

DEVELOPMENT OF HYDROPHILIC COATINGS FOR PRACTICAL APPLICATION OF LAMINAR FLOW WINGS

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Abstract

Natural laminar flow (NLF) wings can improve aircraft fuel efficiency; however, insect contamination on the wing leading edge during takeoff and landing degrades laminar flow performance. In this study, two hydrophilic coatings, a water-based hydrophilic coating (WBHC) and a polymer-brush photocatalytic coating (PBPC), were developed to facilitate the removal of insect residues. Cleaning performance was evaluated through coupon tests, vehicle tests, and flight tests. WBHC exhibited the highest cleaning efficiency, achieving over 70 % cleaning rate after 26 days in coupon tests and over 80 % after 67 days in vehicle tests. Flight tests also demonstrated superior cleaning rate of WBHC, although cleaning efficiency decreased with increasing exposure time. Qualification testing confirmed that the developed coatings satisfied aircraft coating requirements. These results demonstrate the potential of hydrophilic coatings for mitigating insect contamination on NLF aircraft wings.

Keywords: Natural laminar flow, Insect contamination, Hydrophilic coating

1. Introduction

Aerodynamic drag is one of the primary factors affecting aircraft fuel consumption, and therefore drag reduction is essential for improving fuel efficiency. Since skin-friction drag constitutes a significant portion of the total aerodynamic drag, reducing skin-friction drag is considered one of the most effective approaches to improving aircraft performance [1]. Natural laminar flow (NLF) wing technology has attracted considerable attention and has been extensively investigated [2]-[4]. NLF wings reduce skin-friction drag by extending the laminar boundary-layer region through optimization of the wing pressure distribution achieved by aerodynamic shaping. Because laminar boundary layers generate lower skin-friction drag than turbulent boundary layers, maintaining laminar flow over a larger portion of the wing surface can significantly improve aerodynamic efficiency. Despite its potential benefits, a major obstacle to the practical application of NLF technology is contamination of the wing leading edge by insects during takeoff and landing [5]. Even small insect residues can trigger premature boundary-layer transition, thereby degrading laminar-flow performance and reducing the expected drag-reduction benefits. As a promising solution to this issue, methods involving the application of special coatings to the wing leading edge to remove insect adhesion have attracted attention, and a wide range of evaluation tests, from laboratory-scale experiments to flight demonstrations, have been conducted [6]-[11]. These coatings can generally be classified into two categories: hydrophilic, highly cleanable coatings and hydrophobic, water-repellent coatings. Hydrophilic coatings promote self-cleaning by allowing water to penetrate the interface between contaminants and the coating surface, thereby facilitating contaminant removal. Photocatalytic coatings belong to this category; under ultraviolet irradiation, photocatalytic reactions induce both organic matter decomposition and surface hydrophilicity. In contrast, hydrophobic coatings can reduce the initial adhesion of contaminants; however, once contaminants become strongly attached,

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such as through high-velocity insect impacts, their removal by water washing becomes difficult. At the Japan Aerospace Exploration Agency (JAXA), research has been conducted on highly cleanable coatings designed to enable the removal of insect residues through simple water washing. Previous studies have demonstrated that such coatings exhibit superior cleaning performance compared with conventional aircraft coatings [12]. The present study introduces two highly cleanable coatings: a water-based hydrophilic coating (WBHC) and a polymer-brush photocatalytic coating (PBPC). Their surface characteristics and cleaning performance were evaluated through coupon tests, vehicle tests, and flight tests. In addition, qualification tests based on aircraft coating specifications were conducted to assess their suitability for practical aircraft applications.

2. Overview of Hydrophilic Coatings

2.1 Water-based Hydrophilic Coating (WBHC)

The WBHC enables a water-based hydrophilic paint (manufactured by a Japanese company) to adhere uniformly over the entire surface of an organic coating, where adhesion of inorganic hydrophilic coatings has conventionally been difficult to achieve. This is accomplished by introducing an appropriately selected silane coupling agent at the interface between the organic coating and the inorganic water-based hydrophilic paint. As a result, the hydrophilic functionality can be effectively imparted to the coated surface. In this study, an aircraft coating (#400) manufactured by Nippon Paint Co., Ltd. was employed as the organic coating substrate. Triethoxy (3-glycidyloxypropyl) silane, an epoxy-functional silane coupling agent, was used as the interfacial modifier, and a silica-based water-based hydrophilic paint was subsequently applied as the topcoat layer. A schematic illustration of the cross-sectional structure of the WBHC is presented in Fig. 1.

2.2 Polymer-brush Photocatalytic Coating (PBPC)

The PBPC consists of tile-shaped polymer brushes formed on a photocatalytic coating layer. This structure enables the coating to retain its photocatalytic activity under ultraviolet (UV) irradiation while maintaining hydrophilic properties through the polymer brush layer even in the absence of UV light. Furthermore, the microscale step-like surface structures created by the tile-shaped polymer brushes are expected to facilitate the efficient removal of adhered insect residues. In this study, the same aircraft coating (#400, Nippon Paint Co., Ltd.) was used as the organic coating substrate, and a photocatalytic coating manufactured by Hoei Sangyo Co., Ltd. was employed as the photocatalytic layer. A schematic illustration of the cross-sectional structure of the PBPC is presented in Fig. 2.

3. Test Method

3.1 Coating Surface Evaluation

The surface wettability was evaluated by water contact angle measurements using a portable contact angle meter (PCA-11, Kyowa Interface Science Co., Ltd., Japan). Surface roughness was measured using a laser scanning confocal microscope (VK-X3000, KEYENCE Corporation, Japan). The water contact angle was determined using a droplet volume of 2 μL after a settling time of 20 s. Surface roughness was evaluated over a measurement area of 2 mm × 2 mm, and the average value from four randomly selected locations was adopted as the representative value.

3.2 Cleaning Performance Test

3.2.1 Coupon Tests

Approximately 25 fruit flies were deposited onto the surfaces of 10 cm × 10 cm coated aluminum coupons prepared with either of the two hydrophilic coatings or the aircraft coating. An aluminum plate was then placed over the insects, and a compressive load of 6 kgw was applied to ensure intimate

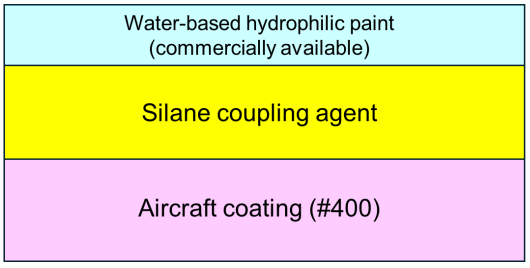


Figure 1 – WBHC.

