EXPERIMENTAL STUDY ON THE SAFETY AND EFFICACY OF LIQUID CARBON DIOXIDE JET CUTTING FOR HIGH-ENERGY HTPB PROPELLANT

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In the present, propellant cutting technologies struggle to balance cutting safety and efficiency. Water jet cutting, as a mainstream cutting method, has improved cutting efficiency and safety to some extent but faces the difficult of waste liquid disposal. Based on this, this paper proposes using liquid carbon dioxide as a cutting medium, analyzing its feasibility in terms of safety and efficiency theoretically, and conducts corresponding experimental verification. The study employed a single-factor experimental method to compare the efficiency and safety of propellant cutting under two modes: single high-pressure cutting and continuous high-pressure cutting. The results show that the propellant remained safe and stable under all cutting conditions, with no ignition or explosion occurring. In the transient cutting mode, significant fracturing of the propellant surface only appeared when the pressure reached 60MPa, demonstrating a high threshold pressure. In the continuous cutting mode, a cutting depth of 20 mm was achieved with 30MPa pressure applied for 2 seconds. Under the same conditions, when the pressure reached 40MPa, the propellant was completely penetrated, indicating that the cutting efficiency meets practical application needs. This study verifies the feasibility of using a liquid carbon dioxide jet as a safe, efficient, and environmentally friendly cutting medium for the decommissioning of high-energy HTPB propellant, providing a new technical pathway for the safe disassembly of propellants and the recovery and reuse of engines.

Keywords: Liquid carbon dioxide; Jet cutting; HTPB propellant; experimental study

1. Introduction

HTPB propellant, as a high-molecular composite solid propellant, is widely used in aerospace and defense fields due to its high energy density and excellent properties. HTPB is widely used as an adhesive for composite solid propellants because it can maintain its performance at high temperatures. In the decommissioning process of rocket engines, it is necessary to first remove the

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propellant contained within the engine through cutting technology to enable engine recovery and subsequent propellant disposal. The current mainstream cutting methods, including mechanical cutting and water jet cutting, both present certain problems in terms of cutting safety and environmental friendliness. In 1967, at a U.S. laboratory, when a band saw was used to cut HTPB propellant, sparks generated from the friction between the saw blade and the propellant ignited propellant powder in the vacuum system, causing the vacuum line to explode. The accident resulted in one death, two minor injuries, the destruction of 7 pounds of propellant, and damage to a reinforced concrete wall. For water jet cutting of propellant, safety cannot be guaranteed due to the high pressures required, and the need for harmless treatment of the waste liquid after cutting increases the cost of disposal [1]. A comparison of various cutting methods is shown in Table 1. Therefore, there is an urgent need to propose a safer and more environmentally friendly cutting method for HTPB propellant to address the above challenges. In response to these risks, using liquid carbon dioxide for cutting presents a feasible new solution. Due to the low-temperature and easy phase-change characteristics of liquid carbon dioxide, it has already shown promising applications in areas such as coal and rock breaking, oil and gas extraction, cutting of non-energetic materials, and removal of surface impurities. Bilz and Uhlmann [2] compared the cutting of plastics using water and liquid carbon dioxide, finding that the liquid carbon dioxide jet offers higher cutting precision, and the cutting process is dry and residue-free, with cutting debris being easy to collect and recycle. Engelmeier [3] experimentally studied the effects of liquid carbon dioxide jets on different materials, verifying their advantages in precise, gentle processing, and cold-dry treatment. In subsequent research, they obtained a relatively stable liquid carbon dioxide jet by varying the ambient temperature, revealing the jet's breakup mechanism [4]. Kim and Song [5] studied the breakup modes of liquid carbon dioxide jets, providing theoretical guidance for the transportation of coal particles in wet-feed gasifiers. Qiao et al. [6] reviewed research on liquid carbon dioxide fracturing technology, analyzing its advantages in efficiency and environmental friendliness for oil and gas extraction. Chen et al. [7] proposed using the high-pressure shock waves generated by the phase change of liquid carbon dioxide for rock breaking and analyzed its rock-breaking mechanism. Abi et al. [8] established a model to calculate the shock wave and gas expansion energy of carbon dioxide, quantifying their roles in rock damage and energy distribution. Zhang et al. [9] proposed using the high-efficiency energy released from the phase change of supercritical carbon dioxide for artillery power drive, breaking through the velocity limits of traditional gas drives. Dzido and Piotr [10] reviewed the application of dry ice blasting technology in pollutant cleaning and pointed out that its core mechanisms are the thermal effect produced by dry ice, the high-speed erosive action of dry ice particles, and the sublimation expansion effect. Máša and Kuba [11] based on a comprehensive discussion of the application scenarios for dry ice blasting technology, proposed energy-saving measures that could significantly reduce its energy intensity. It is evident that liquid carbon dioxide as a cutting medium already has favorable application scenarios, with researchers mostly utilizing the low-temperature environment created by its phase change and the generated high-pressure gas for the cold treatment and fragmentation of materials. The processing and disposal of energetic materials must prioritize safety. The phase-change characteristics of liquid carbon dioxide, on one hand, create a favorable low-temperature environment that can dissipate heat generated during cutting, and on the other hand, the released carbon dioxide creates an inert atmosphere, theoretically making it an excellent method for processing energetic materials [12, 13]. However, research in this field is still in its nascent stage, particularly lacking systematic studies on operational safety boundaries, cutting efficiency, and mechanisms.

