

Hydrophobic Windscreen Coating for Next Generation Civil Tilt Rotor: Experimental Testing and Qualification

E. Benini¹

University of Padova, Padova, 35131, Italy

Marco Bertolini², Lorenzo Dal Toso, Elisabetta Poli, Guglielmo Macrelli

Isoclima SpA, Este, 35042, Italy

Mike Kerr, Luca Patricelli³, Michela Faraoni

Leonardo SpA Helicopter Division, Cascina Costa di Samarate, 21017, Italy

The paper describes the results achieved in the HaSU project, a European Research Program funded by the European Commission, which dealt with design, fabrication and experimental testing/qualification of hydrophobic specimens suitable for the Next Generation Civil Tilt Rotor windscreen development. Evidence from tests on hydrophobicity, UV stability, transparency and environmental tests are documented and discussed to demonstrate airworthiness. The proposed technological solution started at TRL4 level and reached TRL6 at the end of the project.

I. Introduction

Helicopter and aircraft windshields shall guarantee pilot's visibility at excellent levels under several operation conditions, particularly under heavy rain occurring during flight [1]. To this purpose, the majority of modern commercial aircraft use wipers to shed water from windshields [2]. Use of wipers is no longer foreseen in some future civil aircraft, such as the Next Generation Civil Tilt Rotor (NGCTR), in order to reduce fuel consumption by reducing aircraft drag.

A durable, surface coating on the windshield to shed water would be an ideal solution to maintain visibility without using wipers and will be of paramount importance to limit the formation of rain-induced ice on the windshield. Today's commercially available rain repellent treatments have poor durability and weather resistance. In fact, present treatments applied onto the surface of the windshield must be re-applied periodically or as needed as their performance degrades rapidly over time; in addition there are no solutions today proven and available on the market for effective and durable hydrophobic coating on plastic materials such as polycarbonate and acrylic. Even hydrophobic coating for glass faceply windshields, such as PPG Surface Seal®, has "a limited-service life and needs to be reapplied on regular basis" according to Airbus engineers [2].

The HaSU project, funded by the European Commission under the ClanSky2 platform was about the design and development of a rain repellent substrate capable of forming highly durable hydrophobic coatings for windshields based on a particulate inorganic homogeneously distributed throughout a polymeric matrix. The present paper describes the results achieved in the HaSU project. In particular, results dealing with experimental testing and qualification on hydrophobic specimens – suitable for NGCTR windscreen development – are presented: evidence from tests on hydrophobicity, UV stability, transparency and environmental tests are shown and discussed.

¹ Professor, Department of Industrial Engineering, and AIAA Member.

² R&D Engineer.

³ R&D Engineer.

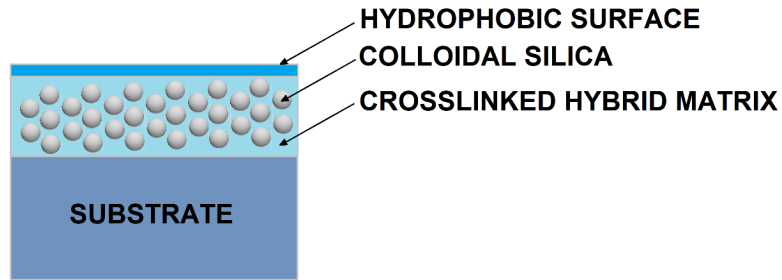


Fig. 1 Schematic cross section of the hydrophobic coating.

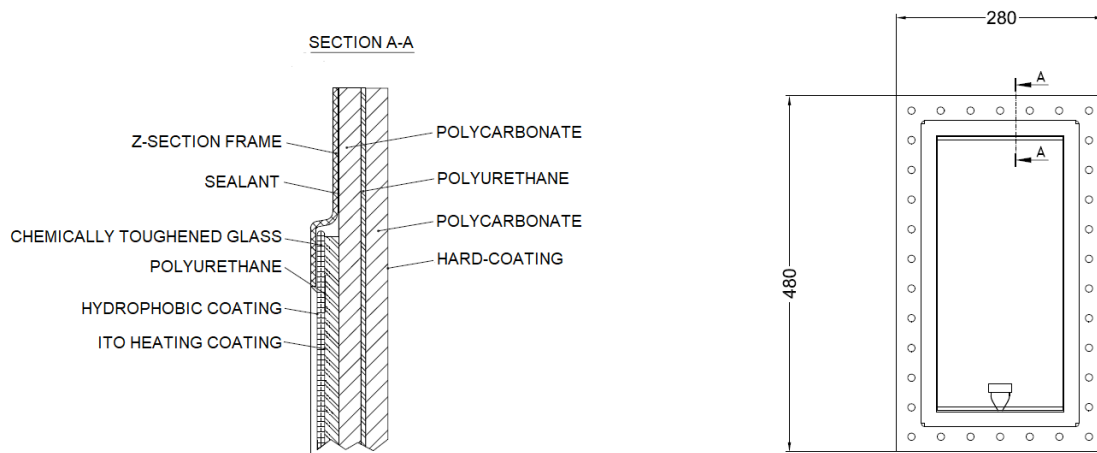


Fig. 2 Design of the final hydrophobic sample representative of the cross-section of a tilt-rotor windshield.