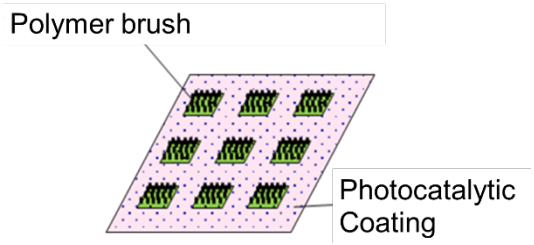


Figure 2 – PBPC.

contact between the insects and the coating surface. Following the adhesion process, the specimens were subjected to water washing under controlled conditions to evaluate the removal efficiency of the adhered insect contaminants. Water washing was conducted using a washer (AJP-1210XX, Kyocera Corporation, Japan). The stand-off distance between the nozzle and the specimen surface was maintained at 1 m throughout the test to ensure constant washing pressure. The insect adhesion method and washing procedure are schematically shown in Figs. 3 and 4, respectively. The effects of the elapsed time between insect adhesion and washing, as well as the washing duration, on the cleaning performance were investigated. Cleaning performance was quantitatively evaluated using image analysis. Images of the specimens were acquired before and after washing under fixed camera settings, including image resolution and viewing angle. The acquired images were then subjected to binarization processing, as shown in Fig. 5. The cleaning rate was calculated from the number of black pixels in the binarized images using Eq. (1). Higher cleaning rates correspond to improved cleaning performance.

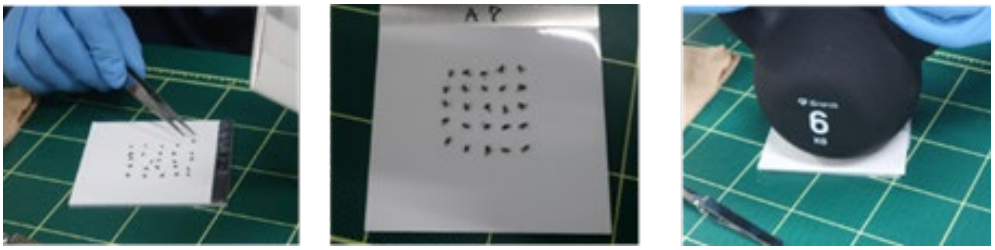


Figure 3 – Insect adhesion.



Figure 4 – Washing procedure.

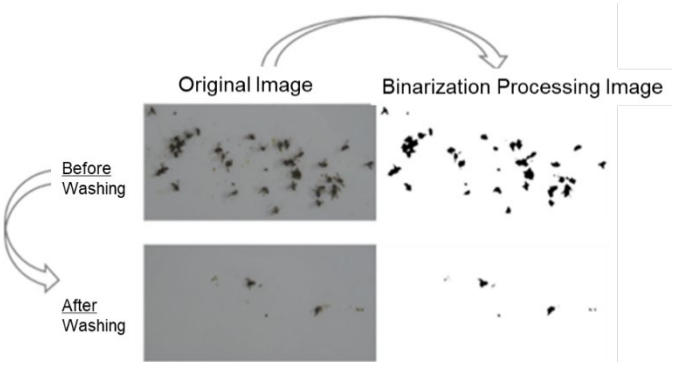


Figure 5 – Image process.



Figure 6 – Installation condition of the coating sheets.

$$\text{Cleaning rate [\%]} = \frac{\text{Number of } b\text{lack pixels } \textbf{before} \text{ washing} - \text{Number of black pixels } \textbf{after} \text{ washing}}{\text{Number of Black pixels } \textbf{before} \text{ washing}} \times 100 \qquad (1)$$

3.2.2 Vehicle Tests

Adhesive sheets coated with the two hydrophilic coatings and the aircraft coating were attached to four locations on the front bumper of a vehicle. Figure 6 shows the installation condition of the coating sheets. The vehicle was then operated under normal driving conditions for an extended period to promote insect adhesion to the sheet surfaces. Subsequently, the sheets were washed with water, and their cleaning performances were evaluated. The total test duration was 101 days, during which the vehicle traveled a cumulative distance of 14,772 km. Cleaning performance evaluations were conducted twice: the first after 34 days of driving (5,372 km) and the second after 67 days of driving (9,400 km). Following each evaluation, all remaining insect residues were completely removed from the sheet surfaces. The washing conditions and evaluation procedures were identical to those employed in the coupon tests. In addition to cleaning performance, changes in the color difference of the coating sheets were measured using a color difference meter (TCD100, Optoscience Co., Ltd., Japan). This field test enabled the durability and performance of the coatings to be assessed under actual environmental conditions, including exposure to rainfall, airborne dust, and ultraviolet (UV) radiation.

3.2.3 Flight Tests

Flight tests to evaluate the cleaning performance of the hydrophilic coating sheets were conducted using JAXA's experimental aircraft, the C680 *Hisho* (Fig. 7), at Nagoya Airfield in Aichi Prefecture. To increase the number of insect impacts on the leading edge, the tests were performed around sunset, when insect activity is highest. Repeated touch-and-go operations were carried out to maximize the number of flight cycles and, consequently, number of insect impacts. After landing, adhered insects were removed with water, and the cleaning performance was assessed by comparing the number of insects before and after cleaning. Figure 8 shows the cross-sectional structure of the hydrophilic coating sheets. Each sheet consisted of an erosion-protection film designed for attachment to the aircraft surface, coated with the aircraft coating layer. The WBHC and PBPC hydrophilic coatings were then applied over the aircraft coating layer. For comparison, a sheet coated only with the aircraft coating was also prepared as a reference. A total of five WBHC sheets, five PBPC sheets, and five reference sheets were installed on the aircraft. For each coating type, four sheets were attached to the leading edges of the main wings (two on each wing), and one sheet was attached to the vertical stabilizer. Figure 9 shows the sheet installation locations on the aircraft. Cleaning of the sheets attached to the main wings and vertical stabilizer was performed from the ground using the washer employed in the coupon tests and a water sprayer, respectively. Water was sprayed from a fixed distance to ensure constant water pressure. The cleaning tests were conducted individually for each hydrophilic coating sheet while the surrounding coated areas were covered to prevent exposure to the spray water. Figure 10 shows the cleaning test setup. The cleaning tests evaluated the following factors: (1) the cleaning rate as a function of the elapsed time after insect adhesion, (2) the cleaning rate as a function of cleaning duration, and (3) the effect of a pre-wetting treatment on the cleaning rate, in which water was sprayed onto the surface and allowed to remain for 20 min prior to cleaning. The cleaning performance was evaluated by comparing the number of insects adhering to the surface before and after cleaning. The cleaning rate was then calculated using Eq. (2).

