

Study on the influence mechanism of high-dynamic droplet impact on delamination damage of aircraft coatings

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Abstract: When an aircraft flies through clouds or rainfields at high speed, the extremely high relative velocity between the aircraft and raindrops can cause damage or even detachment of the coating on windward structural surfaces, thereby shortening aircraft service life. Polyurethane coatings offer excellent wear resistance, weather resistance, chemical corrosion resistance, strong adhesion, and good flexibility, and are therefore widely used in aerospace applications. However, research on their rain erosion resistance remains limited. Therefore, this paper investigates the delamination damage mechanism under high-speed raindrop impact to improve rain erosion resistance. T800 carbon fiber composite laminates were used as the substrate, onto which polyurethane coatings of different

interlaminar bond strengths were applied. Based on single-jet and pulsed multi-jet impact test platforms, the influence of interlaminar bond strength between the coating and the substrate on rain erosion damage characteristics and the occurrence mechanism of delamination failure were systematically examined. Under single-jet impact, coatings with low interlaminar bond strength first experience interfacial adhesion failure at the impact center, leading to localized delamination. The reflected stress waves cause significant interfacial stress concentration, resulting in uneven stress transfer and crack propagation along the interface. The characteristic damage morphology includes coating spallation at the impact point, peripheral uplift, and circumferential cracking. By contrast, coatings with higher interlaminar strength better dissipate the impact load and suppress the initiation and growth of microcracks, maintaining coating integrity. Under multiple-jet impacts, the interface is subjected to long-term cyclic loading, making it prone to stress fatigue and the formation of microcracks, which gradually evolve into pronounced delamination. The typical damage morphology appears as elongated delamination bands extending along the carbon fiber orientation, with significant uplift and circumferential cracking at the boundaries, and local carbon fiber fracture may also be observed. Weaker interlaminar bond leads to shorter time to delamination and more severe damage. Based on the experimental results and numerical stress-response analysis, the delamination mechanism under raindrop impact is clarified: shear waves generated during droplet impact nucleate interfacial microcracks, which continue to propagate and lead to interlaminar cracking and delamination. The stress waves generated by impact reflect at the coating–substrate interface, and under pulsed droplet loading, stress superposition generates high tensile stress. Continuous lateral jet loading further acts on the interface, causing coatings with low interlaminar bond strength to experience delamination after fewer impacts.

Keywords: High-speed aircraft; Rain erosion damage; Skin coating; Jet impact; Numerical simulation

1 Introduction

When an aircraft flies at high speed through cumulonimbus clouds or rainfields, the windward structural surfaces of the aircraft body will be continuously impacted and eroded by raindrops, causing surface damage and shortening the life cycle of the aircraft. The erosion and degradation of the surface coating of the aircraft body are the main forms of rain erosion damage ^[1–7]. Therefore, it is necessary

to apply protective coatings to body structure surfaces that are easily affected by raindrop impact to slow down erosion damage and extend service life. Various methods have been proposed to delay erosion damage, including applying protective coatings, protective tapes, and erosion guards. Due to their strong adhesion and applicability, as well as the advantage of not altering the aerodynamic shape of the original components, coating materials have been widely used^[8,9].

In 1968, the Materials Laboratory at the Wright-Patterson Development Center in the United States attempted to use erosion-resistant materials on aircraft to mitigate rainwater erosion^[10,11]. Although coating materials exposed to rainy environments will still experience erosion and peeling, the use of coatings significantly delays the erosion and damage progression of key components and prevents their surfaces from completely failing due to raindrop impacts. The U.S. Navy has also adopted special surface coatings on F-14 and F-16 aircraft to resist rainwater erosion^[12]. In recent years, in order to enhance the rain erosion resistance of coatings, Grundwurmer et al.^[13] conducted a study on the rain erosion resistance of transparent sol-gel coatings based on aluminum alloy (AA2024) coated with an epoxy primer. By varying the ratio of organic to inorganic compounds, the influence of coating hardness on rainwater erosion resistance was revealed. In addition, the mechanical properties of the obtained hybrid coating were adjusted by adding nanoparticles (such as zirconium dioxide). The results show that the rain erosion resistance of the particle-reinforced hybrid sol-gel coating is significantly improved. Zhou et al.^[14] prepared metallic glass/graphene multilayer films by the repeated deposition of Cu₅₀Zr₅₀ metallic glass with alternating layers of graphene, providing a reference for the design of other novel metallic glass films with excellent nano-wear resistance for rain erosion protection. Mahdipoor et al.^[15,16] investigated the relationship between the microstructure,

phase composition, and mechanical properties (microhardness and fracture toughness) of WC-Co coatings and their water droplet erosion resistance. They found that coatings with uniform microstructures exhibited significantly better rain erosion resistance than Ti6Al4V, whereas coatings with non-uniform microstructures performed worse than Ti6Al4V.

As one of the core fields in surface engineering, coating materials play an important role in mechanical, aerospace, electronics, and biomedical applications. The performance of a coating depends not only on the intrinsic characteristics of the material, but is also closely related to the interlaminar bond strength. Interlaminar bond strength refers to the interfacial adhesion between the coating and the substrate, or among the internal layers of the coating, and it directly affects the durability, resistance to delamination, and functional stability of the coating. Insufficient interlaminar bond strength is one of the primary factors under raindrop impact. When bond strength is inadequate, stress concentrations tend to develop at the interface, promoting crack initiation and propagation. Keegan^[17] noted that brittle coatings usually maintain adequate adhesion during curing, resulting in a relatively low risk of peeling, whereas the greater toughness mismatch between flexible coatings and substrates makes debonding more likely. Slot et al.^[18] conducted empirical fitting to correlate coating lifetime with rainfall intensity, droplet size, and fatigue performance, thereby establishing a prediction equation for the rain erosion incubation period of wind turbine blade leading-edge coatings. Owing to the multifactorial nature of rain erosion damage, existing theoretical erosion models cannot fully capture the damage evolution process. Schwartzentruber et al.^[19] developed a FEM-CFD coupled framework in ANSYS to numerically simulate high-speed water jet impacts on composite materials, with emphasis on near-surface delamination. Verma et al.^[20] employed the Smoothed Particle

Hydrodynamics (SPH) approach in LS-DYNA to simulate continuous impact processes under different rainfall intensities. Using restart techniques, multiple impact events were modeled to obtain damage morphology and stress distributions, providing insight into coating failure mechanisms.

This study is motivated by the common rain erosion damage issues encountered during the operation of high-speed aircraft. Using a high-dynamic raindrop impact test method, aviation polyurethane protective coatings were investigated. Single-jet and pulsed multi-jet impact tests were conducted on coated specimens with different interlaminar bond strengths, and the layered damage in the rain erosion damage type is mainly studied and analyzed. The factors influencing delamination and its damage mechanism were analyzed through single-jet tests. Based on long-term and periodic high-speed pulse impact tests, the delamination damage morphology characteristics of coating specimens under fatigue stress were studied, revealing the influence of the interfacial bond strength between the coating and the substrate in rain erosion protection. The research results provide reliable experimental data for the multi-scale structural design of protective coatings for high-speed aircraft, wind turbine blades and other equipment in extreme service environments.

2. Rain erosion test procedure

2.1 Liquid-solid impact process

When high-speed raindrops impact the aircraft skin coating, the process can be regarded as a transient fluid-solid coupling phenomenon: the droplets strike the wall at high velocity, inducing strong compression waves that propagate laterally along the surface and into the substrate. Based on the evolution characteristics, the process can be divided into two stages: “compression and expansion” (Fig. 1). At the instant when the leading edge of a droplet contacts the surface, sharp compression occurs. Part of the kinetic energy (approximately two-thirds) is converted into Rayleigh surface waves

propagating along the surface, generating tensile stress in the normal direction and shear stress in the tangential direction. Meanwhile, longitudinal and transverse stress waves are excited within the solid. The former travels deeper into the material in an alternating compression–dilation manner and induces radial tension at the wavefront, while the latter causes shear and circumferential tensile stresses due to lateral particle motion. Because the boundary diffusion speed is higher than the propagation speed of internal perturbations within the liquid, the central region of the droplet is instantaneously compressed, producing a short-duration “water hammer” high pressure. Its amplitude depends on the impact velocity and the compressible wave speed, and has no direct correlation with raindrop size. The stresses generated during the liquid-solid impact lead to the initiation and propagation of material damage. Additionally, the reflection of stress waves at free surfaces and their interactions within the solid result in wave superposition and reinforcement, causing internal material damage.

The water hammer pressure p can be expressed by the following equation (predicting the pressure generated at the initial stage of contact):

$$P = \rho_l C_l V \frac{1}{\frac{\rho_l C_l}{\rho_s C_s} + 1} \quad (1)$$

Where V is the impact velocity of the droplet, ρ_l and ρ_s are the densities of the liquid and solid substrates, respectively, and c_l and c_s are the velocities of propagating sound in the liquid and solid, respectively.

