Research Progress on Biaxial Tensile Testing

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Abstract. Since the 1970s, part of the solid rocket motor (SRM) has experienced disintegration when the tactical missile is launched at a low temperature of -40°C. Analyses of the emission of a large number of solid missiles revealed that the destruction of the structural integrity of the solid propellant grain was the major contributor to SRM failure. Due to the coupled effects of low temperature and the ignition pressure load, the structure integrity of solid propellant grain is aggravated. Therefore, improving the structure integrity of propellant grain during the ignition of SRM for tactical missiles at low temperatures is one of the key problems to tackle during the research and production of weapons. As previous reports show, the mechanical behaviors of solid propellants at low temperatures and strain rates from 1 to 102 s^{-1} are very important to effectively analyze the structure integrity of propellant grain for SRM of the tactical missiles during ignition at low temperatures. However, the mechanical behaviors of thermal aging solid propellants at low temperatures under dynamic loading are rarely reported. It is urgent to carry out research in this regard through new mechanical test methods. In this paper, we analyze the research progress of biaxial tensile testing schemes for different materials such as metals and composite materials. It was found that there are currently many biaxial tensile tests on rubber and composite materials, which can provide effective references for other materials.

Keywords: Research Progress; Biaxial tensile; Testing

1 Introduction

Since the 1970s, part of the solid rocket motor (SRM) has witnessed the disintegration phenomenon when the tactical missile was launched at a low temperature of - 40°C. Through analysis of the emission of a large number of solid missiles, it was found that structural disintegration of the solid propellant gain contributes considerably to the failure of SRMs. Due to the coupled effects of low temperature and the ignition pressure load, the structure integrity of solid propellant grain is aggravated. Therefore, in the research and production of weapons, it is necessary to enhance the structural integrity of the propellant grain during low-temperature ignition of SRMs in tactical missiles. Previous studies have revealed that controlling the mechanical behaviors of the solid propellants at a low temperature and a strain rate within a range between 1 and 102 s^{-1} is a solution to effective analysis of the structural integrity. However, reports on the mechanical behavior of the thermal aging solid propellant at low temperatures under dynamic loading are rare or even lacking. It is urgent to carry out studies in this regard via new mechanical test methods.

Given what is specified above, the tri-component Hydroxyl-Terminated Polybutadiene (HTPB) propellant used in the SRM of a typical tactical missile was chosen as the research object in this thesis. Then, a method combining experimental investigation and theoretical analysis was applied to systematically study the mechanical behaviors of the thermal aging propellant under low-temperature dynamic loading conditions, which contains dynamic biaxial tensile and compressive mechanical properties at low temperatures, microscopic damage, and the strength criterion. The fault envelope of thermal aging HTPB propellant was established according to the twin shear strength theory.

At present, both domestically and internationally, mechanical biaxial tensile testing is a popular method for the investigation of the mechanical characteristics of materials. Regarding biaxial mechanical property experimental research, according to material properties, it mainly includes metal mechanical property tests and composite material mechanical property tests. This article mainly summarizes the mechanical property tests of two types of materials and points out the shortcomings in current research and the need for further focused research.

2 Multi-Axis Mechanical Performance Test of Propellant

Wang Zhejun [1] simulated the stress ratio relationship between horizontal and vertical directions when Flat noodles propellant is stretched, as shown in Figure 1, through finite element software, and found that Flat noodles can perform approximately 1:2 biaxial stretching. Based on the domestic and foreign experiments, it is shown that flat noodles propellant can effectively simulate the stress state of real grain. Therefore, Wang Zhejun obtained the same change rule as the uniaxial tensile test by relying on the high strain rate testing machine to test the flat noodles test piece, as shown in Figure 2.

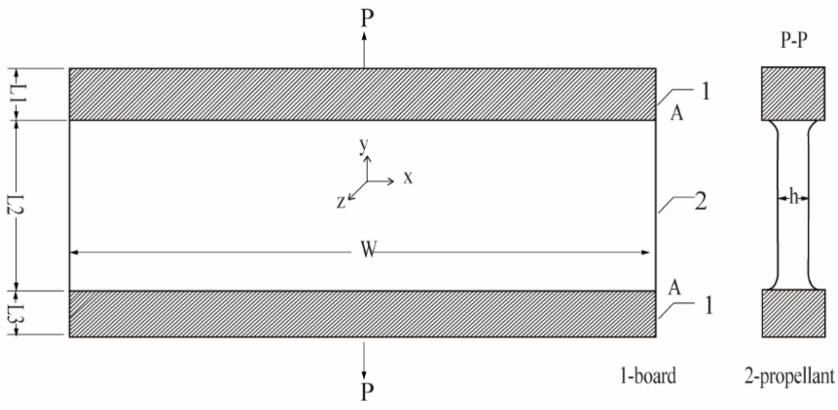


Fig. 1. Schematic diagram of flat noodles propellant.