In view of this, this paper proposes using a liquid carbon dioxide jet as a cutting medium for HTPB propellant. It aims to explore its mechanism for safe and efficient cutting through theoretical analysis and related experiments, evaluate the safety boundaries of the cutting process, and quantitatively analyze the cutting efficiency under different cutting modes, thereby providing a reference and guide for the pre-treatment technology of propellant decommissioning.

Table 1

Comparison of various cutting methods

Cutting Method	Advantages	Disadvantages
Mechanical Cutting	High precision, strong material adaptability	High safety risks, significant tool wear
High-Pressure Water Jet	Low cutting cost, high safety [14]	Difficult to treat waste liquid, high subsequent disposal cost
Liquid Nitrogen Cutting	Clean and environmentally friendly, relatively high efficiency	High equipment cost, relatively poor safety
Premixed Abrasive Water Jet	High cutting efficiency, high safety [15]	Abrasive wears the nozzle, difficult to treat waste liquid

2. Theoretical basis and model construction

HTPB propellant is a typical heterogeneous energetic material. When the powerful load of a shock wave continuously acts on the propellant surface, it faces the risk of shock initiation or thermal initiation. The triggering mechanisms for these two modes are fundamentally different. Shock initiation generates a powerful detonation wave in an extremely short time, causing the breaking of chemical bonds within the propellant and instantly releasing immense energy, causing the propellant to detonate. In contrast, thermal initiation occurs under the prolonged loading of the jet, where heat gradually accumulates, simultaneously triggering chemical reactions within the propellant. Under the coupled effect of these two factors, the propellant reaches a hot spot, ultimately leading to combustion or detonation [16]. Based on these two modes, the safety of the impact process is theoretically analyzed from the principles of jet impact and hot spot generation. The cutting efficiency is analyzed based on the principles of crack propagation in the propellant under impact loading.

