Analysis on Sealing Reliability of Bolted Joint Ball Head Component of Satellite Propulsion System

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Abstract. Propulsion system is one of the important subsystems of satellite, and its performance directly affects the service life, attitude control and reliability of the satellite. The Paper analyzes the sealing principle of bolted joint ball head component of satellite propulsion system and discuss from the compatibility of hydrazine anhydrous and bolted joint ball head component, influence of ground environment on the sealing performance of bolted joint ball heads, and material failure caused by environment, showing that the sealing reliability of bolted joint ball head component is good and the influence of above three aspects on sealing of bolted joint ball head component can be ignored.

1. Introduction
Bolted joint ball head component of satellite propulsion system pipeline is used as key component that affects the leak rate of propulsion system, and there is no definite theoretical analysis and experimental verification for the influence factors of atmospheric corrosion resistance of parts and components material, material compatibility and electrochemical corrosion on sealing performance after satellite assembly and later long-term storage of ground environment.

As early as the 1950s, the United States started the study on the compatibility of hydrazine with materials [1]. In 1967, the United States Jet Propulsion Laboratory began a 10-year rocket propellant/material compatibility study to provide comprehensive reliable compatibility data for the design of spacecraft especially for the spacecraft propulsion system with long on-orbit operation [2]. Above studies are all based on the simulation of the real experimental environment and the data obtained are true and reliable, but the experimental period is too long. In order to shorten the experimental period, some researchers have proposed the experimental temperature to speed up the experimental process. However, increasing the temperature increases the decomposition rate of hydrazine and changes the structure and thickness of the material interface. Thus, the data obtained does not match the actual situation and cannot be used as the basis for the spacecraft propulsion system design.

In this paper, comprehensive analysis will be carried out on the sealing reliability of screw joint components of satellite propulsion system from three aspects including material compatibility, the ground environment and material failure.
2. Sealing principle

The bolted joint ball head components contain entry ball head of bolted joint, entry conical surface and materials added. The materials of entry ball head of bolted joint are titanium alloy, and that of entry conical surface are 1J36 soft magnetic alloy, and the materials added is pure aluminum. Titanium alloy has the characteristics of high strength, heat resistance and good corrosion resistance [3-5], and soft magnetic alloys have the characteristics of low yield strength and good corrosion resistance, and aluminium has high oxidation resistance and plasticity [6].

Ball head’s seal structure is a typical metal-to-metal contact seal structure, and the extrusion of metal to metal will produce plastic deformation. When the plastic deformation is less than 0.05mm, closed seal ring is formed to achieve the sealing effect, with the manner shown in Figure 1.

The factors including parts processing quality, pipeline welding quality and ball head assembly quality, etc. will all affect the sealing performance. In the case that sealing performance of the bolted joint ball heads of thrust is not enough to meet the requirement of leak rate after being adjusted and installed for several times, the gasket is generally used for processing, as shown in Figure 2. At present, the sealing performance of bolted joint ball heads added with gasket added can meet the requirements of leak rate at a time.

![Figure 1. Assembly diagram of bolted joints](image)

![Figure 2. Schematic diagram of bolted joint ball head added with gasket](image)

3. Analysis on materials compatibility

3.1. Catalytic decomposition of bolted joint component on hydrazine

Anhydrous hydrazine (with hydrazine content> 98.5%) is added to the satellite propulsion system as the fuel, and hydrazine is the extremely stable and almost not decomposed in the absence of a catalyst. The transition metal elements with relatively strong electronegativity such as Mo, W, Ru, Rh, Pt, Au and Ir, etc. are used as the hydrazine decomposition catalyst, while that of titanium and aluminium electronegativity is much smaller and it is difficult to produce catalysis to hydrazine.

Seen from the material characteristics, hydrazine, titanium, and aluminium alloy are the materials with best compatibility [7]. Hydrazine has no corrosive effect on these alloys, and these alloys have no obvious decomposition effect on hydrazine. Through above analysis, it can be excluded the catalytic decomposition effect caused by the materials of entry ball head and gaskets in bolted joint ball head components on hydrazine.

In the research and experiment, it was found that although hydrazine is compatible with some soft magnetic alloys and stainless steel, etc., its compatibility is closely related to the processing technology, the state of heat treatment and the surface cleaning treatment of components. The decomposition of some soft magnetic alloy is sharply increased on hydrazine after quenching or
nitriding; and their decomposition on hydrazine is sharply reduced after the treatment of nitric acid plus hydrofluoric acid pickling and nitric acid passivation. However, based on the principle, the 1J36 soft magnetic alloy of entry conical surface of bolted joints ensures the technology of compatibility with hydrazine during the materials selection, processing and treatment process, which is verified for a long time among numerous on-orbit models.

At present, seen from the use of ground materials, the special container for hydrazine storage generally uses the same material with that of bolted joint ball head component with long service cycle, which also verified the theoretical analysis of good compatibility between hydrazine and materials of bolted joint ball head components.

3.2. Corrosive effect of hydrazine on the materials of bolted joint component

The ball head of bolted joint component is made of metal materials with reducibility. Although metal materials have different standard potentials, metal materials have no such ability of gaining electrons, and the difference of electrical potential only shows the different overflow powers of electrons in the primary cell system [8].