When the propagation speed of internal disturbances within the droplet exceeds the spreading rate of the liquid–solid contact edge, the compression wave detaches from the boundary constraint, and the accumulated high pressure is released in the form of a high-speed lateral jet (Fig. 1(b)). At this moment,

the impact process enters the second stage: after unloading, the compressed droplet is instantaneously expelled laterally, forming a jet along the wall surface that may reach a velocity up to ten times the initial impact speed. This high-speed liquid film imposes severe shear and scouring effects on the solid surface, readily initiating microcracks and facilitating their rapid propagation, eventually leading to surface erosion^[21–24]. Subsequently, the liquid gradually forms a stable and incompressible layer on the solid surface. At this stage, the pressure at the center of the solid surface remains at a relatively low level, which can be described by the Bernoulli static pressure:

$$P_i = \frac{\rho V^2}{2} \quad (2)$$

In addition, the evolution of the droplet morphology during high-speed raindrop impact is also affected by aerodynamic effects such as shock waves. When the flight vehicle reaches transonic or even supersonic speeds, non-negligible shock structures will be generated in the flow field. As the Mach number increases, the compressive effects in the flow field are significantly enhanced, causing noticeable changes in the morphology and velocity of the droplet. Such shock-induced variations in the jet not only increase the instantaneous peak pressure at the impact point but also accelerate the propagation of stress waves within the surface structure, thereby further promoting superficial material damage and crack growth. The corresponding influence can be quantitatively characterized by the following formula:

$$C_1 = C_0 + kV \quad (3)$$

Where C_0 is the sound speed of water, usually 1500 m/s, and k is a constant. In the case of impact speed $V < 1000$ m/s, k can be taken as 2^[25].

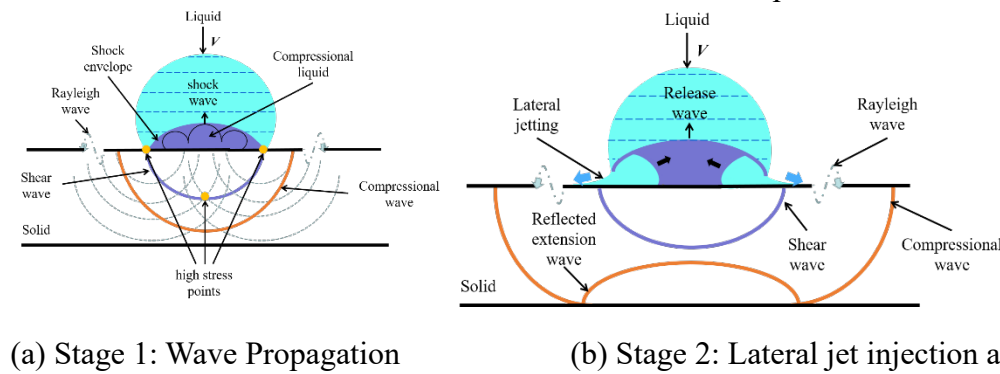


Fig.1 Schematic diagram of the liquid–solid surface impact process

2.2 Test methods

Among the numerous methods for assessing droplet impact damage, the dimensions of damage features are commonly used to evaluate the extent of rain erosion, including the rocket sled method [26,27], the rotating arm method [28], as well as single-jet and pulsed-jet impact tests. Among these methods, single-jet and pulsed-jet impact tests are currently the most widely used in laboratory research due to their simple operation and low cost. In the present study, improvements were made to existing equipment based on these two methods, generating high-speed droplets with front-end profiles more similar to real raindrops, so as to simulate the rain erosion process under natural environmental conditions more realistically [29,30].

2.2.1 Construction of a single-droplet impact test platform

The single-droplet Impact test platform was constructed based on the jet emission principle of the Single Impact Jet Apparatus (SIJA) at the Cavendish Laboratory and is modified on the existing 10 mm caliber first-stage light gas cannon, as shown in Fig. 2. According to the functional areas of the platform, it can be divided into the impact area and the launch area: The launch area mainly includes

the air chamber, the gun barrel, the sabot, the projectile, and the deflector (the deflector is located at the end of the gun barrel). The impact area mainly includes the rubber pad, the nozzle, the jet, the constant light source, the high-speed camera, the sample, and the fixed fixture.

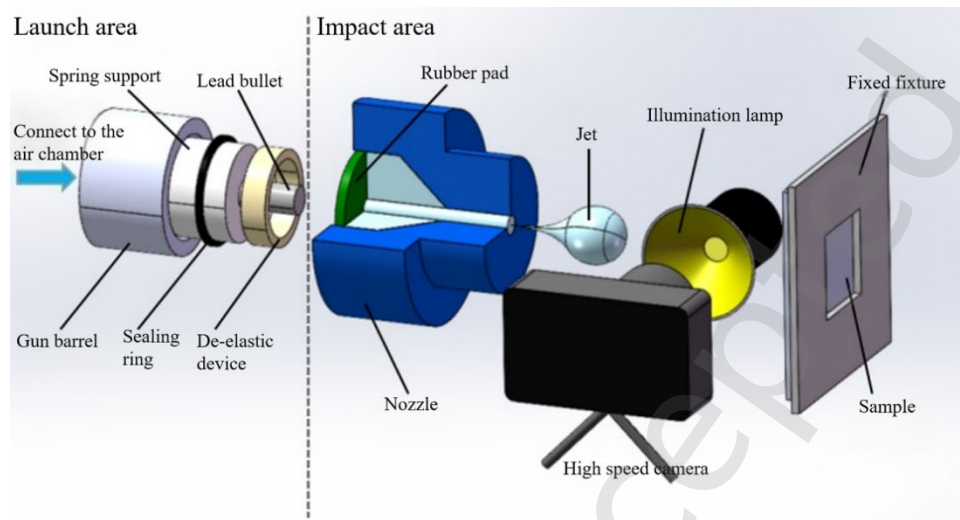


Fig.2 Schematic diagram of the single-jet impact test platform

The air chamber is connected to the control system, and the impact air pressure and launch control are regulated through the control system. The test platform achieves high-speed water jet through pneumatic ejection and hydraulic conversion: Firstly, the sabot is loaded into the sabot holder and a sealing ring is added to ensure the airtightness of the gun barrel. After assembly, it is installed onto the gun barrel and securely connected. Pure water was injected into the nozzle, and a rubber gasket was used to seal it, fix the sample, and adjust the impact position. After adjusting the air pressure, high-pressure gas is released to accelerate the movement of the sabot. The sabot is blocked at the end of the barrel, and the sabot continues to move forward due to inertia and collides with the rubber pad at the bottom of the nozzle, squeezing the internal water to form a high-speed jet. The entire process was recorded by a high-speed camera, enabling simulation of droplet impacts at various speeds, diameters, and angles.

A Phantom V1310 high-speed camera was used to record the entire impact process during the experiment. The droplet's flight distance was determined by calibrating the pixel-to-length conversion using a ruler. For example, by calculating the difference between two adjacent pixels at the leading edge of the jet and applying the calibrated pixel-to-length relationship, the impact velocity of the jet can be determined as:

$$V = \frac{v(X_2 - X_1)}{1000N} \quad (4)$$

Here, V represents the jet velocity; v represents the frame rate ($v = 210,000$ Hz); X_1 and X_2 represent the horizontal pixel coordinates of the first and second frames of the jet head, respectively; and N represents the pixel-to-length conversion factor. The jet diameter is estimated by measuring the diameter of the curvature circle at the jet head:

$$d = \frac{(Y_2 - Y_1)}{N} \quad (5)$$

Here, d represents the equivalent diameter of the jet; $(Y_2 - Y_1)$ represents the length of the curvature circle at the jet tip.

2.2.2 Construction of the pulse droplet impact test platform

The Pulsed droplet impact Test platform used in this study is based on the jet generation principle of the Pulsed Jet Erosion Test (PJET) developed by EADS Innovation, Germany, and was built by refitting high-pressure water cutting equipment. As shown in Fig. 3, this platform is mainly composed of the following three subsystems: The droplet generation system uses a CNC (Computer Numerical

Control) ultra-high-pressure water cutting machine as the core component. Filtered tap water is pressurized by a high-pressure water pump and then forms a continuous and stable high-speed water column (the jet speed range is 200 -500 m/s) after passing through the nozzle. The pulse modulation system is equipped with a high-precision rotating disc at the front end of the nozzle. The circumference of the disc can be evenly distributed with 1, 2, or 4 through-holes with a diameter of 1.5mm. It is driven by a servo motor to rotate at a adjustable speed from 0 to 3000 r/min. When the water column is aligned with the through-hole, a pulse short jet is formed. At other times, the water column is cut off by the disc, thereby achieving the regulation of the jet frequency (50Hz, 100Hz, 200Hz). The impact and measurement system uses high-speed cameras to synchronously record the impact process. The sample is fixed in front of the jet by a special fixture. This platform achieves droplet pulsing through mechanical modulation of rotating discs, effectively simulating the continuous impact characteristics of high-speed raindrops, providing reliable experimental conditions for studying the mechanism of continuous raindrop impact damage to materials.

