Pretreatment of CFRP by Amino Thermoset Abrasive Air Jet Machining

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Abstract

An effective pretreatment method of carbon fiber reinforced plastic (CFRP) aircraft skin was proposed. In this article, the function of the amino thermosetting abrasives entrained by the airflow on the CFRP aircraft skin is introduced and discussed to achieve the purpose of enhancing the coating adhesion and prolonging the service life. An orthogonal experiment with five factors and four levels was designed and carried out, including jet pressure, target distance and impact angle, moving speed and particle size. The best pretreatment process was obtained by analyzing surface morphology, wettability and adhesion. The erosion mechanism of CFRP coating pretreatment with abrasive impact was studied emphatically. The results show that the critical pressure for fiber damage is 0.4 MPa, and the better surface energy is 38.0 mN/m. Semi-ductile erosion has been identified as the main erosion mechanism of amino thermosetting abrasives eroding CFRP. Effective assurance was provided for the improved surface of the aircraft CFRP skin and enhanced coating adhesion in this study.

1. Introduction

Since the advent of reinforced composite materials in the 1960s, it has gradually been favored by aircraft designers and manufacturers for its unique advantages such as light weight, high strength, and beautiful appearance^[1]. The US military has licensed carbon fiber reinforced Plastic(CFRP) for fighters skinning^[2]. The application of reinforced composite materials in military aircraft ranges from the tail and secondary surface load-bearing components to the wing-level main load-bearing components to the main load-bearing components with integrated structural and stealth functions. The above applications have fully verified the feasibility of using composite materials in military aircraft skins. At present, the composite material usage of Airbus A350 has exceeded 50% of the entire fuselage material^[3].

It was universally known that coating is one of the most effective ways to ensure the service life of composite materials. However, the adhesion of the coating depends on the surface situation. The compactness and smooth surface of the material caused by the special manufacturing process are extremely detrimental to adhesion. No exception is aluminum alloy or titanium alloy skins. The purpose of pretreatment is to remove the release agent between the mold and the substrate, so as to enhance the adhesion^[4]. Nowadays, mechanical grinding and manual sanding are still commonly used in many airlines or enterprises. However, the problems of damaged skin surface and low removal rate cannot be solved by traditional methods. Although it is possible to control emergencies during manual sanding, due to human error or uneven force distribution, surface damage and residual coating on the metal skin can cause negative adhesion to the repaired coating. Therefore, the pretreatment method of medium-soft abrasive jet instead of manual sanding has been recommended by Boeing, which can effectively avoid the shortage of manual sanding. The medium-soft abrasive has been defined as the hardness between the resin-based material and the carbon fiber. A closed dust-free workshop equipped with precise temperature and humidity control devices is used in the above work to ensure the effectiveness of the coating.

Abrasive Air Jet Machining (AAJM) is an unconventional processing technology^[5], which has the advantages of strong adaptability, no heat-affected zone, no stress, low processing cost and environmental friendliness. It is widely used in the finishing of precision parts. The erosion of traditional abrasives (such as quartz sand (SiO_2), silicon carbide (SiC), white corundum, etc.) can seriously damage CFRP. The erosion of plastic particles on workpieces was first proposed by Robert^[6] in 1985 and recommended for the removal of aircraft coatings in the following year^[7]. Subsequently, plastic media with a Mohs hardness of 2.0-4.0 was approved by the US military in 1998, usually driven by dry air at 1.5-4.0 bar. However, each of these methods proves that mechanical pretreatment is feasible, but not always performed without damaging the substrate (including metallic substrate). Since then, various aspects of solid particle erosion began to be studied by many scholars.

In terms of process parameters, the optimal value of process parameters has been studied by some scholars^[7-10]. The flow characteristics of the micro-abrasive jets were studied by Fan et al.^[11]. The particle velocity was analyzed using particle image velocimetry (PIV) and the downstream correlation of the jet was studied, such as jet expansion angle and instantaneous velocity. The effect of separation distance, mixing ratio, carrier pressure, particle size and other parameters on material removal rate and permeability was studied by Verma et al.^[12] based on the erosion model. Li et al.^[13] studied the effects of different air pressure, particle mass flow and drilling time on the evolution of micro-holes and blind holes in glass. Particles are not the main factor of erosion as described by Neilson et al.^[14], based on the study of the effects of particle shape, particle velocity and angle of attack. The influence of PMB method on the structure of composite materials was studied by Lennon and Mallon^[15], and the influence of parameters was observed through experiments. Regarding the erosion effect of abrasives on composite materials, related research on epoxy resin was conducted by G. Tilly^[16]. The results show that it causes pitting corrosion and compression, and may be broken into fragments that are impacted by the initial particles, thereby causing secondary damage to the initial impact point in the radial direction. Afterwards, a graph of the hardness- erosion efficiency of composite materials was drawn^[17]. In recent years, a method using response surface methods to establish a model for predicting the steady state erosion rate of polyetherimide and its glass fiber composites was proposed by Avinash A. Thakre^[18]. Studies have shown that the maximum corrosion rate of these composites occurs at about 45-60°, and the semi-ductile erosion behavior is demonstrated. The main mechanisms of erosion are ploughing, micro-cutting, crack development and fiber exposure. However, there are few studies on jets for pre-treatment on aircraft skins, and relatively few studies on erosion of composite fuselages.