Hydrazine is also reducible, there is no ion current between metal materials and hydrazine, and it cannot constitute the current circuit or form corrosive primacy cell in the traditional sense, and the metallic electrochemical corrosion can be basically ignored.

At present, for the communication satellites with on-orbit operation for more than \( m \) years and the remote sensing satellite with on-orbit operation for more than \( n \) years, the propulsion system is in normal operation during the on-orbit process, and the use condition of hydrazine in container is basically the same as the expected design, which can prove that the electrochemistry corrosion of bolted joint ball head materials is not obvious in hydrazine environment and the normal operation of propulsion system is not influenced.

To sum up, it can be concluded that the material of the bolted joint ball head component has a good compatibility with hydrazine, and the sealing reliability of the bolted joint ball head component is not affected by the hydrazine.

4. Analysis on the influence of ground environment

4.1. Analysis of influence factors

After the tightening of bolted joint ball heads and before the launch of satellite, they shall experience the 10W-class ground environment storage for 1 to 2 years generally, and the factors that might affect the sealing performance of bolted joint ball head component include temperature, humidity, redundancy, absolute ethyl alcohol and helium.

4.1.1. Temperature factor. Environmental temperature and its changes will affect the metal surface water condensation and electrochemical corrosion reaction rate. Seen from the storage environment of bolted joint ball head components, its maximum temperature interval is 20 °C ±5 °C, which basically does not cause moisture condensation on the metal surface; besides, the condensation of moisture without water will also not cause electrochemical corrosion. Therefore, the influence of temperature factors of bolted joint ball head components of propulsion system on corrosion can be basically ignored.

4.1.2. Humidity factor. The oxygen content of the air is always constant, and the rate of corrosion reaction mainly depends on the moisture content; if it reaches or exceeds a certain relative humidity, corrosion will soon occur and develop. Seen from the storage environment of bolted joint ball head component, its maximum humidity interval is 30% to 60% with low humidity; and the surface of bolted joint ball head component is provided with stable oxide layer and a certain degree of corrosion resistance. Therefore, the influence of environmental humidity factor of general assembly hall on influence of corrosion of bolted joint ball head component can be basically ignored.
4.1.3. **Redundancy factor.** Aerospace products are processed, manufactured, transported and stored in strict accordance with the relevant requirements, and the bolted joint ball head component is cleaned, wiped and checked strictly during the general assembly process. Therefore, the influence of redundancy factor can be basically ignored.

4.1.4. **Absolute ethyl alcohol factor.** Clean the bolted joint ball head components with absolute ethyl alcohol before the installation of them. There will be a certain absolute ethyl alcohol remained on the bolted joint ball head, with ethanol concentration more than 99% and water content less than 1%. Since ethanol has strong volatility and the water on the surface of joint will be taken away during the volatilization process, it can be considered that the water quickly evaporates after the cleaning with anhydrous ethanol. Therefore, the influence of absolute ethyl alcohol can be basically ignored.

4.1.5. **Helium factor.** After the leak detection work on propulsion system is finished, the bolted joint ball head component is in helium environment for long. As an inert gas, helium does not chemically react with other factors or compounds generally. Therefore, the influence of helium environment can be basically ignored.

4.2. **Salt spray test**

Although the various factors can be excluded in the 10W-class environment, whether the ultra-long time has an influence on the sealing performance of bolted joint ball head components is not determined. Salt spray corrosion is one of the more common and most destructive atmospheric corrosion. Compared with the 10W-class ground environment, salt spray environment has the chloride salt concentration increased by several times or even a hundred times and has the corrosion rate greatly improved. Salt spray test can provide verification and data for the anti-corrosion performance study of bolted joint ball head components in the harsh environment [9].

4.2.1. **Test process.** Select three groups of samples from the test piece to check the ball head and conical surface seriously to ensure there is no scratch. Number the three groups of test samples as 1#sample piece, 2#sample piece and 3#sample piece. Of which, 1#sample piece is connected, and 2#sample piece and 3#sample piece are separated, as shown in Figure 3.

![Figure 3. Test Pieces](image)

Connect the nut and conical surface of bolted joint ball head of # 1 test piece by screwing manually and then place them in the salt spray box, and place the 2 # test piece (not assembled) in the salt spray box, as shown in Figure 3 and the salt spray environment is shown in Table 1; the 3 # test piece is not carried in spray salt test and it is kept in the storehouse (with temperature of 20 °C±5 °C, relative humidity of 30%-60% and cleanliness of10W-class), for the comparison with 1 # and 2 # test pieces.
Table 1. Spray test environment

|                  | National standard | Test index    | Conformity |
|------------------|-------------------|---------------|------------|
| Temperature      | 35℃±2℃            | 34.5℃-35.6℃  | Conform    |
| Humidity         | More than 90%     | More than 90.2% | Conform   |
| PH value         | 6.5-7.2           | 6.7-7.0       | Conform    |
| Salinity         | 50g/L±5g/L        | 48.5g/L       | Conform    |

4.2.2. Test results. After 15 days, the salt spray test was completed. Visually inspect the surface conditions of 1# test piece, 2# test piece and 3# test piece (with magnifying glass of 5 times), as shown in Figure 4, where there was no significant change on the surface of the test piece.

