Research progress on crack propagation behavior of solid propellant

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Abstract. Crack sprouting will lead to the mechanical properties of propellant degradation, and the additional combustion surface formed by crack propagation may cause over-pressurization, resulting in uneven combustion of propellant, significantly changing the thrust characteristics of the engine, reducing the range of the vehicle, and may even cause catastrophic accidents such as explosions. Therefore, the study of crack propagation law of solid rocket propellant pillar is an important basis to ensure the structural integrity and safety of the engine. In order to study the crack propagation pattern of propellant pillar under different working conditions, three aspects of propellant crack initiation criterion, crack propagation model, and crack propagation influencing factors are systematically reviewed. On this basis, the next research focus is sorted out, and it is considered that the construction of crack propagation model by establishing a multi-scale model, the characterization of crack propagation by using various test characterization means, and the analysis of damage evolution under the coupling of multiple working conditions will be the next research focus.

Keywords: Solid propellant; mechanical properties; constitutive models; crack propagation; fracture

1. Introduction

Solid rocket motors are devices powered by burning chemical propellant, mainly composed of combustion chamber, propellant grain, ignition torch and nozzle, which have the advantages of high energy density, simple structure and low cost, and have long been widely used in the power system of rockets, missiles and sounding rockets and other equipment [1]. Solid propellant is the power source of solid rocket motor, which is composed of polymer matrix and solid particles, and has a specific geometric configuration to ensure that the propellant column can be burned according to the predetermined initial combustion surface and the law of combustion surface retreat. Under the action of various complex loads, the mesoscopic structure of solid propellant is easily changed, accompanied by phenomena such as interface dewetting, particle breakage, micro-crack initiation and micro-pore propagation along the interface and so on. These phenomena are manifested as crack propagation and fracture at the macro level, which seriously affect the structural integrity of solid rocket motor charge [2].

In recent years, the analysis of fracture mechanics problems of viscoelastic materials with defects is the basic problem of solid mechanics, and it is also a key technical problem that needs to be solved urgently in the field of aerospace propulsion. Therefore, in order to avoid excessive crack size or fracture in the propellant grain, it is very necessary to carry out research on the crack propagation behavior of solid propellant [3]. According to the rules obtained by the research, the design of solid rocket motor is guided to improve the safety and reliability of the engine [4]. At present, there are few reports on a comprehensive review of the research on the crack propagation behavior of solid propellant. The paper systematically reviews the research on propellant crack initiation criterion, crack propagation model, and crack propagation influencing factors, and on this basis, the direction is prospected in order to provide a reference for the design of solid propellant charge.
2. Crack initiation criterion

Propellant grain of solid rocket motor is usually subjected to various loads, which may lead to cracks and other defects. Cracks and other defects seriously affect the structural integrity of the engine, destroy the original designed burning surface and cause disruption of the combustion law, which greatly affect the thrust performance of the engine and even cause engine explosion. Therefore, it is of great significance to study the law of grain crack initiation and propagation for engine integrity research and life assessment [5]. Crack initiation criterion is an important issue in fracture mechanics theory that deserves continuous in-depth study and is an important basis for achieving safe component design. Currently, there are many crack initiation criteria for solid propellants, commonly used are K criterion, J-integral criterion, COD criterion, strain energy release rate criterion and compound fracture criterion [6].

As early as 1979, Gledhill and Kinloch [7] applied the theory of continuum fracture mechanics to double-base solid propellant and found that the stress intensity factor was the sum of the stress intensity factor of the plane strain and plane stress state. The stress intensity factor of the plane strain state is related to temperature, while the stress intensity factor of the plane stress state is temperature dependent, and it was shown that the plane stress state stress intensity factor and its yield stress are linearly related. The results created a unique failure criterion where the crack begins to expand when the plane stress-plastic zone at the crack tip reaches a critical value.

Generalizing the classical Griffith crack expansion criterion, Christensen [8] obtained a time-dependent crack initiation and expansion criterion. The Griffith energy dissipation rate was applied to viscoelastic materials to obtain the crack growth rate as a function of the creep properties of the material, the loading conditions, and the energy required to generate a new crack surface. Finally, the analytical predictions were compared with the experimental results of polyimide ester rubber, and the predictions were in good agreement with the experimental results.