2.1 Jet Impact model

During the cutting process, the action of the jet on the propellant is divided into two stages: water hammer pressure and stagnation pressure, corresponding to dynamic loading and quasi-static loading modes, respectively. When the jet first contacts the propellant surface, its front is compressed, generating a water hammer pressure several times greater than the jet's impact force. Under the effect of the water hammer pressure, the jet produces a strong stress wave. Furthermore, when the liquid carbon dioxide jet is sprayed into the atmospheric environment, the pressure drops sharply, causing a "flash evaporation" phenomenon, which creates conditions for the formation of cavitation nuclei. When the local pressure drops below the saturated vapor pressure at that temperature, gas bubbles form inside. These bubbles move with the jet, and when a local high pressure is generated or a bubble collides with the propellant surface, the bubble collapses, creating a strong shock wave and a micro-jet. This process enhances the shear force of the jet, promoting the fracture of propellant molecular chains, but generates high temperatures, which can easily create local hot spots, promoting increased molecular activity within the propellant and increasing the risk of the cutting process. However, because the bubble collapse time is very short, heat accumulation is unlikely. Therefore, the shock wave generated is the main source of danger in this process [17-19]. Studies have shown that the pressure value generated by the shock wave can be approximated by the water hammer pressure. According to the critical initiation model:

$$p^2\tau = const \tag{1}$$

In equation (1), p is the shock wave loading pressure, τ is the loading time, and const is a constant related to the properties of the propellant itself. When the water hammer pressure exceeds the critical pressure of the propellant, there is a risk of detonation. The water hammer pressure of liquid carbon dioxide can be expressed as [14]:

$$p_p = v_d \frac{(\rho_l c_l)(\rho_s c_s)}{\rho_l c_l + \rho_s c_s} \tag{2}$$

In equation (2), ρ_l is the density of liquid carbon dioxide, g·cm⁻³; c_l is the speed of sound in liquid carbon dioxide, m·s⁻¹; ρ_s is the density of the propellant, g·cm⁻³; c_s is the speed of sound in the propellant, m·s⁻¹; v_d is the theoretical velocity of the liquid carbon dioxide jet, which is 0.92 times that of a water jet. Its theoretical velocity is derived from the theoretical velocity of a water jet as:

$$v_d = 41.12\sqrt{p_a} \tag{3}$$

The physical properties of liquid carbon dioxide under different jet pressures are shown in Table 2:

Table 2

Physical properties of liquid carbon dioxide

Temperature(K)	Pressure(MPa)	Density(/kg/m³)	Sound Speed(m/s)	Speed(m/s)
298.15	20.00	914.24	596.70	183.89
298.15	30.00	966.52	694.81	225.21
298.15	40.00	1004.2	770.63	260.08
298.15	50.00	1034.2	834.27	290.76
298.15	60.00	1059.3	889.86	318.51

Furthermore, because the speed of sound and density of liquid carbon dioxide are both lower than water under the same conditions, and its working pressure range is typically 20-60MPa due to equipment limitations, the water hammer pressure it generates is far less than that produced by a water jet under equivalent conditions. By analogy to the safety of water jet cutting of HTPB propellant, it can be considered that the liquid carbon dioxide jet cutting process is safer, and theoretically, this process can be regarded as risk-free.

When the jet acts continuously, the cutting process transitions to a quasi-static loading process, and the water hammer pressure decreases to the stagnation pressure. In this process, the kinetic energy carried by the jet is converted into internal energy, thereby increasing the propellant's temperature and forming local hot spots. As the impact continues, the hot spots expand throughout the propellant, potentially leading to thermal initiation. The stagnation pressure can be expressed as:

$$p_0 = p_j + p_b \tag{4}$$

Where P_j is the static pressure and P_b is the dynamic pressure. The static pressure is related to the initial pressure and decreases as the standoff distance increases.

After the liquid carbon dioxide jet exits the nozzle, its diameter expands due to the effects of jet phase change, turbulent dissipation, and entrainment of surrounding air, and the axial velocity decays. Consequently, the dynamic pressure at the nozzle outlet is slightly lower than the dynamic pressure at the nozzle inlet. The dynamic pressure at the nozzle outlet can be expressed as:

$$p_b = \frac{1}{2}\rho_l v_0^2 = \frac{1}{2}\rho_l \phi^2 \frac{2p_a}{\rho_l} = p_a\phi^2 \tag{5}$$

In equation (5), ϕ is the velocity coefficient, p_b is the dynamic pressure at the nozzle outlet, and v_0 is the velocity of the jet after exiting.

