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The Mechanical Response of a Composite Propellant under Harsh Conditions

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***Abstract*—**The aim of this paper is to study the mechanical properties of HTPB (Hydroxyl-terminated polybutadiene) composite propellant under harsh conditions. It describes two tests involving uniaxial tensile tests of various strain rates (ranging from 0.0005 s^{-1} to 1.5 s^{-1}), temperatures (ranging from 223 K to 343 K) and high-cycle fatigue tests under low-temperature (223 K, frequencies were set at 50, 100, 150 Hz) using DMA (Dynamic Mechanical Analyzer). To highlight the effect of small pre-strain on fatigue properties of HTPB propellant, quasi-static stretching was carried out before fatigue loading, and uniaxial tensile tests at constant strain rates were successively applied. The results reveal that flow stress of propellant increases with reduction in temperature and rise in strain rate, and the strain rate-temperature equivalence relationship could be described by TTSP (time-temperature superposition principle) incorporating a modified WLF equation. Moreover, the rate of performance degradations and damage accumulation of propellant during fatigue tests increased with increasing strain amplitude and loading frequencies, while initial quasi-static loading has a negative effect on fatigue properties by comparing stress-strain relations after fatigue tests.

***Keywords*—**Fatigue, HTPB propellant, tensile properties, time-temperature superposition principle.

I. Introduction

SOLID rocket motor (SRM) has been widely applied in the military and aerospace fields [1]. The main concern of SRM herein lies in the analysis of structural integrity of grain, which is supposed to obtain the mechanical properties of solid propellants under different working conditions. SRM will suffer high/low temperatures and overloading at launch, while the mechanical properties under these situations need to be thoroughly understood. HTPB propellant has high specific impulse and excellent mechanical properties, which is projected to be a promising composite propellant. The study of mechanical response of HTPB propellant helps to evaluate the working of SRMs in extreme environments. As a particle-filled elastomer, HTPB exhibits viscoelasticity, and its mechanical properties is strongly dependent on temperature and strain rate. HTPB propellant's elastic modulus, breaking strength and etc., are closely related to the temperature. With the temperature decreasing and strain rate increasing, the overall mechanical properties of the propellant see a great strengthening experience. In addition, Xu et al. [2] built HTPB propellant viscoelastic constitutive model based on irreversible thermodynamics, combined with the research results of Schapery [3].

We have implemented tensile and fatigue tests of HTPB propellant at harsh conditions, in which case extreme temperatures and strain rate are included.

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II. Experiment

A. Materials and Specimens

The HTPB propellant investigated is a particle-filled composite composed of 17-wt.% Al (aluminum), 70-wt.% AP (ammonium perchlorate), and 13-wt.% of a HTPB matrix and other additives. Fig. 1 is a scanning electron microscopy (SEM) image of HTPB propellant. From the image, information about contents distribution can be determined; that is, the large particles are ammonium perchlorate and the main portion of the propellant is the HTPB matrix, with Al and other additives distributed randomly inside the matrix.

The specimens were prepared according to the configuration shown in Fig. 2. Prior to each test, the specimens were stored inside the temperature chamber for 24 hours to eliminate potential moisture from the surrounding environment.

B. Equipment and Test Procedure

The uniaxial tension and fatigue tests were carried out by means of DMA (Model No. DMA-ELF3200, BOSE® Corp., USA), which possesses excellent capacities to control the applied loading range (from –225 to 225 N), frequency (from 5×10-5 to 200 Hz) and temperature (with temperature control device, from −150 to 315 °C). The force and displacement data were recorded by sensors with high accuracy, whose resolutions were 0.01 N and 0.001 mm respectively. The configurations of the test equipment are illustrated in Fig. 3.

The uniaxial tests were performed at various strain rates (ranging from 0.0005 s^{-1} to 1 s^{-1}) and temperatures (ranging from 223 K to 343 K).

The loading sequence of HTPB propellant specimens were as: Initially a quasi-static tensile loading and a successive displacement-controlled fatigue loading. The applied loading profile is illustrated in Fig. 4.

