Application of rubber sealing materials in small and medium-sized aero-engines and analysis of typical failure modes

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Abstract: Rubber materials have become indispensable sealing materials for small and medium-sized aero-engines with their excellent sealing properties. This article primarily introduces the application of rubber sealing materials in small and medium-sized aero-engines, as well as typical forms and analysis of sealing failures. It also provides an outlook on rubber sealing materials and products for small and medium-sized aero-engines.

Key words: rubber seal; small and medium-sized aero-engine; application

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Rubber materials possess excellent sealing properties and are widely used in the sealing of air, lubricating oil, fuel, hydraulic oil, and other systems in small and medium-sized aero-engines. Rubber sealing materials are divided into liquid rubber sealants and solid rubber materials. Among them, solid rubber sealing materials are further categorized into static seals and dynamic seals based on the sealing form. Static seals mainly include O-rings, rubber-metal composite sealing blocks, etc., which are used for sealing air, fuel, and lubricating oil systems. Dynamic seals mainly include cups (rotating shaft lip seals) and sealing rings, which are used for oil and gas sealing of rotating shafts. The structure of rubber sealing products is shown in Figure 1.

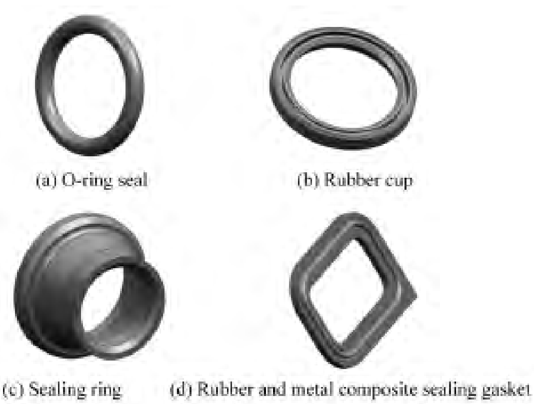

Figure 1 Rubber sealing products

1 Overview of the application of rubber sealing materials in small and medium-sized aero-engines

The selection of rubber sealing materials for aero-engines primarily relies on their operational conditions. Currently, the rubber sealing materials predominantly used in aero-engines include nitrile rubber, fluororubber, silicone rubber, and fluorosilicone rubber. As aviation technology continues to advance, aero-engines are evolving towards higher power and longer lifespan. The operating conditions, such as temperature and medium, in aero-engines are becoming more stringent. Perfluoroether rubber, with its excellent performance, has garnered attention and is gradually being applied in aero-engines.

1.1 Fluororubber

Fluororubber refers to a type of polymer elastomer containing fluorine atoms on the carbon atoms of its main chain or side chains. Currently, fluororubbers mainly used in aero-engines include F275, F370, FX-4, FX-16, and FX-17, with operating temperatures generally ranging from -20 to 200 ℃. Due to its excellent resistance to chemical media, heat, and

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fuel, fluororubber is applied to the sealing of lubricating oil and fuel systems in aero-engines, often in the form of traditional O-ring structures. For example, an FX-17 fluororubber O-ring is used to fix the lubricating oil seal of an output gearbox assembly in a turboprop engine. Additionally, fluororubber has a low friction coefficient and is used for high-speed rotating shafts or sliding seals in air, hydraulic oil, and lubricating oil systems. For instance, an FX-17 fluororubber sealing ring is used for the oil-gas seal of a high-speed rotating shaft in the torque measurement reference shaft of a turboshaft engine; an FX-16 fluororubber cup is used for the lubricating oil seal of a rotating shaft in the output gearbox assembly of a turboprop engine.

1.2 Silicone rubber

Silicone rubber is a semi-inorganic and semi-organic compound with a main chain composed of silicon-oxygen bonds and side groups consisting of organic groups. It exhibits high elasticity, resistance to high and low temperatures, and aging resistance. However, silicone rubber has poor oil and solvent resistance, making it primarily used for sealing in gas systems. Currently, the silicone rubber applied in aero-engines consists of both liquid sealants and solid sealing materials.