In studies on the use of J-integral to calculate crack-related parameters, Devereaux [48] used J-integral to analyze the crack initiation of propellant pillars and to predict the hazard of the pillars. The correlation of the J-integral with load and shape was investigated, the integral values of the plane strain state of the cylindrical peripheral pre-cracked specimen were calculated, the safety limits of the engine were predicted using finite element calculations, and the predictions were verified by scaled-down engine tests. Long Bing et al [10] carried out a study on crack initiation characteristics for HTPB propellants. A method to calculate the J-integral and JV-integral of solid propellants based on individual specimens was established, and relaxation tests and J-integral tests of flat specimens containing type I cracks were carried out for HTPB propellants to calibrate the crack configuration factors of the specimens, and finally the values of crack initiation J-integral and JV-integral were obtained, and the results are shown in Fig. 1. The results show that the J-integral and JV-integral of HTPB propellant have a significant rate correlation, and the value of the integral is larger as the strain rate increases, where the effect on the JV-integral is larger than that on the J-integral.

Fig. 1 HTPB propellant J-integral and JV-integral variation curves with displacement [10].
LIU C et al [10] analyzed the results of a significant increase in the stress intensity factor required for crack initiation propagation with increasing loading rate for brittle materials derived from tests and found that the strain rate dependence of the material must be considered at very short fracture times and high loading rates. Ravi-Chandar [11] studied the composite crack fracture behavior of solid propellant and performed different composite crack fracture tests at different temperature and strain rate conditions. The results showed that the maximum circumferential stress criterion can predict the crack initiation well, but the crack extension direction cannot be predicted due to the development of crack tip damage. The adsorption zone damage model is introduced and applied to the boundary element method to simulate crack propagation under complex loading, and the crack prediction results based on the K-criterion are compared with the calculated results of the simulation based on the adsorption zone model.

There are also many studies related to the use of stress criteria to study propellant cracking. Hongfu Qiang et al [12] proposed a maximum stress three-dimensional criterion (M criterion) for brittle materials, and introduced a unified strength theory to define the plastic zone of the crack tip, and modified the criterion of critical load in the M criterion to extend it to ductile materials. Combining the uniaxial tensile test results of HTPB propellants with composite type I-II cracks and comparing them with other criteria, the study shows that the crack initiation angle of propellants and the modified M criterion predict closer results. Shijun Zhi et al [13] used the maximum circumferential stress criterion and the maximum energy release rate criterion as the criterion of crack extension direction and the J-integral as the criterion of crack extension to calculate the initial extension direction of cracks with different inclination angles, and the calculation results showed that the method can effectively simulate the fracture process of solid propellants.

The cracking criterion of solid propellant mainly considers the external and internal factors of propellant. The internal factors generally include the microstructure, material properties and defects of the propellant, while the external factors mainly include load, geometry and environment. At present, there are many studies on material properties, defects, load and geometry of propellants, but there are relatively few studies on the influence of microstructure and environmental factors on the cracking criterion, which can be studied by molecular dynamics simulations and multi-scale simulations, starting from the fine mechanics.

3. Crack propagation model

Crack propagation models are usually closely related to damage containing intrinsic structure models, and most of the damage containing intrinsic structure models can well describe the mechanical response of the material to crack propagation. At present, the research on crack extension models is mainly focused on the construction of damage containing intrinsic model, and the research scholars study the crack extension indirectly through the intrinsic model, so the following research on the development situation is investigated.

In order to predict the crack initiation and propagation process in the propellant pillar, Han Bo et al [15] established a native model of the cohesive zone of HTPB propellant and numerical simulation studies. The parameters of the intrinsic model were obtained by designing uniaxial tensile tests, unilateral crack tensile tests and numerical simulations. The established fracture model of the cohesive zone can well reflect the failure process of crack initiation and crack extension of HTPB propellant. Based on ABAQUS, a bonding unit was established to simulate crack extension and an embedded bonding unit method was established to simulate the crack crack cracking process of composite type, using which the crack extension path of HTPB propellant can be successfully predicted.

Long Bing et al [16] modified the inherent defect model (IFM) and stress fracture criterion model to predict the tensile strength of solid propellants containing cracks, and established fracture strength equations for three different fracture models. The relationship between the characteristic size and the ultimate fracture strength was established using the modified two-parameter fracture
criterion, and the models were verified by using solid propellant fracture tests. The results show that the predicted results of the three models are consistent with the experimental values. Yang Junhui et al [17] established a finite element model for a typical viscoelastic interfacial crack plane problem with "loading". Using the results of the elastic interface crack tip displacement field, the tip displacement field of the viscoelastic interface crack is obtained by the correspondence principle and Laplace transform, which can accurately solve the elastic/viscoelastic interface crack and viscoelastic/viscoelastic interface crack extension parameters, and can well reflect the creep and relaxation characteristics, and the model can be applied to the calculation and analysis of viscoelastic interface fracture problems.