The tensile rate of quasi-static loading was 0.0075 mm/s (corresponding strain rate was 0.0005 s^{-1}). During fatigue process, the applied strain was given in (1).

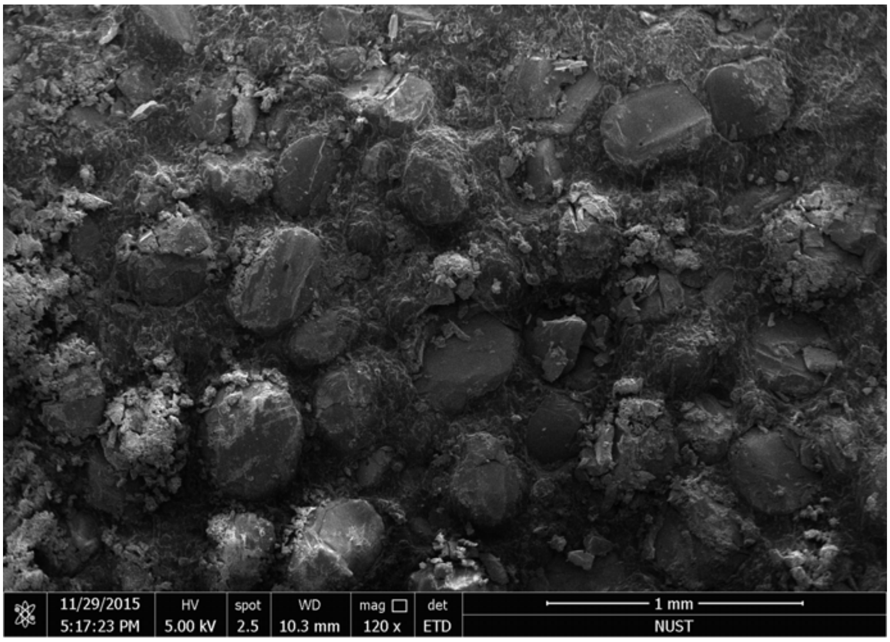


Fig. 1 SEM image of HTPB propellant

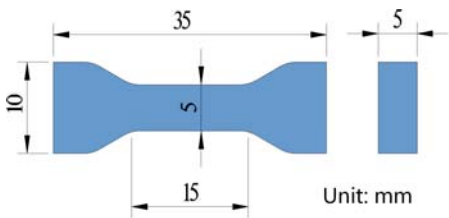


Fig. 2 Dimensions of tested sample

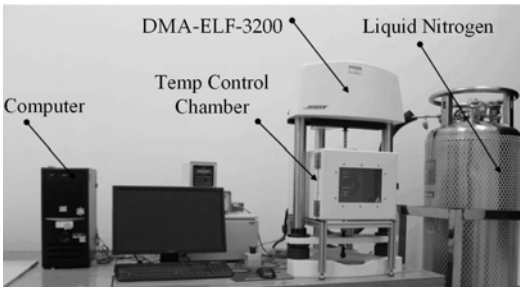


Fig. 3 DMA apparatus

$$\varepsilon = \varepsilon_a + \frac{\varepsilon_{\max} - \varepsilon_{\min}}{2}\sin\left(2\pi ft\right) \quad (1)$$

where $\varepsilon_{\max}$ (0.13, 0.14, 0.15) denotes applied maximum strain, $\varepsilon_{\min}$ (0.12) denotes applied minimum strain, $\triangle\varepsilon = \varepsilon_{\max} - \varepsilon_{\min}$ denotes the amplitude of applied strain, $\omega = 2\pi f$ denotes angular frequency, f denotes frequency, and t denotes time. During the test, f was set at 50, 100 and 150 Hz. The environmental conditions, e.g., temperature, were maintained constant at a room temperature of −50 °C during all the tests. Each test was repeated three times to ensure repeatability. After the fatigue tests, loaded specimens were taken down and then subjected to tensile test with the tensile velocity of 15 mm/s (corresponding strain rate was 1 s^{-1}).