Liquid silicone rubber sealants primarily consist of single-component GD414 sealant and two-component XJ55 sealant. The single-component GD414 sealant is primarily used for sealing and protecting against corrosive media in naval engine studs. The two-component XJ55 sealant, operating within a temperature range of -60~300 ℃, is mainly employed for sealing the joint surface between the compressor casing and the combustion chamber casing of aviation engines. Liquid sealants exhibit excellent filling properties, capable of filling uneven gaps on the joint surface. Upon vulcanization, they crosslink to form a three-dimensional silicone rubber elastomer, effectively blocking leaks and achieving sealing effects.

Solid sealing silicone rubber materials mainly include 6146 general-purpose silicone rubber and SE6180 high-temperature resistant silicone rubber. The working temperature of 6146 general-purpose silicone rubber ranges from -60 to +250℃. For example, 6146 general-purpose silicone rubber O-rings are used for fixed sealing on a gas generator of an engine. The working temperature of SE6180 high-temperature resistant silicone rubber can reach up to 300℃. For instance, SE6180 silicone rubber O-rings are used for fixed sealing in the compressor assembly of a turboshaft engine.

1.3 Fluorosilicone rubber

Fluorosilicone rubber is obtained by introducing fluorine-containing side groups into the polysiloxane molecular structure. It not only retains the excellent properties of silicone rubber but also exhibits characteristics such as resistance to organic solvents, which are typical of fluororubber. Currently, the fluorosilicone rubbers primarily used in aero-engines include XJ56 liquid fluorosilicone rubber sealant and solid sealing material FS6265 fluorosilicone rubber, with operating temperatures generally ranging from -55 to +200 ℃.

XJ56 liquid fluorosilicone rubber sealant can fill the uneven gaps on the joint surface. After vulcanization, it cross-links into a three-dimensional silicone rubber elastomer, blocking leakage and thus achieving a sealing effect. It is mainly used for sealing joint surfaces in lubricating oil and fuel systems, such as the sealing of the joint surface between an engine accessory transmission component and a fuel-oil pump regulator.

FS6265 fluorosilicone rubber is widely used in important parts such as fuel sealing gaskets. Its main structures are O-rings and composite gaskets. For example, FS6265 fluorosilicone rubber O-rings are used for sealing on a certain engine fuel nozzle; the sealing gasket assembly of a certain turboshaft engine fuel supply and discharge pipe is made of FS6265 fluorosilicone rubber and 2A11 aluminum alloy, bonded together through thermal vulcanization using AFS-R-A001 adhesive, serving to seal the fuel.

1.4 Perfluoroether rubber

Perfluoroether rubber is a kind of fluorinated elastomer developed in the 1970s, copolymerized from tetrafluoroethylene, perfluoromethyl (oxy) vinyl ether, and a small amount of third monomer with sulfurized points. Due to its skeleton structure similar to that of polytetrafluoroethylene, the carbon-carbon bonds in the main chain are largely protected by the surrounding fluorine atoms, endowing perfluoroether rubber with superior resistance to chemical media. Compared to ordinary fluororubber, its molecular main chain contains no carbon-hydrogen bonds, greatly enhancing its high-temperature resistance. Furthermore, its molecular structure contains long and flexible ether bond side chains, significantly lowering the glass transition temperature Tg. Therefore, it also exhibits excellent thermal stability and low-temperature resistance, with an operating temperature range of -50 to +300℃. Currently, perfluoroether rubbers mainly used in aero-engines include FM-1, FM-5, FM-9, FF7501A, etc. Due to its high cost, perfluoroether rubber is generally used for organic solvent sealing in high-temperature areas of aero-engines above 200℃, such as the oil and gas fixed sealing of O-rings made of FF7501A perfluoroether rubber in a turboshaft engine.

1.5 Nitrile rubber

Nitrile rubber is polymerized from butadiene and acrylonitrile monomers in an aqueous lotion. Currently, the nitrile rubbers used in aero-engines mainly include types such as 5080, 5260, 5470, and P214. Nitrile rubber has a dense structure and high strength, but its ozone resistance is poor and its processability is inferior. It is mainly used for movable sealing parts or static fixed seals in hydraulic oil, jet fuel, and lubricating oil systems. The operating temperature range is generally -50 to +150 ℃. For example, a certain turboprop engine uses 5260 nitrile rubber for the fire extinguishing joint to tightly seal air and fire extinguishing fluid.