2.2 Hot spot mechanism model

Under impact, viscous dissipation heating in the matrix and frictional heating at the micro-crack interfaces can easily form hot spots. Although the HTPB binder reduces the rate of frictional heating on the crack surfaces later on, thereby lowering the local temperature, the risk still exists during the impact process due to the large amount of energetic material in the propellant. Studies have shown that when the internal temperature of the propellant exceeds 280°C, the risk of ignition increases sharply [13]. For a liquid carbon dioxide jet vertically impacting the surface of HTPB propellant, assuming the jet is completely stopped, its kinetic energy is entirely converted into work done on the propellant. The power of this work can be expressed as:

$$P_0 = P_j + P_b = p_j A v_0 + \frac{1}{2}\rho_l A v_0^3 \tag{6}$$

where P_0 is the total power, P_j is the power generated by static pressure, P_b is the power generated by dynamic pressure, and A is the cross-sectional area of the jet. The total energy generated is then:

$$E = P_0 t = p_0 A v_0 t \tag{7}$$

From this, it can be seen that the longer the impact time and the greater the impact pressure and velocity, the more energy the jet produces. Part of this energy is converted into elastic potential energy and dissipated by the propellant, while the other part is converted into thermal energy, causing the propellant's temperature to rise. Therefore, to determine the boundary conditions for cutting HTPB propellant with this jet technology, the jet pressure and continuous cutting time were increased in subsequent experiments to explore the jet parameters that achieve efficient cutting of the propellant while ensuring safety.

To observe the main factors affecting the temperature rise of the propellant, considering that both frictional heating and exothermic chemical reactions can cause temperature increase during the quasi-static cutting process, the one-dimensional Frank-Kamenetskii heat conduction model is used to describe the formation of hot spots in the propellant [20]:

$$\frac{\partial}{\partial y}(k\frac{\partial T}{\partial y})+\rho_s \Delta HZe^{-\frac{E}{RT}}+\mu p_b\frac{\partial v_x}{\partial y}=\rho_s c_s\frac{\partial T}{\partial t} \quad (8)$$

In equation (8), k is the material's thermal conductivity coefficient, $g\cdot m\cdot s^{-3}\cdot K^{-1}$; ΔH is the heat of detonation, $m^2\cdot s^{-2}$; E is the activation energy, $g\cdot m\cdot m^2\cdot ms^{-2}\cdot mol^{-1}$; R is the gas constant, $g\cdot m\cdot m^2\cdot ms^{-2}\cdot mol^{-1}\cdot K^{-1}$; Z is the pre-exponential factor, $m\cdot s^{-1}$; $\frac{\partial v_x}{\partial y}$ represents the strain rate, ms^{-1}; c_s is the propellant's specific heat capacity, $m\cdot m^2\cdot ms^{-2}\cdot mol^{-1}$. From the above equation, it can be seen that when the temperature of the reaction process decreases, the reaction rate decreases exponentially, and the higher the activation energy, the more significant the decrease in reaction rate. Therefore, it can be concluded that the cooling effect brought by the "flash evaporation" of liquid carbon dioxide can greatly reduce the reaction rate of HTPB propellant.

For the quasi-static loading process, as the loading time increases, on one hand, it accelerates the process of heat accumulation. On the other hand, a large amount of heat is carried away by the gas phase change and the cooling effect of the jet. When the heat dissipation is greater than the heat accumulation, the formation of hot spots is effectively suppressed, improving the safety of the entire process. The heat absorbed by the phase change of liquid carbon dioxide can be expressed as[21]:

$$Q_x = c_p m\Delta t + 518.16 \quad (9)$$

In equation (9), Q_x is the total heat absorbed, kJ; c_p is the specific heat capacity of liquid carbon dioxide, KJ/(kg·K); 518.16 kJ is the latent heat absorbed during the jet's phase change.