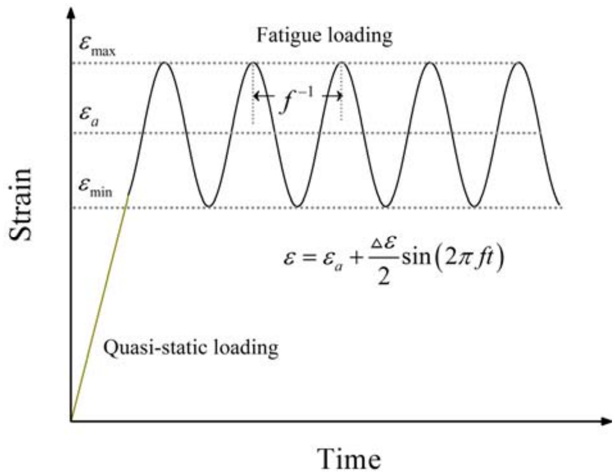


Fig. 4 Loading profile of HTPB propellant

III. The Tensile Properties of HTPB Propellant

A. Mechanical Response

As widely accepted, solid composite propellant is a typical viscoelastic material. When subjected to various loading conditions, the mechanical properties of solid propellant show strong dependences on strain rate and temperature. Fig. 5 demonstrates the results of uniaxial tensile tests, in which covering five strain rates and three temperatures. HTPB propellant is a polymer filled with a variety of particles, with complicated mechanical behavior, including large deformation and damage effects, resulting in varied profiles of stress-strain curves.

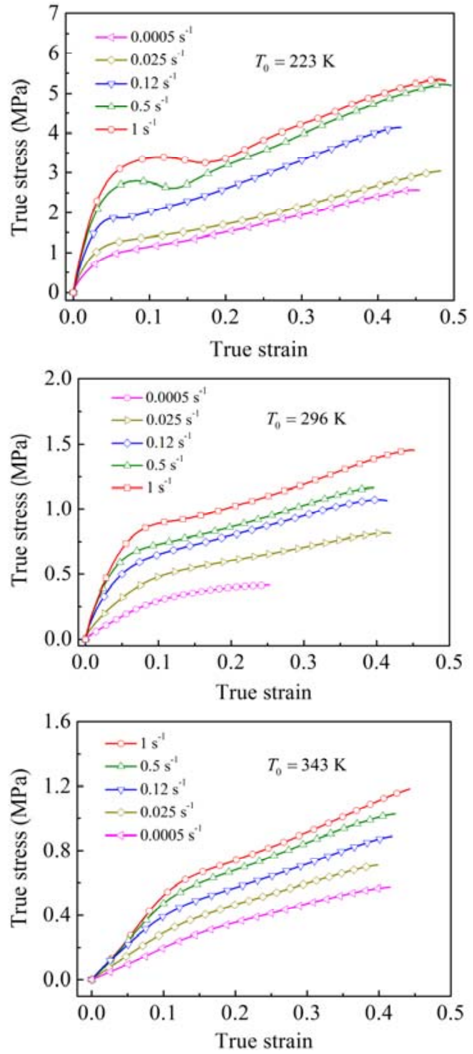


Fig. 5 Stress vs. strain curves at various temperatures

B. TTSP

The same mechanical relaxation phenomenon of the polymer can be observed at higher temperatures, while it could also be witnessed under a lower temperature of a shorter period of time. The viscoelastic behavior of the solid propellant under different time and temperatures is equivalent, which is named as the TTSP. Furthermore, rate-temperature equivalence is an extension of TTSP, that is, the effects on mechanical properties of improving (or reducing) the temperature and lengthening (or shortening) the time (reduction or increase in strain rate) is equivalent.