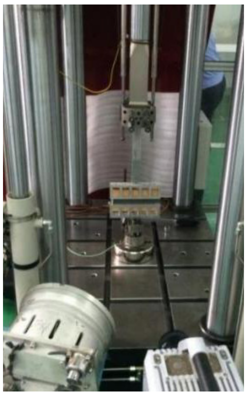


Fig. 2. Wang Zhejun et al. carried out flat noodles test.

At present, biaxial tensile research mainly relies on cross-shaped propellants. Zhang Lihua employed a uniaxial testing machine and self-developed the testing equipment to perform biaxial tensile tests on the propellants, which verified the anisotropic characteristics of solid propellants. To conduct a true biaxial tensile test, Qiang Hongfu et al. thinned the central region of a cross-shaped test piece with a biaxial tensile machine in Figure 3. Subsequently, Jia Yonggang et al. conducted biaxial tests by improving the bathtub-type propellant designed by Qiang Hongfu and combining it with a cross-shaped test piece with grooves on the arm in Figure 4.

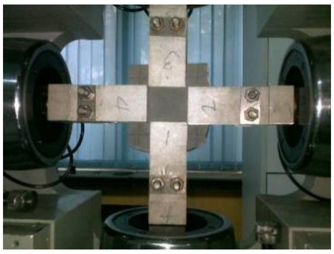
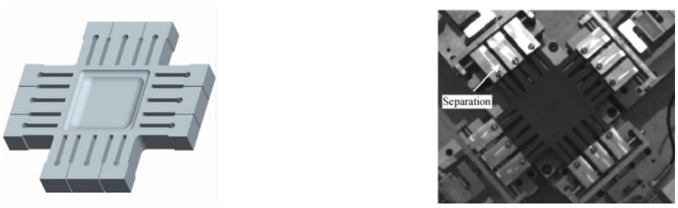


Fig. 3. Qiang Hongfu et al. experimental system.

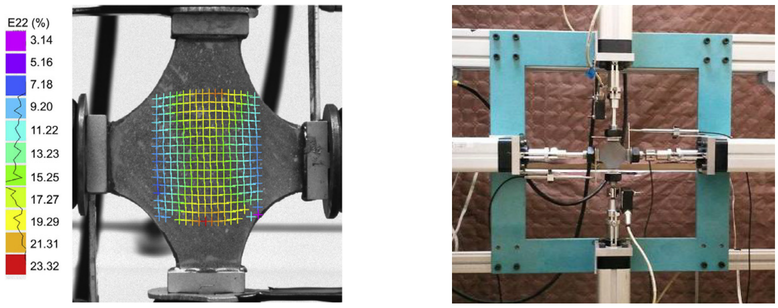


(a) Optimization of the cross-test piece

(b) Test piece and machine loading

Fig. 4. Jia Yonggang et al. experimental system.

Foreign researcher Jalocha believes that the experimental scheme adopted by Jia Yonggang is not very reliable. Therefore, he redesigned the cross-shaped test piece by canceling the slotted design and expanding the radius of the propellant arc area, finally achieving the biaxial tensile test research in Figure 5.



(a) Improve cross propellant (b) Test piece and device system

Fig. 5. Jalocha et al. experimental setup.

Zhang et al. conducted biaxial tensile, biaxial compression, and tensile compression performance tests on bathtub-shaped specimens, rectangular specimens, and similar dumbbell-shaped specimens using a biaxial testing machine.

To simulate the effects of the pressure environment in SRM of propellant columns, Liu et al. [2] conducted mechanical experiments on solid propellants by adding confining pressure devices and applying pressure loads. The action of pressure makes it difficult to observe the damage and increase the strength of the propellant. This agrees with the conclusions reached by He Tieshan et al. in simulating the ignition and pressure building of NEPE propellant in a high-pressure testing machine. Zhang Ya et al. conducted mechanical tests under confining pressure on HTPB propellant specimens of different ages and found that when pressure exists, the propellant has higher mechanical tensile strength. In the confining pressure environment, the propellant can be stored better.