According to the test results, it can be judged that both the separated and contacted titanium alloy and soft magnetic alloy have good corrosion resistance in the salt spray environment. Salt spray environment is far harsher than the ground environment where satellite is stored; therefore, it can be determined that the atmospheric environment will not cause corrosion to the bolted joint components when satellite is stored in the over ground general assembly plant and the propulsion system is not filled.

Figure 4. Good surface condition

To sum up, on the one hand, the storage environment for satellite is well controlled; on the other hand, the bolted joint components are provided with relatively strong salt-spray resistant and corrosion resistant abilities, and the sealing reliability of bolted joint component will not be influenced by the ground environment.

5. Analysis on materials failure

After the bolted joint ball head components are assembled and tightened, they are in the condition of pressure stress and plastic deformation occur, which forms seal ring with entry ball head and conical surface. If metal materials are in plastic deformation condition for long, whether the mechanical performance changes will have an important influence on the sealing performance of bolted joint ball head components. Below is the analysis conducted on whether there is failure of bolted joint ball head components from several aspects including micro-vibration influence, alternating cold-heat influence and stress corrosion, etc.

5.1. Influence of mechanical environment

According to the mechanical model test data of the previous models, that leak rate of bolted joint ball heads of individual propulsion system exceeds the standard after the mechanical vibration test ever occurred, but the failure ratio of sealing performance is extremely low, especially when the satellite propulsion system experienced the harsher verified vibration test assessment than the satellite launch condition and on-orbit operation, indicating that mechanical environment has extremely limited influence on the sealing performance of bolted joint ball head of propulsion system piping.

During the long on-orbit period of satellite, CMG and momentum wheel and other position adjustment equipment will cause micro-vibration effect on the propulsion system under working conditions. For partial models, ground test was ever carried out on the on-orbit micro-vibration condition of satellite, and the magnitude of micro-vibration transmitted to installation deck of piping is...
5-20mg. Considering that the vibration attenuation, the vibration amplitude of bolted joint component of the system is calculated within 1-5mg, which is small and can be ignored.

Seen from the current operation of on-orbit satellites, the mechanical environment does not cause influence to the leak rate of propulsion system, and the on-orbit service life of satellite is not influenced by the excessive leak rate of propulsion system.

5.2. Influence of alternating cold and heat
The temperature of propulsion system piping is controlled between 0 and 60 °C during its on-orbit period, and it is generally about 20°C. Before the ignition of the thruster, the temperature of the thruster catalytic bed will reach 160-190 °C; and after the ignition of the thruster, the temperature of the thruster ejector will reach 900°C. The distance between the ejector and the bolted joint is about 200mm, and the distance between the catalyst bed and the bolted joint is about 100mm. After experiencing the heat conduction between materials and self-thermal radiation, there is little heat of ejector and catalyst bed reaching the bolted joint. According to the on-orbit test data, the temperature of bolted joint component is not larger than 60°C in general. Therefore, the maximum interval of alternative temperature suffered by bolted joint components is the same as the on-orbit temperature control interval of piping, and its maximum temperature difference is 60°C. The coefficient of linear expansion of titanium alloy is 1×10⁻⁵/°C, and the length of bolted joint component is not more than 20mm, therefore, the maximum deformation of bolted joint ball head under the alternative changes of on-orbit temperature is as follows:

\[ \Delta L_{\text{max}} = \alpha L \Delta T = 1 \times 10^{-5} \times 20 \times 60 = 0.012 \text{mm} \]

The amount of maximum deformation is 0.05mm less than that of plastic deformation, therefore, the influence of alternating cold and heat on the seal failure of bolted joint components can be ignored.

5.3. Stress corrosion
Stress corrosion cracking is mainly caused by the stress rupture during the anodic dissolution, and it is closely related to the electrochemical process of materials in corrosive medium.

After installing the bolted joint ball head components with stars, it will suffer from stress for long. The occurrence condition for stress corrosion is that materials suffer from the dual effects of stress and electrochemical corrosion at the same time, and both of them are mutually promoted. Due that there is no possibility of electrochemical corrosion on the bolted joint ball head components, stress corrosion will also not exist.

In summary, the micro-vibration, alternating cold and heat and stress corrosion and other factors have small influence on the bolted joint ball head and there will be no materials failure on the bolted joint ball head components.

6. Conclusion
There are many factors that affect the sealing reliability of the bolted joint components of satellite propulsion system. Among them, the compatibility of hydrazine with materials is one of the important factors. The analysis results show that the sealing reliability of the bolted joint components of the satellite propulsion system meets the requirements of material compatibility, ground environmental influence and material failure, etc. And years of ground tests and satellite on-orbit operation data have analysed and verified the correctness of the analysis results that propulsion system does not affect on-orbit service life of satellites due to excessive leakage rate, and the bolted joint components of satellite propulsion system is reasonably designed and assembled and with reliable sealing performance.

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