The free volume theory based WLF model [4] is widely utilized. We assumed that the relation between free volume of the material and temperature was non-linear, and we in turn put forward a modified WLF equation. In terms of uniaxial tensile test, time was linearly dependent on strain, see (2):

$$\varepsilon = \dot{\varepsilon} \times t = \dot{\varepsilon} \times \alpha_T \times \frac{t}{\alpha_T} = \dot{\varepsilon}_\xi \times \xi \tag{2}$$

where $\dot{\varepsilon}$ denotes strain rate at current temperature, α_T denotes time-temperature equivalent factor, $\xi\left(=t/\alpha_T\right)$ denotes reduced time at reference temperature, and $\dot{\varepsilon}_\xi\left(=\dot{\varepsilon}\times\alpha_T\right)$ denotes reduced strain rate at reference temperature. It is presumable that time-temperature equivalent factor is a function of temperature. A modified WLF model was presented as (3):

$$\log \alpha_T = \frac{C_1\left[1-\exp\left(C_3(T-T_0)\right)\right]}{C_2+\exp\left(C_3(T-T_0)\right)} \tag{3}$$

where T represents current temperature, T_0 represents reference temperature, and C_1, C_2, C_3 represent material parameters. According to [5], the model parameters were obtained under a reference temperature of 293 K, i.e. $C_1 = 2.82669$, $C_2 = -0.20323$, $C_3 = 0.00825$. Thus a master curve of tensile strength of HTPB propellant was acquired (Fig. 6) using the results of uniaxial tensile tests.

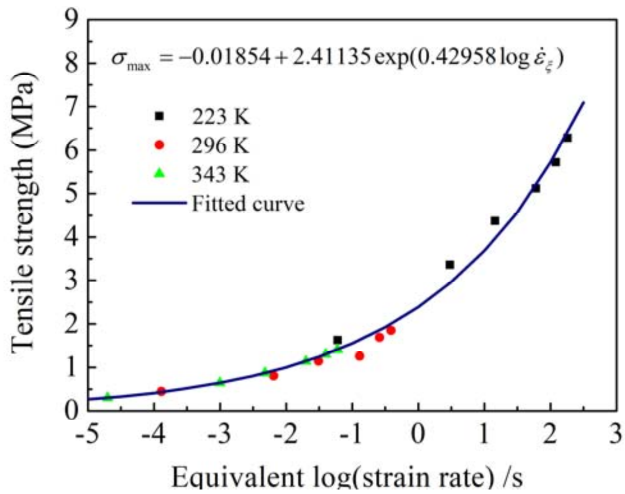


Fig. 6 The master curve of tensile strength of HTPB propellant

The relationship of equivalent exponential strain rate and tensile strength could be fitted as:

$$\sigma_{\max} = -0.01854 + 2.41135\exp(0.42958\log\dot{\varepsilon}_\xi) \tag{4}$$

where $\sigma_{\max}$ denotes tensile strength. The tensile strength of HTPB propellant subjected to tensile test at the strain rate form 10^{-5} to 10^{3} s^{-1} could be predicted from (4).

III. The Tensile Properties of HTPB Propellant

A. Stress-Strain Relationship

HTPB propellant is a viscoelastic material and when there are sinusoidal periodic changes in stress, the according strain is left behind stress. The phase difference between stress and strain is called loss factor (or lag angle). Consequently, the stress-strain hysteresis loop is shown in Fig. 7. It is clearly shown that the peak stress decreased with increasing fatigue numbers, reflecting the strain-controlled fatigue test in the course of stress relaxation phenomenon, which also depicting the viscoelastic properties of the propellant, showing that the peak stress during fatigue sees a cyclic softening.

