Research on the effect of superimposed pressure on the mechanical properties of solid propellants

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Abstract: In order to study the superimposed pressure and strain rate dependence of the compressive mechanical properties of solid propellants, compressive tests were conducted under various superimposed pressure conditions and strain rates using a new-designed superimposed pressure testing machine. The mechanical properties of solid propellants under varying superimposed pressure conditions were studied and analyzed. The results shows that the mechanical properties of propellant materials are remarkably influenced by the varying superimposed pressure conditions. With increasing the superimposed pressure, the yield strength of solid propellants increases.

1. Introduction

Solid propellant grains are one of the key component of any solid rocket motors (SRMs), which structural integrity play an important role in the lifetime and safety of SRMs [1-3]. In general, SRMs are subjected to diverse loading during storage, transportation and ignition pressurization. It is universally known that under these loading, crakes can develop in the propellant grains because of the excessive stress or strain, which will lead to a serious accident. Therefore, the analysis of structural integrity has been a research hotspot. Accurate mechanical parameters of propellant materials are essential to analyze the structural integrity of solid propellant grains. In order to determine the structural integrity of solid propellant grains, experimental investigations on the mechanical properties of solid propellants under different load conditions should be conducted.

In recent years, numerous researchers have conducted a wide range of tests to characterize the mechanical properties of solid propellants. Sun et al. [4] studied the quasi-static and dynamic compressive properties of a composite modified double-base (CMDB) propellant under a wide range of strain rate and low temperature. The results showed that the yield stress, initial compressive modulus and ultimate strain are greatly affected by the strain rate and temperature. Further, the intermediate rate tests of CMDB propellant was considered by Yang [5]. They found that the yield stress increases with the logarithm of strain rate. In addition, Yang et al. [6] performed low, intermediate, and high strain rate compression testing of HTPB propellant at room temperature. Besides, a rate-dependent constitutive model was developed. Chen et al. [7] investigated the compressive mechanical properties of HTPB propellant at high strain rates and low temperature. The results showed that the strain rate and low temperature have a remarkably influence on the variations in stress. Wang et al. [8] found that continuously decreasing temperature and increasing strain rate, the characteristics of stress-strain curves and damage for HTPB propellant are more complex and are significantly different from that at room temperature or at lower strain rates. These studies mainly focus on the low temperature, low/middle/high strain rate, aging and tension/compression. However, these studies cann't truly reflect the mechanical behavior of solid propellants under ignition pressurization conditions. During the operation of SRMs, solid propellant grains are in a triaxial pressurized state. Thence, superimposed pressure experiments were developed to evaluate pressure-dependent mechanical properties of solid propellants. There are two approaches to create a superimposed pressure condition, which are passive superimposed pressure

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and active superimposed pressure [9]. Since passive superimposed don't provide a stable pressure value, active superimposed pressure tests are widely carried out [10-12]. As for compressive tests of solid propellant under superimposed pressure condition, Zhang et.al [13, 14] researched mechanical properties of a double-base propellant under hydrostatic compressive loading using a triaxial compressive device. It was found that the yield strength and compressive strength under hydrostatic loading have obtained more remarkable enhancement than those without the hydrostatic pressure effect. However, compared to other experimental conditions, experimental reports about the influence of superimposed pressure conditions of the propellant materials are relatively limited in current literature due to the fact that experiments are difficult to conduct.

According to previous numerical simulation results [2], under the ignition condition, the hoop of the solid propellant grains are subjected to tensile strain and the radical of the solid propellant grains are subjected to compressive strain. In order to accurately analyze the mechanical properties of solid propellant grains during the ignition and work period of solid rocket motor, a kind of triaxial compressive device for solid propellant material was designed. Compressive tests were conducted under various superimposed pressure conditions and strain rates. The mechanical properties of solid propellants under varying superimposed pressure conditions were studied and analyzed. It is believed that the research will promote the interpretation of mechanical properties of solid propellants under superimposed pressure.