$$\text{Cleaning rate } [\%] = \frac{\text{Number of insects removed after washing}}{\text{Total number of adhered insects}} \times 100 \quad (2)$$



Figure 7 – JAXA's experimental aircraft, the C680 "Hisho".

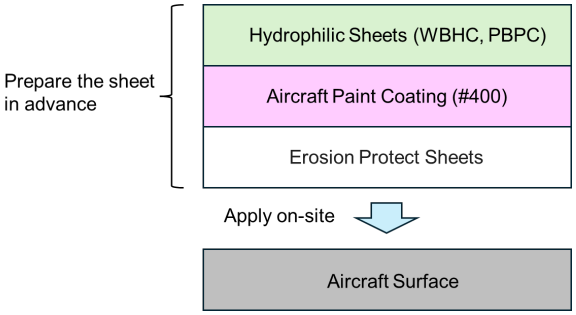


Figure 8 – Cross-sectional structure of the hydrophilic coating sheets.

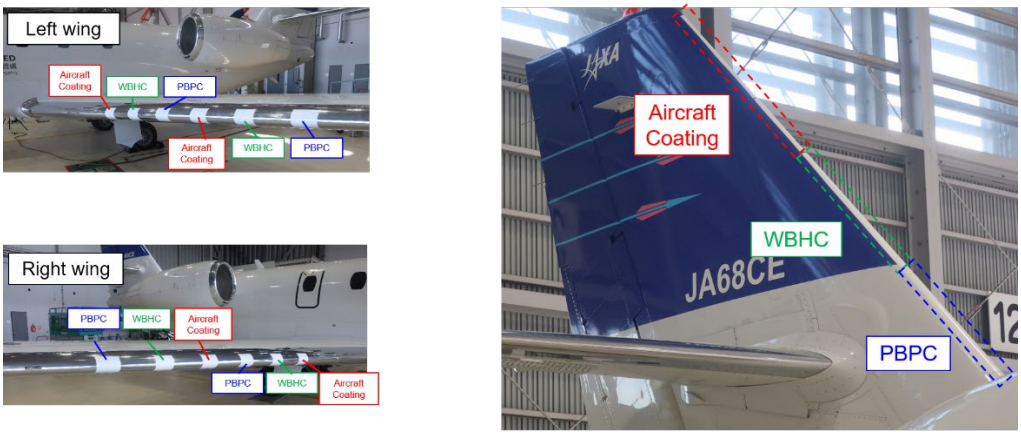


Figure 9 – Locations of the sheets attached to the leading edges.



Main wing



Vertical stabilizer

Figure 10 – Cleaning test.

3.3 Qualification Testing of Aircraft Coatings

To verify the suitability of the hydrophilic coating sheets for aircraft applications, specification tests were conducted by Nippon Special Paint Co., Ltd. Five representative performance characteristics were evaluated: water resistance, oil resistance, salt spray resistance, impact flexibility, and low-temperature flexibility. The test items and conditions are summarized in Table 1. In addition to the tests listed in Table 1, an accelerated weathering test was conducted to evaluate UV resistance. The test was performed using an accelerated weathering tester (Super Xenon Weather Meter SX75, Fig. 11). The hydrophilic coating sheets applied over the aircraft coating layer were exposed to UV radiation corresponding to five years of outdoor exposure. For the PBPC coating, however, the exposure duration corresponded to four years of outdoor exposure. After the accelerated weathering test, the retention of hydrophilicity was assessed by measuring the water contact angle. The irradiance was set to 180 W/m², and an exposure period of 10 days was assumed to be equivalent to one year of outdoor UV exposure.

4. Results

4.1 Coating Surface Evaluation

The surface roughness measurement results and coating surface morphologies are shown in Table 2 and Figure 12, respectively. The surface roughness (Ra) of the WBHC was comparable to that of the aircraft coating. This result can be attributed to the thin WBHC layer, which closely follows the surface morphology of the underlying aircraft coating. In contrast, the roughness of the PBPC was approximately six times higher than that of the aircraft coating. This increase is likely attributable to the

Table 1 – Qualification test items and conditions.

Qualification test items	Conditions
Resistance to water adhesion	After soaking in distilled water for 24 hours and performing the X-cut test, check for any peeling of the coating.
Oil resistance	After immersing in MIL-PRF-23699 at 121° C for 24 hours, check for discoloration or other abnormalities.
Salt spray resistance	After 500 hours of salt spray testing, check for any blistering or rust.
Impact flexibility	Use a GE impact tester to check for any peeling of the coating.
Low-temperature flexibility	Inspect for cracks after a bending test at -51° C using a 1-inch mandrel.