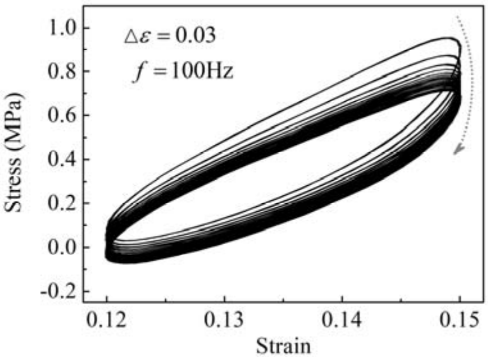


Fig. 7 Stress-strain hysteresis loop

As Fig. 8 implies, the phase angle remains constant at steady stage. The phase angle was attributed to the internal friction of solids, known as the frictional interaction between adjacent portions, such as polymeric binders, and crystal oxidizers in the interior of a solid propellant, which is due to viscous deformation, and thus acts as a heat source during fatigue tests.

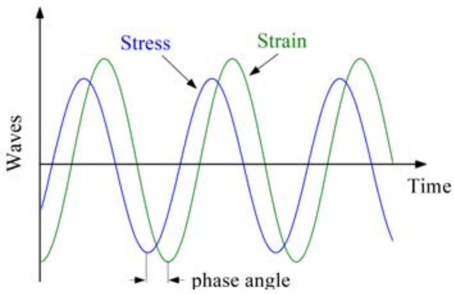


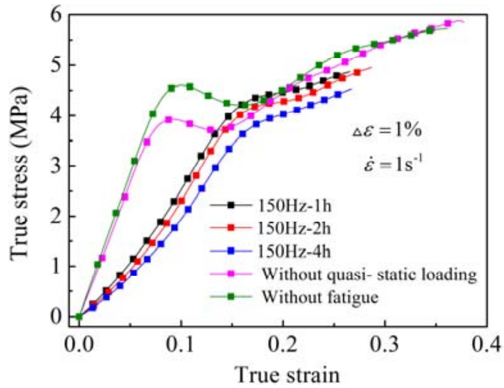
Fig. 8 The lag angle between stress and strain

B. Mechanical Properties after Fatigue Loading

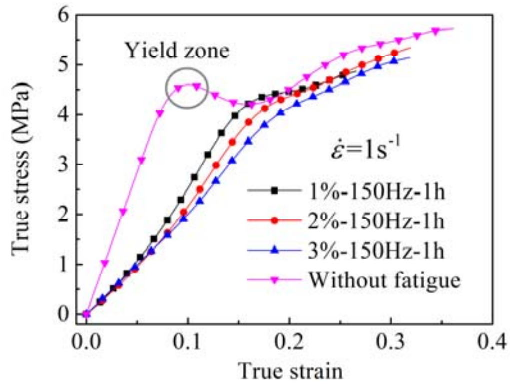
The mechanical properties of the propellant during fatigue process degenerated with increasing cyclic numbers, so it may be necessary to test mechanical parameters before and after fatigue by using constant velocity uniaxial tensile test after fatigue test.

As a result of initial quasi-static loading, internal micro-voids had emerged and evolved within the specimen. In order to investigate the effect of quasi-static loading on fatigue damage evolution, direct fatigue test without quasi-static loading and uniaxial test are shown in Fig. 9 (a). Uniaxial tensile tests after fatigue show that stress-strain relationship are similar, for example, there are both manifested yield phenomenon, whereas yield stress of the latter is higher than that of the former, and the initial modulus of the former is higher than the latter likewise.

Fatigue damage is dependent on strain amplitude, as shown in Fig. 9 (b), revealing that the greater strain amplitude, the greater cumulative fatigue damage.



(a) Identical frequency with various fatigue time



(b) Identical frequency with various strain amplitudes

Fig. 9 Comparison of true stress-strain curves under various conditions

IV. Conclusions

In the present study, several conclusions are drawn:

1. The tensile response for HTPB propellant is both temperature and strain rate dependent, which could be correlated by TTSP.
2. The quasi-static loading at initial stage before fatigue tests has a negative effect on fatigue properties of HTPB propellant, without which mechanical properties after fatigue would be greatly improved. Therefore the occurrence of small deformation during storage or transportation should be prevented.
3. From the microcosmic aspect, main causes of damage is dewetting between propellant matrix and particles.

Acknowledgments

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