In this paper, commercial amino thermosetting plastics are used as abrasives, and the research is mainly carried out by experimental methods. The hardness of the abrasive meets the requirements of the Boeing Company in this research. Firstly, the pretreatment erosion experiment is completed in the sand blasting machine. A reciprocating mobile platform that can accurately control the traverse speed is equipped in the system. The surface roughness, surface morphology, wettability and adhesion were used as research indicators. Secondly, the optimal value of the pretreatment process was determined compared with manual sanding, and the erosion mechanism was analyzed. This research can provide technical

guidance for the pretreatment of composite aircraft skins to free up manual sanding and to promote the development of aviation maintenance technology in China.

2 Experimental Details

2.1 Apparatus

The pretreatment erosion experiment were performed in a commercial sand-blasting chamber (JCK-9060A, Sandblasting machine, Shang Hai, China). The working chamber size is $900\text{mm}\times600\text{mm}\times580\text{mm}$, the required air source is $2\sim7\text{ bar (kg/cm}^2\text{)}$, and the flow rate is $0.8\sim1.0\text{ m}^3/\text{min}$. Nozzle diameter is $\varnothing8\text{ mm}$, bag filter. The nozzle possess 6 degrees of freedom in the working chamber, and the workpiece is clamped on the moving device at a controlled speed. The abrasive and air are mixed in the nozzle. Fig. 1 shows the experimental device.

In this paper, the five-factor and four-level orthogonal design method with process obvious rapid and accurate results are selected for pretreatment experiments. The detailed experimental condition is summarized in Table 1.

Table 1 Detailed pretreatment experimental condition.

Pretreatment equipment	JCK-9060A type abrasive jet machine tool
Nozzle material	Boron Carbide (B_4C)
Nozzle dimension(d_N)	$\varnothing8\text{mm}\times\varnothing20\text{mm}\times35\text{mm}$
Abrasive size (mesh size)	60-20 ($250\mu\text{m}-850\mu\text{m}$)
Compressed air pressure (MPa)	0.2-0.65
Distance between nozzle and workpiece surface(mm)	$2d_N-8d_N$
Impacting angle	$30^\circ-90^\circ$
Traverse speed (mm/s)	4-16

2.2 Abrasive and CFRP

In this experiment, an amino thermosetting plastic was used to prepare abrasive. The plastics have the properties of self-extinguishing, anti-poison, water resistance, arc resistance, heat resistance, easy coloring, good electrical insulation, etc. Mohs hardness 3.5-5. The novel preparation process of plastic abrasives is given in detail in Zhu's^[19] paper, which not repeat them. The key performance indicators of abrasive are shown in Table 2. It is worth mentioning that in order to regulate the mechanical properties

of abrasive, elemental components such as calcium and barium are added during the production process.

Table 2 Key property indexes of the abrasive.

Hardness (Mohs hardness)	3.5-5.0
Impact strength (kJ/m^2)	<7
Bulk density (g/cm^3)	1.4–1.6
Water absorption (mg)	<200
Martin heat resistance ($^{\circ}C$)	<120

The unidirectional T700-12K continuous epoxy base CFRP (Laying method $[0^{\circ}/90^{\circ}/0^{\circ}/90^{\circ}]$, carbon fiber diameter is $7\ \mu m$, and carbon cloth is 150 grams weight (Toray, Japan)) were supplied by Nantong Junzhang New Material Technology Co., Ltd., China., and the length, width and height of the laminate are $550mm\times550mm\times2mm$. Properties of CFRP composites are given in Table 3. Bending performance, tensile performance and flat compression properties of CFRP was tested on the universal testing machine (UTM 4000) by Shanghai Institute of Metrology and Testing Technology according to GB/T 3356-1999, GB/T 3354-1999, GB/T 3856-2005 technical specifications. The samples with $65mm\times45mm\times2mm$ and $150mm\times70mm\times2mm$ in dimension were machined and tested.

Table 3 Properties of continuous carbon fiber reinforced plastic composite.

Sample	Tensile Strength(MPa)	bending strength(MPa)	compressive strength(MPa)
CFRP	1982.8	1587.4	Vertical:902.4 Horizontal:133.4

2.3 Skin primer

CFRP skin primer adopts S06-12 polyurethane primer and curing agent according to the proportion (mass ratio) of 38:9 uniformly mixed, and the two-component polyurethane primer coating is allowed to stand for 2 minutes. The pretreated substrate sample must be scrubbed with acetone (or alcohol) before coating. Use high-pressure air spray gun to paint according to the normal process. The nozzle diameter is 1.2 mm, the pressure is 0.36 MPa, and the painting work is completed in the oil-based spray paint cabinet. Spray two steps uniformly during the coating process, the thickness of the primer is about $30\ \mu m$, and the adhesion test needs to stand at room temperature for 7 days after the coating is completed. All the above work is done by professional technicians in Changzhou CNOOC Environmental Protection Coating Co., Ltd..