Nitrile rubber, a traditional and widely used rubber material, is currently mainly applied to older models of aero-engines. As aero-engine technology advances, rubber materials continue to evolve. Nitrile rubber sealing materials are gradually being phased out. Starting from the fourth-generation aero-engines represented by a certain turboshaft engine, high-performance sealing materials such as fluorosilicone, fluoroether, and fluororubber are widely used, and nitrile rubber seals are no longer employed.

2 Typical failure modes and analysis of rubber seals

2.1 Gap bite

Gap extrusion is the most common failure mode of rubber seals. Due to movement and other reasons, hydraulic and pneumatic systems inevitably have gaps. Under the action of system pressure, rubber seals are pushed towards the side with no pressure or low pressure and come into contact with the groove edge, resulting in deformation. A part of the seal is squeezed into the sealing gap, causing local stress concentration on the O-ring, which is cut off during movement, resulting in gap bite of the O-ring, as shown in Figure 2. For example, a 5260 nitrile rubber O-ring used in a turboprop engine is forced to squeeze into the gap between the installation groove under pressure, causing gap bite. The hardness of the O-ring has a significant impact on gap bite. The higher the system pressure, the lower the hardness of the seal ring, and the more severe the bite phenomenon. Gap bite often occurs due to a lack of coordination between the hardness of the rubber seal compound, working pressure, and sealing gap. The relationship between the values of O-ring compound hardness, working pressure, and sealing gap is shown in Table 1.

The hardness of 5260 nitrile rubber is 67±5. After analysis, it was replaced with 5080 nitrile rubber with a hardness of 80±5. The 5080 rubber O-ring has been installed and used in this turboprop engine for more than two years, and it has maintained good sealing performance.

Table 1 Relationship between working pressure, hardness, and sealing gap of O-shaped rubber sealing rings

Working pressure / MPa	Rubber hardness/HSA		
	70	80	90
	Sealing clearance / (radius / mm)		
0~5	0.15~0.10	0.20~0.15	0.25~0.15
5~10	0.10~0.06	0.15~0.08	0.15~0.10
10~15	0.06~0.03	0.08~0.06	0.10~0.08
15~20	0.03~0.02	0.06~0.04	0.08~0.06

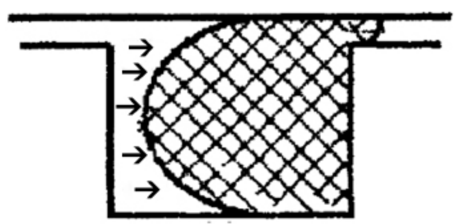


Figure 2 Gap bite of O-ring

2.2 Swelling failure

Swelling failure refers to the process where rubber seals undergo swelling under the combined effects of organic solvents and high temperatures, resulting in severe permanent plastic deformation and subsequent failure. It is one of the primary failure modes of aeroengine seals. For instance, when an F275 fluororubber O-ring used for sealing the turbine casing of a turboshaft engine operates at a working temperature of approximately 200°C and in the presence of Pegasus II oil as the medium, the rubber ring swells, increasing in volume by 30%, and then squeezes into the installation slot gap, causing damage, ultimately leading to seal failure, as illustrated in Figure 3.

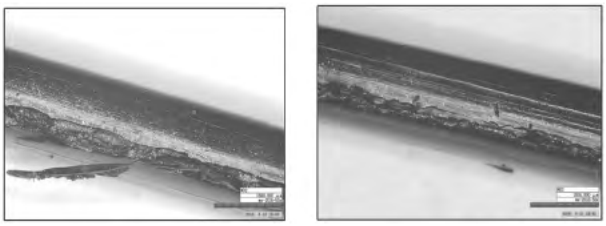


Figure 3 Swelling-induced failure of O-ring

One basis for evaluating the level of resistance to oil volume swelling of rubber materials is their chemical resistance, which refers to the compatibility of rubber materials with chemical media. This is typically assessed by immersing rubber components in chemical media. The most important and intuitive evaluation is the volume swelling rate of the rubber after immersion. The general evaluation results are referred to in Table 2.