3. Materials and methods

3.1 Experimental materials

The experimental samples used were high-energy HTPB propellant, containing 15% RDX ($C_3H_6N_6O_6$). The samples were rectangular, with dimensions of 18cm×15cm×3cm, and their appearance is shown in Fig. 1. The relevant physicochemical properties of the propellant are shown in Table 3.

Table 3

Physicochemical properties of HTPB propellant

Parameter	Value Range or Typical Value
Density/kg/m³	1730~1780
Elastic Modulus/MPa20℃	24.3
Impact Strength/(MPa)20℃	0.5
Impact Strength/(MPa)-40℃	0.3
Specific Heat Capacity/J/(g·K)	1.256~1.512
Activation Energy (AP decomposition) /kJ/mol	92
Activation Energy (overall decomposition)/ kJ/mol	79~188
Static Yield Strength/MPa	0.06
Dynamic Yield Strength/MPa	4~9

Fig. 1. Propellant sample

The liquid carbon dioxide cutting test system consists of three parts: a preparation system, a control system, and a cutting system, as shown in Fig. 2. Its workflow is as follows: Firstly, CO_2 from a gas storage cylinder is sent to a cold bath, where the temperature is stably controlled at -20~0℃ to form liquid carbon dioxide. It is then pressurized by a plunger pump (up to a maximum of 100MPa). Subsequently, the high-pressure liquid carbon dioxide is transported to the cutting system to cut the material. Throughout the process, the pressure and cutting time are controlled by a main control console and a jet control cabinet, and the safety of the cutting process is monitored in real-time. The nozzle used in the experiment was a conical-straight nozzle with a diameter of 1mm.

Fig. 2. Experimental system

3.2 Experimental plan design

Due to the unknown safety of cutting HTPB propellant with a liquid carbon dioxide jet, and in conjunction with previous liquid carbon dioxide jet parameter settings, a single-factor experimental method was adopted based on the theoretical analysis above. The standoff distance was fixed at 5mm and the nozzle diameter at 1mm, with the pressure adjusted from low to high. Two cutting modes, high-pressure single impact and high-pressure continuous impact, were compared. By increasing the jet pressure or cutting time, the safety boundary conditions of the cutting process were verified, and cutting parameters that meet efficiency requirements while ensuring safety were explored. In the high-pressure single impact mode, the jet dissipates quickly, maintaining a high-pressure state only at the moment of cutting, after which the pressure gradually decays, resulting in a short effective action time. In the high-pressure continuous impact mode, the jet can maintain a high-pressure state well, resulting in a long effective action time. The parameter settings for the experiment are shown in Table 4.

Table 4

Cutting parameter settings

Impact Mode	Nozzle Diameter (mm)	Standoff Distance (mm)	Jet Pressure (MPa)	Action Time (s)
High-pressure single impact	1	5	20	0.1
			30	
			40	
			50	
			60	
High-pressure continuous impact			30	2
			20	15
			40	15
			40	30

4. Results and discussion

4.1 Description of experimental phenomena

During the high-pressure single impact process, considering the unknown safety of the cutting, the initial pressure was set to 20MPa and then gradually increased until the experiment was stopped at 60MPa. The propellant remained safe and stable under all test conditions. When the jet pressure was below 50MPa, the jet only formed local black spots on the propellant surface and did not cause any damage. At a pressure of 50MPa, the cutting depth was 4mm, and at 60MPa, the cutting depth reached 13mm. The cutting results are shown in Fig. 3.

