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Research Advance of Mechanical Properties Test of Solid Propellant Compression

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Abstract

This paper summarizes the current research status of test articles and corresponding test loading devices in ranges of quasi-static and dynamic strain rate in mechanical properties test of solid propellant compression. The future development trend of mechanical properties test of solid propellant compression is prospected, and it is considered that the experimental study of mechanical properties of multiaxial compression, especially multiaxis mechanical properties under dynamic loading conditions, is a future research focus, which is helpful to more comprehensively and deeply understand the mechanical properties of solid propellant under complex stress.

Keywords

Solid Propellant; Compression; Mechanical Properties; Research Progress.

1. Introduction

Solid propellant is a widely used energy-containing material and is the main energy source for the missile power device, the Solid Rocket Motor (SRM) [1]. However, in the overall structure of SRM, the grain composed of solid propellant is also one of the weakest links [2]. Therefore, the study of a relevant mechanical behavior for solid propellant has attracted much attention to ensure that the missile weapon better exerts its weapon efficacy.

The solid propellant grain is subjected to continuous compressive loading throughout the life cycle of the missile weapon. The protective pressure during the production pouring process as well as during storage can subject the grain to quasi-static compression loading, and the high overload at the moment of blast-off as well as during flight can produce dynamic compression loads acting on the solid propellant grain [3,4]. Therefore, the mechanical response of solid propellant under quasi-static and dynamic compression loading must be fully mastered.

At present, domestic and foreign scholars have carried out masses of experimental studies on the compression mechanical properties of solid propellant under different strain rates for test articles and a variety of experimental devices, and gained some results. However, due to the complexity of working state of missile weapon and solid propellant mechanical properties, there is still a big gap between the relevant research that has been carried out and engineering practice. Therefore, this paper mainly summarizes the test articles and test devices used in mechanical properties test of solid propellant compression from two aspects: quasi-static compression and dynamic compression, respectively, and discusses and analyzes the existing problems in the study.