Regarding triaxial mechanical performance tests, both domestically and internationally, tests are mainly conducted within the quasi-static ($<1s^{-1}$) range. Jones J W designed thick disc specimens for research and conducted radial compression tests using a compression testing machine to simulate their stress state from multiple perspectives. In fact, during the SRM operation, the multi-axis specimen presents a stress state that has a higher resemblance with the real situation of the internal grain. Therefore, foreign researcher Sanal Kumar provided a research circular tube test piece to better simulate the stress state of the grain during ignition and compression. Relaxation tests were designed for different stress states. The tests showed that at the beginning of the test, the stress composition was not enough to change the relaxation modulus of the propellant. As the test continued to be loaded under tension, the relaxation modulus increased with the dimension of stress. Under the same test conditions, the relaxation modulus of the triaxial test was the highest.

3 Research Progress on Influencing Factors of Mechanical Properties of Propellants

(1) Temperature is the influencing factor that causes changes in the mechanical properties of HTPB propellants. Pang et al. found that the initial modulus and maximum tensile strength of solid propellants are inversely proportional to temperature, but there is no significant proportional relationship between the maximum elongation. Lai Jianwei and Wang Xiaoying [3] both conducted low-temperature and low-temperature recovery tensile tests at room temperature to study the effects of low temperatures on propellants. Through low-temperature tensile tests, Wang Zhejun studied the performance changes of propellants under uniaxial and biaxial tensile tests. Shekhar compared the changes in propellant performance caused by various temperatures and found through experiments that low temperatures increase the maximum tensile strength of propellants.

(2) In terms of strain rate, the experiment mainly relies on changing the tensile or compression rate of the test piece. Lai Jianwei et al. compared the mechanical properties of the propellant at different compression rates by changing its compression rate and found that the magnitude of the compression rate can change the strength of the propellant. Via mechanical tests on the modified double-base solid propellants under varied strain rates, Sun et al. established constitutive equations based on the mechanical performance parameters. Sun Chaoxiang [4-5] conducted research on solid propellants by changing the strain rate and found that high strain rates have a greater impact.

(3) Solid propellants face aging problems from the moment they are produced. To study the changes in mechanical properties of propellants after aging, natural aging and thermal aging tests are mainly conducted in current experiments. Currently, domestic and foreign research mainly relies on the Time-Temperature Superposition Principle (TTSP) to conduct high-temperature thermal aging tests on test specimens. Kivity et al. analyzed the intrinsic causes of propellant aging from a mechanistic perspective. Zhang Ya and Wang Zhejun [6] conducted experiments on propellants with different aging times and found that the strength of aged propellants increased compared to those without aging.

(4) To simulate the real force state of propellants during SRM operation, researchers at home and abroad have proposed experimental schemes from one-dimensional to multi-dimensional for research. For uniaxial tensile testing, JANNAF standards and GJB 770B-2005 standards have been introduced as references, but there is still a lack of standards that can be referenced for multiaxial mechanical testing. To better study the mechanical properties of propellants under multidimensional stress states, Zhang Ya conducted biaxial tensile and biaxial compression tests using a biaxial testing machine. Compared with his uniaxial tensile and compression studies, it was found that the biaxial tensile strength increased, but the elongation rate decreased; Wang Zhejun also found that biaxial will enhance the maximum tensile strength of propellant by carrying out flat noodles test pieces, and found that solid propellant will be constrained in two directions under biaxial conditions, so its elongation will decrease.

4 Conclusion

(1) At present, only testing standards for single-axis quasi-static conditions have been issued domestically and internationally. Due to device limitations, testing under dynamic loading is still very rare, especially for biaxial high strain rate loading tests. Although Qiang Hongfu and others have conducted dynamic single-axis biaxial tensile tests, there is still insufficient understanding of the mechanical properties of real propellants.

(2) There is a lack of multi-factor analysis. Currently, only single-factor mechanical performance tests such as temperature, strain rate, stress state, or aging have been conducted, and multi-factor loading tests for HTPB propellants under biaxial tension after low temperature, high strain rate, and thermal aging have not been carried out yet.

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