of thermal sealing materials, and select thermal sealing materials based on their properties. By analyzing the compression rebound and friction wear performance of thermal seals, refining the thermal sealing scheme, and finally conducting a comprehensive evaluation of the thermal sealing effect, the design of the thermal sealing structure is completed.

There are several key elements in the design of thermal sealing structures, including the following:

3.1 The main properties of thermal sealing materials

The main properties of thermal sealing materials include their operating temperature, resilience at high temperatures, airtightness at high temperatures and pressures, and wear resistance in harsh environments. By studying and analyzing the main properties of thermal sealing materials, ideas can be provided for subsequent structural design and a design direction can be established.

3.2 Definition of performance parameters for thermal sealing materials

Define the performance parameters of thermal sealing materials, such as compression rate, rebound rate, thermal weight loss rate, and stress relaxation rate, based on the relevant mechanical industry standards for sealing.

The compression rate and rebound rate are defined according to the testing method specified in JB T 9141.4-1999. It can be calculated using equations (1) and (2). In the formula, *C* represents the compression rate； *R* is the rebound rate; t_0 is sample thickness under initial load,unit: mm; t_1 is sample thickness under final load,unit: mm; t_2 is sample thickness after unloading to initial load,unit: *mm*.

$$C = \frac{t_0 - t_1}{t_0} \times 100\% \tag{1}$$

$$R = \frac{t_2 - t_1}{t_0 - t_1} \times 100\% \tag{2}$$

The thermal weight loss rate is defined according to the testing method specified in JB T 9141.7-1999 and calculated according to equation (3). In the formula, *Wt* is the thermal weight loss rate at *t ℃*; *G* is the weight of the sample before burning, unit: *g*, G_1 is sample weight after burning,unit: *g*.

$$W_t = \frac{G - G_1}{G} \times 100\% \tag{3}$$

The stress relaxation rate is defined according to the testing method specified in JB T 7758.7-2008 and calculated according to equation (4). In the formula, D_0 is the elongation of the bolt before heat treatment, unit:*mm*; *D1* is the elongation of the bolt after heat treatment and cooling, unit: *m*.

$$Stress\ relaxation\ rate = \frac{D_0 - D_1}{D_0} \times 100\% \tag{4}$$

3.3 Experimental testing of key performance parameters for thermal sealing

The key performance parameters of thermal sealing include thermal physical performance, compression rebound performance, airtightness, wear resistance, etc. Test methods for thermal physical properties such as thermal conductivity and specific heat. Verify the gap between the theoretical and actual performance of different thermal sealing materials through testing.

3.4 Analysis method for thermal seal design

Usually, thermal sealing design pays more attention to the installation of thermal sealing components, their impact on surrounding structures, and the most crucial thermal sealing effect from a usage perspective. Generally, the design of thermal sealing structures is further improved by analyzing their compatibility and evaluating their performance.

4. Typical thermal sealing structure of spacecraft

4.1 Gap sealing structure

A large number of gap sealing structures are used in American spacecraft to block gaps and prevent aluminum structures from overheating. The types designed include pill shaped or cushion shaped types and Ames type. The gap sealing structure has the advantages of easy installation and good insulation sealing effect for medium and high temperatures.[9]

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4.2 Flexible hot press sealing structure

Flexible thermal sealing is an excellent thermal sealing structure for positions with large gaps in spacecraft. Flexible hot press sealing is a sealing form that can withstand high temperature, high pressure, and adapt to relative movement. The flexible hot press sealing structure consists of three parts, with an insulated cotton body at the center; The outer layer of the cotton tire is made of steel/nickel alloy metal wire that can provide strength, flexibility, and resilience; In order to further enhance the insulation effect, the metal wire is wrapped with a layer of ceramic sleeve, and the outer layer of the sleeve is insulated glass fiber and silicon coating. This sealing form can seal gas with a pressure of 34 kN/m^2, and the high-temperature surface can withstand a high temperature of 1066 ℃, while the temperature on the other side is less than 177 ℃, which has a good sealing effect.

4.3 Baseline structure

The baseline seal mainly consists of three parts, which are high-temperature alloy wire woven elastic elements to ensure resilience; Internally filled with high-temperature cotton for sealing purposes; Two layers of ceramic fiber braided layers are wrapped outside the elastic element as heat and wear barriers. This sealing mode can withstand high temperatures of no less than 1400 ℃ on the surface of the spacecraft and ensure that the internal instruments and equipment of the spacecraft are not damaged.

4.4 Grid plate sealing

Grid type seals were first applied in the stamping engine of the X-51, and can adapt to the working conditions of stress heat combined action. After multiple thermal cycles, they can still ensure reliable sealing performance. The grid plate sealing structure can self seal under external pressure difference conditions. Compared with braided tube sealing, it not only has a higher temperature thermal barrier, but also lower gas leakage rate and better durability。

5. Conclusion

With the continuous development of aerospace manufacturing technology in our country, spacecraft are flying faster and adapting to increasingly harsh environments. Therefore, thermal sealing structures have become an important part of aerospace manufacturing. The development of thermal sealing technology has laid a technological foundation for China's spacecraft to move faster, higher, and further.

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