Study on the Pre-strain Aging Constitutive Model of HTPB Coating

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Abstract： In order to study the effect of aging on the mechanical properties of HTPB coatings, accelerated aging tests were carried out for HTPB coating. the hardness change rate was used as the aging characterization. Based on the Polynomial hyper-elastic constitutive model, the aging hardness change rate model is introduced, and a pre-strain aging constitutive model is established. The results show that the hardness change rate can be used as an auxiliary characterization of aging performance change, and The aging constitutive model can accurately describe the aging relationship of HTPB coating.

1. Introduction

The structural integrity of the solid rocket motor has a significant impact on the stability and effectiveness of the rocket engine itself, and the bonding structure between the propellant and the lining is the weak link of the structural integrity of the solid rocket engine. Many engine accidents are due to debonding of this interface [1]. HTPB coating is polymer composite material with fillers such as ablative fillers added to the butyl hydroxy (hydroxyl-terminated polybutadiene) rubber matrix. Its material must have good storage aging performance to prevent the coating layer from being damaged by external environmental loads, thereby avoiding damage to the structural integrity of the solid rocket motor [2]. Therefore, studying the aging characteristics of HTPB coating and accurately revealing its aging constitutive model would provide an important reference for the evaluation of the solid rocket motor charge structure integrity.

To know exactly the storage life of a propellant, it is better to store propellant samples or propellant engines naturally. However, this method is not only expensive, but also time-consuming. In this paper, the change of mechanical properties of HTPB propellant under storage aging was studied by accelerated aging. The hardness change rate is selected as the aging characteristic of HTPB coating, combined with the existing aging hardness model with pre-strains and aging days as the impact factors. The established aging hardness model was introduced into the Polynomial hyper-elastic constitutive model, then the aging constitutive model of HTPB coating was established. Through specific aging test data, the model is verified, and the model can effectively describe the aging constitutive relationship of HTPB coating.

2. Pre-strain aging constitutive model

2.1. Hyperelastic constitutive model

HTPB coating is deformed due to the straightening of the molecular chain. The volume does not change much under the action of external force. So HTPB coating has mechanical properties such as incompressibility, large deformation, and hyperelastic [3]. Hyperelastic constitutive models include Neo-Hookean model, Mooney-Rivlin model, Polynomial model and Ogden model, etc., which are widely used in materials with large deformation such as rubber and polymers. Compared with other hyperelastic models, the Polynomial model can better adapt to filled and unfilled rubber

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materials, and can describe the mechanical behavior of the material well [4], so this paper introduced the Polynomial hyperelastic constitutive model. The stress-strain relation-ship is shown in equation (1).

$$\begin{aligned}\sigma = 2\left(\lambda-\lambda^{-2}\right)\Bigg[&C_{10}+2C_{20}\left(\lambda^2+\frac{2}{\lambda}-3\right)+C_{11}\left(\frac{1}{\lambda^2}+2\lambda-3\right)\\ &+\lambda^{-1}\left(C_{01}+C_{11}\left(\lambda^2+\frac{2}{\lambda}-3\right)+2C_{02}\left(\frac{1}{\lambda^2}+2\lambda-3\right)\right)\Bigg]\end{aligned} \tag{1}$$

In formula: C_{10}, C_{20}, C_{11}, C_{01} and C_{02} is material hyperelastic parameters; λ is elongation, and $\lambda = 1+\varepsilon$.

2.2. Constant strain aging hardness model

Under homoeothermy storage conditions, HTPB coating has the phenomenon of aging hard [5], which is specifically manifested as an increase in tensile strength and a decrease in maximum elongation. According to this feature, Kumar [6] proposed a temperature-dependent aging hardness model. The value of the hardness of the material after aging is given by the function of the initial performance, time, and temperature. The form is as follows:

$$P(t,T) = P_0(T)\left[1+\beta_T \ln(t)\right] \tag{2}$$

$$\beta_T = Ae^{-B/T} \tag{3}$$

In formula: P_0 is initial mechanical properties; $P(t,T)$ is mechanical properties after aging; t is accelerated aging time; β_T obey the Arrhenius equation; A is parameter; B is activation energy change rate.

Due to the fact that HTPB coating is always subjected to external loads during actual storage, this paper considers the effect of different pre-strains on the aging mechanical properties of HTPB coating. The form is as follows:

$$P(t,\varepsilon_0) = P_0(\varepsilon_0)(1+\gamma(\varepsilon_0)\ln(t)) \tag{4}$$

In formula: ε_0 is pre-strain; $P(t,\varepsilon_0)$ is change rate of hardness after accelerated aging; t is accelerated aging time; $\gamma(\varepsilon_0)$ is parameter; $P_0(\varepsilon_0)$ is initial change rate of hardness.

The definition form of hardness change rate in the paper is shown in formula (5):

$$P = H/H_0 \tag{5}$$

In formula: P is hardness change rate; H is surface hardness value after aging; H_0 is Initial surface hardness value.