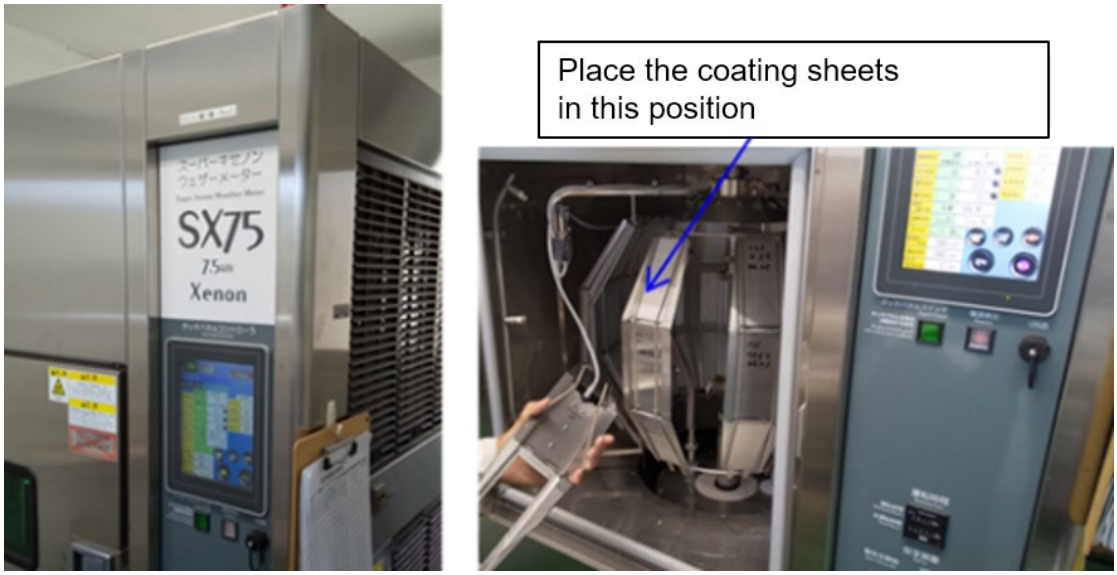


Figure 11 – Accelerated weathering tester.

protrusion of the photocatalytic particles and the step-like surface features formed by the polymer brush structure.

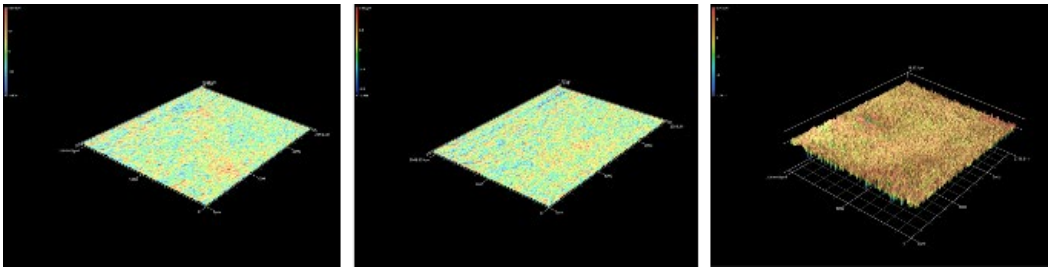
4.2 Cleaning Performance Tests

4.2.1 Coupon Tests

Figure 13 shows the effect of the elapsed time after insect adhesion on the cleaning rate for a cleaning duration of 90 s. For all coatings, the cleaning rate tended to decrease with increasing elapsed time after insect adhesion, particularly after approximately one month. This decline is attributed to the gradual fixation of insect body fluids on the coating surface, making them more difficult to remove by washing. Figure 14 shows the effect of cleaning duration on the cleaning rate. The results were obtained from evaluations conducted approximately one month after insect adhesion. For all coatings, the cleaning rate increased with increasing cleaning duration. In particular, the WBHC exhibited a more pronounced improvement in cleaning performance than the other coatings as the cleaning duration increased, achieving a cleaning rate of 100 % after 150 s of cleaning. This behavior is attributed to the enhanced hydrophilic effect during prolonged water exposure, which promotes water penetration into the interface between the insect residue and the coating surface, thereby facilitating their separation and removal.

Table 2 – Surface roughness.

	Aircraft Coating	WBHC	PBPC
Surface Roughness, Ra (μm)	0.26	0.27	1.53



a) Aircraft coating b) WBHC c) PBPC

Figure 12 – Coating surface morphologies.

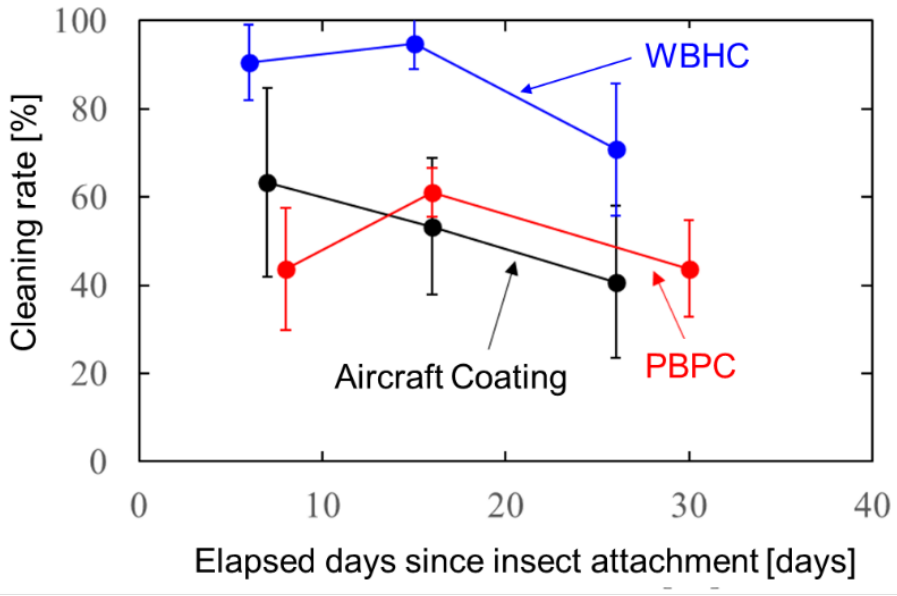


Figure 13 – Effect of elapsed days since insect attachment to cleaning rate in the coupon tests.