II. Materials and Methods

A set of hydrophobic samples were manufactured which are representative of a tiltrotor windshield. Each sample consists in a curved composite assembly capable of acting as part of the fuselage structure and carry membrane loading. All interlayers are made from thermoplastic urethane. The face-ply material is made of glass due to its higher thermal conductivity compared to plastic.

A. Hydrophobic Coating and Preparation

The hydrophobic coating is composed by a polyurethane silane (polycaprolactone polyol, isocyanate silane and the catalyst dybutyltindilayurate). The overall compound is composed as follows: a non-fluorinated compound, i.e. tetraethoxysilane (TEOS), a fluorinated one, i.e. perfluoropolyether silane with a fluoro-surfactant to allow for a better mixing, a colloidal silica (10 nm) to improve abrasion resistance, solvents, 2-propanol and 1-propanol, and HNO₃ acidified water. The polyol, the isocyanate silane and the catalyst dybutyltindilayurate are mixed together to obtain the polyurethane silane.

The silanes are mixed together, and solvents are added to the mixture. Afterwards, acidified water is added to the mixture to have the hydrolysis of the coating. The coating is mixed for around 2 hours to complete the hydrolysis. Once the hydrolysis is complete the coating is applied to samples in a clean room by flow coating. To perform such an operation the coating is put into a dried air pressurized dispensing vessel, filtered by a two-step filtering system and applied via a solvent dispenser. During the application of the coating the sample is hold in vertical or sub-vertical position.

The coating is initially dried for 15-20 minutes in the application clean room and later cured in an oven at a temperature in the range 90-130°C for 30 minutes holding time to improve abrasion resistance. Figure 1 shows the

cross-section of the coating. Silica nanoparticles provide high abrasion resistance and durability while highly crosslinked flexible polymeric resin binds particles with flexibility and high durability. Self-assembled surface groups result in proper water-shedding and easy cleaning properties.

B. Hydrophobic Sample Preparation

In order to qualify the hydrophobic coating, it was decided to manufacture a representative sample of a tiltrotor windshield. In this way, the hydrophobic coating before being environmentally tested according to the agreed protocol, underwent all the typical manufacturing processes following the coating application, the most significant of which is the lamination process.

Figure 2 shows a cross-section view and the size of the manufactured sample. The sample size is 480 mm x 280 mm. The cross-section lay-up and total thickness is typical of a tiltrotor/business-jet composite windshield. There are two structural plies. In this case it was chosen to use two polycarbonate plies to reduce the windshield weight. The thickness of the two structural polycarbonate plies has been designed to beat the differential pressure load and the bird strike impact load. In order to improve ice-removal from the windshield a transparent conductive heating coating has been applied on the inner surface of the glass outer ply. For this purpose, an ITO coating has been deposited by DC magnetron sputtering. To be able to apply the voltage to the coating, two silver bus-bars have been printed on the two opposite short sides of the samples. The outer glass has been chemically strengthened to improve mechanical strength of the glass. The hydrophobic coating has been applied on the outer glass surface. A Z-section composite frame is applied all around the perimeter to avoid moisture penetration into the interlayer. Polycarbonate and glass plies are laminated together through an aliphatic polyurethane interlayer. A micro-foil Pt100 sensor has been laminated into the sample to provide a feedback for the heating power unit. In fact, during some environmental testing, the sample has been heated as happens in flight.

C. Manufacturing Cycle

Figure 3 shows the manufacturing cycle of final hydrophobic samples.

The glass sheet is first cut, ground and polished using a pencil edge by CNC machines and later chemically strengthened to improve mechanical strength. After chemical strengthening, bus-bars are silk-screen printed onto the inner glass surface with a silver-filled epoxy paste. The paste is cured in an oven at the temperature and for the time prescribed by the supplier. The following step is the deposition of the transparent conductive coating for de-icing on the inner surface of the glass face-ply. The coating is ITO (Indium-Tin Oxide) deposited by DC magnetron sputtering under high vacuum. At this point the hydrophobic coating has been applied on the outer surface of the glass face-ply. The coating has been prepared and mixed in advance, applied by flow coating and cured in an oven.

In parallel with these processes, polycarbonate sheets are cut over-size and the inner one has been hard-coated on the inner surface with a poly-siloxane hard-coating. Printed bus-bars are reinforced with a tin-coated copper tape before assembling the glass face-ply and polycarbonate layers together in a clean room interposing a polyurethane interlayer between one sheet and the other according to the technical documentation. A Pt100 temperature sensor is embedded into the interlayer to give a feedback to the power control unit. Samples are vacuum bagged and autoclaved with the prescribed cycle.