2.4 Measurement

The surface morphology of the samples was observed with a JEOL-JSM-6360 scanning electron microscope (SEM). The surface roughness Sa was measured by MICRO XAM1200 3-D optical profiler produced by Kla Tencor, Inc., Beijing, China. Take the average of three measurements. Relying on the preparation of military aircraft paint samples provided by CNOOC Changzhou Environmental Coatings Co., Ltd., skin coating painting and adhesion tests were carried out according to the national standards "Paints and varnishes—Pull-off test for adhesion"(GB/T 5210-2006), "General requirements for painting of military aircraft"(GJB 4439-2002) and other standards(GJB 385A-1996, GJB 386-1987), and adhesion is the protagonist.

3 Results And Discussion

For a long time, manual sanding has been the most common method for pretreatment in aviation, automotive, and anti-erosion fields. Of course, smart sanding machines have been used by many foreign companies. Preventing the exposure of carbon fiber filaments as much as possible (non-destructive) is the original intention of this research and needs to be emphasized. Therefore, manual sanding is used as a "standard", although manual sanding can cause damage to the substrate. In other words, the test results of this study are compared with manual sanding, because the CFRP is commonly processed by manual sanding.

3.1 Roughness

The main influencing factors in the adhesion between the coating and the substrate is the surface morphology. The initial purpose of particles eroding the surface of CFRP is to remove the release agent rather than to change the surface condition, but uneven morphology has a positive effect on adhesion. The "boundary conditions" of prevent carbon fiber damage are set in the pretreatment process. It is more difficult to remove the release agent because the thickness is only tens of microns. The precise operation is due to process control. There are many models for roughness analysis, including various processes, such as injection pressure and impact angle. Some are obtained through regression analysis, or erosion rates. The roughness model was analyzed according to the Ref. [20].

$$R_a = k \cdot \frac{E^\beta \rho_a^b d^\epsilon D^\epsilon \mu^f v^\xi}{H_w^h \rho_w^i P^j S^i \alpha^m} \quad (1)$$

Where it can be found that erosion is affected by many factors, involving nozzle diameter(D), standoff distance(S), impact pressure(P), traverse speed(u), impact angle(α), and material properties of abrasive and workpiece, such as average diameter of abrasive particle(d), velocity of abrasive particles(v), abrasive density(ρ_a), elastic modulus of workpiece(E), workpiece hardness(H_w), workpiece density(ρ_w). Others are expressed as constants. There are also some default factors, such as nozzle diameter. It is ignored in this article because it is a supporting device. The roughness inspected by the 3-D optical profiler is shown in Fig. 2. The roughness Sa was measured as $0.343 \mu m$, $2.548 \mu m$, $0.838 \mu m$ and $1.605 \mu m$ in order from Fig. 2(a)-(d), respectively. Obvious impact pits and plough marks were observed due to

particle erosion. However, the release agent is left in areas that are not eroded by the particles. The adhesion of the paint is affected by poor removal conditions. The results of this study are similar to the Ref. [20].

The test results show that the poor removal effect is caused by the smaller impact pressure, as shown in Fig. 2(a). Compared with other pressures, elastic impact is mostly displayed except for the areas where plastic deformation occurs. The same appears in other impact pressures. And these plastic deformation craters are exhibited due to the impact of larger particles. However, the discontinuity of the impact crater is due to the longer particle travel (large impact distance) and faster transverse velocity. Therefore, impact can be ignored under normal erosion and low pressure conditions. The smoothness is maintained and most of the release agent remains. Even if the particle travel distance is large, the traces of the plough are shown in Fig. 2(b) at extremely low traverse speed. This is due to the oblique erosion with an erosion angle, the increase in impact pressure and also due to the smaller particle size. However, not all normal erosions are bad, and not all oblique impacts are good. This view is proved in Fig. 2. (C) and (d). The plough was shown under normal impact and a low lateral speed, but the plough was lonely and did not spread in Fig. 2(c). This is attributed to the uneven distribution of particles in the jet due to the larger particle size. The unsatisfactory erosion is shown in Fig. 2(d), which is attributed to the larger lateral velocity, but other conditions are ideal, including oblique impact with erosion angle, larger impact pressure and smaller particle size. The influence of these parameters corresponds to the Eq. (1). In summary, a more ideal surface is shown in Fig. 2(b). Although the surface roughness S_a is too large, the release agent is basically removed and can be observed from the figure. The particle erosion effect is beneficial to adhesion. In addition, the continuous surface favorable for adhesion is determined, and the erosion process is strictly controlled. The average roughness is about $2\ \mu m$.

3.2 Mechanism

The surface morphology and state due to the process has been reviewed in detail. The erosion mechanism will be analyzed in detail in the following process. The erosion rate of CFRP is shown in Fig. 3. The sketch diagram of erosion mechanism and SEM morphological analysis are shown in Fig. 4 and 5, respectively.