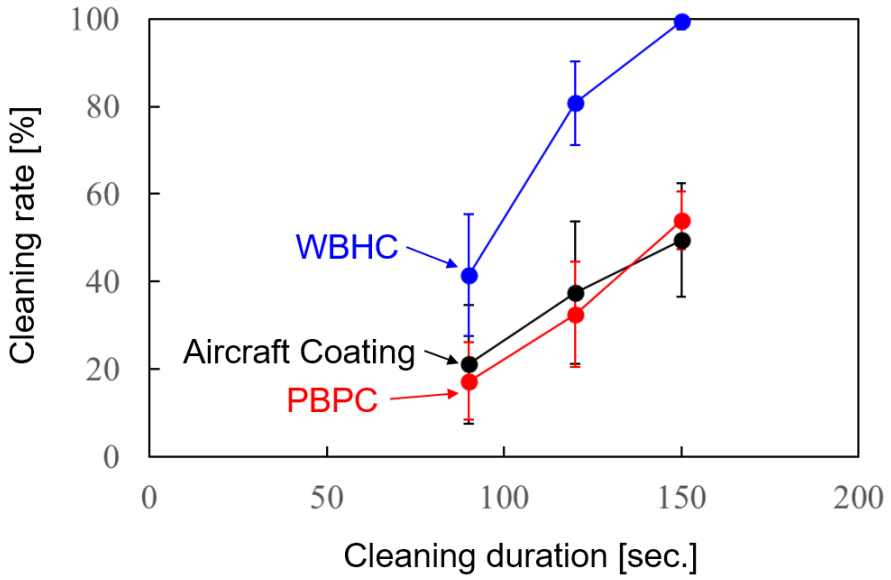


Figure 14 – Effect of cleaning duration to cleaning rate in the coupon tests.

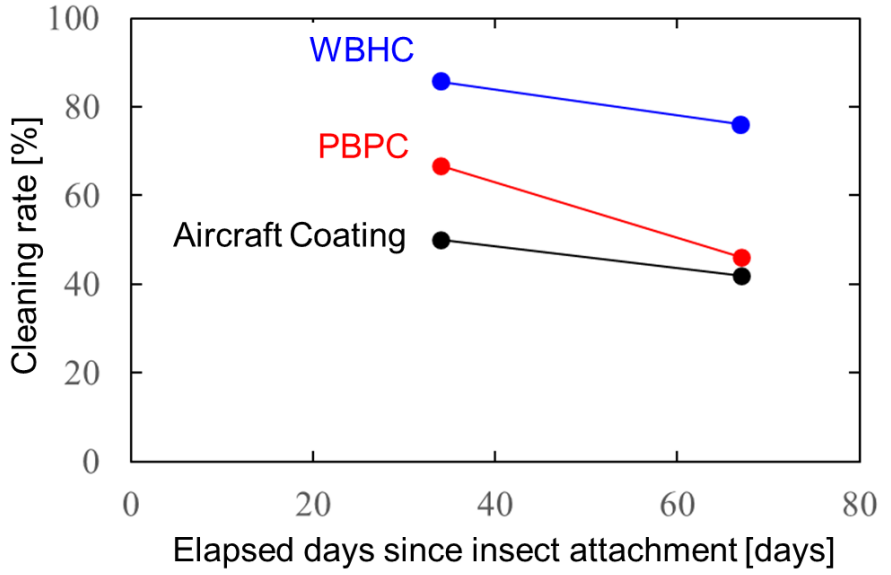


Figure 15 – Effect of elapsed days since insect attachment to cleaning rate in the vehicle tests.

4.2.2 Vehicle Tests

Figure 15 shows the effect of the elapsed time after insect adhesion on the cleaning rate in the vehicle tests. Similar to the coupon test results, the cleaning rate decreased with increasing elapsed time for all coatings. Nevertheless, both hydrophilic coatings maintained higher cleaning rates than the aircraft coating throughout the test period. In particular, the WBHC exhibited a cleaning rate of approximately 80 % even after 67 days, indicating that its superior cleaning performance was preserved under driving environmental conditions, including exposure to ultraviolet radiation and dust. In contrast, the PBPC showed a marked reduction in cleaning rate after 67 days. This deterioration is presumed to be attributable to coating degradation and/or partial delamination caused by prolonged exposure to the driving environment. Figure 16 shows the effect of cleaning duration on the cleaning rate, evaluated 34 days after insect adhesion. Consistent with the coupon test results, the cleaning rate increased with increasing cleaning duration for all coatings. The WBHC exhibited the highest cleaning performance among the tested coatings, followed by the PBPC and the aircraft coating. After 90 s of cleaning, the WBHC achieved a cleaning rate of 85.7 %, highlighting its excellent cleaning performance under the test conditions. Figure 17 shows the change in color difference (ΔE) relative to the initial condition at the start of the vehicle tests. For all coatings, the ΔE values after 34 and 101 days were approximately 1.1 and 1.4, respectively. These values were below the allowable color difference

specified by the JIS standard (ΔE = 3.2), indicating that the coatings maintained their original appearance throughout the test period. Accordingly, no significant color degradation was observed during the vehicle tests.

4.2.3 Flight Tests

As shown in Fig. 18, the scattered black dots correspond to insects that adhered to the leading edges of the main wings and the vertical stabilizer during takeoff and landing. No significant difference was observed in the number of adhered insects among the different coating types. Figure 19 presents the three-dimensional surface profiles of the adhered insects prior to cleaning. The measured insect heights showed no discernible dependence on coating type, ranging from approximately 50 to 60 μm for all specimens.

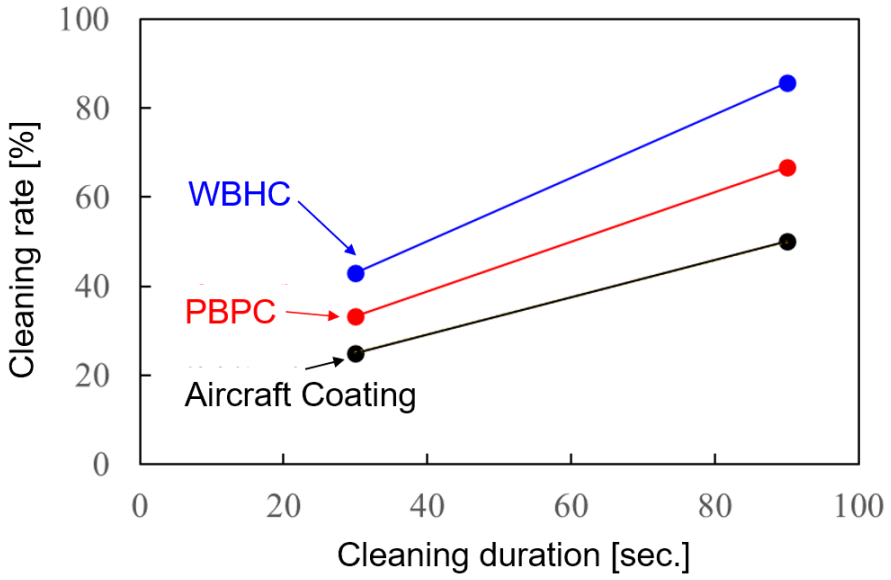


Figure 16 – Effect of cleaning duration to cleaning rate in the vehicle tests.