Manufacturing the composite Z-section frame and bonding it to the sample with the sealant were subsequently performed. Before bonding composite straps to samples, the hydrophobic coating has been masked with a polyester tape with silicone adhesive and the coating has been removed with a 3000-grit sandpaper in the bonding area. Before bonding, the surface has been cleaned with isopropyl alcohol (IPA).

Samples have been finally edge trimmed using a 3-axis CNC machine and the primer has been applied to the composite straps (Figure 4).

All the samples underwent tests regarding:

1. Water contact angle (WCA);
2. Light transmission, reflection and distortion;
3. Environmental testing, in particular Ground Survival Low/High Temperature Test and short-Time Operating Low/High Temperature; Temperature Variation and Humidity; Spray, Sand/Dust, Salt Fog and Fungus resistance; Resistance to Solar Radiation.

according to DO-160 “environmental conditions and test procedures for airborne equipment” and MIL-STD-810 “environmental engineering consideration and laboratory test”. The first two sets of tests (i.e. Water contact angle and Optical distortion) were carried out before and after the execution of the other tests (No. 3. – 6.).

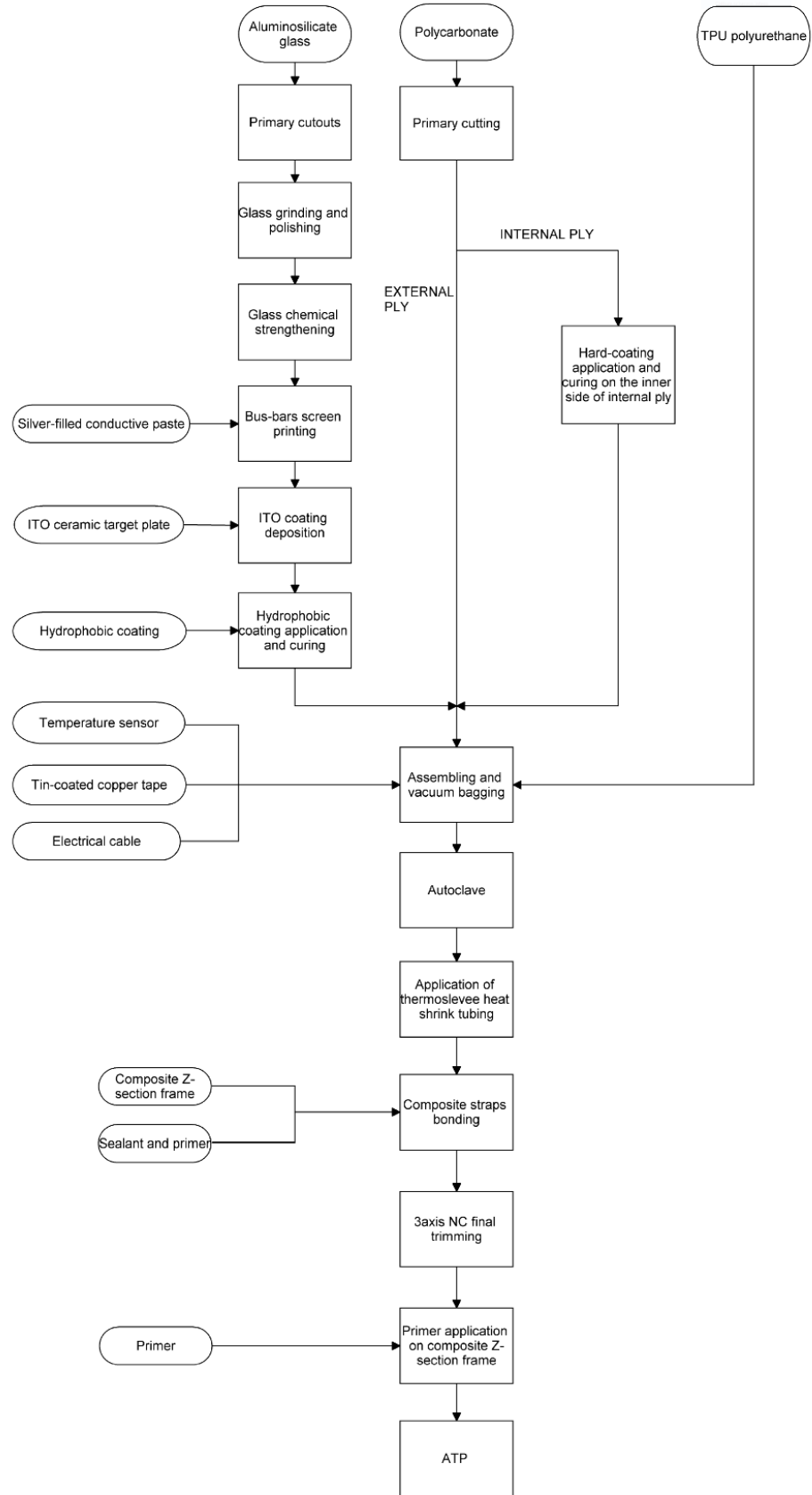


Fig. 3 Hydrophobic samples manufacturing flow chart.