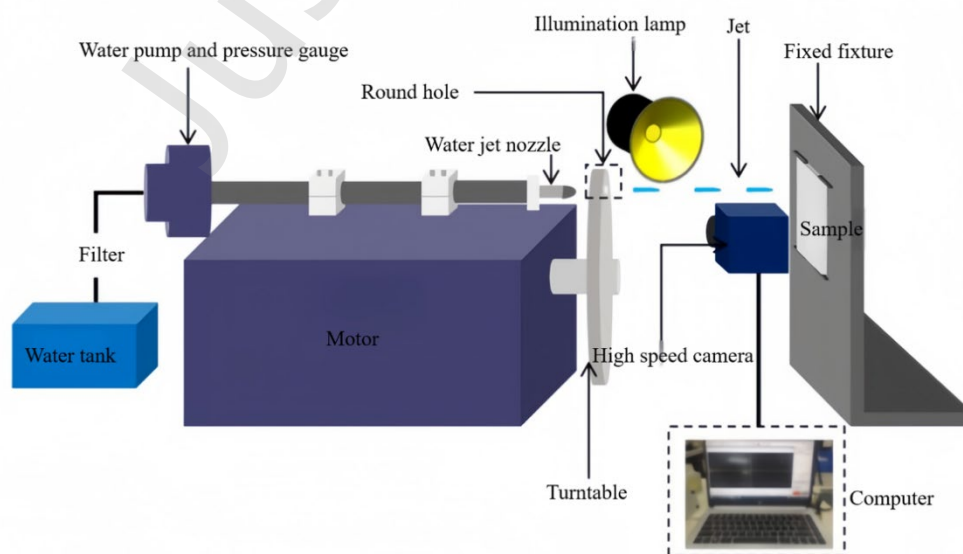


Fig.3 Schematic diagram of the pulsed droplet impact test platform

2.3 The preparation process of coating samples

In this study, the aircraft skin coating material consists of a substrate and a paint layer. The substrate is a T800 carbon fiber reinforced resin-based composite, which is widely used in aircraft skin structures such as wings and tail surfaces [31–36]. The process for preparing carbon fiber composite laminates using T800/epoxy resin is as follows: After thawing the T800/epoxy prepreg stored at low temperatures at room temperature and inspecting it, clean the mold and apply a release agent. Cut the prepreg to the specified angles and lay it up layer by layer. The process involves segmented vacuum pre-compaction to remove interlaminar air. Once layering is complete, a breathable mat and vacuum bag are placed in sequence, sealed, and leak-tested. The assembly is then transferred to an autoclave for high-temperature curing under pressure, resulting in a carbon fiber epoxy laminate. The paint layer mainly comprises a Cr-free high-solid-content epoxy primer and a high-solid-content polyurethane (PU) topcoat. Specifically, the topcoat uses TS70-1 polyurethane matte enamel (Lighthouse Coatings Co., LTD.), while the primer employs the corresponding TB06-9 acrylic polyurethane primer to enhance adhesion between the topcoat and the substrate surface, ensuring that the sample surface remains smooth during topcoat application. Thickness of primer is 90 μm , thickness of topcoat is 180 μm . The specifications of the polyurethane coatings and substrate used in this study are listed in Table

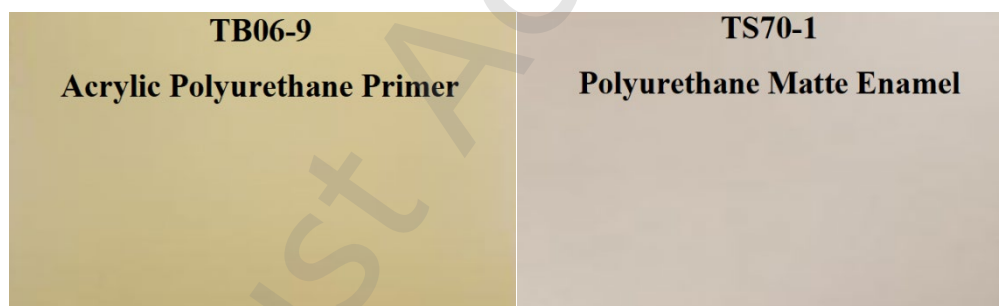
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Table 1 Specifications of the coating and substrate

Length $\times$ Width $\times$ Sample Thickness, mm	Primer Type / Thickness, μm	Topcoat Type / Thickness, μm	Substrate/Thickness, mm
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50×50×3.27	TB06-9 Acrylic Polyurethane Primer/90	TS70-1 Polyurethane Matte Enamel/180	Carbon-fiber plain weave T800/3
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When preparing coating samples, the surface stains and the outermost layer containing the mold release agent are first removed through pretreatment, allowing the coating to directly contact the resin part and further enhancing adhesion between the coating and the substrate. The coating was prepared by the cross-spraying method. Through spraying tests, it was found that one cross-spraying pass produced a thickness of approximately 46 μm . The coating thickness is adjusted by the number of sprays. First, the primer is sprayed (as shown in Fig. 4(a)), and after the primer is fully cured, the topcoat is sprayed (as shown in Fig. 4(b)). The topcoat is cross-sprayed four times, with a thickness of 182 μm (error $\pm 24 \mu\text{m}$), and the primer is cross-sprayed twice, with a thickness of 92 μm (error $\pm 12 \mu\text{m}$).



(a) Surface topography after primer spraying (b) Surface topography after topcoat spraying

Fig.4 Schematic diagram of the coated specimen after spraying

The coated samples were cured after spraying using different methods, namely at room temperature (F1), at 50 °C for 48 h (F2), and at 120 °C for 1 h (F3), to obtain different mechanical performance parameters. Because the coating is sprayed as a whole, to facilitate fixation of the coating sample by the rain erosion test fixture and to improve sample utilization, the test piece was cut into 40 mm × 40 mm samples, which is convenient for conducting tests under different working conditions.

Cutting methods include water jet cutting, diamond wire saw and wire cutting. Owing to the poor electrical conductivity of the material, the electric sparks from wire cutting can damage the surface of the coating. A diamond wire saw is suitable for cutting small-area specimens. Therefore, water-jet cutting was used to obtain 40 mm $\times$ 40 mm coated specimens. The processing procedure and the coated specimens after cutting are shown in Fig. 5.

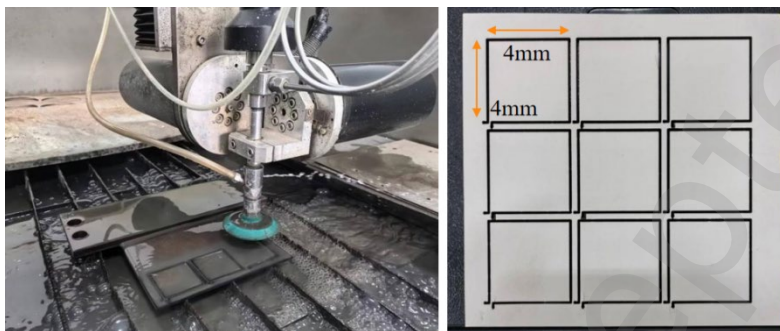
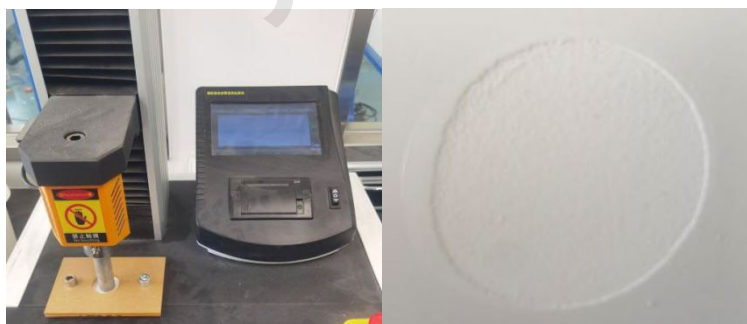


Fig.5 Water-jet cutting and coating dimensions

Next, the prepared coated specimens were tested for interlaminar bond strength and mechanical properties, and the test results are shown in Fig. 6. The material properties and structural compositions of the different coating systems are presented in Tables 2 and 3, respectively. The basic properties of the T800 carbon fiber are listed in Table 4, while the structural parameters and mechanical properties of the T800/epoxy composite substrate are provided in Tables 5 and 6, respectively.