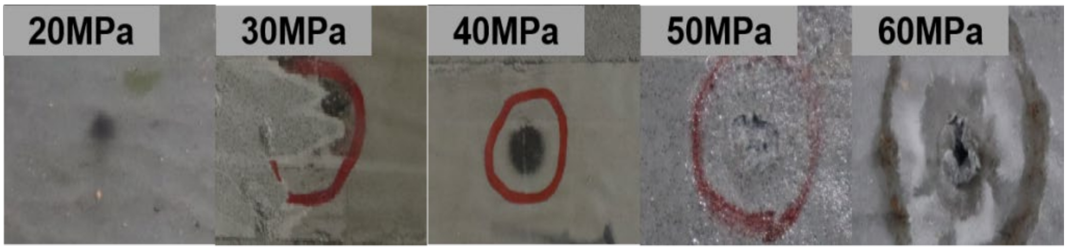

Fig. 3. High-pressure single impact results

Based on the results of the high-pressure single impact tests, the jet parameters for the high-pressure continuous impact process were set. The jet pressure and cutting time were continuously adjusted to determine the safety boundaries of the cutting process and to explore the optimal parameters for effective cutting. In this mode, all cutting processes remained safe and stable. After cutting, the propellant surface was covered with a large number of dry ice particles, and the cutting depth was significantly increased compared to the single impact. At 30MPa for 2s, the depth reached 20mm. Under the 40MPa condition, the propellant was completely penetrated in all tests. The cutting area was cone-shaped, narrow at the top and wide at the bottom. At jet pressures of 30 and 40MPa, the cutting area was observed to be filled with dry ice. The cutting results are shown in Fig. 4.

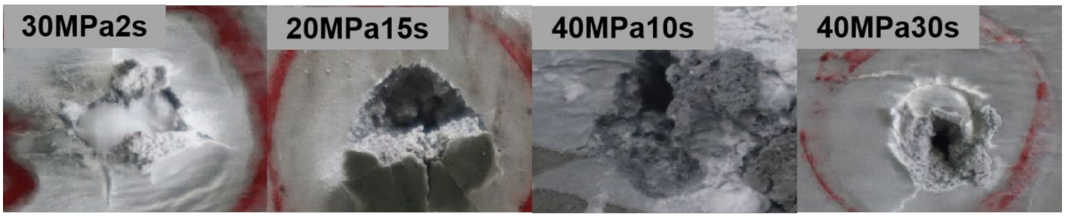

Fig. 4. High-pressure continuous impact results

Under almost all working conditions, the cutting surface of the propellant presents an approximately circular shape, consistent with the spray shape of the jet, and the projection of the nozzle is approximately at the center of the cutting surface. However, due to the phase change of the jet, the diameter of the propellant's cutting surface is much larger than that of the jet itself, which is consistent with the characteristics of liquid carbon dioxide cutting. Under the premise of ensuring cutting effectiveness, the positioning accuracy meets the expected requirements. In continuous cutting mode, as the jet flow rate and cutting time increase significantly, the cutting efficiency is greatly improved.

4.2Analysis of experimental results

The ability to maintain safety and stability throughout the above experiments is closely related to the unique phase change mechanism of liquid carbon dioxide. The phase change of the jet absorbs a large amount of latent heat, lowering the temperature of the surrounding environment and the jet itself. Under the continuous impact of the jet, heat is rapidly transferred, making it difficult for heat to accumulate in the impact zone, thus effectively inhibiting the formation of hot spots. In addition, the generated carbon dioxide gas dilutes the concentration of oxygen released from the reaction, providing an inert environment that suppresses the chemical reactions within the propellant, thereby reducing the heat released by the reaction. Under low-temperature conditions, the propellant transitions from a high-elastic state to a glassy state, increasing its brittleness and reducing its viscosity, which lowers the temperature rise caused by viscous friction. Furthermore, according to the Arrhenius equation, the low-temperature environment slows down the chemical reaction rate of the propellant, effectively preventing the rapid accumulation of heat. The combined effect of these mechanisms ensured the safety and stability of the experimental process.

In the high-pressure single impact test, the cutting depth of the propellant showed a linear relationship with the jet pressure, but the propellant's damage threshold was high. Damage to the propellant surface only appeared when the jet pressure reached 50MPa or more. The cutting efficiency was far from meeting practical application requirements, which also indicates that significant energy is required to damage the propellant, and high-pressure conditions consume more energy and pose a higher risk. In contrast, under continuous impact, the propellant showed significant damage even at lower pressures. In addition to the direct factors of time and pressure, the change in the mechanical properties of the propellant at low temperatures and the "gas wedge" effect also greatly improved cutting efficiency.