2. Mechanical Test of Quasi-Static (< 1s-1) Compression

2.1 Test Article of Quasi-Static Compression

At present, for the uniaxial compression mechanical test of solid propellant at low strain rate, domestic and foreign scholars mainly carry out uniaxial compression test based on cuboid test articles and cylindrical test articles with different aspect ratios. According to the JANAF [5] standard established in the United States, the solid propellant uniaxial compression test article uses a cuboid configuration, which has the advantage that it can accurately measure the rupture angle, but it is required for the processing technology. The AWE standard developed by Atomic Weapons Establishment (AWE) uses cylindrical compression test articles with an aspect ratio of 2.5 and easier processing to study the relevant compression mechanical properties. Korean scholar Park, C [6] used the ASTM D695 standard for uniaxial compression performance of rigid plastics formulated by the United States (the test article was a cylinder with aspect ratio of 2). Considering the difficulty in processing the test article and the particle size composed of solid propellant, the test article size was determined as a cylindrical test article with smaller aspect ratio of $\Phi 18\text{mm} \times 18\text{mm}$ to carry out the test study. In the quasi-static uniaxial compression test of solid propellant by Qiang Hongfu [7], the test article was designed as a cylinder with an aspect ratio of 1 by referring to foreign standards, which reduced the processing difficulty on the basis of ensuring that it meets the one-dimensional stress loading conditions. Zhang Ya [8] continued to use the cylindrical compression test article with the aspect ratio of 1 on the research basis of Qiang Hongfu to study the uniaxial compression mechanical properties of another model of solid propellant, but when studying the biaxial compression mechanical properties, considering the characteristics of high elongation of solid propellant and large deformation under biaxial compression loading, the cuboid configuration test article with the size of $30 \times 40 \times 40\text{mm}$ was redesigned to carry out the biaxial compression test. During the studying of the mechanical properties of Nitrate Ester Plasticized Polyether (NEPE) under uniaxial compression loading with low strain rate by Zhang Junfa [9], a cylindrical test article of $\Phi 10\text{mm} \times 10\text{mm}$ was also used. Wu Huimin [10,11] then used cylindrical test articles with a diameter of 14 mm and a length of 8 mm (length/diameter ratio < 1) to study the strain rate effect of composite solid propellant and two explosives under quasi-static compression loading, and carried out mesoscopic observations of their respective failure characteristics using scanning electron microscopy. In order to obtain the modulus parameters of propellant pillar compression, Ren Ping [12] of Northwestern University of Technology designed the cuboid configuration compression test article with reference to the distance zone size of the tensile standard test article, and finally determined the compression test article size by carrying out the comparative test at different heights. Subsequently, Hu Shaoqing [13] processed the uniaxial compression test article of double lead-2 solid charge according to the requirements of plastic compression property test method in GB/T1041-1992, and the specific dimensional parameter was a cylindrical test piece with aspect ratio equal to 2. Li Jianwei [14] carried out uniaxial compression tests at different temperatures (-40~25 ° C) and strain rates (1/300~1/12 s -1) using a cylindrical test article of $\Phi 20\text{mm} \times 20\text{mm}$, and analyzed the rate-temperature equivalent characteristics of Hydroxyl Terminated Polypropadiene (HTPB) composite solid butellant. Sun Chaoxiang [15] studied the quasi-static compression mechanical properties of composite double modified base (CMDB). In order to weaken the effect of end friction of the test article on the test results, the uniaxial compression test was carried out by using the cylindrical test article with nominal size $\Phi 10\text{mm} \times 15\text{mm}$ (length-diameter ratio of 1.5) in combination with the universal coupling fixture. Xia Zhichao [16], Yang Long [17] and Zhou Haixia [18], Beijing Institute of Technology, used the quasi-static uniaxial compression mechanical property test method [19] (GJB 770B-2005 method 415.1) of explosive test standard to determine the size of test article as $\Phi 16\text{mm} \times 20\text{mm}$ when studying compound solid propellant. When studying modified double-base propellants, Wang Hongli [20] at Nanjing University of Science and Technology used cylindrical test articles with the same aspect ratio, but reduced in size by half, and the specific size was $\Phi 8\text{mm} \times 10\text{mm}$. In order to measure the failure angle more accurately, the uniaxial compression failure test was also performed on the $8 \times 8 \times 10\text{mm}$ cuboid test article, and the failure angle $\alpha_f = 53^\circ$ was finally obtained.

2.2 Test Loading Device of Quasi-static Compression

The test loading device of quasi-static compression can be divided into uniaxial material tester and biaxial material tester according to the type. In view of the fact that the uniaxial compression test with

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low strain rate at home and abroad is usually carried out based on the uniaxial material tester, and the test technology of the uniaxial material tester is relatively mature so far, with high reliability of the results, this paper will not be repeated. In terms of biaxial loading equipment, Zhang Ya [8] successfully carried out the biaxial compression test study of solid propellant based on the SZ-20KN biaxial material tester produced by Changchun Tester Research Institute. The tester adopts a biaxial four-cylinder electrohydraulic servo mechanism. The four cylinders are independently controlled. The maximum displacement of loading is 50 mm and the maximum speed is 100 mm/min. The biaxial loading test of any proportion can be realized. However, the disadvantage is that the displacement cannot be directly output, and the data storage and stuck often occur due to the failure of timely update of the software.

2.3 Summary Review

Although the test technology of uniaxial universal material tester is relatively mature nowadays, and the reliability of the results is high, there is still a lack of domestic test standards for the mechanical properties of solid propellant uniaxial compression, which is mainly reflected in that the actual quasi-static uniaxial compression test usually refers to the test methods of other materials and the size and configuration of the test article are not unified. At present, although most domestic researchers consider the difficulty of machining the test article and the friction effect of too small length-diameter ratio, cylindrical compression test articles with length-diameter ratio of 1~2 are usually selected when studying the mechanical properties of quasi-static uniaxial compression of propellants. However, cylindrical test articles with different aspect ratios have a very significant effect on the compression test results of solid propellant [21], so it is urgent to unify the standard based on the existing interval for this parameter. In addition, biaxial mechanical behavior tests of propellants have been carried out abroad, and corresponding standards have been established [22], but there are relatively few studies on biaxial mechanical behavior of solid propulsion in China. In this case, more advanced biaxial material testers need to be used for the test of solid propellant biaxial mechanical behavior under quasi-static conditions, such as SDS100 biaxial testers developed by Changchun Institute of Mechanical Sciences Co., Ltd., and TR174L series planar biaxial testers produced by Testresources, USA. For the accuracy and reliability of the loading device of uniaxial material tester, on the basis of establishing the uniaxial compression test standard, the biaxial mechanical properties test of solid propellant compression standard under quasi-static conditions is gradually established.