The carbon fiber bundle is wrapped by epoxy resin, and the release agent near the nozzle on the surface of the workpiece is eroded when the abrasive hits the workpiece. Erosive wear of abrasive is a typical wear mode, which is the material loss caused by repeated impact of fine solid particles^[21]. The research results of many scholars have been summarized, there is two types of erosion wear, brittle erosion to remove material formed by cracks generation and extension, and ductile erosion to remove material from micro-cutting and ploughing. This difference depends on the erosion rate (ER) as a function of impact angle^[22]. Brittle erosion has been proved by some scholars^[18,22,23] under particles eroded on thermosetting polymer; plastic (semi-ductile) erosion has been proven by other scholars^[24-27]. The maximum erosion rate of plastic erosion is achieved at an erosion angle of 30° , brittle erosion occurs at 90° , and semi-ductile erosion occurs at $50-70^\circ$. Until now, there is no precise statement about the polymer

corrosion mechanism, because particle erosion has a strong dependence on material properties and different experimental conditions. The maximum erosion rate occurs at 50-70° under impact pressures of 0.32 and 0.38 MPa in this study (Figure 3).

The specimens were eroded for 0.5 min at different impingement angle and impact velocity and each time the weight loss (Δw) was measured after machining. This procedure was repeated for 5 times for a total exposure time of 2.5 min until the erosion rate attains a constant steady-state value. The erosion wear rate (Er) in g/g was calculated as per the following formula:

$$E(r) = \frac{\Delta w}{w_e} \quad (2)$$

Where Δw is the mass loss of CFRP in g, and w_e is the initial mass of CFRP in g. It should be noted that the erosion rate is calculated through the mass loss in the experiment. Compared with large angles, tangential erosion plays an important role in cutting and ploughing under low angle erosion conditions. This view is fully proved by Zhao et al.^[28]. The particle erosion mechanism of CFRP is shown in Figure 4. Includes two modes: elastic fatigue erosion and ductile erosion. Among them, ductile erosion includes three form: micro-cutting and ploughing, accumulation into "ridges" and large pieces falling off. A large piece fell off described here can be roughly understood as brittle erosion, because no better explanation has been found, but it actually exists(Figure 5 (a)).

However, ductile or brittle erosion mechanism is not absolute because smaller particles tend to make the material removal behaviour more ductile^[29], and the AFWAL-MLBE E glass-epoxy composites exhibited semi-ductile erosion behavior^[30]. The obvious groove traces can be seen in Fig. 2(b) and (c), which are caused by particle sliding, micro cutting and ploughing. There are "fish scales" with ductile erosion, flake accumulation and plough marks can be seen from Fig. 5(b-f), which illustrates the plastic deformation that occurred during the impact. Finnie^[31] first proposed the micro-cutting wear mechanism. The particle wedging into the surface is caused by the vertical partial velocity, while the particle sliding along the surface is caused by the tangential partial velocity. The "plough" effect is caused by the combination of speeds in two directions^[32]. Material removal is caused by the shear action and the micro-cutting of the particles at high traversing speed on the solid surface. The resin matrix impacted by the particles is considered to be in a semi-ductile cutting state when the particles come into contact with the material at a large angle or strike vertically. Hutchins et al.^[33] elaborated on this point of view. The erosion mechanism is a process in which sheet-like wall materials are continuously generated and disappeared on the surface of the material. These uplifted ridges and lip-shaped sheets have been repeatedly hit by a large number of particles for a long time, and the plastic deformation layer is gradually peeled off and removed^[33,34]. The ideal preprocessing state is shown in Fig. 5(d), close to 90% of the epoxy resin layer is peeled off by impacting. Seven intact carbon fibers were exposed to the scanning electron microscope, and the others were tightly wrapped in epoxy resin. However, individual "fragments" were exposed on the

washed-out surface. Nevertheless, the pretreatment effect is better. Despite the "boundary conditions" set above, the carbon fiber damage cannot be avoided in the experiment.

It can be seen from Fig. 5(a) and (f) that about 90% of the epoxy resin layer is not removed, and the impact pressure is the main factor determining the kinetic energy (velocity) of the particles. Regardless of the combination of larger impact pressure and small particle size, or the combination of smaller impact pressure and large particle size, it is impossible to completely remove the epoxy resin due to the dispersion of particles, which is affected by the larger traverse velocity, but the particle impact area will have a obvious effect on the surface layer. The occurrence and propagation of cracks in the impact zone may provide evidence for the brittle mechanism. Not only did the crater appear after the impact, but also pitting and scratches. In addition, the epoxy resin was dropped from the fiber surface in the severe impact area (A large piece fell off). This phenomenon is undesirable because it is most likely caused by the low bonding of the polymer to the fiber. These invisible debonding can cause skin failure. Compared with Figure 5(d), the impact effect is worse.

Erosion of abrasive is a complex phenomenon during jet machining. It cannot be summarized as one or several erosion mechanisms. Taking into account the influence of substrate characteristics, this process coexists with one or more erosion mechanisms. In general, the essence of particle erosion is energy exchange. Based on the above analysis, the fish scale fragments, scratches, pitting and ploughing show that ductile erosion and elastic deformation are exhibited under the process. The occurrence and propagation of cracks (lateral or longitudinal), the peeling of epoxy group from fiber, and the fatigue impact of surface particles all indicate the possibility of brittle erosion. In order to provide more support, more in-depth research is needed. Fully consider that the maximum erosion rate occurs at 60°, the semi-tough erosion mechanism is demonstrated by the particle impact CFRP.

