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Storage life of silicone rubber sealing ring used in solid rocket motor

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Abstract It is urgent to carry out detailed research on storage performance of rubber sealing ring to get the criterion for its storage life. This paper acquires material ageing regularity by theoretical analysis and experimental confirmation. On this condition, failure mode and failure criterion of typical sealing structure is studied, and the failure mechanism is found. Thus by analyzing the stress distribution, the relationship between ageing state and sealing condition is established. Rationalization proposal is put forward and storage life of sealing ring is evaluated. The research mentioned-above has special reference to the design of sealing structures and can provide reference for prolonging their service life.

1. Introduction

Silicon rubber sealing ring is widely used to encapsulate different components of the solid rocket motor (SRM). Its reliability plays an important role in the safety and service life of the solid rocket motor. Developed countries have devoted to extend the solid rocket motor service life and have gotten significant achievements. It is reported that the service life of the solid rocket motor in America and Russia has been reached as long as 20 years, which cannot be separated from the theoretical and experimental study on sealing materials and structures. Clinton and Turner[1] conducts researches on stress decay of the sealing ring and points out that its storage life can reach 6 months when the compression ratio is more than 15%. Bower[2] comes to a conclusion that the compression ratio of the O-ring is inversely proportional to the stress decay. Ralph[3] carries out experimental research on storage life of the O-ring from the permanent deformation in compression perspective. The related literature[4] summarizes molecular theory of elasticity of the rubber materials used in sealing rings, and Rivlin[5] puts forward their stress–strain relationship. In the 1980s, the stress characteristics of the sealing ring have been widely researched. Salita[6] compiles simplified finite element programs to calculate the stress and strain. Gadia[7] performs his researches on incompressibility of the materials used in sealing rings.

Over the past 40 years, great changes have taken place in storage life of the solid rocket motor in our country. Test method for accelerated aging and properties of materials for

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sealing rings has been researched, but their storage performance data is still deficient. With the rapid development of the finite element technique, a lot of stress–strain analyses have been carried out. Hu et al.[8] inquires into the stress distribution of the sealing, and Ren et al.[9–11] calculates the deformation and stress state of the O-ring with model Neo–Hookean and model Mooney–Rivlin. Mu and Xing[12] conducts researches on necessary and sufficient conditions for sealing and the distribution law of contact stress. The study on aging property of sealing materials also strengthens gradually. Rong[13] introduces the accelerated aging test method of the rubber materials and Xiao and Wei[14] evaluates the storage of the vulcanized rubber.

Although more and more attention has been paid to sealing structures, most of the study still focuses on the theoretical level. The theoretical analysis concerns about the various stress state of the sealing structure except the correlation between the stress state and the compression storage of the sealing ring, which directly results in deficiency in the storage life analysis of the sealing ring.

This paper devotes to seek a breakthrough in the correlation between the stress state and the aging state. In the course of this study, stress distribution and the compression aging law of the sealing structure have been researched in full detail. The permanent compression deformation is taken as the main aging characteristics to establish contact between stress distribution and aging time, thus to obtain the stress state in various storage periods. The evaluation criterion related with the compression ratio of the sealing ring is also proposed, and a reasonable evaluation for storage life of the sealing ring is given which is verified by experiments.

2. Aging property experiment

Thermal acceleration experiment is carried out to test aging property of rubber sealing ring. The compression ratio of standard cylindrical specimen in permanent compression deformation is 25%, and test temperature varies from 100 °C to 140 °C according to different material characteristics. The permanent compression set value in different aging states is achieved by different tests at different aging temperatures and different aging time, and compression aging property depending on the aging time at normal temperature or aging temperature is obtained by data fitting. Compression aging property in different aging states is shown in Table 1. The conclusion that compression permanent deformation increases with the storage time and aging temperature is drawn from the analysis of the experimental data.

Table 1 Compression aging property of silicon rubber.

Aging time (day)	Compression permanent deformation ratio				
	100 °C	110 °C	120 °C	130 °C	140 °C
1	0.92	0.91	0.89	0.86	0.86
2	0.90	0.87	0.87	0.82	0.79
4	0.87	0.82	0.80	0.73	0.69
10	0.80	0.74	0.69	0.62	0.59
20	0.73	0.68	0.64	0.56	0.51
30	0.69	0.65	0.60	0.50	0.45
40	0.70	0.66	0.61	0.50	0.42
50	0.69	0.57	0.64	0.44	0.38
70	0.63	0.56	0.48	0.38	0.28
82	0.62	0.59	0.49	0.35	0.29
90	0.61	0.55	0.46	0.34	0.24

According to the aging property of rubber material and related Refs.[10,15], this article assumes that the compression aging property of silicon rubber is consistent to power index model as shown below:

$$f(P) = B\exp(-Kt^{\alpha}) \tag{1}$$

$$K = Z\exp(-E/RT) \tag{2}$$

where $f(P)$represents compression aging property in different time nodes, P is compression permanent deformation ratio, B and α are model parameters. Both aging reaction rate K and thermodynamic temperature are in accordance with Arrhenius formula.[16,17] In the Arrhenius formula, Z is aging rate parameter, while E is material apparent activation energy, R represents Molar gas constant, and T is aging temperature.

According to the test data lists above, model parameters and aging reaction rate at different temperatures can be fitted, and model parameters at normal temperature can be derived. Parameter model α is processed by successive approximation. Taking total departure I (see Eq. (3)) as the criterion, α is solved to be 0.4, and aging reaction rate K at room temperature is 0.0123. Taking value of model parameter B for 1, aging property model $f(P)$ at room temperature is obtained as shown in Eq. (4). In the successive approximation, f_{ij} is the function value under a certain parameter, and $\hat{f}_{ij}$ is its optimal value. Aging property curve of silicon rubber at room temperature is shown in Fig. 1.

$$I = \sum_{i}^{p}\sum_{j}^{n}(f_{ij} - \hat{f}_{ij})^2 \tag{3}$$

$$f(P) = \exp(-0.0123t^{0.4}) \tag{4}$$

Aging property experiments of sealing ring are also carried out to grasp the difference between sealing ring and standard cylindrical specimen, and experiments with and without lateral constraint are also compared. The test results are shown in Table 2, from which we can see that the permanent compression ratio and the equivalent storage time of sealing ring are positive correlated. Permanent compression ratio without lateral constraint of sealing ring is 5%–10% higher than the sealing ring with lateral constraint, and it is 20%–25% higher than the standard specimen. Test photos are shown in Fig. 2.

Aging property model of sealing ring can be corrected according to the results of comparative tests mentioned above.

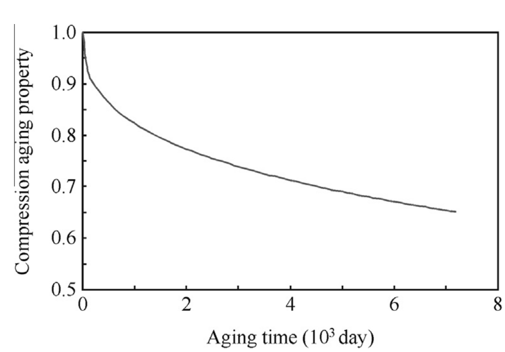

Fig. 1 Compression aging property curve of silicon rubber at room temperature.