(a) Interlaminar Bond Strength Tester (b) Coated sample after testing

Fig.6 Test equipment and results

Table 2. Material properties of different coating systems

Materials	Indentation modulus /GPa	Hardness GPa	Poisson's ratio	Fracture strength/MPa	Surface roughness/ μm
1	5.805 602 2	0.240 234 6	0.3	43.81	0.18
2	3.850 652 0	0.161 498 6	0.3	43.81	0.18
3	2.414 338 2	0.110 977 8	0.3	43.81	0.18

Table 3. Structural composition of different coating systems

Coating	Primer	Topcoat	Substrate
Material 1	acrylic polyurethane primer	polyurethane matte enamel	T800 carbon fiber woven material
Material 2	epoxy self-drying primer	acrylic polyaliphatic polyurethane enamel	T800 carbon fiber woven material
Material 3	chrome-free high-solid epoxy primer	matte high-solid polyurethane enamel	T800 carbon fiber woven material

Table 4. Properties of T800 carbon fiber

Material	Density/ $\text{g}\cdot\text{cm}^{-3}$	Filament diameter / μm	Tensile strength / GPa	Tensile modulus / GPa	Elongation / %
T800 carbon fiber	1.81	5.0	5.5	294	1.9

Table 5. Properties of T800/epoxy composite substrate

Material	Fiber architecture	Matrix	Fiber volume fraction / %	Thickness / mm	Density / $\text{g}\cdot\text{cm}^{-3}$
T800/epoxy composite	Plain weave (T800/3)	Epoxy resin	55 ± 5	2.0	1.55

Table 6. Mechanical properties of T800/epoxy composite substrate

Material	Tensile strength / MPa	Tensile modulus / GPa	Compressive strength / MPa	Interlaminar shear strength / MPa	Poisson's ratio
T800/epoxy composite	650	55	600	70	0.30

3 Effects of droplet impact on delamination damage

According to existing research results ^[37-39], droplet velocity, droplet diameter and impact frequency are the key factors affecting the degree of rain erosion damage. The primary damage

mechanism is coating delamination and peeling caused by the shear effects of water hammer pressure and the lateral jet. Among the damage modes, delamination is one of the most common and central issues in coating failure. Local or large-scale peeling or internal debonding of the coating from the substrate seriously affects coating performance and service life of the coating, and the interlaminar bond strengths is a key factors affecting delamination damage. Therefore, this paper mainly studies the differences in the rain erosion damage of coatings with different interlaminar interlaminar bond strengths, and further reveals the generation mechanism and action mechanism of delamination damage.

3.1 The influence of interlaminar bond strength on the delamination damage of coating materials

3.1.1 The result of stratified damage caused by single-drop impact

The influence of interlaminar bond strength on the rain erosion resistance of the coating was studied using a single-droplet impact test device. The three coatings with interlaminar bond strengths of 2.2, 2.4, and 2.8 MPa were named F1, F2, and F3, respectively. This study investigated the damage of coatings with different interlaminar bond strengths under single-jet impact conditions with a jet velocity of 610 m/s and a head diameter of 4.5 mm, as shown in Fig. 7. The F1 coating (2.2 MPa) showed peeling damage at the impact point, exposing the black substrate and yellow primer. The coating slightly bulged and delaminated, with circumferential cracks appearing at the raised edge (Fig. 7(a)). The F2 coating (2.4 MPa) showed only slight peeling of the topcoat, forming a ring-shaped damage area (Fig. 7(b)). The F3 coating (2.8 MPa) showed only minor ring-shaped scratches on the

topcoat (Fig. 7(c)), with a damage area smaller than that of F2. No delamination occurred in either F2 or F3 coatings.

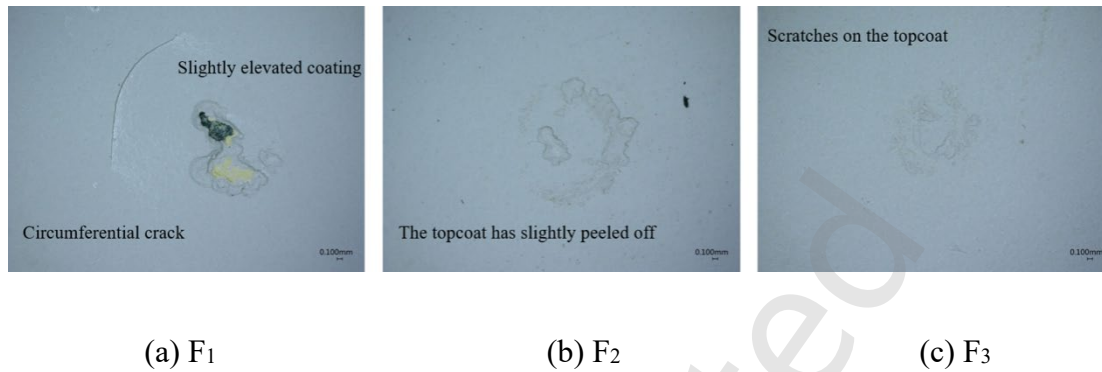


Fig.7 Impact test results at 610 m/s

To observe the internal delamination damage of the F₁ coating in greater detail, Computed Tomography (CT) was used for internal scanning. The scanning image of the most severely damaged yellow dotted section is shown in Fig. 8. Large-scale delamination damage occurs between the coating and the substrate. Moreover, due to the deformation and lifting of the coating, longitudinal cracks are generated from the inside out at the delamination boundary. Under lateral jet impact, the coating in the delamination area further cracks causing delamination. In addition, gaps caused by delamination were also observed between the fiber layers within the matrix of the impact area.

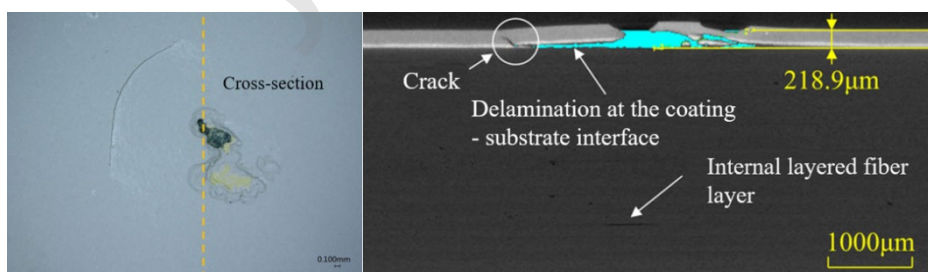


Fig.8 CT scan image of the F₁ coating at the dashed-line cross-section

The cause of delamination damage can be explained by the reflection and transmission behavior of stress waves at the coating interfaces. As shown in Fig. 9, a schematic diagram illustrates the mechanism of interfacial delamination. When high-speed droplets impact the material surface, compression waves (incident waves) are generated in the subsurface and propagate into the interior. When the compression wave reaches the interface between the topcoat and primer, or between the primer and the substrate, the change of transmission medium and the significant differences in density, elastic modulus, and other mechanical properties cause an impedance mismatch, resulting in partial reflection of the wave energy. If the acoustic impedances differ greatly, the intensity of the reflected wave increases significantly. Additionally, due to variations in the layering sequence of carbon fibers and the interface defects from processing, stress wave reflection is also likely to occur within the material.

Based on the above analysis, the fundamental causes of interfacial delamination under single-droplet impact are as follows: The high-amplitude compression wave generated by the high-speed impact is reflected at the interface, and the high-amplitude reflected tensile wave cyclically loads the interface, resulting in local stress concentration and the microcracks formation. Further expansion of the microcracks leads to interlaminar cracking and delamination. The relatively high water hammer pressure rapidly causes damage to the coating surface and, under the shear superposition effect of the lateral jet, leads to deflection and peeling of the surface coating.

Under the same impact conditions, the direct cause of different damage modes is the different interlaminar bond strengths at the interface, which mainly depend on the integrity of the internal microstructure and the interfacial bond strength.

When the interlaminar bond strength is low, the reflected waves cause local stress concentration at the interface under droplet impact. The release and transmission of internal stress are uneven, and the tensile force exceeds the bond strength between the coating and the substrate, resulting in microcrack formation at the coating–substrate interface. Because the bond strength between coating layers is stronger than that between the coating and the substrate, microcracks form at the coating–substrate interface. These cracks accelerate coating failure, leading to substrate exposure. During the lateral jet phase, hydraulic penetration and shear forces cause the microcracks to propagate further, leading to delamination. Subsequently, upward-growing cracks appear at the tip, ultimately resulting in annular cracks at the edges of the coating surface. Continuous microcrack expansion eventually leads to coating delamination.

When the interlaminar bond strength is relatively high, the water hammer pressure during the compression phase does not exceed the bond strength at the interface, and no initial delamination cracks form; however, during the release phase, the high pressure at the liquid–solid interface exceeds the material’s damage threshold, resulting in an annular damage zone. The load-bearing capacity of the coating is significantly enhanced, enabling it to dissipate impact energy more effectively and suppress the formation and propagation of microcracks, thereby maintaining the integrity of the coating.