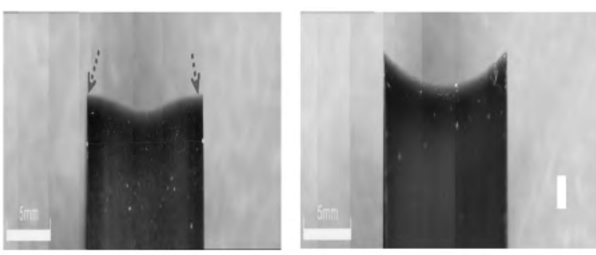
Table 2 Rubber volume swelling evaluation table

Description	Volume change rate/%	Annotation
Outstanding	< 10%	Excellent applicability, with almost no impact on contact time with liquids. The material's performance and physical properties barely change, exhibiting excellent resistance.
Good	10~20	Good applicability, with moderate expansion and changes in physical properties when in contact with fluids, may be suitable for static applications
Restricted use	20~40	Due to limited applicability, the material exhibits significant volume expansion and changes in physical properties when in contact with fluids. Caution should be exercised during use.
Unavailable	> 40	Rubber materials are not suitable for use in this medium.

After analysis, the rubber compound of the O-ring used for sealing the turbine casing of the turboshaft engine was replaced with FF7501A perfluoroether rubber, which has a volume change rate of ≤5% when used with Pegasus II lubricating oil, resulting in good sealing performance.

2.3 Aging failure

The aging of rubber primarily refers to the phenomenon where rubber products undergo physical and chemical changes due to the influence of external factors such as heat, oxygen, light, ozone, and chemical media during storage or use, resulting in deteriorated rubber properties and gradual loss of use value. Aged rubber seals exhibit surface cracking, decreased elasticity, increased hardness, or becoming sticky and soft, and decreased strength. For example, a P214 nitrile rubber cup used in a turboprop engine fuel regulator, after operating for 1,722 hours, showed a certain degree of aging, with the cup size shrinking and deforming, leading to sealing failure. As shown in Figure 4.



(a) Faulty part (b) New part

Figure 4 Nitrile rubber cup

The usual approach to addressing the aging of rubber seals is to store them in a sealed, shady and cool place, away from heat sources, and maintain appropriate temperature and humidity levels, ensuring they are used within their shelf life. Additionally, it is important to monitor the rubber seals in use and replace them promptly when the aero-engine reaches its overhaul period.

3 Outlook

Although the amount of rubber sealing materials used in small and medium-sized aero-engines and the dimensions of their products are small, their performance level and reliability directly affect the overall performance and reliability of these engines, playing a crucial role. After years of development, significant progress has been made in aero-engine rubber sealing materials and technologies. However, there are still some shortcomings in the current situation. The outlook is as follows:

(1) Given the characteristics of aero-engines, such as high temperature, organic oil medium, and high rotational speed, a comprehensive and in-depth study should be conducted on the performance and service life of rubber sealing materials. Currently, some rubber sealing materials in service exhibit insufficiently comprehensive performance, with incomplete understanding of their overall performance and uncertain service life, making it impossible to predict the timing of aero-

engine maintenance and seal replacement. Based on their intended use, a thorough investigation should be carried out into the performance of rubber sealing materials and their service life under aero-engine operating conditions, providing a solid basis for the application, maintenance, and replacement of rubber sealing materials in aero-engines.

(2) Establish a comprehensive and unified system for aeroengine rubber sealing materials. Currently, there are numerous brands of similar rubber sealing materials with similar performance. To facilitate material selection and the design of rubber product molding processes, the aeroengine rubber sealing material system should be simplified and the number of rubber brands reduced, based on classification by process and application.

(3) Develop composite rubber sealing products with higher comprehensive performance. Currently, the sealing products for small and medium-sized aero-engines mainly consist of traditional pure rubber structures such as O-rings, leather cups, and sealing rings, as well as a small number of rubber-metal composite structures. Research on rubber surface treatment technologies with low surface energy, such as fluorosilicone and fluoroether, should be conducted. Composite sealing structures combining rubber with reinforced fabrics, polytetrafluoroethylene (PTFE) plastics, etc. should be developed to achieve functional integration and meet the sealing requirements of aero-engines under harsh conditions.