In the low-temperature environment created by the phase-change heat absorption of the jet, the mechanical properties of HTPB propellant undergo significant changes, transitioning from a highly elastic state to a glassy state, which reduces the dissipation capacity of the jet and provides favorable conditions for jet cutting. Additionally, the synergistic effects of jet impact load, gas wedge action, and dry ice erosion lead to a substantial increase in cutting efficiency.

During the transient phase, the stress wave generated by the water hammer pressure propagates within the propellant, initiating the formation of initial cracks and providing pathways for subsequent gas penetration. The characteristic length of the crack depends on the ratio of the stress amplitude to the material's toughness. In the quasi-static phase, in addition to the impact effect of the jet itself, high-pressure CO2 gas penetrates along the crack and applies wedge pressure on the crack surfaces, causing further crack propagation. The driving force for crack extension can be expressed as:

$$K_w = C_w p_0 \sqrt{a} \tag{10}$$

Here, K_w represents the stress intensity factor due to the gas wedge, the C_w is related to the crack morphology, p_0 is the inlet pressure, and a is the crack length. This equation shows that the driving force for crack extension is proportional to the pressure and the square root of the crack length. The crack propagation rate follows Paris' law, meaning the propagation rate is proportional to the power of the total stress intensity factor. When both jet impact and gas wedge effects work together, the total stress intensity factor is the sum of the two.

In the free jet region, affected by phase change, a large number of high-speed solid dry ice particles are formed. These dry ice particles generate strong kinetic energy, causing repeated micro-impact erosion on the propellant surface. The erosion depth is proportional to the square of the particle velocity. Under the erosive action of dry ice, the impact of the particles causes the micro-protrusions on the crack surface to be removed, increasing the new surface area. Furthermore, dry ice fills the cutting pores, and when the subsequent jet acts on this dry ice, the resulting impact force is transmitted to the pore walls, leading to secondary fragmentation. Additionally, the sublimation expansion of dry ice within the pores generates extra internal pressure, promoting the radial expansion of cracks and forming the conical cutting surface observed in the experiments.

Under the combined effects of these multiple factors, the jet core pressure and velocity attenuation caused by phase change are effectively counteracted, allowing the cutting performance of the liquid CO2 jet to fully meet practical application requirements.

Due to the pressure-bearing capacity of the equipment, this study was limited to a cutting pressure range of 20–60 MPa, and no research was conducted on the applicability of liquid carbon dioxide jet cutting under higher pressure conditions. This study only verified the applicability of the technology for high-energy HTPB propellants, without exploring its performance for highly sensitive propellants with different formulation ratios, so the scope of application needs further expansion. In subsequent studies, we will conduct simulation studies based on relevant experimental data to extend the analysis of how jet parameters affect propellant cutting performance to a broader scope and conduct cutting experiments on highly sensitive propellants to expand the applicability of this jet technology.

5. Conclusion

Through systematic theoretical modeling and experimental verification, this study investigated the safety boundaries, cutting efficacy, and action mechanism of cutting high-energy HTPB propellant with a liquid carbon dioxide jet. The main conclusions are as follows:

The process of cutting HTPB propellant with a liquid carbon dioxide jet has a high safety margin. In all cutting tests, the HTPB propellant did not burn or explode. Even when cutting for 30s at a pressure of 40MPa, the propellant remained safe and stable. The analysis suggests the main reason is that the phase change creates a low-temperature environment, and the released CO_2 gas creates a favorable inert atmosphere, suppressing the propellant's chemical reactions.

High-efficiency cutting of HTPB propellant can be achieved in the continuous impact mode, and the cutting efficiency can meet the needs of practical applications. Influenced by the "gas wedge effect," the propellant cracks continuously expand, and even at a lower pressure of 30MPa for 2s, the cutting depth can reach 20mm.

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