4. Factors of crack propagation

Up to now, a large number of experimental studies on the fracture performance of propellant pillars have been conducted by international research scholars. Among them, C T Liu and C W Smith from the Air Force Research Work Laboratory, Edwards Air Force Base, USA, have conducted more and systematic experimental studies on the fracture of propellants [18, 19]. The experimental studies were mainly focused on various factors affecting its fracture properties, such as temperature, loading rate, thickness, pressure, etc.

As early as 1993, Smith [18] studied the effect of temperature on propellant crack extension behavior and found that at 22.2°C and 72.9°C, the crack-containing specimens showed localized porosity at the front of the passivated crack tip, followed by a highly nonlinear "passivation-extension-passivation-extension" mechanism, but at -53.9°C due to the increase in matrix strength, inhibiting the generation of holes; as the temperature increases the load-bearing properties of the propellant decreases, at 73.9°C fracture plastic zone between the holes ligament fracture before the matrix material softening, can only withstand a small amount of stress. Later, some scholars found on this basis [19] that the heat generated during loading promotes the sliding of the interacting chain segments in the adhesive, and the ligaments in the fracture plastic zone rapidly become thin and thus lead to fracture at lower stresses; with the increase in temperature, the interfacing strength of the particles in the propellant and the matrix decreases, which leads to a larger fracture plastic zone and a larger crack opening displacement at the crack tip.

Bencher et al [20] studied the microstructural damage and fracture processes of solid propellants at three loading rates (3.2, 6.4, and 8.4 mm/min) and three temperatures (-54, 25, and 71°C) using intermediate penetration type flat plate specimens. The results showed that the crack extension was associated with a microcrack zone of approximately 1 to 2 crack tip opening displacement sizes in front of the crack tip, and this microcrack zone was mainly formed by the dehumidification of the particles. At low temperatures the strength of the polymer increases and the air pockets and particle delamination increase, producing a larger crack tip plastic zone and fracture toughness, but the analytical results do not give a relationship between fracture toughness and strain rate.

Liu et al [21] studied the effect of force temperature and strain rate on the crack extension behavior of particle-reinforced composites and found that the mechanism of change in the mechanical properties of the crack tip under the loaded test conditions were basically the same, i.e., the mechanisms of passivation, microcrack sprouting, and crack propagation were basically the same, but the crack propagation rates were different. The crack propagation rate satisfies a power function relationship with the type I crack stress intensity factor, and the strain rate has less effect on the crack propagation rate, which is larger at low temperatures. Later, a study in the literature [22] showed that crack propagation is also correlated with time and that the effect of loading rate on crack propagation is smaller relative to temperature. Knauss [23] conducted an experimental study of solid propellant fracture under large deformation conditions and monitored the crack extension process. It was found that: the strain inhomogeneity at the crack tip is much larger than that mentioned in the literature; the strain inhomogeneity at the crack tip has a significant effect on the crack extension; the crack extension process is closely related to the shape and size of the solid
particles in the propellant, the particle orientation and the particle interaction, and the crack tip is most likely not a continuum.

Ide et al. [24] investigated the effect of thermal damage on the fracture properties of HTPB propellants. The results showed that the degree of degradation of propellant mechanical properties after thermal damage was related to the degree of thermal loading. Under thermal shock and thermal cycling conditions, although the critical strain of propellant crack propagation decreases and the crack propagation rate increases, the crack propagation mechanism remains unchanged and there is a repeated propagation process of "passivation-damage-passivation", and the size of the crack tip damage zone is similar to that of undamaged specimens. However, under accelerated aging conditions, not only the critical stress and strain of crack propagation were significantly reduced, the crack propagation rate was significantly increased, and the crack propagation mechanism was changed.