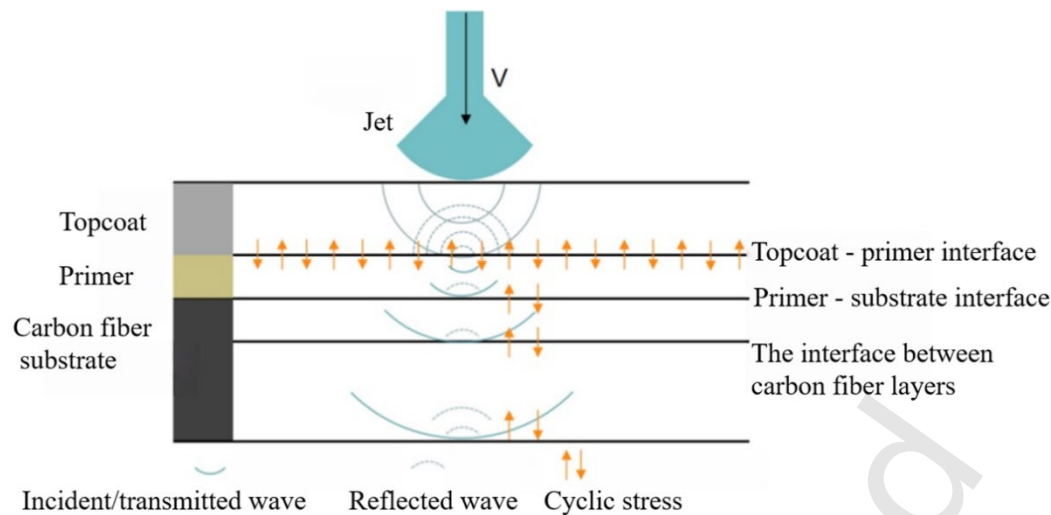


Fig.9 Cyclic stress loading process at the interface after impact

To better verify the resistance of interlaminar bond strength to delamination damage, the F3 coating was impacted at the maximum speed of 776 m/s in a single-droplet test device. The damage morphology is shown in Fig. 10. Peeling damage occurs at the impact center, exposing the substrate, but no delamination damage propagates outward from the peel. This indicates that under high-speed impact, the combined effect of the high-intensity water hammer pressure and the lateral jet shear force causes peeling at the impact point, while the strong bond strength between the coating and the substrate suppresses delamination damage.



Fig.10 Micrograph of the F₃ coating after impact at 776 m/s

The morphology of droplet impact damage at high speed can also be explained by the macroscopic impact kinetic energy and the water hammer pressure given by Heymann:

$$E_k = \frac{1}{2} m V^2 \quad (4)$$

Where E_k is the kinetic energy of impact, m is the mass of the impinging liquid, and V is the velocity of impact.

According to formulas (1) and (4), under the same conditions, the droplet mass and impact velocity are the key factors determining the impact kinetic energy and water hammer pressure. Therefore, in addition to the interlaminar bond strength property of the material, impact velocity and droplet mass also influence the delamination damage of the coating.

3.1.2 Effect of pulsed droplet impact on delamination damage

Fig. 11 shows the damage morphologies of three coatings with different interlaminar interlaminar bond strengths observed under a digital microscope when delamination occurs under the continuous impact of droplets with a diameter of 1.4 mm and a speed of 415 m/s.

The delamination damage morphologies of the three coatings are similar, all presenting long strip-shaped damage. The long side L_x of the damage is consistent with the fiber direction at the coating-substrate interface, and some fibers in the substrate damage area are broken. Fig. 11(a) shows the peeling damage of the F₁ coating after 650 consecutive impacts, where delamination damage is clearly visible in the impact region due to the coating lifting. After 750 consecutive impacts, the F₂ coating showed delamination damage. The damage morphology is shown in Fig. 11(b). The peeling area is along the fiber direction, the damaged area is slightly raised, and circumferential cracks appear at the edge of the impact area. However, the F₃ coating with stronger interlaminar bond strengths only showed delamination damage after 1500 impacts. The

coating in the impact area swelled and the peeling area in the impact area decreased, as shown in Fig. 11(c).

Based on the post-test observations, the lower the interlaminar bond strength of the coating, the shorter the impact duration required for delamination and the more severe the damage. This is because, under continuous droplet impact, a relatively high stress level exists at the coating–substrate interface on the side wall of the erosion pit. Under long-term and periodic impact, stress fatigue occurs at the interface, forming microcracks. Meanwhile, the lateral jet generated by the droplet impact continuously impacts and expands along the interface stratification of the erosion pit. Under shear action, the damaged area expands laterally, and the delamination area gradually increases.

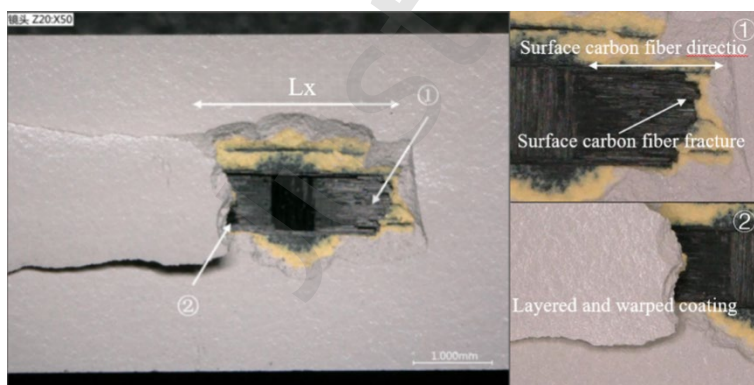
Based on the damage results, the interlaminar bond strength along the fiber direction is significantly lower than that perpendicular to the fiber direction, and microcracks and delamination are more likely to propagate along the path of least resistance (i.e., the fiber direction).

Furthermore, research has shown ^[40–42] that the oriented arrangement of fibers is the fundamental source of the anisotropic characteristics of composite materials, and this microstructural orientation directly determines the directional dependence of the material's macroscopic mechanical properties. Specifically, in the fiber direction (Direction 1), the load is primarily borne by the high-strength, high-modulus fibers, resulting in excellent mechanical properties; whereas in the transverse directions perpendicular to the fibers (Directions 2 and 3), load transfer relies mainly on the matrix phase, and the fiber-matrix interface becomes the

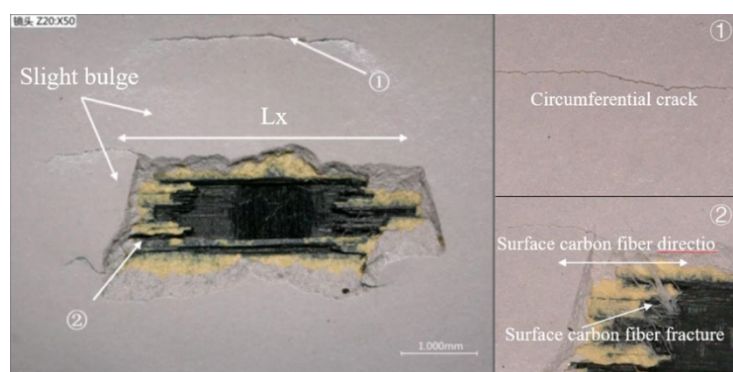
mechanical weak point, leading to a significant reduction in elastic modulus, strength, and toughness.

Experimental data indicate ^[43] that the longitudinal elastic modulus of high-performance carbon fiber-reinforced epoxy composites (CFRP) can reach 140 GPa, while the transverse elastic modulus is only about 10 GPa, with a difference of one order of magnitude (14 times); although the anisotropy ratio of glass fiber-reinforced composites (GFRP) is relatively low, the difference between the longitudinal and transverse moduli can still reach 6 times. This severe mismatch in stiffness is not only reflected in static mechanical properties but also profoundly influences the material's response behavior under dynamic loading.

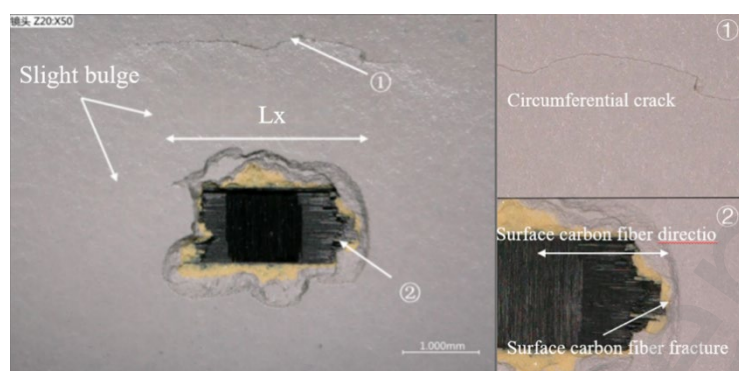
Through the coupled action of various mechanisms, anisotropic elastic moduli cause stress wave propagation velocity, interfacial stress distribution, and crack resistance to exhibit significant directional dependence, which constitutes a major reason for delamination propagation along the fiber direction.