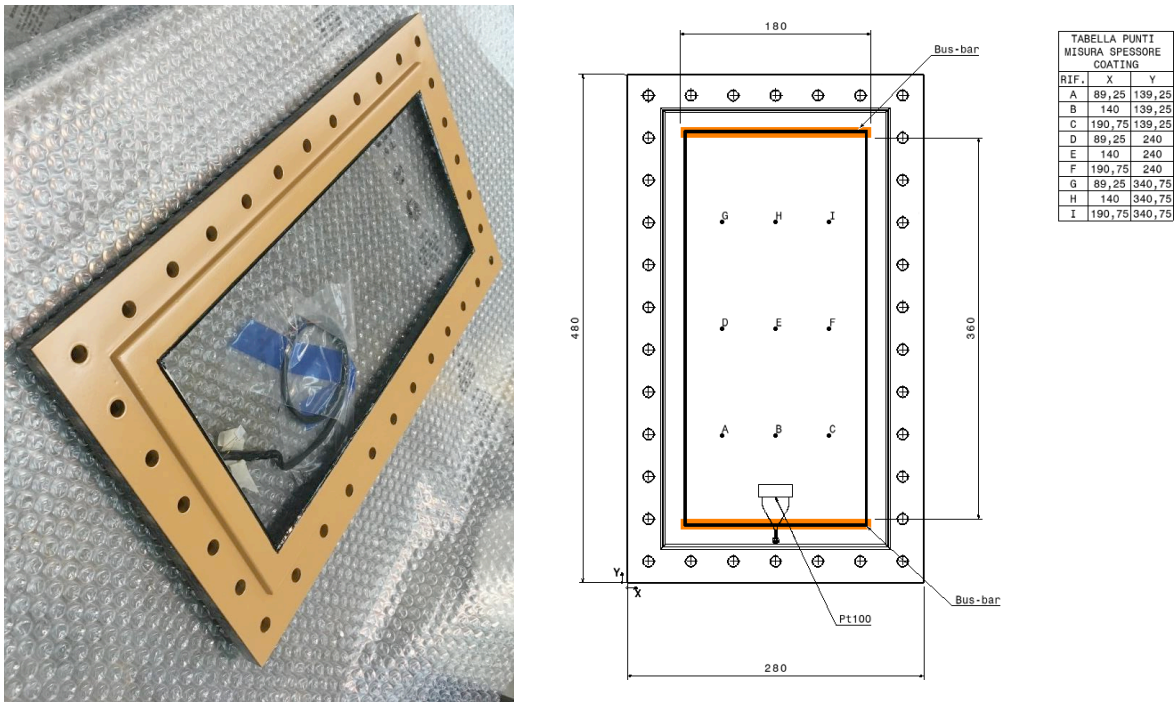


Figure 4 Final hydrophobic sample to be environmental tested (left). Coating measuring points on the final hydrophobic sample (right).

III. Results and Discussion

Sections A and B in the following refer to the experimental results before environmental testing. Section C deals with experiments carried out afterwards.

A. Water contact angle (WCA)

In this work, contact angles were measured with the Drop Shape Analyzer DSA100 and the Mobile Surface Analyzer by Krüss through the ADVANCE Drop Shape software using the sessile drop method. Water and diiodomethane are used as standard test liquids. The polar and dispersive components of surface tension of these liquids are listed in Table 1.

The drop contour fitting method chosen for all measurements is the conic section. In this model an elliptical drop shape is assumed. The conic section method (or tangent method 1) fits a general conic section equation to the drop shape. The contact angle is determined as the angle between the baseline and the tangent to the conic section curve at the three-phase contact point.

The water contact angle has been measured on all final samples on 3 different points, respectively A, E, I, according to Figure 4 - right. Every sample was cleaned with isopropyl alcohol (IPA) and a microfiber cloth before taking any measurements. The volume of the droplet was set to 2.0 μl . The fitting method chosen was the conic section (ellipse). Table 2 summarizes the results of the performed measurements. All water contact angle measurements are greater than 105° , in the range $105^\circ\text{--}108^\circ$, diiodomethane water contact angle measurements are greater than 85° , in the range $85^\circ\text{--}89^\circ$, the surface free energy (SFE) is less or equal to 16 mN/m with a polar component of less than 2 mN/m.

The water contact angle obtained is in the expected range. Measured values are consistent with the chemistry of the coating considering that this is manufactured with an organic polymeric silane, an inorganic metal alkoxide and fluorinated silane and that the coating has no nano-, micro- or hierarchical structure which are not suitable for

aerospace applications due to erosion that occurs in flight with blowing sand and ice. Surface free energy is consistent with a fluorinated coating and the low polar component is a clear indication of poor wettability of the coated surface.

