IOP Conf. Series: Materials Science and Engineering **378** (2018) 012009 doi:10.1088/1757-899X/378/1/012009

Study on the Compressive Mechanical Properties of HTPB Propellant at Low Temperature

Xiangdong Chen[1,2,*], Xin-long Chang[1], Youhong Zhang[1], Lei Zhang[1]
[*]Corresponding author: chen987dong@163.com
[1]Xi'an High-tech Institute, Xi'an 710025, shannxi, China
[2]96630 Unit of PLA, Beijing 102206, China

Abstract. To study the low temperature effects of compressive mechanical properties on Hydroxyl-terminated polybutadiene (HTPB) propellant, a quasi-static mechanical experiment was conducted. The results show that compressive mechanical parameters are closely related to strain rate and low temperature. With the decrease of temperature and increase of strain rate, the modulus and compressive strength of HTPB propellant increase obviously. Based on the time-temperature equivalence principle (TTEP), the master curves of compressive strength and initial modulus for HTPB propellant were obtained, which can facilitate the structural integrity analysis of the propellant.

1. Introduction

Hydroxyl-terminated polybutadiene(HTPB) propellant is a kind of energetic material filled with a certain amount of ammonium perchlorate particles and aluminum particles. HTPB propellant is widely used in solid rocket motors (SRMs) for the propulsion of missile and space transportation because of its high energetic characteristics and good mechanical properties. The compressive mechanical properties of HTPB propellant are extraordinary important for structural integrity of solid rocket motor grain. Furthermore, SRMs are often required to operate in cold areas, which can cause significant changes in mechanical properties of the propellant. So it is necessary to research the compressive mechanical properties at low temperature [1-2].

It is important to fully understanding of mechanical properties on energetic material at different conditions. Himanshu [3-4] examined the temperature effects and aging time on mechanical properties of solid rocket propellants. He found that any change in temperature and aging time brought significant change in the tensile strength, percentage elongation, and elastic modulus of the propellant. Thompson et al. [5] conducted compressive and tensile testing for plastic-bonded explosives(PBXs) 9501 and 9502, spanning a wide range of strain rates and temperatures. Williamson et al. [6] measured the compressive strength of the energetic composition EDC37 at a strain rate of 10^{-3}/s over a range of temperatures from 208 K to 333 K. Based on the experimental results, the failure stress was found to exhibit a similar trend with increase of the logarithm of strain rate and decrease of temperature. Riadh et al. [7] investigated viscoelastic response of high-density polyethylene(HDPE) under long-term tensile and compressive creep. Yang et al. [8] examined compressive mechanical testing of HTPB propellant at room temperature over strain rate ranging from 1.7×10^{-4}/s to 2500/s. And he proposed a rate-dependent constitutive model to described the mechanical behaviour. Wang et al. [9] studied the biaxial tensile stress responses of HTPB propellant at room temperature, and they [10] also conducted the uniaxial tensile tests at low temperatures.

To sum up, most scholars mainly focused on the energetic material tensile properties or the properties at room temperature, but there are relatively little related reports in compressive mechanical properties

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of HTPB propellant at low temperature. In this paper, the compressive properties were investigated at low temperature, and the master curves of compressive mechanical properties for HTPB propellant were obtained. Our goal is to study the compressive mechanical behaviours of HTPB propellant, which will facilitate the structural integrity analysis.

2. Experimental part

2.1 Materials and sample configuration

The HTPB propellant investigated here was manufactured by casting method consisting of 86% by weigh AP power and Al power, 10% by weigh HTPB binder and 4% by weigh other liquid additives. The propellant was machined into small cylindrical specimens of both diameter and height 20mm (Figure.1). All specimens were machined from the same manufacturing batch, and then stored in a desiccator cabinet at 40°C for 24h before testing to remove any residual stresses and eliminate any variability caused by humidity.