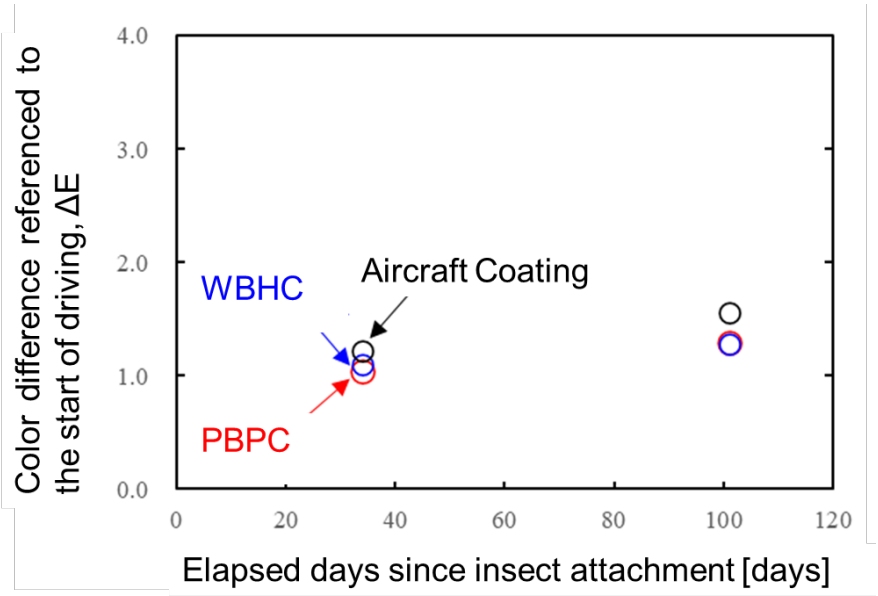


Figure 17– Changes of color difference (ΔE) in the vehicle tests.

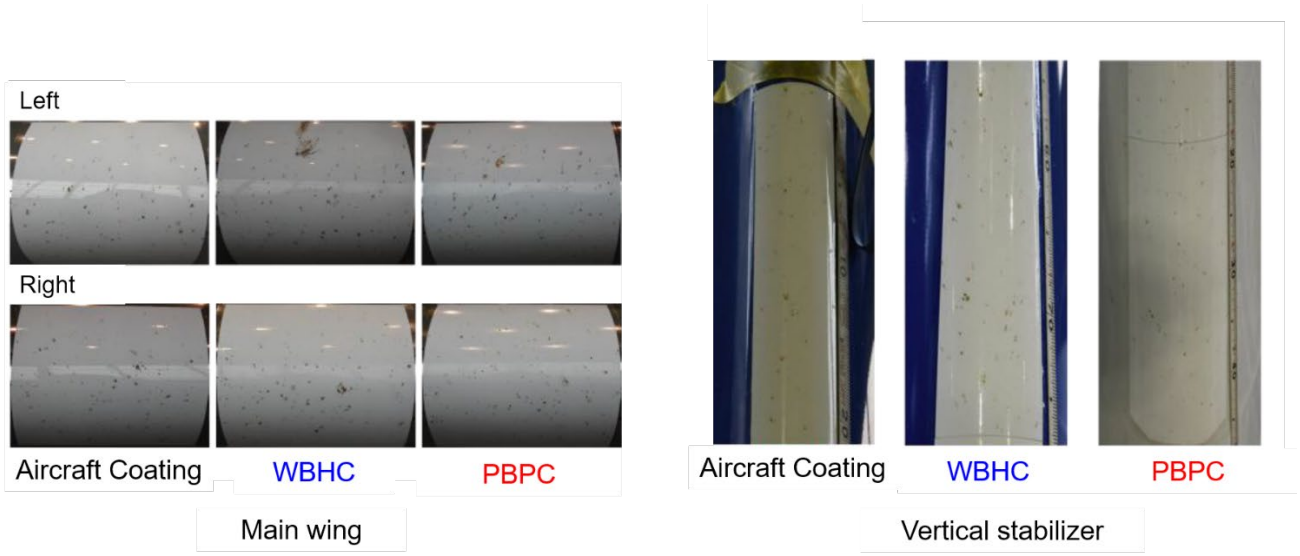


Figure 18 – Insect adhesion.

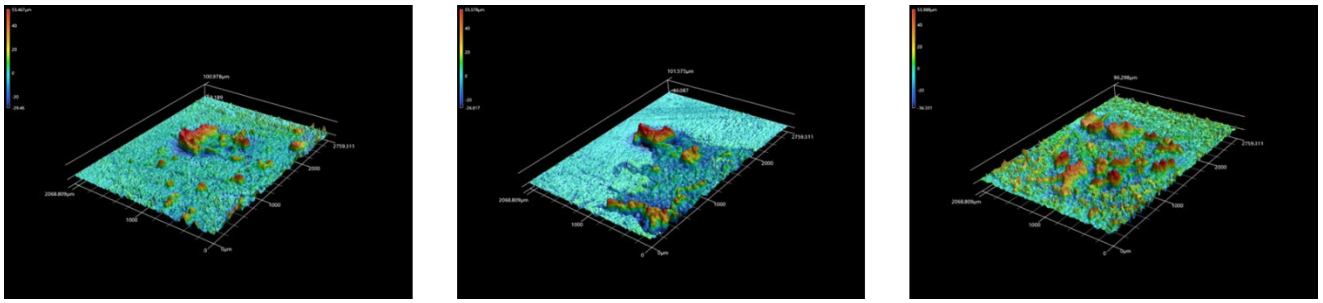


Figure 19 – Three-dimensional measurements of adhered insects.