On the other hand, the water contact angle of standard uncoated glass was measured to be around 27°, the diiodomethane contact angle around 41°, consequently the SFE is around 70 mN/m with a polar component of 31 mN/m and a dispersive component of 39 mN/m.

The coating thickness has been measured in all points (see Figure 4 right) and for all samples it was in the range 4÷6 µm. After laboratory testing, it has been proven that there is a thickness threshold limit under which abrasion resistance becomes an issue. If the thickness is under 3-4 µm the coating does not provide proper abrasion resistance to plastic substrates, while if the coating is thicker than 12-20 µm the durability against delamination, blistering and coating cracking is lower. The coating is applied by “flow” and the thickness of the coating can be controlled adjusting the viscosity of the coating.

Table 1 Test liquid data.

Liquid	Surface tension σ_l (mN/m)	Polar component σ_l^p (mN/m)	Dispersive component σ_l^d (mN/m)
Water	72.8	51.0	21.8
Diiodo-methane	50.8	0.0	50.8

Table 2 Water contact angle measurements.

Serial Number	Water mean Contact Angle [°]	Water CA standard deviation [°]	Diiodo-methane mean Contact Angle [°]	Diiodo-methane CA standard deviation [°]	Surface free energy [mN/m]	Disperse [mN/m]	Polar [mN/m]
190801968	107.33	0.69	87.99	0.56	14.97	13.60	1.36
190801970	105.10	1.41	86.55	0.97	15.96	14.27	1.69
190801972	105.52	0.60	86.94	0.84	15.73	14.09	1.64
190801974	105.55	1.31	85.97	0.92	16.08	14.55	1.53
190801976	107.23	0.69	88.30	1.29	14.88	13.47	1.41
190801978	106.32	3.22	87.85	0.83	15.23	13.67	1.56

B. Light transmission, reflection and distortion

Experimental tests have shown that the light transmission of the coated windshield is equal to or even slightly higher than the uncoated one. The reason is that the refraction index of the hydrophobic coating is 1.49, lower than the soda-lime glass one, equal to 1.52. Light transmission measurements have been taken on a 2 mm extra-clear soda-lime glass substrate with and without the hydrophobic coating with a Perkin Elmer Lambda 900 Spectrophotometer equipped with a Labsphere PELA 1000 integrating sphere.

As shown in Figure 5, the coated substrate exhibits a reduced light reflection in the visible range (380-780 nm of wavelength) and consequently a higher light transmission as the light coating absorption is negligible.

Light transmission and haze have also been measured on all samples according to ASTM D1003, illuminant C with haze-gard by BYG. The light transmission of all samples was greater than 80% with haze equal to or lower than 1.3%.

Final samples have been tested also for optical distortion according to ASTM F 2156, setup A, using software Topins® from CPS and optical deviation according to ASTM F 733 method “I”, with an installation angle of 35°. It has been proven that a proper application of the hydrophobic coating had no appreciable effect on the optics of the windshields. This result was expected because the thickness of the coating is relatively thin and without sudden variations. These features due to the “flow” application method, minimize the impact on optical properties of the windshield’s specimen.

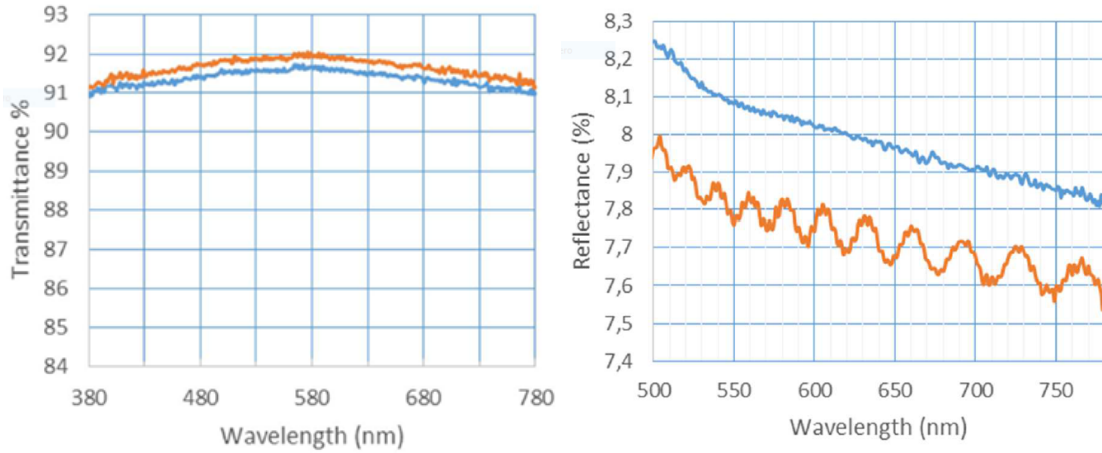


Fig. 5 (Left) Light transmission in the visible range (380-780 nm wavelength) for an extraclear 2 mm thickness soda-lime glass (substrate, blue line) and for the same substrate coated with hydrophobic coating (coating, red line). Light transmission for the hydrophobic coated substrate is higher. (Right) Light reflection in the relevant visible range (500-780 nm wavelength) for an extraclear 2 mm thickness soda-lime glass (substrate, blue line) and for the same substrate coated with hydrophobic coating (coating, red line).