Figure 1. Geometrical shape and the specimen

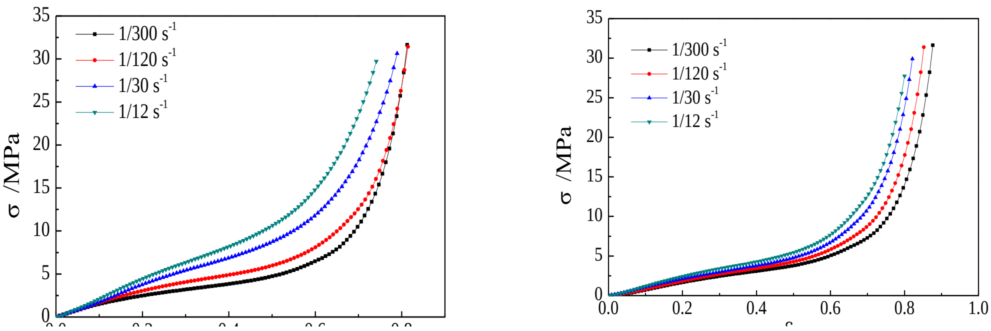
2.2 Experiment condition design

The experimental temperatures were 25°C, -10°C, -20°C,-30°C, -40°C and -50°C. The experimental compression speed of specimens was about 4 mm/min（$1/300s^{-1}$）, 10mm/min（$1/120s^{-1}$）, 40mm/min（$1/30s^{-1}$） and 100mm/min（$1/12s^{-1}$）. Each test was repeated at least five times to measure repeatability of the experimental results. The temperature change was realized by the temperature controller. The specimens were stored for at least 1h at the specified temperature before test.

3 Results and discussion

3.1 Stress-strain curve

(1) The experimental stress-strain data is transformed into true stress and strain. The typical curves of at 25℃ and -30℃ are represented in Figure 2. Because of the viscoelastic material nature, temperature and strain rate greatly affect the mechanical behaviour of HTPB propellant. With the decrease of temperature and the increase of strain rate, the stress increase obviously. In addition, the curves show strong nonlinear characteristics under various condition.



(a) stress-strain curve at 25℃ (b) stress-strain curve at -30℃

Figure 2. typical stress-strain curves

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(2) By analyzing the curves of Figure 2, the curve can be divided into three regions, and the characteristics of the curve are showed in Figure 3. The three regions are initial linear elastic region, strain hardening region and stress failure region. In elastic region (region I), the stress is linearly related to strain, and the slope is defined as the initial elastic modulus, and the damage of the specimen is not particularly severe at this stage. In strain hardening region (region Π), the stress increases slowly as the strain increases. The middle part of the specimen is subjected to circumferential tensile stress. With the increase of strain, the cracks around the specimens obviously expand, and the greater the strain rate and the lower the temperature, the greater crack growth rate. In stress failure region (region Ш), the slope of the curve increases rapidly, which means the specimen has failed. In Figure 3, the A and B point represents the boundaries of each phase, where the B point means the compressive yield strength. The analysis of the mechanical properties is based on the definition of modulus and compressive yield strength.

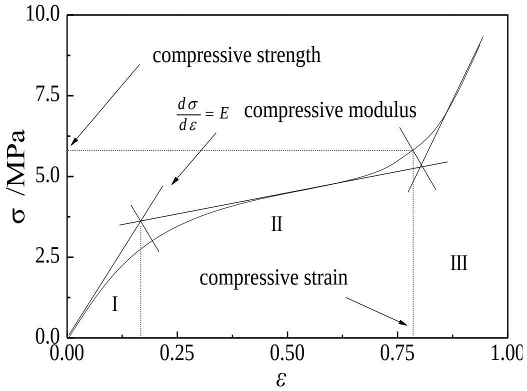

Figure 3. characteristics of stress-strain curve

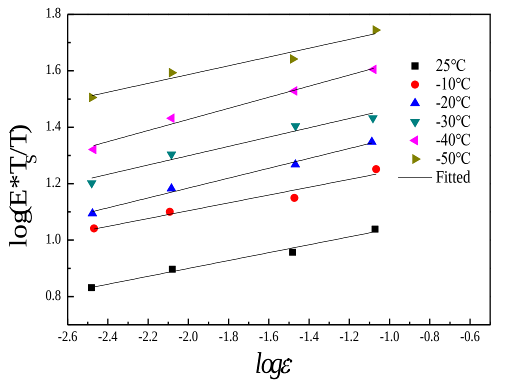

Figure 4. modulus vs. logarithmic strain rate at various test temperatures

3.2 Mechanical properties and master curve

Figure 4 indicates that the modulus is linearly related to the logarithm of strain rate, with a higher slope at lower temperatures. The modulus at -50℃ and 1/12s^{-1} is 33.5MPa, which is 3.41 times of the value at 25℃ and 1/300s^{-1}. The interaction of strain rate and low temperature strongly influence the change of modulus.