3. Mechanical Test of Dynamic Compression

According to the division of strain rate range by Field [23] et al., the dynamic compression mechanical test includes the compression test with medium strain rate (1~102 s-1) and the compression test with high strain rate (102~104 s-1). The following summarizes the dynamic mechanical properties test of solid propellant compression from these two aspects.

3.1 Mechanical Test of Medium Strain Rate (1~102 S-1) Compression

3.1.1 Test Articles of Medium Strain Rate Compression

The selection of the size of the test article under medium strain rate compression conditions varies, but the population is divided into two categories: one is to keep the size of the test article under quasi-static loading in line with the effect of the size when the mechanical properties of the quasi-static are compared, for example, the ASTM standard in the United States specifies and unifies the uniaxial compression test article under quasi-static and medium strain rates, and cylindrical test articles with size $\Phi 12.7\mathrm{mm} \times 25.4\mathrm{mm}$ and aspect ratio of 2 are used [24]. In the other category, the size of the test article under the same Test article of high strain rate compression is unified, which mainly meets the needs of the corresponding medium strain rate loading equipment. For example, Williamson [25] of the University of Cambridge, UK, used a Schenk hydraulic tester to perform a loading study of medium strain-rate compression of solid propellant, in order to maintain the stress balance of the test article during the test and limit the inertial effect, a cylindrical test article with length-diameter ratios

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of 0.38 and 0.4, respectively, was selected, which belonged to the length-diameter ratio range (0.28~0.63) of the test article under high strain-rate loading indicated by Gray [26]. In order to eliminate the data change caused by size, domestic scholars usually carry out the experiment by referring to the size of the test article under quasi-static conditions during the ongoing strain rate compression test. When Wang Zhijun [27, 28] studied the uniaxial compression mechanical properties of HTPB combined with solid propellant under the condition of strain rate in the study, the design of the test article and the design of quasi-static uniaxial compression loading remained unified, and cylindrical test articles with an aspect ratio of 1 were used. Li Meng [29] proposed a composite solid propellant stress-strain test method under medium strain conditions, which still uses a cylindrical test article with an aspect ratio of 1. Yang Long [30] and Zhou Haixia [18] carried out uniaxial compression tests on rate-dependent mechanical properties covering medium strain rate conditions for CMDB propellants and HTPB propellants, respectively, and the cylindrical test article of $\Phi 16\mathrm{mm} \times 20\mathrm{mm}$ was used for the Test article of medium strain rate compression, which was also consistent with the size of the low strain rate compression test article.

3.1.2 Loading Equipment for Medium Strain Rate Compression

At present, the test equipment that can realize medium strain rate loading mainly includes high speed cam deformation tester, drop weight impact test device, medium strain rate SHPB pressure rod, high speed hydraulic servo machine and fatigue tester. However, due to the requirements and limitations of loading principle, test materials and constant strain rate, domestic and foreign scholars mainly based on high-speed hydraulic servo tester for solid propellant uniaxial compression test of medium strain rate. Williamson [25] tested the compressive mechanical response of solid propellant in the strain rate range of 2~230 s -1 using a Schenk compressor independently developed by the University of Cambridge, and pointed out that the device was a quasi-static universal material tester, a dynamic drop weight testing device, and a strain rate bridge between the SHPB device. Wang Zhijun [31] successfully tested the compression mechanical properties of HTPB composite solid propellant under low-temperature dynamic loading by a self-designed loading fixture combined with an INSTRON VHS 160/100-20 high-speed tester, and analyzed the mesoscopic damage effects of different temperature and strain rate conditions on the test article. Xia Zhichao [16] and Yang Long [32] also used this model of high-speed hydraulic servo tester to study the strain rate correlation and constitutive model of HTPB and CMDB propellants. The maximum loading speed of INSTRON VHS series testers can reach 20 m/s, and the corresponding compression test strain is 85 s-1, which belongs to the dynamic loading range. In addition, the tester adopts a mechanical control system, and the speed control accuracy is very high during the test. Park [6] of the Korean Academy of Sciences carried out the uniaxial mechanical properties test of solid propellant compression with medium strain rate for solid propellant with HTPB as the matrix based on a self-designed high-speed hydraulic servo test device (Kistler 9051A), which had a maximum load force of 30 kN and a maximum load speed of up to 7800 mm/s.