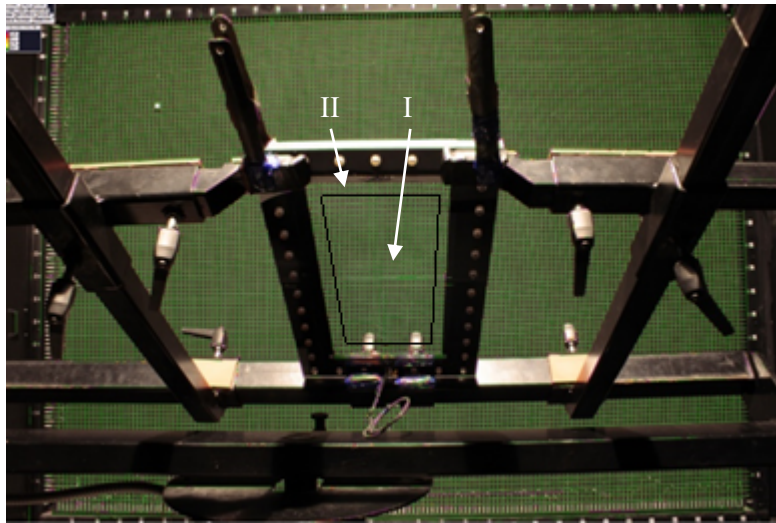


Fig. 6 Optical distortion evaluation using software Topins® on S/N 190801974. Distortion in both ZONES I and II is $\leq 1:15$.

C. Environmental testing

No visible or apparent signs of degradation such as coating delamination, blistering, color variations, spots, were visible on samples after environmental testing with the exception of the Sand and Dust test that generated some barely visible micro-scratches.

After environmental testing, further measurements have been taken on each sample.

No appreciable light transmission or haze variations have been found with the exception of the delta haze in the samples subjected to the Sand and Dust test; in that case the increase of haze was 1.4% and the final haze value was 2.1%. A slightly increase in delta haze after blowing sand and dust was expected considering that the matrix of the coating is polymeric. Oxide nanoparticles in the coating helps increasing abrasion resistance but a slight erosion is still unavoidable. UV stabilizer and corrosion inhibitors made it possible to have no appreciable variations in light

transmission and haze after solar radiation and salt spray tests: UV stabilizers avoid coating yellowing, and the dense coating network provides a high physical barrier to electrolytes that cause corrosion.

Table 1 reports measurements of water and diiodomethane contact angles and surface free energy after environmental testing, while

Table 2 highlights the variation between final and initial measurements. These tables show that, although there was a slight decline in water contact angle and slight increase in the surface energy, the coating still maintains good hydrophobic properties.

By analyzing the data results after environmental testing, the outcomes were the following:

- water contact angle after testing was between 95° and 101° , the value was found to be reduced by a range of variation between -7° and -12° ; the average variation in percentage is -7% ;
- diiodo-methane contact angle after testing is between 87° and 94° , the value is found to be generally increased by a range of variation between -1° and $+8^{\circ}$; the average variation in percentage is $+5\%$;
- surface free energy is between 16 and 19mN/m, the value is found always increased with a range of variation between 0 and +4mN/m; the average variation in percentage is 8% ;
- the polar component of surface free energy is between +4 and +5mN/m; the value is found to be generally increased with a range of variation between +2mN/m and +4mN/m; the average variation in percentage is $+207\%$;
- the disperse component of surface free energy is between 11 and 14 mN/m; the value is found to be generally decreased with a range of variation between -4mN/m and 1 mN/m; the average variation in percentage is -14% .

Variations in terms of water contact angle, diiodo-methane contact angle and surface free energy seemed to be independent of the test performed. In all cases, there is almost the same trend: it seems there was an “aging effect” increasing the polar component of surface free energy. Final measurements have been taken after 8 months from initial ones. The phenomenon is not fully understood but similar behavior have been observed in literature with fluoropolymer coatings [5]. The hypothesis is that it is possible for the coatings to absorb or adhere to hydroxyl groups of water molecules without causing a detectable film thickness change.

In Table 5, the results on water contact angle and surface free energy after fluids susceptibility testing are reported. By analyzing the data results, the outcomes were the following:

- water contact angle after testing is between 109° and 111° ; the value is found always increased with a range of variation between $+1^{\circ}$ and $+2^{\circ}$; the average variation in terms of percentage is $+2\%$;
- surface free energy is between 13 and 14mN/m; the value is found always decreased with a range of variation between 0 and -2mN/m; the average variation in terms of percentage is -6.5% ;
- the polar component of surface free energy is 1 mN/m; the value is found always decreased with a range of variation between 0 mN/m and -1 mN/m; the average variation in terms of percentage is -20% ;
- the disperse component of surface free energy is between 12 and 13 mN/m; the value is found always decreased with a range of variation between 0 mN/m and -2 mN/m; the average variation in terms of percentage is -5% .