By shifting the modulus value horizontally along the logarithmic strain rate axis with the reference temperature of 25℃, we can get the modulus shift factor α_T curve represented in Figure 5. By means of Figure 4 and Figure 5, the compressive initial modulus master curve can be obtained in Figure 6.

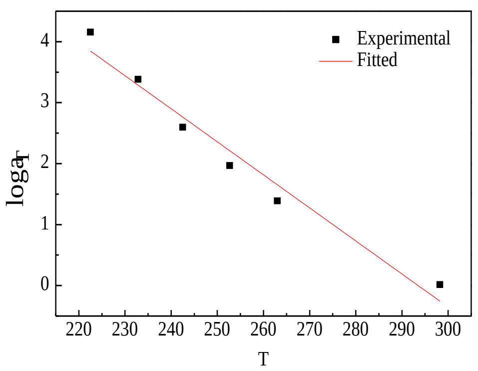

Figure 5. modulus logarithmic shift factor vs. temperatures

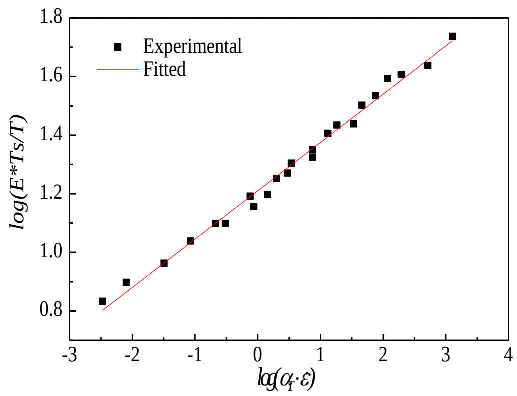

Figure 6. the master curve for compressive modulus

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Using the same way above, we also obtain the compressive strength master curve (Figure 7) with the reference temperature of 25°C. And the strength shift factor α_T is inserted in Figure 7. Table1 summarizes two equations, which describe the relationship of mechanical parameters with the reduced strain rate $\alpha_T \cdot \dot{\varepsilon}$.

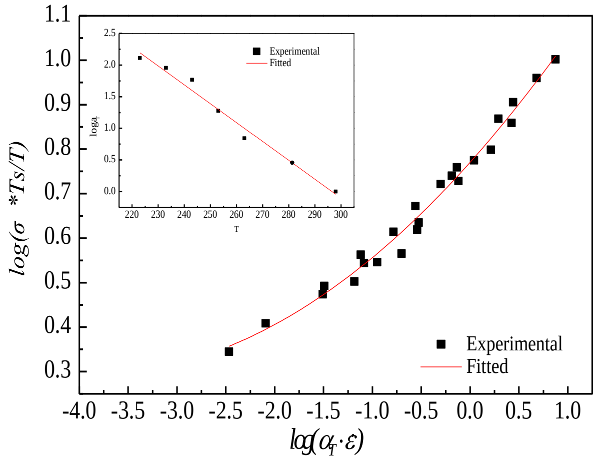

Figure 7. the master curve for compressive strength

Table 1 Equations for mechanical parameters

Mechanical parameters	Fitted formulas	Correlation coefficient/R^2
Compressive strength	$log(\sigma \cdot T_S / T) = 0.77 + 0.24 \cdot log(a_T \cdot \dot{\varepsilon}) + 0.03 \cdot log^2(a_T \cdot \dot{\varepsilon})$	0.98
initial modulus	$log(E \cdot T_S / T) = 1.2 + 0.16 \cdot log(a_T \cdot \dot{\varepsilon})$	0.99

4. Conclusions

In this paper, the mechanical behaviours of HTPB propellant under low temperatures and quasi-static compression were investigated. From the experiment, we can draw the following conclusions.

(1) Results show that HTPB propellant are closely related to temperature and strain rate. The stress and modulus change more obviously at lower temperature and higher strain rate.

(2) The master curves of mechanical parameters and their expressions are shown in this investigation. The master curves of compressive strength and initial modulus are expressed as the quadratic and linear function of the reduced strain rate, which can provide the theoretical basis for further analyzing the structural integrity of propellant grain.

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