3.1.3 Summary Review

Due to the lack of effective loading equipment with medium strain rate of solid composite propellants, it is difficult to carry out experimental studies on mechanical properties at medium strain rate. However, in order to obtain the test data of materials under medium strain rate, domestic and foreign scholars have conducted a lot of research and exploration on the technical difficulties of medium strain rate equipment [33-37]. Among them, the high-speed hydraulic servo tester as a mature research results has been applied to the mechanical performance test of medium strain rate. However, through the above review, it can be found that the mechanical properties of medium strain rate compression in multiaxis state have hardly been carried out, and the current research mainly focuses on the test of uniaxial compression mechanical properties.

In response to this deficiency, the next step can be carried out in two directions. First, to further break the limitations of high-speed hydraulic servo tester and realize the polyaxialization of loading systems like universal material testing machines. Second, based on the uniaxial test loading device, a special

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fixture is designed, and the multi-axial mechanical properties under medium strain rate are studied by using the principle of force decomposition. For example, Kossa [38] specifically designed the test fixture shown in 1 when studying closed-pore polymer foams and successfully obtained the biaxial mechanical response based on a uniaxial material tester. Bailly [39] designed a confining device consisting of a brass ring, and successfully studied the mechanical properties of energetic materials under dynamic triaxial compression in combination with a uniaxial device with separated Hopkins pressure bar (SHPB).

Fig. 1 Diagram of Biaxial Compression Fixture Designed by Kossa [38]

3.2 Mechanical Test of Medium Strain Rate (1~102 S-1) Compression

3.2.1 Test Article of High Strain Rate Compression

When carrying out mechanical properties test of solid propellant compression with high strain rate, domestic and foreign scholars usually use short cylindrical test articles. However, when the specific aspect ratio is determined, it is found that a smaller aspect ratio is beneficial to reduce the inertial effect of the test article and maintain the stress balance state during the test, and it can also minimize the dispersion effect of the wave in the measured strain signal [40]. Davis [41] et al., theoretically gave the aspect ratio of the test article to be $\sqrt{3}\nu/2$ when there is no inertial effect, where ν is the Poisson's ratio of the test article material. However, if the aspect ratio is too small, the consequent increased friction effect will change the uniaxial stress state of the test article, which in turn affects the effectiveness of the test results [42]. Therefore, the aspect ratio of the test article with high strain rate is usually in the range of 0.36~1. Lu Yunfang [43] et al studied the mechanical response of composite solid propellant at two high strain rates, 980 s-1 and 1300 s-1, and the failure characteristics of the test piece under dynamic loading using a cylindrical test piece with $\Phi 14\mathrm{mm}\times 5\mathrm{mm}$ (aspect ratio of 0.36). Sun [44] designed the CMDB propellant test article as a cylinder of $\Phi 10\mathrm{mm}\times 4\mathrm{mm}$ (aspect ratio of 0.4) from the point of view of reducing the inertial effect. Chang Xinlong [45] and Yang Long [17] carried out uniaxial mechanical properties test of solid propellant compression with high strain rate for HTPB propellant and CMDB propellant, respectively, based on $\Phi 10\mathrm{mm}\times 5\mathrm{mm}$-based cylindrical compression test articles, and successfully constructed constitutive models considering temperature and strain rate effects. In order to further weaken the effect of additional axial force on the uniaxial compression test of NEPE with high strain rate in dynamic experiments, the test article size shown in Fig 2 is determined on the basis of the annular cylindrical test article proposed by Song [47].