Also in this case, we can make reference to the previous hypothesis to justify the above reported results considering the behavior of fluoropolymer coatings observed in the literature [5]. During the fluid susceptibility test, specimens have to be dried for 16 hours at 65°C according to the testing procedure. It is believed that this drying cycle is able to evaporate hydroxyl groups of water molecules bonded to the coating surface and for this reason the polar component of the surface free energy may likely decrease after the test.

In the fungus resistance test, no trace of fungus greater than 1 was found on the sample.

Table 1 Water and surface free energy measurements after environmental testing.

GENERAL INFO		AFTER ENVIROMENTAL TESTING								
Test	Measuring Point	Water/Air CA(m) [°]	Diiodo-methane/ Air CA(m) [°]	Water mean CA [°]	Water CA standard deviation [°]	Diiodo-methane mean CA [°]	Diiodo-methane CA standard deviation [°]	Surface free energy [mN/m]	Disperse [mN/m]	Polar [mN/m]
DO-160 – Section 4 – Temperature and Altitude. Category B2.	A	100.48	93.66	100.19	0.36	92.39	1.5	15.51	11.66	3.85
	E	100.3	90.73							
	I	99.79	92.79							
DO160 – Sec. 5 - Temperature Variation. Category A.	A	99.54	92.19	98.58	1.25	92.52	0.32	16.05	11.61	4.45
	E	97.17	92.55							
	I	99.03	92.83							
DO160 – Sec. 6 - Humidity. Category C.	A	97.64	91.03	97.69	1.45	91.77	0.65	16.58	11.93	4.65
	E	96.27	92.06							
	I	99.16	92.22							
DO160 – Sec. 14 - Salt Fog. Category T.	A	95.69	94.32	96.72	0.89	94.32	0.52	16.4	10.93	5.47
	E	97.14	93.8							
	I	97.32	94.84							
MIL-STD-810 - Solar Radiation (A1, 100 hours, Sulphur dioxide >=10%)	A	99.83	93.71	97.97	1.69	93	0.79	16.17	11.41	4.76
	E	96.54	92.15							
	I	97.55	93.15							
	A	95.72	87.2							
DO160 – Sec. 12 - Sand and Dust. Category S.	E	94.42	86.04	94.64	0.99	86.66	0.58	19.15	14.22	4.93
	I	93.77	86.75							

Table 2 Water contact angle and surface free energy difference after environmental testing.

GENERAL INFO		DIFFERENCE									
Test	Measuring Point	Δ Water mean CA [°]	Δ Diiodo-methane mean CA [°]	Δ Surface free energy [mN/m]	Δ Disperse [mN/m]	Δ Polar [mN/m]	Δ Water mean CA [%]	Δ Diiodo-methane mean CA [%]	Δ Surface free energy [%]	Δ Disperse [%]	Δ Polar [%]
DO-160 – Section 4 – Temperature and Altitude. Category B2.	A	-7.14	4.4	0.54	-1.94	2.49	-6.70%	5.00%	3.60%	-14.30%	183.10%
	E										
	I										
DO160 – Sec. 5 - Temperature Variation. Category A.	A	-6.52	5.97	0.09	-2.66	2.76	-6.20%	6.90%	0.60%	-18.60%	163.30%
	E										
	I										
DO160 – Sec. 6 - Humidity. Category C.	A	-7.83	4.83	0.85	-2.16	3.01	-7.40%	5.60%	5.40%	-15.30%	183.50%
	E										
	I										
DO160 – Sec. 14 - Salt Fog. Category T.	A	-8.84	8.35	0.32	-3.62	3.94	-8.40%	9.70%	2.00%	-24.90%	257.50%
	E										
	I										
MIL-STD-810 - Solar Radiation - Method 505 procedure 1 (A1, 100 hours, sulphur dioxide >=10%)	A	-9.26	4.71	1.29	-2.06	3.35	-8.60%	5.30%	8.70%	-15.30%	237.60%
	E										
	I										
DO160 – Sec. 12 - Sand and Dust. Category S.	A	-11.69	-1.19	3.92	0.55	3.37	-11.00%	-1.40%	25.70%	4.00%	216.00%
	E										
	I										

Table 3 Water contact angle and surface free energy after DO160 – Section 11 - Fluid Susceptibility, category F, testing.