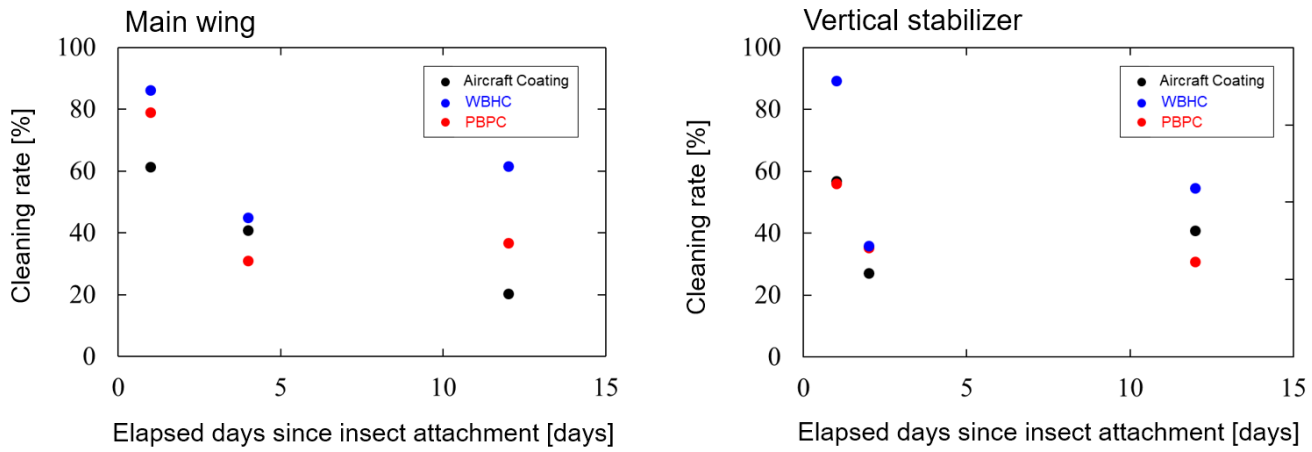


Figure 20 – Effect of elapsed time since insect attachment to cleaning rate in the flight tests.

Figure 20 shows the effect of the elapsed time after insect adhesion on the cleaning rate for the main wings and vertical stabilizer for a cleaning duration of 180 s. The cleaning tests were conducted with pre-wetting treatment. Overall, the cleaning rate tended to decrease with increasing elapsed time after insect adhesion; however, the WBHC consistently exhibited the highest cleaning rate among the tested coating sheets. A decrease in cleaning rate was observed for all paint sheets on day 4 for the main wing and day 2 for the vertical stabilizer. This deterioration may be attributable to environmental conditions that promoted insect fixation, such as high temperature and low humidity, which could have dried the adhered insects and made them more difficult to remove. Compared with the results obtained in the coupon and vehicle tests, the reduction in cleaning rate with elapsed time was more pronounced in the present flight tests. However, because the present test was conducted only once, additional data is required to confirm this trend and enable a more comprehensive evaluation.

Figure 21 shows the relationship between cleaning duration and cleaning rate for the main wing and

vertical stabilizer. The results for the main wing correspond to measurements obtained 1 and 12 days after insect adhesion, whereas those for the vertical stabilizer correspond to measurements obtained 1 day after insect adhesion. Unlike the coupon and vehicle test results, increasing the cleaning duration did not consistently improve the cleaning rate. This behavior may be attributable to the higher insect impact velocities encountered during flight, which could have increased the degree of insect residue adhesion to the surface. In combination with environmental exposure after adhesion, this enhanced adhesion may have reduced the effectiveness of water cleaning. Figure 22 shows the effect of pre-wetting on the cleaning rate. The elapsed time after insect adhesion was 1 day, and the cleaning duration was fixed at 120 s. For all coating sheets, the cleaning rate was higher when pre-wetting treatment was applied. Furthermore, the improvement in cleaning rate due to pre-wetting was more pronounced for the two hydrophilic coatings than for the aircraft coating. This result may be attributed to the fact that pre-wetting increased the moisture content of the adhered insect residues, thereby enhancing the effectiveness of the hydrophilic surface properties and facilitating their removal during water cleaning.

4.3 Performance Evaluation as Aircraft Coatings

Table 3 summarizes the results of the specification tests conducted to verify the performance requirements for aircraft coatings. Both hydrophilic coatings satisfied all of the test criteria evaluated in this study. Figure 23 shows the changes in hydrophilic performance as a function of the equivalent years of UV irradiation. In this figure, a lower water contact angle corresponds to higher hydrophilicity. The water contact angle of the aircraft coating ranged from approximately 70° to 90°, whereas those of the WBHC and PBPC remained in the range of 30°–40°. These results indicate that the hydrophilic performance of both hydrophilic coatings was maintained even after prolonged UV irradiation, and no degradation of the coating films was observed.

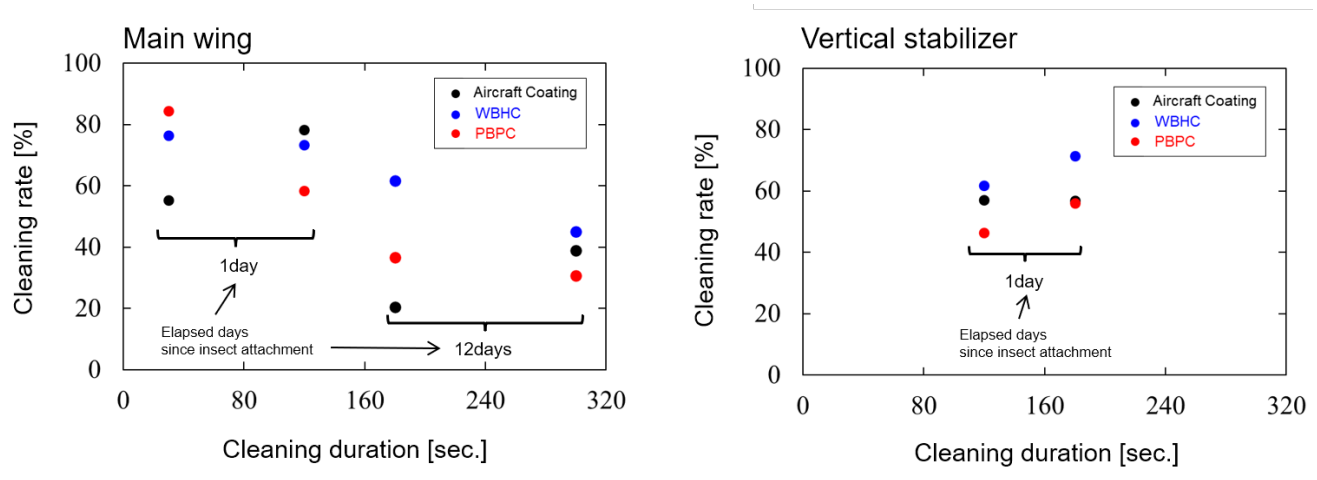


Figure 21 – Effect of cleaning duration to cleaning rate in the flight tests.