2.2. Pre-strain aging constitutive model

In order to accurately describe the constitutive relationship of materials. based on the Polynomial model ,this paper introduces pre-strain aging hardness model to describe the effects of different pre-strains and aging stages. The constitutive relationship of pre-strains and aging times of HTPB coating is shown in formula (6)

$$\sigma\left(t,\varepsilon_0,\varepsilon\right) = P\left(t,\varepsilon_0\right)\sigma\left(\varepsilon\right) \tag{6}$$

In formula: $\sigma\left(t,\varepsilon_0,\varepsilon\right)$ is uniaxial tensile stress; $\sigma\left(\varepsilon\right)$ is hyperelastic constitutive model; $P\left(t,\varepsilon_0\right)$ is change rate of hardness after accelerated aging.

3. Acquisition and verification of constitutive model parameters

3.1. Acquisition of constitutive model parameter

The experimental data in this paper comes from Du [7]. According to the stress-strain test data of HTPB coating sample without aging and pre-strain, the least square method is used to fit equation (1) to obtain the hyperelastic parameters C_{10}, C_{20}, C_{11}, C_{01} and C_{02} of the material. The value of hyperelastic parameters are shown in Table 1.

Table 1 fitting results of Polynomial constitutive model Parameters

ε_0 /%	t / d	C_{10}	C_{20}	C_{11}	C_{01}	C_{02}	R
0	0	-0.0924	0.0009	-0.0045	0.6675	0.1023	0.9999

According to the stress-strain test results of HTPB coating under different pre-strains at different aging times, the change rate of hardness is obtained. The parameter values are shown in Table 2. The fitted aging hardness change rate is compared with the aging hardness test results of HTPB materials in references[5,8], which proves that the fitting results are close to the aging hardness test results, and the error is within the acceptable range. The results are credible.

Table 2 Fitting results of hardness change rates with different pre-train

t / a	P $(\varepsilon_0=0\%)$	R	P $(\varepsilon_0=3\%)$	R	P $(\varepsilon_0=6\%)$	R	P $(\varepsilon_0=9\%)$	R
0.67	1.1489	0.9924	0.9872	0.9988	0.9442	0.9889	0.8288	0.9982
1.34	1.1678	0.9962	1.0301	0.9916	1.0389	0.9991	0.8863	0.9998
2.01	1.2098	0.9988	-	-	1.1488	0.9994	1.0051	0.9937
2.68	1.2889	0.9933	1.3226	0.9913	-	-	1.1457	0.9997
3.36	1.3180	0.9998	1.2585	0.9996	1.3029	0.9894	1.2140	0.9959
4.48	1.3591	0.9996	1.2422	0.9993	1.3007	0.9997	1.2886	0.9991
6.72	1.4489	0.9991	1.3396	0.9989	1.3994	0.9989	1.3431	0.9989
8.95	1.4688	0.9993	1.4084	0.9972	1.4524	0.9998	1.5881	0.9984

According to the curve of hardness change rate with aging time, the least square method is used to fit the equation (4), and the values of γ and P_0 are obtained respectively, as shown in Table 3.

Table 3 Fitting results of $\gamma(\varepsilon_0)$ and $P_0(\varepsilon_0)$

ε_0 / %	P_0	γ	R
0	0.9486	0.1461	0.9704
3	0.8017	0.2043	0.9309
6	0.7064	0.2884	0.9916
9	0.4307	0.6675	0.9688

From the data in Table 3, the function forms of γ and P_0 with respect to ε_0 are fitted:

$$P_0(\varepsilon_0) = P_0 + k\varepsilon_0 \quad (7)$$

$$\gamma(\varepsilon_0) = A\exp(B\varepsilon_0) \quad (8)$$

In formula: P_0 is change rate of hardness after accelerated aging for 3 days; k , A and B are parameters. The value of P_0 , k , A and B are shown in Table 4.

Table 4 Parameter fitting results

P_0	k	R	A	B	R
0.9692	-0.0549	0.9758	0.0999	0.2078	0.9807

3.3. Model validation

The pre-strain aging constitutive model shown in equation (6) is used to fit the test data. The fitting curve is shown in Figure 1. The stress-strain curve of HTPB coating at 70℃ (343.15K) accelerated aging for 9 days under pre-strain of 3% and 70℃ (343.15K) accelerated aging for 12 days under pre-strain of 6% are used to fit verification, the fit results are shown in Figure 2, the correlation coefficients are 0.9997 and 0.9987 respectively.

By fitting and verifying the established pre-strain aging constitutive model, the results show that the aging constitutive model can accurately describe stress-strain curves of HTPB coating at different aging stages. Comprehensively considering the overall fitting effect, combined with the results of Table 2, Figure 2 and Figure 3 verification, it can be seen that the pre-strain aging constitutive model proposed in this paper has a high correlation with the test results (R > 0.990). Therefore, the pre-strain aging constitutive model can effectively describe the aging constitutive relationship of HTPB coating.