3.3 Wettability

The wettability of a solid surface can be described by observing the shape of a drop deposited on the surface. A surface having a high wettability tends to allow the drop to spread over a relatively wide area of the surface, thereby wetting the surface. For a surface with low wettability (hydrophobic), the liquid tends to retain a spherical shape^[35]. As mentioned in the previous two sections, the CFRP laminate surface properties is changed by the particle erosion, in other words, the surface wettability of the workpiece is changed by particle erosion. The contact angle is used to characterize the wettability of the solid surface, which is the angle formed between the liquid–solid and the liquid–vapor interfaces. The ideal surface wettability promotes liquid molecules to repel each other on the solid surface through capillary forces, thereby infiltrating the solid surface. In general, the contact angle on a smooth surface will be greater than $\pi/2$, indicating that the liquid will not wet the surface and the liquid will keep the droplet. However, the eroded surface is uneven, with obvious peaks and troughs, and the contact angle of the liquid surface is less than $\pi/2$, which means that the liquid is easy to wet the surface. Therefore, it is necessary to improve the surface energy in this study in order to increase the adhesion of the coating. The contact angle^[36] is given by

$$\cos \theta_{eq} = \frac{\gamma_s - \gamma_{sl}}{\gamma_l} \quad (3)$$

where θ_{eq} is the equilibrium contact angle, and subscripts indicate the corresponding interfaces. The untreated laminate with a surface roughness Sa of 188nm is shown in Fig. 6(a), and the manual sanding with a surface roughness Sa of 978nm is shown in Fig. 6(b). The manually sanded samples are qualified by test of Water film continuous test. The continuous ability of the water film is reflected by the contact angle of the droplet penetration. The droplet contact angle was measured by the JC2000DM penetration angle measuring instrument (produced by Beijing Zhongyi Kexin Technology Co., Ltd.), and then the surface energy was calculated. In contrast, the surface has better wettability and wider droplet spreading (Fig. 6(b)) under the manual sanding, while the droplets remain hemispherical without pretreatment in Fig. 6(a). Compared with untreated, the surface wettability is better after manual sanding. The average contact angles are 82.25° and 73.8°, and the surface energy is about 35.598 *mN/m* and 38.664 *mN/m* for untreated laminates and manual sanding, respectively.

The effect of impact pressure and impact angle on surface energy is shown in Fig. 7. Generally speaking, the wettability of small angle impact is usually better than that of large angle, which is attributed to the more obvious tangential ploughing effect on the surface under small angle erosion. It is detected that the surface energy decreases with the increase of the angle and then increases again under the larger impact pressure. Supports a better impact effect under plough or normal impact. On the contrary, the peak of the surface energy appears at the middle angle under a small impact pressure. The kinetic energy of micro-cutting erosion at a small angle mainly depends on the initial speed of the particles. When the impact angle is 30°, the surface energy is forced to increase due to the increase in erosion pressure. It is worth mentioning that the surface energy reaches its peak in the experiment at an impact pressure of 0.6MPa and an impact angle of 30°. This peak may be attributed to the strong plough action of the particles with enough kinetic energy. The better surface energy appears at 50-70°, when the impact pressure is 0.3-0.4MPa. The idea that normal impact is not the most ideal condition is again proved by experimental data. It is also confirmed that the normal erosion has little effect on the release agent in section 3.1. Further analysis, the surface energy curve also verifies that the good surface energy is attributable to the ideal surface morphology (Figure 5(d)). In particular, the surface energy of the manually sanded sample is represented by a red horizontal dashed line. It can be seen that the surface energy value is expressed when the erosion angle is 50°, which is similar to manual sanding. The pretreatment by particle erosion is reasonable and verified by experimental data.

3.4 Adhesion

The reason why water droplets are used for continuous water film testing is that polyurethane coatings have the same wettability as water droplets. The two-component polyurethane coating and adhesion test of CFRP skin were provided by Changzhou CNOOC Environmental Coating Co., Ltd. According to the standard (GB/T 5210-2006), the pull-out test of coating adhesion is shown in Fig. 8(a) by the digital

display automatic adhesion tester (Positest-ATA-20A, DeFelsko Corporation, New York, USA. The test range is 0.7-24 *MPa*, the resolution is 0.01 *MPa*, the accuracy is $\pm 1\%$ of full scale, and the standard aluminum dollies diameter is 20 *mm*). Before the adhesion test is performed, the coated coating must be allowed to stand at room temperature for 7 days. The sticky area of the dollies needs to be sanded with 400 grit sandpaper. The dollies has been bonded to the coating surface using a two-component epoxy resin adhesive.