2. Experimental Methodology

2.1. Experimental System

The superimposed pressure test system is shown in Figure 1, which mainly consists of three components. (I) A high pressure chamber is used to provide high pressure for the test chamber through the pressure pipeline. Nitrogen is chosen as high pressure gas for its safety and inertia. (II) The test chamber is installed in a material testing machine. In order to avoid that the experimental results are affected by the friction between the tie rod and the upper cover, the force sensor is installed in the test chamber. A pre-test was conducted to prove that the accuracy of the force sensor can't be affected by the superimposed pressure. A tempered glass is placed on the side of the test chamber to observe the tensile process for NEPE propellant under low superimposed pressure conditions. Due to the limited strength of tempered glass, it is replaced by aluminum plate under high superimposed pressure condition. The propellant specimen is clamped by two grip jaws. Owing to the test chamber can't be completely sealed, the pressure regulating value is used to control that the test chamber reaches a stable pressure level. The displayed value of pressure gauge 3 is the experimental pressure value and its accuracy is up to 0.01 MPa. (III) A Computer system is used to record the displacement and the force.

2.2. Materials and Methods

The materials is a Nitrate Ester Plasticized Polyether (NEPE) propellant used in this investigation. Table 1 lists the composition of the NEPE propellant.. NEPE propellant is designed as a cylinder, with a dimeter of 20mm and a length of 16mm.

The compressive tests were conducted at crosshead speeds of 0.6, 3, 15 and 60 mm/min (namely 0.0006667 s^{-1}, 0.003333 s^{-1}, 0.01667 s^{-1} and 0.06667 s^{-1}) and relative atmospheric pressures of 0, 0.5, 2MPa. A preloaded force of 3 N was applied to the propellant specimen by means of the material test machine, which keeps the specimen in the same position in the pressure chamber. Petroleum jelly is used to reduce friction between the two ends of the specimen and the indenter of the testing machine. Each test condition was performed at least three times and the stress-strain curves in the following sections were the average of the three replicas. Because the mechanical properties of solid propellants were obviously influenced by the humidity and temperature, the propellant samples were all stored under the constant temperature and humidity prior to testing.