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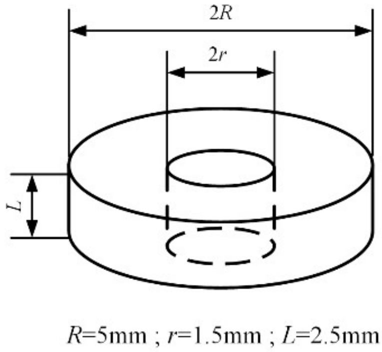

Fig. 2 Schematic diagram of SHPB dynamic compression test article designed by Zhang Junfa [48]

3.2.2 Loading Equipment of High Strain Rate Compression

Currently, SHPB is the main loading device to study the mechanical properties of solid propellant under high strain rate conditions. SHPB was first improved by Kolsky [49] on the basis of Hopkins pressure bar, so SHPB is also known as Kolsky device. In the following decades, this technology has been in continuous improvement, and is widely used in the mechanical property test of materials under high strain rate conditions. In order to successfully apply the SHPB device to solid propellant materials, domestic and foreign scholars have improved the device in combination with the characteristics of non-metallic materials with low strength, low modulus and low impedance of solid propellant materials, in order to meet the one-dimensional stress wave assumption and stress uniformity assumption. Balzer [50] used titanium and magnesium alloys with low impedance as materials for the piezers. Wu Huimin [11] used the incident wave shaping technique based on copper shaping sheet in the test to balance the internal stress of the test article by increasing the rise time edge. Zhang Junfa [9] and Sun Chaoxiang [15] used LC4 ultra-high strength aluminum alloy as the ballast material when studying NEPE propellant and CMDB propellant, and also increased the length of the bullet, using a bullet of 300 mm in length. Chang Xinlong [45] used semiconductor strain gauges to enhance the measured values of transmission signals when studying the dynamic mechanical properties of HTPB propellants at low temperatures, in addition to using aluminum alloy materials as pressure rods and further increasing the bullet length. In addition, to reduce the influence of friction effect on the test results, domestic and foreign scholars always apply lubricant to the end of the incident rod or the end of the test article when carrying out the test of SHPB device.

3.2.3 Summary Review

The selection of test article size is particularly important for uniaxial mechanical properties test of solid propellant compression with high strain rate based on SHPB device, which directly affects the effectiveness of test result. In addition, in order to meet the one-dimensional stress wave hypothesis and stress uniformity hypothesis and improve the reliability of the test, it is also necessary to carry out more in-depth study from the aspects of impedance matching, friction effect, diffusion effect and stress balance. Faced with the research needs of biaxial mechanical properties under dynamic loading of solid propellant, further improvement of SHPB device is also the direction of future development. Li Yulong [51] of Northwestern University of Technology proposed a biaxial bidirectional Hopkins rod (ESHPB) based on electromagnetic drive for brittle materials, which solves the problem of asynchronous loading time of incident waves generated by traditional mechanical SHPB devices in different loading directions to the end surface and can realize the dynamic biaxial bidirectional synchronous loading of materials, but further exploration is required on whether it can be used in solid propellant materials.

4. Conclusion

The In this paper, the research progress of mechanical properties test of solid propellant compression at low, medium and high strain rates and the shortcomings in the current research are analyzed and

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summarized in detail from two aspects: compression test article and compression loading test device. It is considered that the possible development priorities in the next step include the following aspects:

(1) On the basis of learning from domestic and foreign uniaxial compression test standards for composites, explosives and other materials, further clarify and unify the standards for uniaxial compression test of solid propellant, especially the determination of the configuration size of the test article under quasi-static loading.

(2) The study of mechanical properties of multiaxial compression of solid propellant is a direction of development, especially for the study of multiaxis mechanical properties test of solid propellant compression under dynamic loading. The biaxial mechanical properties of solid propellant have been experimentally studied abroad, and the corresponding standards have been established. However, the research on this area in China is significantly lagging behind. In addition, restricted by the test loading conditions, the study on the biaxial mechanical properties test under dynamic loading is almost blank.

(3) Optimization and improvement of compression test device under dynamic loading. Dynamic loading equipment is the basis for carrying out dynamic mechanical performance test, and its optimization and improvement help to improve the reliability of test results of test materials under dynamic loading. However, there is still room for further optimization and upgrading of dynamic compression loading equipment, which can be upgraded and improved from the aspects of loading principle, loading mode and device materials.

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