During the test, the adhesion is defined as the shearing force of the dollies being pulled out of the primer. The adhesion test results are roughly divided into three types: cohesive fracture (within a layer), adhesive fracture (between layers) and glue failure (coating/ glue). The results of the experiment should be attributed to the primer adhesive fracture in Fig. 8(b). Because the black substrate can be clearly seen. Each test piece was tested twice and the adhesion was average.

The adhesion curves of impact angle, impact distance, lateral velocity and particle size as a function of impact pressure are shown in Fig. 9. In particular, the adhesion test value after manual sanded is represented by a horizontal line. The study showed that the best adhesion did not appear under the maximum impact pressure. The surface state of oblique impact does not play a decisive role in the adhesion of the experiment. Because the adhesion of normal impact is better than that of oblique impact, under the maximum impact pressure (Fig. 9(a)). Therefore, it is preliminary inferred that the mechanical interlock has little effect on adhesion. However, the better value of adhesion appears at an impact angle of 50-70° and an impact pressure of 0.4-0.5 *MPa*. The judgment about the better surface condition in section 3.2 is correct, as shown in Figure 5(d), which is proved by above view. Similarly, better adhesion occurs in large-angle erosion, rather than normal erosion. It can be seen from Fig. 9(b) that the erosion distance (particle running time) shows a trend of first increasing and then decreasing under the influence of increasing impact pressure, except for 48mm. In fact, the surface is caused more obvious damage in the smaller particle erosion distance. Because the smallest erosion distance leads to the best adhesion. It shows that the influence of erosion distance on adhesion is not dominant. But it can be determined that the adhesion is relatively poor at the lowest impact pressure. The impact distance effect is not obvious, at the maximum impact pressure.

The traverse speed in Fig. 9(c) determines the number of particle impacts per unit time. This is a mathematical statistics problem. As mentioned above, the material is removed due to repeated impacts of many particles. The erosion of the particles is continued at a reasonable traverse speed, which is beneficial to the surface morphology and adhesion. Although the average diameter of the impact site of a single abrasive is about 1/10 of the average particle size^[37]. The particle size does not seem to be important. However, the erosion mechanism is fatigue shedding due to the impact of a large number of particles. The stable erosion is attributed to the smaller particle size in Figure 9(d).

The wettability and surface energy (adhesion) are more prominent when the pressure is higher (excluding normal erosion), in the above analysis of surface morphology and wettability. Polyurethane coatings and epoxy resins are similar high molecular polymers with the same functional groups. Intermolecular

hydrogen bonds are more conducive to changes in surface morphology (increasing contact area). Adhesion is more helpful under the additional "mechanical interlock". Of course, the premise for this research to be meaningful is that the substrate is not damaged (the carbon fiber is not damaged).

The protection of the skin is more effective in improving the adhesion of the coating. However, the skin coating is necessary to maintain and repair after a period of flight. This work needs to be considered and executed for ground service engineers. Too strong adhesion caused unnecessary trouble during maintenance and repair of damaged coating. Improving the adhesion of the CFRP skin coating and extending the service life without damaging the substrate are the original intentions in this research, but maintenance and repair of damaged coatings should also be considered. This is also the difficulty in this research.

4 Conclusions

An experimental study of erosion CFRP with amino thermosetting plastic particles is presented in this paper. Compared with traditional paint stripping, it is more suitable for CFRP skin coating to use the method in this article. The ideal state of adhesion is that the surface energy with a wetting angle of 70° is 38 mN/m . The carbon fiber filaments are exposed and damaged when the impact pressure is greater than 0.4 MPa . The results show that the ideal process conditions are $P=0.36 \text{ MPa}$, $H=64 \text{ mm}$, $\theta=70^\circ$, $v=8 \text{ mm/s}$ and the particle size is $40\text{-}50 \text{ mesh}$. Semi-ductile erosion is the erosion mechanism studied in this paper. Amino thermosetting particles have broad development prospects due to the advantages of multiple recycling and environmental friendliness. This research laid the foundation for follow-up research and provided guidance for the pretreatment of aircraft CFRP skins.

Declarations

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Conflicts of interest/Competing interests (include appropriate disclosures)

The authors report no declarations of interest.

Availability of data and material (data transparency)

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability (software application or custom code)

Not applicable.

Authors' contributions (optional: please review the submission guidelines from the journal whether statements are mandatory)

Yangyang Zhao: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Wenzhuang Lu*: Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Funding acquisition.

Yansong Zhu: Writing - Review & Editing.

Dunwen Zuo: Conceptualization, Methodology, Supervision, Visualization.