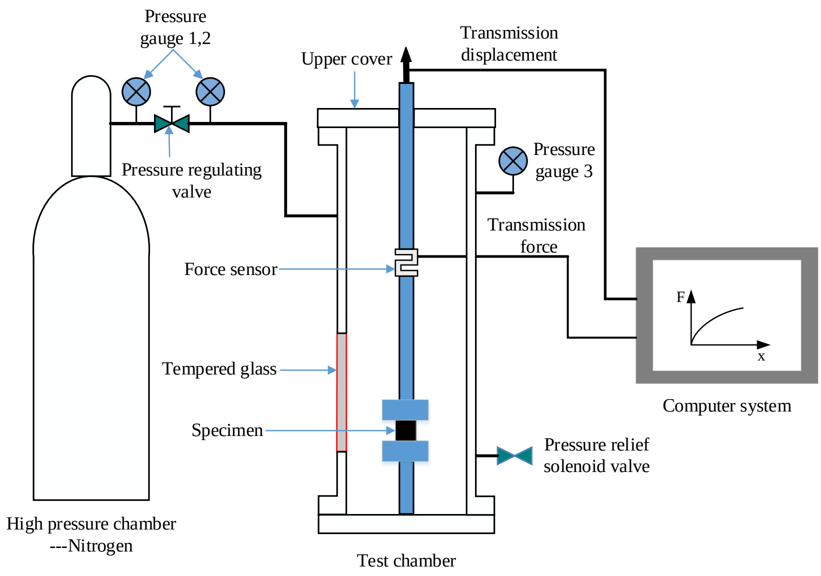


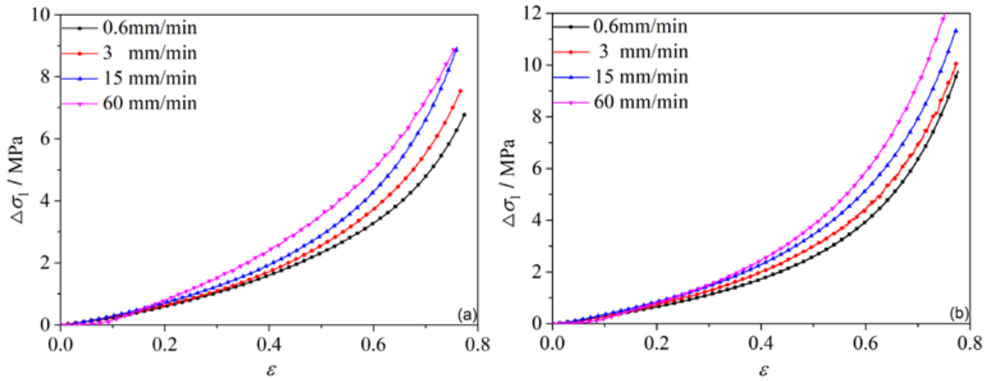
Figure 1 Schematic diagram of the superimposed pressure test system.

Table 1 Composition of NEPE propellants.

Components	Adhesive	Plasticizer	AP (Ammonium Perchlorate)	Al (Aluminum)	RDX	Catalyst
Content (wt %)	6-8	17-21	20-30	20-30	18-20	1-3

3. Results

When the studies on the influence of superimposed pressure on the mechanical properties of propellant, the propellant is usually regarded as compressible at large deformation [15]. Therefore, the engineering stress-strain curves are used to characterize the mechanical properties of the NEPE propellant. The engineering stress-strain curves of the NEPE propellant under different conditions are presented in Figure 2. It can be clearly seen that superimposed pressure and strain rate have a remarkably influence the compressive behavior of the NEPE propellant due to the viscoelastic material nature. Figure 2(a) and 2(b) shows that the rate-dependence of mechanical properties under superimposed pressure still exists. From Figure 2(c) and 2(d), we can find that for a given strain rate, the effect of superimposed pressure on the stress increases with increasing the strain. When at large strain (after 0.4), stress will increases as superimposed pressure increases. In addition, the NEPE propellant show the same nonlinear material behavior under different superimposed pressure conditions, which includes an initial elastic behavior and an obvious yield phenomenon. With increasing the superimposed pressure, the yield strength of the NEPE propellant increases.



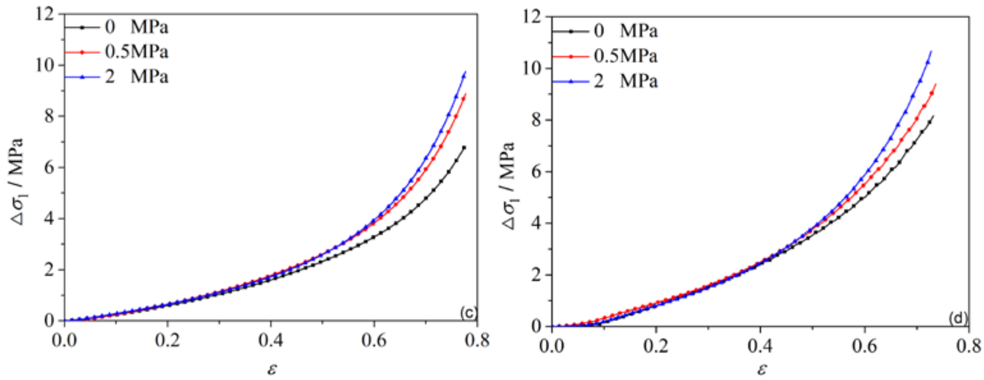


Figure 2 Engineering stress-strain curves of the compressive tests for the NEPE propellant under various superimposed pressure conditions and strain rates. (a) 0 MPa; (b) 2 MPa; (c) $0.00333s^{-1}$; (d) $0.0667s^{-1}$.

4. Conclusion

Because the superimposed pressure experiment is difficult to perform, the mechanical properties of solid propellant under various superimposed pressure were rarely reported. In this paper, the design of a superimposed pressure test device modified by the material testing system was described. The compressive tests of NEPE propellant were conducted under different superimposed pressure conditions and strain rates. The superimposed pressure had a pronounced influence on the mechanical properties of NEPE propellant. The yield value and compressive strength of the NEPE propellant increased as the superimposed pressure increases. This research will provide a theoretical foundation for analysis of the structural integrity of solid propellant grains of SRMs under ignition conditions.

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