Response analysis of HTPB propellant under extreme high temperature conditions

TianPeng Li¹,², Bang Lu² and ZhenTao An*¹
¹Nanjing University of Science and Technology, School of Mechanical Engineering, Nanjing, China
²Army Engineering University, Shijiazhuang campus, shijiazhuang, China

*Corresponding author: lixiaonan13@nudt.edu.cn

Abstract. Temperature load is one of the loads that propellant grains are often subjected to. Temperature shock or temperature cycling will affect the structural integrity of propellant grains to a certain extent. How to ensure that the propellant grains meet the structural integrity requirements under temperature load conditions and ensure equipment the significance of a smooth launch is very important. In this paper, the HTPB propellant sample response analysis test is carried out based on the global temperature environment distribution of different temperature grades, and the extreme high temperature impact simulation experiment is carried out for the grains under the specific structure considering the impact of extreme high temperature conditions, and finally different models are constructed. The constitutive model of HTPB propellant under extreme high temperature, its grain meets the structural integrity criterion after being subjected to the impact of extreme high temperature.

1. Introduction
As a long-range high-precision strike weapon with a simple structure and low cost, solid rockets are important to countries all over the world. The composition structure of the solid rocket motor is relatively complex, the mechanical properties of the composition are different, and the coefficient of thermal expansion is different. The complex design of the propellant grain to meet the steady change of the pressure curve in the combustion chamber and the range requirements, plus the deployment area the situation is complex, the topography and the climatic conditions are also quite severe. According to the extreme temperature of the world climate, the temperature changes between -51°C~71°C, which increase the difficulty of storage, transportation and use in varying degrees. Temperature load can change the viscoelastic properties of the propellant, cause stress concentration in certain parts of the grain, and even cause the interface to debond due to the different expansion coefficients of each part, and serious cases may cause accidents. Especially at the extreme temperature of 50°C~71°C (high temperature), the temperature effect is more obvious, which will directly affect the quality and even safety of the solid rocket. Therefore, the study of extreme temperature loads is particularly important for the structural integrity of propellant grains.

As HTPB is generally cured with multifunctional isocyanate agents, this kind of composite can be seen as a highly filled elastomer (up to 90% in weight of solid content). The mechanical behavior of solid propellants [1] is mainly influenced by the polymeric nature of binder, curing agent, and binder-
filler interaction. The mechanical properties of solid propellant are rate-dependent. Xu Jinsheng [2] calculated the mechanical response characteristics of the various components of the solid rocket motor under the action of temperature shock load, and conducted an in-depth study on the influence of the stress release structure parameters and the charge modulus on the structural integrity of the grain. Zhou Hongmei [3] calculated the viscoelastic dynamic response of round-hole grains during long-term storage, and the calculated results can provide a basis for judging the damage value of dangerous parts of the engine after a certain period of time. Yue Xiaoliang [4] found that the internal temperature field of the grain is unevenly distributed when studying the response of the engine grain under a temperature shock load, and there will be a temperature gradient along the radius. The maximum stress value reached at the beginning of the impact is greater than the stress after the temperature equilibrium. If it is too large, the maximum strain appears in the middle part of the inner hole wall, and the maximum stress appears at the bonding point between the two ends of the grain and the insulation layer. After constructing the propellant [5] containing a typical grain model, the dynamic mechanical properties during the high temperature accelerated aging process were tested, and the relationship between the relaxation modulus and the temperature was obtained, and finally the relaxation modulus was reduced to the complete grain structure. The time required for the value of the performance to fail, that is, the service life of the solid rocket motor.

At present, the research on the structural integrity of the propellant under high temperature load has made great progress, but there are few reports about the extreme high temperature load conditions, especially considering the impact of the extreme temperature load conditions on the safety of the propellant grains.

2. Solid propellant relaxation characteristics test

Solid propellant is a typical particle-reinforced viscoelastic material. The change of its mechanical properties has a strong dependence on environmental temperature and loading time. Therefore, it is necessary to accurately determine the relaxation mode of the propellant sample under extreme high temperature with time. The quantity is an important prerequisite for analyzing the stress-strain response law of propellant grain structure, and it is also the basis for the evaluation of the structural integrity of propellant grain under extreme high temperature loading environment. The curves of relaxation modulus of propellant samples under high temperature (50℃, 60℃, 70℃) were selected and measured.

2.1. Test equipment and samples

The relaxation modulus test of the propellant sample was completed on the WDW programmable universal material testing machine. The accuracy of the pressure sensor part of the uniaxial tensile tester can reach ±1% of the indicated value; while the temperature control range of the high and low temperature test box using air compression temperature control is -70~250℃, and the accuracy is controlled at ±0.1℃. The extension rate and initial constant strain used in the propellant relaxation test refer to GJB 770B-2005 [6], and are set to 500 mm/min and 5% according to the uniaxial stretching method of the master curve of the stress relaxation modulus.