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References

1. Soo-Jin Park, Min-Kang Seo. (2011) Chapter 7-Types of Composites. Interface Science and Technology 18:501-629. <https://doi.org/10.1016/B978-0-12-375049-5.00007-4>
2. Y. Han, P. Zhang, T.Y. Zheng, H.Y. Fu. (2020) Research progress of forming process of fiber reinforced polymer composite grid structure. Acta Materiae Compositae Sinica 4:845-858. <https://doi.org/10.13801/j.cnki.fhclxb.20190628.003>
3. Maria MRAZOVA (2013) Advanced composite materials of the future in aerospace industry. INCAS BULLETIN 5:139 – 150. <https://doi.org/10.13111/2066-8201.2013.5.3.14>

4. Rauh, S. Kreling, M. Kolb, M. Geistbeck, S. Boujenfa, M. Suess, K. Dilger (2018) UV-laser cleaning and surface characterization of an aerospace carbon fibre reinforced polymer. *International Journal of Adhesion & Adhesives* 82:50-59. <https://doi.org/10.1016/j.ijadhadh.2017.12.016>
5. Fengjun Chen. Xiangliang Miao. Yu Tang. Shaohui Yin (2017) A review on recent advances in machining methods based on abrasive jet polishing (AJP). *Int J Adv Manuf Technol* 90:785–799. <https://doi.org/10.1007/s00170-016-9405-7>
6. Roberts (1985) Paint removal through plastic bead blasting—the sensible way[J]. *SAE International Journal of Aerospace* 94(4):156-158. <https://doi.org/10.4271/850712>
7. Roberts (1986) Paint removal through plastic media blasting—a dream come true[R]. *SAE Technical Paper*,. <https://doi.org/10.4271/860703>
8. Ümit Üner, Sezan Orak, Mehmet Alper Sofuoğlu (2016) Effect of plastic media blasting method on mechanical properties of Al 2024-T6 alloy. *Journal of Mechanical Science and Technology* 30 (10):4559-4564. <https://doi.org/10.1007/s12206-016-0926-7>
9. Dong Sam Park, Myeong-Woo Cho. Honghee Lee (2004) Effects of the impact angle variations on the erosion rate of glass in powder blasting process. *Int J Adv Manuf Technol* 23:444–450. <https://doi.org/10.1007/s00170-003-1724-9>
10. P. Amro (1992) The effect of mechanical paint stripping on the fatigue and fracture of thin aluminum airplane skin. *Ph.D Thesis*, Dissertation. Wichita State University, USA.
11. M. Fan, H.Z. Li, J. Wang, C.Y. Wang (2011) A study of the flow characteristics in micro-abrasive jets. *Experimental Thermal and Fluid Science*. (35):1097–1106. <https://doi.org/10.1016/j.expthermflusci.2011.03.004>
12. P. Verma, G.K. Lal. (1984) An experimental study of abrasive jet machining. *International Journal of Machine Tool Design and Research* 24(1):19-29. [https://doi.org/10.1016/0020-7357\(84\)90043-X](https://doi.org/10.1016/0020-7357(84)90043-X)
13. Huaizhong Li, Jun Wang, Ngaiming Kwok, Thai Nguyen, Guan Heng Yeoh (2018) A study of the micro-hole geometry evolution on glass by abrasive air-jet micromachining. *Journal of Manufacturing Processes* 31: 156–161. <https://doi.org/10.1016/j.jmapro.2017.11.013>
14. H. Neilson. A (1968) Gilchrist. Erosion by a stream of solid particles. *Wear* 11(2):111-122. [https://doi.org/10.1016/0043-1648\(68\)90591-7](https://doi.org/10.1016/0043-1648(68)90591-7)
15. J. Lennon, P. J. Mallon (1992) Investigation of the Effects of Plastic Media Blasting (PMB) on Advanced Composites. *Key Engineering Materials* 72-74:323-330. <https://doi.org/10.4028/www.scientific.net/KEM.72-74.323>
16. P. Tilly, W. Sage (1970) The interaction of particle and material behaviour in erosion processes. *Wear* 16(6):447- 466. [https://doi.org/10.1016/0043-1648\(70\)90171-7](https://doi.org/10.1016/0043-1648(70)90171-7)
17. Arjula, A.P. Harsha (2006) Study of erosion efficiency of polymers and polymer composites. *Polymer Testing* 25(2):188-196. <https://doi.org/10.1016/j.polymertesting.2005.10.009>
18. Avinash A. Thakre (2015) Prediction of Erosion of Polyetherimide and Its Composites Using Response Surface Methodology. *Journal of Tribology* 137(1):1-7. <https://doi.org/10.1115/1.4028267>