(a) Delamination morphology of coating F₁ after 650 continuous impacts



(b) Delamination morphology of coating F₂ after 750 continuous impacts



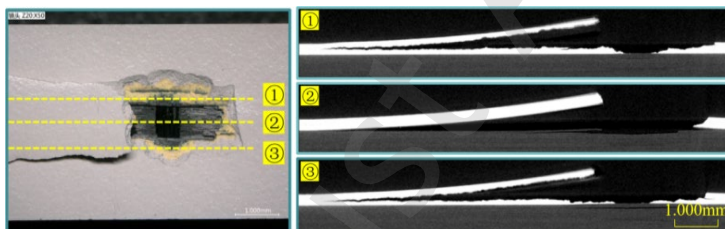
(c) Delamination morphology of coating F₃ after 1500 continuous impacts

Fig.11 Surface morphologies of delamination damage in F₁, F₂ and F₃ coatings

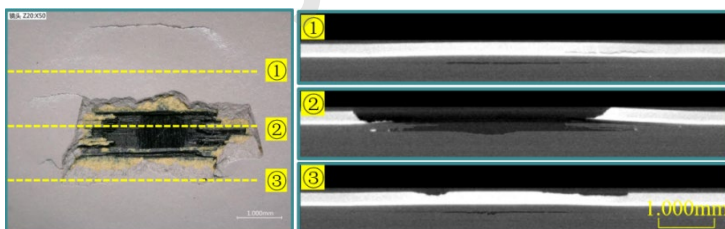
The damaged regions were further analyzed using CT. Fig. 12 shows the CT scan results of the three coatings. Besides delamination damage at curve position ② (center of peel damage), delamination is also present at curve positions ① and ③ outside the surface peel damage. The internal delamination area is generally larger than the surface damage area. On the side wall of the erosion pit, clear delamination occurs between the primer and the substrate, and between the surface carbon fiber layer and the second carbon fiber layer. The delaminated area on the side wall continues to extend into the interior of the sample, causing bulging of the coating in the impact region and the appearance of circumferential cracks at the boundaries. Under continuous droplet impact, stress waves are repeatedly reflected at the interfaces, cyclically loading them and maintaining a prolonged high-stress state. Uneven release and transmission of internal stress lead to the formation of microcracks at the interface.

These microcracks rapidly propagate under continuous impact, causing material peeling on the coating surface. As the number of impacts increases, the erosion depth increases too, eventually reaching the carbon fibre matrix, as can be seen in the cavity in Fig 13. Simultaneously, when high-speed fluid enters the cavity, microdroplets are generated that impact the side walls a second time, as indicated by the orange arrows in Fig 13. The combined effects of hydraulic penetration and lateral jet flow result in the formation of small cracks on the side walls that propagate inward, leading to delamination.

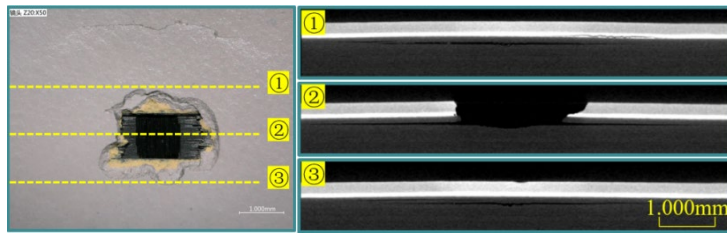
From the number of impacts required to produce delamination in the three coatings, it is evident that the F3 coating, with higher interlaminar bond strength, requires more impacts for delamination to occur. Its stronger interface can effectively disperse impact energy, suppress the formation and propagation of internal microcracks, thereby delaying delamination and conferring strong rain erosion resistance. In contrast, the F1 coating, with weaker interfacial bonding, experiences fatigue damage at the interface under continuous impact, leading to local crack formation and large-scale peeling damage.



(a) CT scan results of coating F₁ after 650 continuous impacts



(b) CT scan results of coating F₂ after 750 continuous impacts



(c) CT scan results of coating F_3 after 1500 continuous impacts

Fig.12 CT scan results of delamination damage in F_1 , F_2 and F_3 coatings

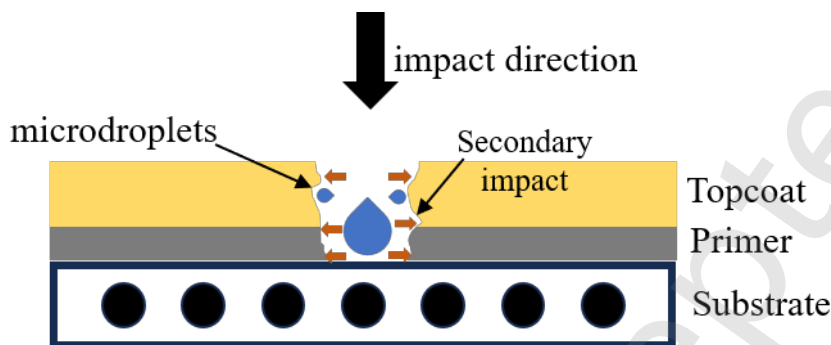


Fig.13 The damage mechanism of pulsed droplet impact

3.2 Simulation analysis of impact process and stratified damage

3.2.1 Establishment of the finite element model

The finite element model in this study was developed using the nonlinear finite element software Abaqus. The entire three-dimensional model consists of a water jet, a coating with a carbon fiber laminate as the substrate, and a rigid fixture, as shown in Fig. 14. The coating is composed of three layers: topcoat, primer, and carbon fiber laminate. The thicknesses of the topcoat and primer are 0.18 mm and 0.09 mm, respectively. Owing to its extremely small deformation, the carbon fiber laminate was modeled as a rigid body in the simulation, with a thickness of 3 mm. A 0.01 mm thick cohesive element layer is inserted between the topcoat and primer, and between the primer and the substrate. The fixture undergoes minimal deformation during the test, and therefore is constrained as a rigid body in the simulation. The rigid fixture is

fully fixed; the edge of the coating is free, while the substrate is fixed to the rigid fixture. The contact between the particles and the coating is Explicit General Contacts, with a coefficient of friction of 0.2. The entire impact event was analyzed using the Abaqus/Explicit solver, with a total duration of 30 μ s, sufficient for the fluid to reach a steady state.

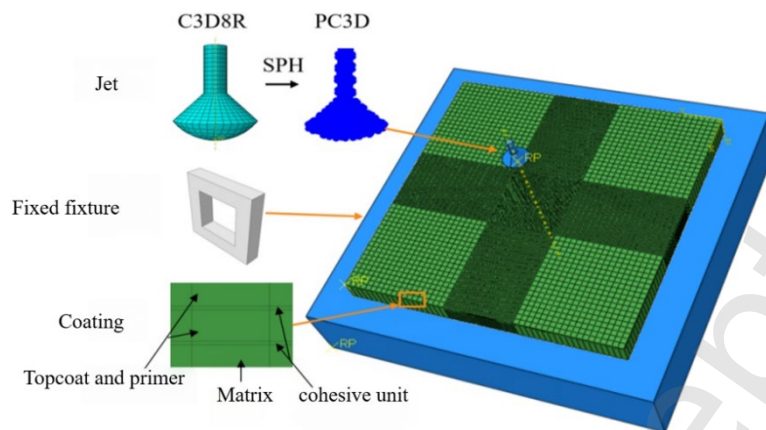


Fig.14 Finite-element model of droplet impact on a composite laminate

The parameters of the coating materials used in the simulation research are shown in Table 7. These constant values are taken from reference [44].

Table 7 Material parameters of the coating

Density/(kg/m ³)	Young's modulus/GPa	Poisson's ratio
1050	3.8506	0.3

The cohesive element built into ABAQUS, which is based on cohesive zone theory and damage mechanics, was used to model interlaminar delamination damage. A quadratic nominal stress criterion was adopted as the damage initiation criterion for the cohesive element. The Benzeggagh-Kenane (B-K) criterion was selected to couple the critical fracture energies (G_n^c , G_s^c , G_t^c) for the three failure modes and the linear softening behavior, thereby predicting the damage propagation process of the cohesive element. The parameters of the cohesive elements used in the simulation research are shown in Table 8. These constant values are taken from reference [45].

Table 8 Material parameters of interlaminar cohesive elements

K_{nn} (GPa/mm)	K_{ns} (GPa/mm)	K_{st} (GPa/mm)	T_n^0 (MPa)	T_s^0 (MPa)	T_t^0 (MPa)	G_n^c (N/mm)	G_s^c (N/mm)	G_t^c (N/mm)	η
100	100	100	20	36	36	0.6	2.1	2.1	1.45

The droplet model was established based on the water jet images captured by a high-speed camera at different impact moments at a jet velocity of 350 m/s, as shown in Fig. 15. When the jet is just ejected from the nozzle, it takes on an overall cylindrical shape with a diameter consistent with that of the nozzle (Fig. 15(a)). As the light gas cannon continuously applies impact loads to the water storage chamber, the water inside the chamber is compressed and ejected at high speed, and the jet head gradually evolves into a water mist shape similar to a "mushroom head" (Fig. 15(b)). As the jet distance increases, the tiny droplets at the very front that decelerate due to air resistance diffuse outward, and the subsequent droplets continue to accelerate and eject, forming a new jet head. This process eventually forms a head with concentrated speed and stable shape, surrounded by a circle of decelerating water mist. The leading edge of the concentrated head is in a regular spherical shape, similar to the appearance of a water droplet. The peripheral water mist ring is actually composed of discrete fine particles, and its influence on the collision process can be ignored, so it is not considered. Based on this, the model is simplified into two parts: the head composed of a spherical crown and a truncated cone, and the tail represented by a cylinder. The radius R of the spherical crown is consistent with the radius of the jet, experimentally measured to be 2.25 mm. The diameter of the cylinder is taken as 1.0 mm (diameter of the experimental nozzle). The total length L of the model is set to twice the radius of the ball crown (4.5 mm). The angle θ between the conical generatrix and its axis is taken

as 45° . Without considering the relationship between the jet shape and the velocity, the final geometric model is shown in Fig. 14(d).