The propellant relaxation sample is made of hydroxy-terminated polybutadiene (HTPB) grain billet, and is processed into a dumbbell shape according to the standards of the Ministry of Aerospace Industry QJ1113-87 [7], QJ1615-93 [8], gauge length 50mm, horizontal The cross-sectional area is 100 mm², and other detailed size parameters are shown in standard. In order to prevent the environmental temperature and humidity from affecting the mechanical properties of the untested samples, they need to be placed in a dedicated heat preservation and humidity box, the temperature is controlled at 20℃, and the humidity is controlled at about 30%. When carrying out the relaxation test, first put the used sample in a high temperature test box and keep it at the corresponding temperature for 3 hours.
2.2. Building a constitutive model

Expression of relaxation modulus of propellant sample:

\[ E(t) = \frac{F(t) \times (1 + e_0)}{A \times e_0} \]  

(1)

In the formula, \( E(t) \) represents the relaxation modulus of the propellant sample at time \( t \), MPa; \( F(t) \) represents the relaxation force carried by the sample at time \( t \), N; \( e_0 \) represents the loading of the sample during the relaxation test, the initial constant strain is taken as 5%; \( A \) represents the initial cross-sectional area of the gauge length section of the specimen, which is 100mm². Table 1 shows the calculation results of relaxation modulus at 70°C.

| Temperature (℃) | Relaxation modulus (MPa) |
|-----------------|--------------------------|
|                 | 2s  | 4s  | 8s  | 20s | 40s | 80s | 200s | 600s | 1000s |
| 70              | 1.106 | 0.966 | 0.714 | 0.560 | 0.476 | 0.423 | 0.322 | 0.252 | 0.210 |

In the simulation analysis of the viscoelastic dynamic response of solid rocket motors, the four-parameter Burgers constitutive model is mainly used to characterize the viscoelastic properties of grains and coatings. The four parameters are the main creep modulus \( K_P \), variable damping \( C_P \), sub-creep damping \( C_S \) and elastic modulus \( K_e \) [9]. Therefore, to construct the Burgers constitutive model, it is necessary to first fit and determine each parameter value in the relaxation modulus function expression of the specimen, and the Prony series expression of the relaxation modulus:

\[ E(t) = E_0 + \sum_{i=1}^{n} E_i \exp(-t / \tau_i) \]  

(2)

\( E_0 \) is the equilibrium modulus; \( n \) is the number of sticky pot-spring pieces in the generalized Maxwell model, where \( n=4 \); \( \tau_i \) is the relaxation time, \( \tau_i = 10^{i-1} \tau_1 \), \( \tau_i \) which can be selected according to actual needs, but generally the sum is proportional to the experimental study describe the results of the initial stress relaxation modulus of HTPB propellant as accurately as possible within the time range, and take 2 here; \( E_i \) is the stress relaxation term [10]. Table 2 shows the results of HTPB propellant initial relaxation modulus fitting at 70°C.

| Relaxation term | \( E_0 \) | \( E_1 \) | \( E_2 \) | \( E_3 \) | \( E_4 \) |
|-----------------|--------|--------|--------|--------|--------|
| 70℃             | 0.072  | 0.791  | 0.499  | 0.130  | 0.258  |

With the aid of the least square method and Matlab data processing, the fitting results of the initial stress relaxation modulus of the propellant at 50℃, 60℃ and 70℃ are obtained. Figure 1 shows the fitting result of 70℃, the results of 50℃ and 60℃ are not listed.
4

Figure 1. The comparison result between test data and fitting curve at 70℃.

It can be seen from the figure that the fourth-order Prony series expressions are well-fitted and substituted into the four-parameter Burgers model to obtain the constitutive models of the propellant samples at 50℃, 60℃ and 70℃.

3. Simulation of HTPB propellant grains under extreme high temperature

Based on the principle of thermodynamics, the temperature effect of the grain is analyzed, taking into account the possibility of withstanding the extreme temperature shock, according to the law of temperature and time, the large-scale finite element software MSC Patran and MSC Marc are used to construct load conditions and simulate analysis to discuss the grain deformation and von Mises stress and strain when subjected to the impact of extreme high temperature 70℃, from which the structural integrity of the grains can be evaluated, and the safety of the solid rocket motor can be evaluated. When the engine grain is cast, the room temperature is 20℃. During storage, when the propellant grain is affected by the natural and induced extreme high temperature, the engine will rise from the room temperature to a high temperature of 70℃ in one day, 50℃ and 60℃, numerically simulate the whole process, and analyze the structural integrity of the solid rocket motor in the process.

3.1. Displacement field of propellant grain under extreme high temperature conditions

Figure 2 shows the distribution of the displacement amplitude of the grain under the impact of the extreme high temperature 70℃, Figure 3 shows the deformation of the inter-segment gap, and Figure 4 shows the distribution of the displacement amplitude along a certain axial characteristic line of the grain.
The results show that the maximum displacement at 70°C is 4.11mm (2.57mm at 50°C, 3.30mm at 60°C), which is 0.22% of the engine length (0.14% at 50°C, 0.18% at 60°C), and the relative amount of deformation is not big. In addition, the grains expand under the action of high temperature, and the deformation causes the gap between the grains to narrow, but the deformation is small. As shown in

Figure 2. The displacement field of propellant at 70°C.