19. Yansong Zhu, Wenzhuang Lu, Dunwen Zuo (2019) Development of abrasive jet polishing by using amino thermosetting plastic abrasive for aluminum alloy. *Journal of Manufacturing Processes* (43):218-228. <https://doi.org/10.1016/j.jmapro.2019.05.016>
20. Tianxiang Chen, Chengyong Wang (2012) Investigation into Roughness of Surface Polished by Abrasive Waterjet with Taguchi Method and Dimensional Analysis. *Materials ence forum* 723:188-195. <https://doi.org/10.4028/www.scientific.net/MSF.723.188>
21. Patnaik, A. Satapathy, N. Chand, N.M. Barkoula, S. Biswas (2010) Solid Particle Erosion Wear Characteristics of Fiber and Particulate Filled Polymer Composites: A Review. *Wear* (268):249-263. <https://doi.org/10.1016/j.wear.2009.07.021>
22. Miyazaki, T. Hamao (1994) Solid particle erosion of thermoplastic resins reinforced by short fibres. *Comp. Mater* (28):871–883. <https://doi.org/10.1177/002199839402800905>
23. M. Hutchings, R.E. Winter, J.E. Field (1976) Solid particle erosion of metals: the removal of surface material by spherical projectiles. *Proc. Roy. Soc. Lond., Ser. A* (348):379–392. <https://doi.org/10.1098/rspa.1976.0044>
24. S. Tewari, A.P. Harsha, A.M. Häger, K. Friedrich (2002) Solid particle erosion of unidirectional carbon fibre reinforced polyetheretherketone composites. *Wear* (252):992–1000. [https://doi.org/10.1016/S0043-1648\(02\)00063-7](https://doi.org/10.1016/S0043-1648(02)00063-7)
25. Feng Cai, Feng Gao, Shashank Pant, Xiao Huang, Qi Yang (2016) Solid Particle Erosion Behaviors of Carbon-Fiber Epoxy Composite and Pure Titanium. *Journal of Materials Engineering and Performance* (25):290-296. <https://doi.org/10.1007/s11665-015-1848-8>
26. Amkee Kim, Ilhyun Kim (2009) Solid particle erosion of CFRP composite with different laminate orientations. *Wear* 267:1922–1926. <https://doi.org/10.1016/j.wear.2009.03.038>
27. S. Tewaria, A.P. Harshaa, A.M. Häger, K. Friedrich (2003) Solid particle erosion of carbon fibre– and glass fibre–epoxy composites. *Composites Science and Technology* 63:549–557. [https://doi.org/10.1016/S0266-3538\(02\)00210-5](https://doi.org/10.1016/S0266-3538(02)00210-5)
28. Weimin Zhao, Chun Wang, Timing Zhang, Min Yang, Bin Han, Anne Neville (2016) Effects of laser surface melting on erosion–corrosion of X65 steel in liquid–solid jet impingement conditions. *Wear* 362-363:39-52. <https://doi.org/10.1016/j.wear.2016.05.006>
29. Finnie (1995) Some reflections on the past and future of erosion. *Wear* 186–187:1–10. [https://doi.org/10.1016/0043-1648\(95\)07188-1](https://doi.org/10.1016/0043-1648(95)07188-1)
30. Zahavi, G.F. Schmitt (1981) Solid particle erosion of reinforced composite materials. *Wear* 71(2):179-190. [https://doi.org/10.1016/0043-1648\(81\)90337-9](https://doi.org/10.1016/0043-1648(81)90337-9)
31. Finnie (1960) Erosion of surfaces by solid particles. *Wear* 3(2):87-103. [https://doi.org/10.1016/0043-1648\(60\)90055-7](https://doi.org/10.1016/0043-1648(60)90055-7)
32. Xinyu Zhang (1998) Study of Gas–Solid Multiphase Flow Characteristics in Impact Rich/Lean Burners and Curved Ducts. *D Thesis*, Dissertation, Zhejiang University, China
33. Hutchings, R. Winter, J. Field (1976) Solid particle erosion of metals: The removal of surface material by spherical projectiles. *Proceedings of the Royal Society of London. A. Mathematical and Physical*

Sciences 348(1654):443-457. <https://doi.org/10.1098/rspa.1976.0044>

34. Bellman, A. Levy (1981) Erosion mechanism in ductile metals. *Wear* 70(1):443-457. [https://doi.org/10.1016/0043-1648\(81\)90268-4](https://doi.org/10.1016/0043-1648(81)90268-4)
35. Antonini, M. Innocenti, T. Horn, M. Marengo, A. Amirfazli (2011) Understanding the effect of superhydrophobic coatings on energy reduction in anti-icing systems. *Cold Regions Science and Technology*, (67):58–67. <https://doi.org/10.1016/j.coldregions.2011.02.006>
36. Young (1805) An essay on the cohesion of fluids. *Philosophical Transactions of the Royal Society of London* (95):65–87. <https://doi.org/10.1098/rstl.1805.0005>
37. Djurovic, É. Jean, M. Papini, P. Tangestanian, J.K. Spelt (1999) Coating removal from fiber-composites and aluminum using starch media blasting. *Wear* (224):22-37. [https://doi.org/10.1016/S0043-1648\(98\)00308-1](https://doi.org/10.1016/S0043-1648(98)00308-1)

Figures

Figure 1

Schematic diagram of experiment device (a) and control system (b).

Figure 2

3D topography of different impact pressures when (a) 0.3MPa, (b) 0.4MPa, (c) 0.5MPa and (d) 0.6MPa.

Figure 3

Erosion rate as a function of impact angle.

Figure 4

Two types removal modes for particles impact workpiece: (a) elastic impact modes; three different forms in ductile erosion modes (b), (c) and (d).

Figure 5

SEM morphology of solid particle erosion CFRP.

Figure 6

Sample of CFRP laminate, untreated (a) and manual sanding (b).

Figure 7

Influence of pressure and angle on surface energy.

Figure 8

Coating adhesion test process (a) and results (b).

Figure 9

shows the adhesion curve of (a) impact angle, (b) impact distance, (c) traverse speed, and (d) particle size as a function of impact pressure.