Liu et al. [25, 26] investigated the effect of pressure on the crack propagation behavior of high filling ratio elastomeric materials. The results showed that the corresponding stress states in the specimens at 3.45 and 6.9 MPa were different, and stress analysis of the stress states around the filled particles showed that high triaxial tensile stresses existed on the surface of the particles at both ambient and applied pressures. Under ambient pressure conditions, tensile stresses surround the region of high triaxial tensile stresses, while at 6.89 MPa it is compressive stresses that surround the region of high triaxial tensile stresses, and damage sprouting and evolution are suppressed, which in turn leads to higher material strength. The rate of crack extension decreases with increasing compressive strength. Later on the basis of this study a three-dimensional finite element calculation was carried out in the literature [27] and the fracture toughness value and the stress intensity factor were obtained as a power function.

Chang X L. et al. [28] conducted a low-temperature crack propagation test study for HTPB propellant. A crack extension test was conducted using specimens containing intermediate penetrating cracks to study the effect of temperature on the crack extension characteristics of HTPB propellant. The crack propagation rate at different temperatures was calculated by using the modified cut-line method, and then the crack propagation resistance curve was obtained, and the relationship between the crack propagation rate and the type I stress intensity factor was fitted. According to the results, it is found that the crack propagation rate at low temperature is larger than that at room temperature, and the lower the temperature, the shorter the response time for crack propagation; the relationship between the crack propagation rate of HTPB propellant and the type I stress intensity factor at different temperatures satisfies the power function.

To comprehensively understand the fracture properties of solid propellants, Zhejun Wang et al. [29] investigated the type I tensile fracture toughness tests of circumferentially notched cylindrical specimens of newly designed end-hydroxy polybutadiene (HTPB) propellants at different temperatures and loading rates. Based on the time-temperature superposition principle (TTSP), a master curve in the form of a logarithmic curve was constructed to predict the type I tensile fracture toughness of the emitting agent under a wide range of loading conditions with different initial crack sizes. Hongzheng Duan [30] et al. conducted a modified split Hopkinson compression bar test on two cross-linked different propellants to study the dynamic mechanical response and damage evolution mechanism. The SHPB device is equipped with a high-performance infrared camera and a high-speed camera to capture images of deformation, damage-ignition characteristics and temperature evolution during the impact. The results showed that the mechanical response of the propellant and the damage ignition mechanism are influenced by the strain rate and crosslink density. As the strain rate increases, the more intense the damage ignition is and the earlier the response occurs. In order to reveal the effect of strain rate on the damage-ignition evolution of propellant, the damage-ignition responses at strain rate 6000 s-1 was studied in Fig. 2.
The above reviews show that the crack extension (fracture) test of solid propellant mainly focuses on various factors affecting the fracture performance of propellant, including temperature, loading rate, crack thickness, initial crack length, pre-damage, applied pressure, thermal damage and preload strain. Among them, the effects of crack thickness, initial crack length and loading rate on fracture performance are only quantitative and do not change the crack extension mechanism; while temperature, applied pressure and thermal aging change the crack extension mechanism of propellant, in which temperature reduction and accelerated aging enhance the bond strength and matrix strength of propellant material matrix particles, which physically change the nature of propellant, while the applied pressure changes the filling. The applied pressure changes the stress state around the filled particles, resulting in a change in crack propagation behavior.

5. Conclusions and outlook

Based on the grain of solid rocket engine crack propagation research, the research status of crack initiation criterion, crack propagation model and crack propagation influencing factors of solid propellant are summarized, hoping to provide some ideas and references for related research scholars and support for solid rocket motor designers to achieve high reliability and high safety design. The research on crack propagation behavior of propellant grain is based on experimental research, focusing on theoretical research and combining with numerical simulation. Different from the general particle filled composites, solid propellants have a complex service environment and usually need to have good mechanical properties in a wide range of temperature and strain rate, which brings great challenges to experimental research, theoretical analysis and numerical simulation. In view of the characteristics of solid propellants and the problems encountered in studying fracture properties, it is believed that the following aspects will become the next research direction.

- How to reflect the time and temperature effects of viscoelastic materials in the crack propagation model of propellant and propose the corresponding time-temperature equivalent model will be a hot research direction in the future.
- Micro-CT, X-ray diffractometer, scanning electron microscope and other techniques will be comprehensively used to trace and characterize the crack propagation process of propellant, and combined with micro-meso-macro multi-scale analysis, detailed statistical characteristics and damage evolution mechanism are obtained.
- The mechanical damage of solid propellant is studied by multi-scale numerical simulation, and a reasonable multi-scale model is constructed to describe the mechanical response of propellant grain.
References