Figure 3. The gap deformation of behind propellant at 70°C.

Figure 4. The displacement along the feature line of propellant at 70°C.
Figure 4, the high temperature does not have the problem of inter-segment extrusion. From the distribution law of the displacement amplitude along the characteristic line, the grain displacement increases toward each end surface, and the maximum value is at the tail end. The overall deformation does not change much, and excessive deformation will not occur.

3.2. The von Mises stress field of propellant grains

Figure 5 shows the local distribution cloud map of the maximum von Mises stress of the propellant grains, and Figure 6 shows the distribution law of the von Mises stress of the grains along the characteristic line.

The results show that the von Mises stress of the grain at the middle of the front wing groove and the rear cylindrical section takes the extreme value. The von Mises stress of the characteristic line is the same at the characteristic line of the rear cylindrical section. The front section characteristic line 2 is the largest and the characteristic line 3 is the smallest. The von Mises stress in the middle of the front wing groove of the engine grain is the global maximum value of 0.0711MPa (0.0537MPa at 50°C, 0.0628MPa at 60°C), and the extreme value of the von Mises stress at the upper part of the rear section is 0.0473MPa (0.037MPa at 50°C, 0.0427MPa at 60°C). The distribution of the von Mises
stress value is mainly used to investigate the stress concentration and the singular area on the surface of the grain. The calculation shows that the engine grain has no prominent singular stress-strain area at high temperature.

3.3. The von Mises strain field of propellant grains
Similarly, three characteristic lines in the axial direction of the grain are taken to explore the distribution law of von Mises strain along the characteristic lines. Figure 7 shows the von Mises strain distribution cloud diagram of some propellant grains, and Figure 8 shows the axial distribution curve of the von Mises strain of the propellant grains.

![Image](image_url)

Figure 7. The von Mises strain field of propellant at 70°C.

![Image](image_url)

Figure 8. The von Mises strain distribution along the feature line of propellant at 70°C.

The results show that there is von Mises strain concentration in the middle part of the anterior wing groove and the middle part of the posterior part of the grain. The characteristic line is the largest in the anterior part, and the characteristic line 3 is the smallest. The characteristic line has the same shape in the posterior part of the grain. The global maximum is the von Mises strain in the middle of the anterior part of the grain, which is 4.44% (2.78% at 50°C, 3.57% at 60°C); the von Mises strain of the upper part of the posterior part is 3.50% (2.17% at 50°C, 2.80% at 60°C). The allowable strain of the propellant at high temperature is 40%, the safety factor is 9.01 (14.4 at 50°C, 11.2 at 60°C), and the
structural integrity of the propellant grain at the extreme high temperature of 70 ℃ meets the requirements.

4. Conclusion
Based on the design criteria of orthogonal experiments and considering the influence of different extreme temperatures, the structural integrity analysis of propellant grains at three different extreme high temperatures of 50 ℃, 60 ℃ and 70 ℃ was carried out. The cloud map results of 50 ℃ and 60 ℃ were not included, only for data comparison. Grain used displacement response and von Mises stress-strain criterion to judge structural integrity. The results of thermodynamic analysis showed that storage under all extreme high temperature conditions meets the structural integrity requirements.

By comparing and analyzing the von Mises stress-strain response law of various components stored under different extreme temperature load conditions, it can be seen that in the extreme high temperature area, the higher the temperature, the larger the response value of the solid rocket motor and the lower the safety factor.

Acknowledgments
The authors would like to thank Dr. Hui Li, Dr. Jiaming Liu for proof reading the paper.

References
[1] R. Zalewski, T. Wolszakiewicz, Analysis of uniaxial tensile tests for homogeneous solid propellants under various loading conditions, Cent. Eur. J. Energ. Mater. 8 (2011) 223-231.
[2] Xu Jinsheng, Experimental and numerical research on thermo-viscoelastic constitutive model of composite propellant, Nanjing University of Science and Technology, 2013.
[3] Zhou Hongmei, Li Jiying, Yuan Song, Wang Bin, Temperature field and stress field analysis of SRM’s grain during cooling process after curing, Missiles and Space Vehicles, 2015, 337: 104-107.
[4] Yue Xiaoliang, Research on mechanical response of grain under temperature shock load, Nanjing University of Science and Technology, 2013.
[5] Xin Sui, Ningfei Wang, Qian Wan, et al. Effects of relaxed modulus on the structure integrity of NEPE propellant grains during high temperature aging. 2010, 35(6):535-539.
[6] GJB 770B-2005, 2005.
[7] QJ1113-87, 1987.
[8] QJ1113-93, 1987.
[9] Meng Shangyang, Tang Guojin, Lei Yongjun, Zhang Hailian, Method of obtaining the burgers model parameters, Journal of Solid Rocket Technology, 2003, 26(2): 27-29.
[10] Du Yongqiang, et al. Research on Storage Properties and Segmented Aging Model for Life Prediction of HTPB Propellant. Ordnance Engineering College, 2016.