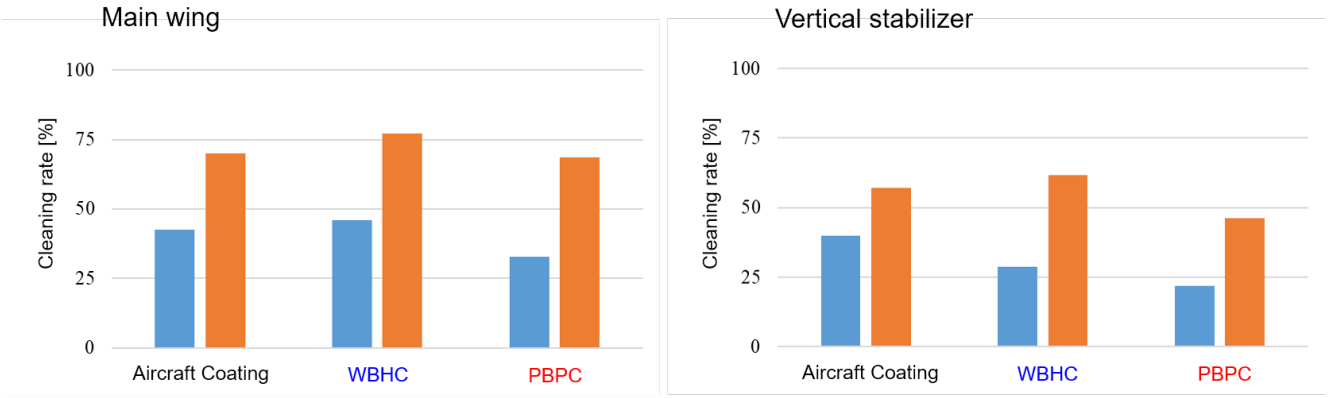


Figure 22 – Effect of pre-wetting to cleaning rate in the flight tests.

Table 3 – Results of the specification tests.

Specification Test Items	Results	
	WBHC	PBPC
Resistance to water adhesion	No delamination	No delamination
Oil resistance	No coating softening, No significant discoloration	No coating softening, No significant discoloration
Salt spray resistance	No blistering, No rust formation	No blistering, No rust formation
Impact flexibility	No cracking after 60% area increase	No cracking after 60% area increase
Low-temperature flexibility	No cracking	No cracking

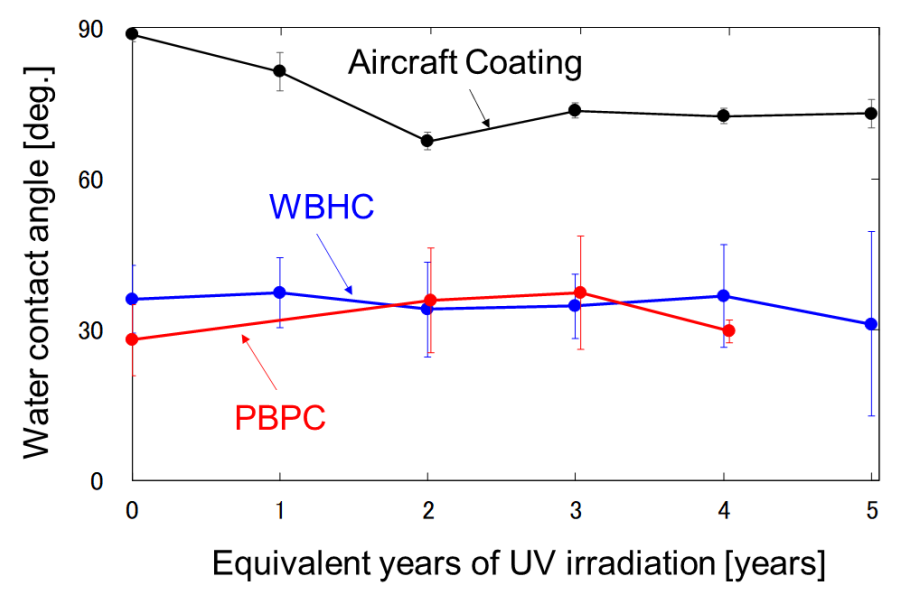


Figure 23 – Hydrophilic performances for UV irradiation.

5. Conclusions

Two hydrophilic coatings, a water-based hydrophilic coating (WBHC) and a polymer-brush photocatalytic coating (PBPC), were developed to facilitate the removal of insect residues adhering to the leading edge of aircraft wings during takeoff and landing, which is one of the major obstacles to the practical application of natural laminar flow wings.

The surface roughness of WBHC was found to be comparable to that of the baseline aircraft coating, indicating that the introduction of hydrophilic functionality did not significantly affect surface smoothness. The cleaning performance of the coatings was evaluated through a series of coupon tests, vehicle tests, and flight tests. In both the coupon and vehicle tests, all coatings exhibited improved cleaning rate with increasing cleaning duration, while cleaning rate decreased as the elapsed time after insect adhesion increased. Among the tested coatings, WBHC consistently showed the highest cleaning performance, achieving a cleaning rate of more than 70 % after 90 s of cleaning and 26 days elapsed since insect adhesion in the coupon tests, and more than 80 % after 90 s of cleaning and 67 days elapsed since insect adhesion in the vehicle tests. In the flight tests, the cleaning rate decreased more markedly with elapsed time after insect adhesion than in the coupon and vehicle tests. Nevertheless, WBHC again exhibited the highest cleaning performance, achieving a cleaning rate of approximately 70 % on the vertical stabilizer after 180 s of cleaning and 1 day of exposure. Since the number of flight-test repetitions under identical conditions was limited, further data acquisition is required to establish a more comprehensive evaluation of coating performance.

To verify the applicability of the developed coatings for aircraft use, qualification tests were conducted for five representative properties: water resistance, oil resistance, salt spray resistance,

impact flexibility, and low-temperature flexibility. The results confirmed that the developed coatings satisfied the required performance specifications for aircraft coatings.

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