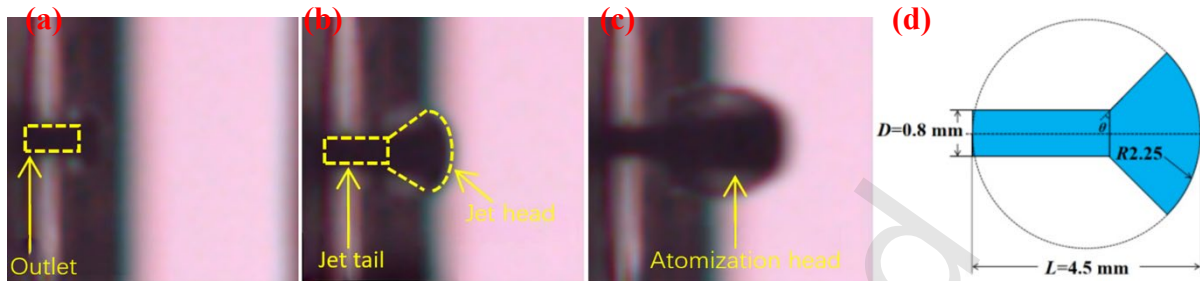


Fig.15 Typical morphology and geometric model of the water jet

Because the water jet undergoes large deformations (e.g., flow, splashing, and jetting) during impact, mesh distortion occurs in traditional Lagrangian mesh calculations. To better simulate fluid behavior, this paper adopts the meshless Smoothed Particle Hydrodynamics (SPH) algorithm embedded in Abaqus to calculate the motion of water jets. The SPH method represents objects with discrete particles, and the particles interact with neighboring particles through a kernel function, as shown in Fig. 16.

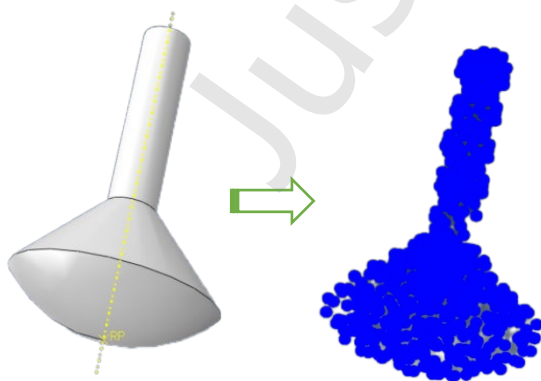


Fig.16 Generation of SPH particles

The parameters of the water jet are set as shown in Table 9. Where ρ_0 represents the density of water droplets, C_0 and s are material constants used to determine the linear relationship between the wave velocity U_s and the particle velocity U_p : C_0 indicates the intercept of the stress wave velocity under specific conditions (such as the standard state), which is related to the initial state of the material. s is the slope coefficient of the U_s - U_p curve, which determines the relationship between pressure and density changes and reflects the response rate of the material to pressure changes. Γ_0 is a dimensionless coefficient used to describe the correlation between volume compression and energy absorption of materials. These constant values are taken from reference [46].

Table 9 Parameters of the water medium

$\rho_0/(\text{kg/m}^3)$	$C_0/(\text{m/s})$	s	Γ_0
1000	1489	2	1.65

Finite element accuracy improves with mesh refinement, however, excessive mesh refinement significantly increases computational cost with diminishing returns.^[47,48] Mesh independence was verified using three mesh sizes: 0.6 , 0.2, and 0.1 mm. As shown in Fig. 18, when the mesh size was 0.6 mm, the numerical results exhibited significant oscillations, and the final Bernoulli static pressure was overestimated. As the mesh was progressively refined, computational stability improved when the mesh size reached 0.2 mm. When the mesh size reached 0.1 mm, the accuracy did not improve significantly compared to the 0.2 mm mesh, but the computation time doubled. In this paper, the coating (40×40 mm) is discretized according to the impact zone: only the central 10×10 mm action zone uses a 0.2 mm fine grid, the periphery uses a 0.8 mm coarse grid to reduce the number of elements, and a 0.2×0.8 mm transition grid is

used to achieve continuous stress and completely capture the possible interlaminar delamination.

The grid division scheme is shown in Fig. 17, and Table 10 presents the statistical results of the grid types and quantities of all model cells.

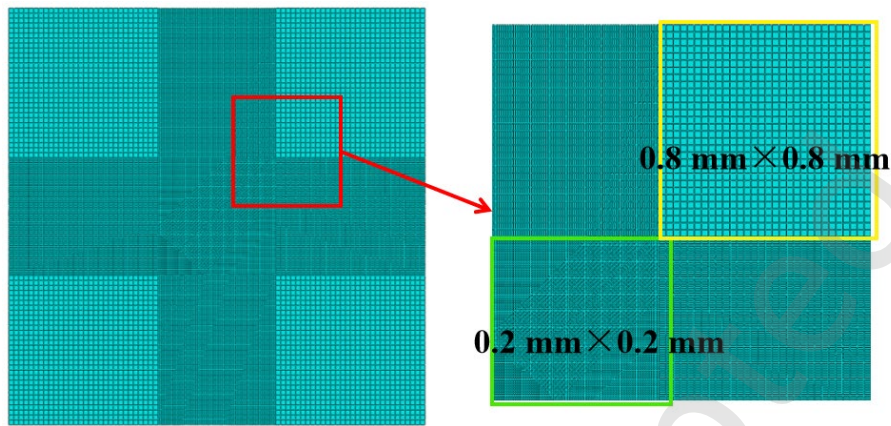


Fig.17 Meshing scheme for the laminated plate

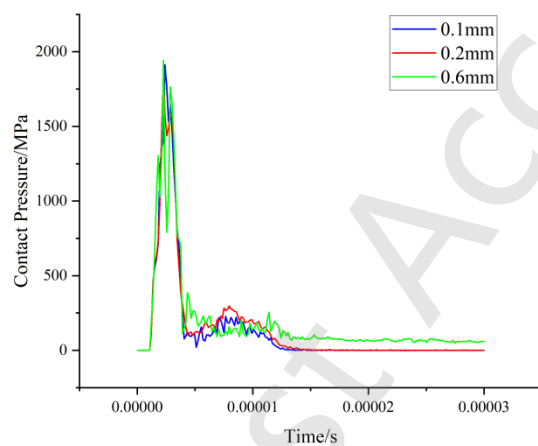


Fig.18 Verification of grid independence

Table 10 Statistics of element types and quantities for the entire finite-element model

Assembly	Element type	Element count
Water jet	PC3D	3980
Rigid support	C3D8R	128
Coating material	COH3D8	15488
	C3D8R	23232

3.2.2 Analysis of Simulation Results of Jet Impact Coating

This section presents simulation analysis of the impact process and mechanical response results of a water jet with an impact velocity of 445 m/s and a head diameter of 4.5 mm impacting polyurethane coating .Fig. 19 shows the numerical simulation results within 12 μ s after the impact. Taking the initial moment of water jet contact with the coating surface as 0 μ s, the stress states were captured at equal intervals 9 times within 12 μ s. As can be seen from the figure, when $t=0$ μ s, the head of the water jet begins to contact the coating surface. When $t=1.5$ μ s, the jet morphology and stress cloud diagram show that the head acts in the impact area, but the SPH particles did not disperse. This is because the expansion speed of the liquid-solid contact edge exceeds the shock wave propagation speed inside the droplet, and the envelope surface formed inside the liquid compresses the SPH particles. The water jet morphology temporarily remains stable, while transient high pressure is generated. The period of 0 -1.5 μ s corresponds to the water hammer pressure action stage. At this time, the central area of the coating sinks and undergoes slight deformation, and delamination damage is observed at the coating-substrate interface. When $t=3$ μ s, the shock wave velocity within the water jet is higher than the expansion velocity of the contact boundary. The compressed liquid breaks through the boundary of the envelope surface and spreads along the coating surface in all directions. The pressure level in the impact area drops rapidly. During the period of 4.5 -9 μ s, the tail column of the water jet continued to act on the coating surface, and the stress in the impact area remained at a relatively low level. After $t=9$ μ s, only the lateral jet acts on the coating surface. During the entire impact process, internal stress shows periodic changes due to stress wave transmission and reflection. However, the stress amplitude gradually weakens as the jet impact ends and stress waves attenuate.