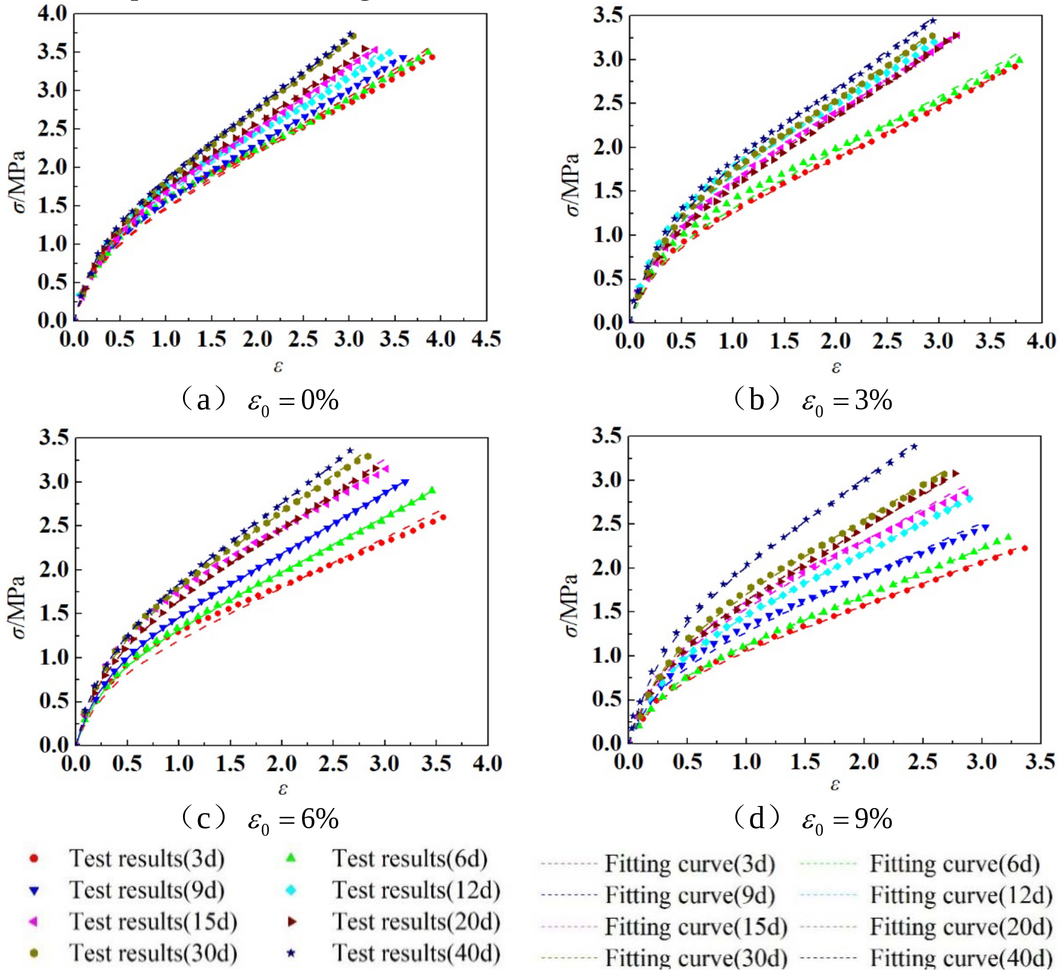

Fig.1 Fitting curves of prestrain aging model

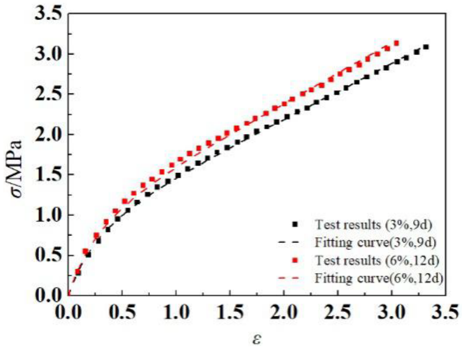

Fig.2 Validation of the pre-strain aging model

4. Conclusions

The aging hardness measurement is easy to operate and has little damage to the sample , so the hardness change rate is used as an auxiliary feature to judge aging, which can greatly reduce the cost of aging test. The main conclusions obtained through the research of this article are:

(1) Combining the Polynomial model and the aging hardness model, a pre-strain aging constitutive model for HTPB coating at 70°C (343.15K) was established. the overall correlation

between the model and the test results is higher than 0.990, which can effectively describe the aging constitutive relationship of HTPB coating;

(2) Using the change rate of aging hardness under different pre-strains as the aging characterization, and introducing accelerated aging times in the change rate model of aging hardness, thus establishing functional relationship between accelerated aging times and storage pre-strain.

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