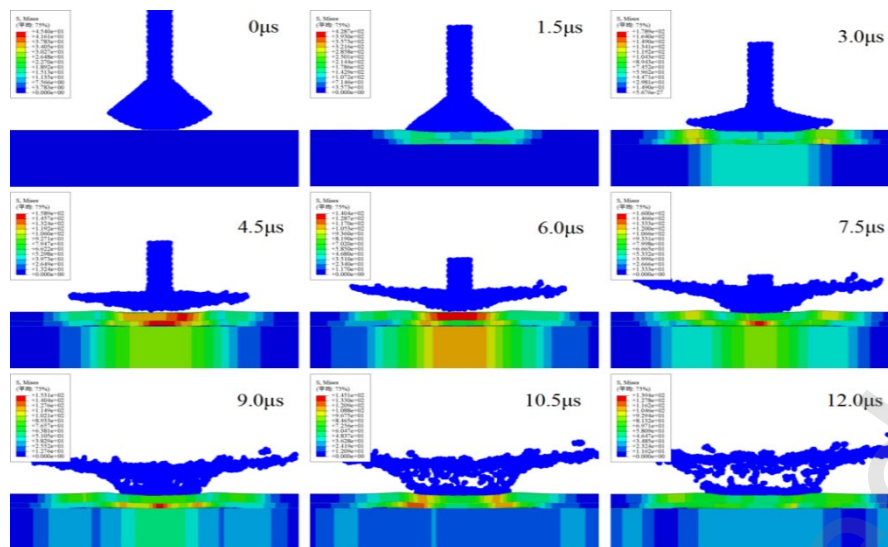


Fig.19 Numerical simulation results of a 4.5 mm diameter water jet impacting a polyurethane coating at 445 m/s

To further validate the simulation results, the simulation damage images at $t=15 \mu\text{s}$ under impact conditions with a speed of 610 m/s and a diameter of 5.6 mm were compared and analyzed with the typical damage morphologies observed experimentally, as shown in Fig. 20. Taking the coating–substrate interface as the damage boundary, the tensile force generated by stress wave reflection at the interface causes delamination damage centered at the impact point, in both test and simulation results. Due to coating deformation and lifting, the bond strength struggles to resist the deformation, and separation between coating and substrate causes transverse cracking. When the subsequent lateral jet flows over the surface, internal hydraulic penetration generates a radial tensile effect, promoting scratch expansion into microcracks and further crack propagation. Ultimately, deep long cracks form in the coating, or existing cracks expand, causing coating peeling ^[49].

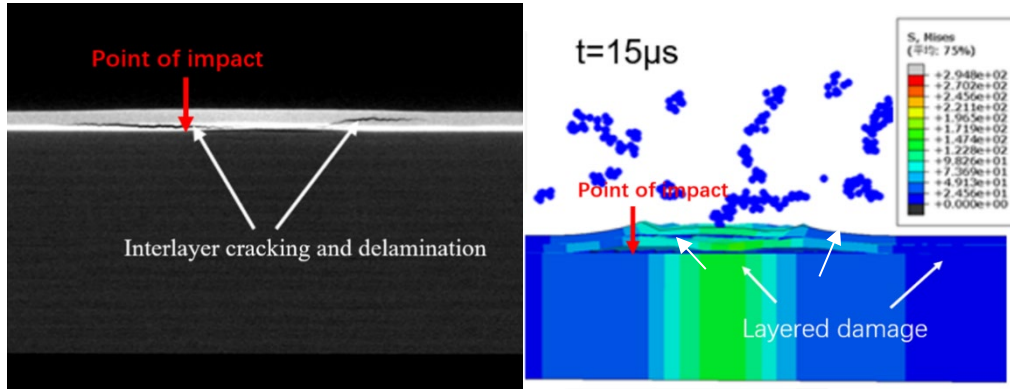


Fig.20 Comparison of delamination damage between experimental and simulation results

Based on the key mechanical role of water hammer pressure in the liquid-solid dynamic impact process, taking the above water jet impact with a speed of 445 m/s and a diameter of 4.5 mm as the reference working condition, the contact pressure variation curve with time at the impact point was extracted, as shown in Fig. 21. As can be seen from the black solid line representing the simulation value in the figure, the pressure variation at the impact point over time can be divided into three stages. The first stage is the water hammer pressure stage: the pressure reaches a maximum of approximately 280 MPa at the first moment of contact, corresponding to the 0–1.5 μs period in Fig. 19. The second stage is the zero-pressure section. As the impact continues, the pressure gradually decreases. Owing to the different diameters of the arc-shaped head and the cylindrical tail, a very brief zero-pressure section occurs during the transition from arc-shaped head impact to cylindrical tail impact. The third stage is the stagnation pressure section, during which the pressure fluctuates over a relatively long period, and the fluctuation amplitude is much smaller than the water hammer pressure. The stagnation pressure duration mainly depends on the tail cylinder length, corresponding to the 3–9 μs period in Fig. 19. The theoretical water hammer pressure variation curve was solved using the approximate formula (5) and the hysteresis formula (6) of water hammer pressure involving the elastic deformation of solids given by

Engel^[49], as shown by the red dotted line in Fig. 21. The peak contact pressure and the average stagnation pressure are respectively consistent with the calculated values of the one-dimensional water hammer pressure formula and the stagnation pressure formula.

$$P_{wh} = \rho_0 C_0 V \frac{1 + kM_0}{1 + \lambda(1 + kM_0)} \quad (5)$$

where λ refers to the acoustic impedance ratio of a liquid to a solid:

$$\lambda = \frac{\rho_0 C_0}{\rho_s C_s} \quad (6)$$

where ρ_0 and C_0 are the liquid density and sound speed, ρ_s and C_s are the density and wave speed of the solid. V represents the impact velocity, k is the material parameter related to the compressibility of the liquid, which is taken as 2 in this paper. M_0 is the corresponding Mach number of the impact velocity, that is, V/C_0 .

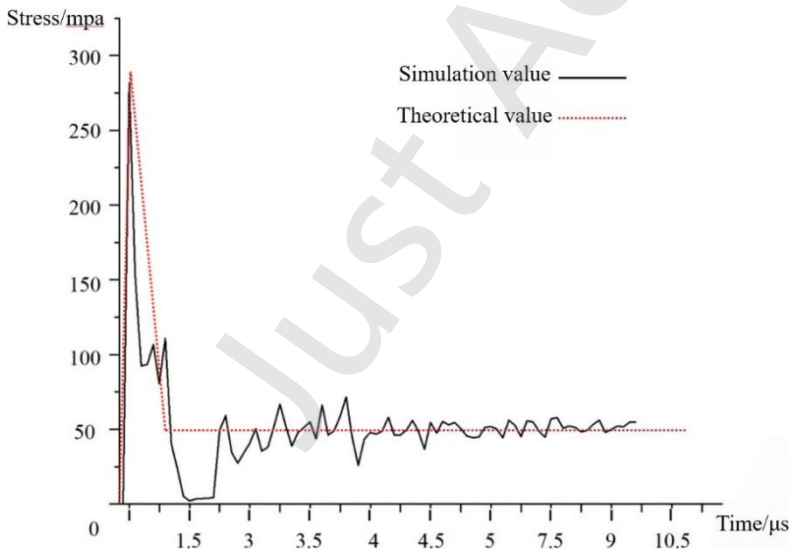


Fig.21 Contact pressure versus time at the impact point for a 4.5-mm-diameter jet at 445 m/s

Damage evolution was analyzed in combination with water hammer pressure. The coating material suffered surface compression damage and delamination damage at the internal coating-substrate interface at the moment of water jet impact. The onset of damage coincided with the

peak water hammer pressure, indicating that water hammer pressure dominates damage initiation.

As the impact proceeds, the cylindrical tail impact generates prolonged stagnation pressure on the coating. The stagnation pressure generates multiple stress wave reflections (typically 3-4 cycles per impact at 200 Hz), leading to cumulative tensile stress concentration and promoting slow crack growth. The stress waves are reflected and stretched at the coating-substrate and topcoat-primer interfaces, resulting in a high stress concentration and further intensifying the delamination damage at the interfaces.

4 Conclusion

This study used T800 carbon fiber composite laminates as substrates and prepares polyurethane coatings with different interlaminar bond strengths. Combined with single-jet/pulsed multi-jet impact tests and finite element simulation, the delamination damage mechanism of aircraft coatings under high-dynamic droplet impact is revealed. The main conclusions are as follows:

(1) Under single-droplet impact, low interlaminar bond strength causes interfacial stress concentration and local delamination at the impact center. High bond strength can better dissipate impact energy and suppress microcrack initiation and propagation.

(2) Under pulsed multi-jet impact, the interface suffers cyclic stress fatigue and forms microcracks, which gradually evolve into strip delamination along the carbon fiber direction. The lower the bond strength, the earlier delamination occurs and the more severe the damage.

(3) The delamination mechanism is driven by two stages: water hammer pressure induces interfacial microcracks at the initial impact moment; subsequent lateral jet and stress wave reflection cause crack propagation and macroscopic peeling.

(4) At the interface between the coating and the substrate, initial damage is likely to occur under the combined effects of repeated tensile stress waves and lateral jet shear. As the damage progresses, cracks propagate due to further erosion, leading to extensive delamination. Consequently, enhancing interlayer adhesion can effectively improve the resistance to rain erosion in vulnerable areas of the material and significantly enhance the protective performance of the coating.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Babaytsev Arseny, Fedotenkov Gregory and Mednikov Aleksei. The first draft of the manuscript was written by Minggong SHA, Zhiqiang HUI and Xiaokang SONG. The Data curation were performed by Ying SUN, Yulong LI and Ruisheng HAN, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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