GENERAL INFO		AFTER TESTING									VARIATION			
Item #	Coating thickness [mm]	Water/Air CA(m) [°]	Diiodo-methane/Air CA(m) [°]	Water mean CA [°]	Water CA standard deviation [°]	Diiodo-methane mean CA [°]	Diiodo-methane CA standard deviation [°]	Surface free energy [mN/m]	Disperse [mN/m]	Polar [mN/m]	ΔWater/Air CA(m) [°]	ΔSurface free energy [mN/m]	ΔDisperse [mN/m]	ΔPolar [mN/m]
1	4.67	110.35	92.29	110.52	0.37	91.89	0.37	12.99	11.88	1.12	2.35	-1.83	-1.74	-0.08
		110.27	91.57											
		110.95	91.81											
2	4.95	109.82	92.3	109.76	0.06	92.41	0.64	12.96	11.65	1.2	2.97	-1.12	-0.65	-0.58
		109.75	93.1											
		109.05	91.1											
3	4.61	109.47	90.13	109.58	0.59	90.34	0.68	13.7	12.55	1.15	1.36	-0.37	-0.14	-0.23
		110.21	89.79											
		110.05	89.93											
4	4.55	109.59	89.23	109.83	0.23	90.37	1.42	13.64	12.53	1.11	1.84	-0.52	-0.22	-0.3
		109.86	91.96											
		110.26	90.75											
5	4.23	110.18	81.85	110.17	0.1	87.87	5.22	13.29	12.17	1.12	2.22	-0.87	-0.56	-0.3
		110.06	91.02											
		109.3	89.91											
6	4.36	109.95	89.66	109.62	0.33	89.88	0.21	13.86	12.75	1.1				
		109.62	90.08											
		110.15	90.68											
7	4.84	110.21	91.6	110.08	0.18	91.29	0.53	13.28	12.14	1.14				
		109.87	91.58											
		110	90.42											
8	4.83	110.2	89.64	110.18	0.17	89.98	0.4	13.72	12.71	1.02				
		110.33	89.88											
		109.82	89.79											
9	4.78	109.69	89.12	109.76	0.07	90.04	1.06	13.78	12.68	1.09				
		109.78	91.2											
		109.1	88.86											
10	4.77	109.47	88.05	109.32	0.19	88.76	0.67	14.26	13.26	1				
		109.38	89.37											
		108.01	90.7											
11	4.21	109.04	89.88	108.68	0.58	90.15	0.48	13.94	12.63	1.3				
		108.98	89.86											

IV. Conclusion

The hydrophobic coating has been applied on tiltrotor’s windshield representative samples that have been subsequently exposed to different environmental testing according to DO-160 “environmental conditions and test procedures for airborne equipment”: temperature and altitude, temperature variation, humidity, fluid susceptibility, sand and dust, fungus resistance, salt fog; and MIL-STD-810 “environmental engineering consideration and laboratory test”: solar radiation. After environmental testing windshield representative specimens have been tested according to the ATP and glass specimens have been tested for water contact angle and surface free energy.

Test results have shown that the hydrophobic coating is able to satisfy ATP (Acceptance Test Procedure) requirements even after environmental testing. No variations of properties such as coating thickness, light transmission, optical properties in terms of distortion and deviation or delamination of the coating have been observed after environmental testing. No fungi growth has been observed on the coating surface.

Regarding hydrophobic properties, the coating was able to satisfy ATP requirements after environmental testing. Test results have however shown a general trend of reduction of water contact angle and a slight reduction of surface free energy after environmental testing with the exception of the DO-160 fluid susceptibility test where the trend was the opposite.

The most critical environmental test was found to be the DO-160 sand and dust. This test generates a micro-abrasion of the coating surface consequently increasing the haze level of the window and reducing hydrophobic properties of the specimen. Nevertheless, the tested specimen was still able to satisfy the ATP even if the mean water contact angle was at the limit of acceptability, that is, 95°.

The coating has been proven to be airworthy for the application on the Next Generation Tilt Rotor (NGCTR) windscreens.

Acknowledgments

The HaSU project was funded under the European Union framework Research Program Horizon 2020, Clean Sky 2 Joint Technology Undertaking, Grant No. 755492.

References

- [1] W. F. Grether, "Optical Factors in Aircraft Windshield Design as Related to Pilot Visual Performance," Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, July 1973. Available online at <https://apps.dtic.mil/dtic/tr/fulltext/u2/767203.pdf> (accessed on 03 Feb. 2021)
- [2] F. Poveda, "Combining Environment Protection and Windshield Rain Production on Airbus Aircraft," FAST - Airbus Technical Digest, no. 23, pp. 19-23, 1998. Available online at https://www.smartcockpit.com/docs/Windshield_Protection.pdf (accessed on 03 Feb. 2021)
- [3] F. P. S. Göran Ström, "Contact Angles, Work of Adhesion, and Interfacial Tensions at Dissolving Hydrocarbon Surface," Journal of Colloid and interface Science, Vol. 119, Vol. 2, pp. 352-361, 1986. DOI: 10.1016/0021-9797(87)90280-3
- [4] F. Thomsen and C. Bilke-Krause, Practical contact angle measurement (4). Technical note: TN314e, Krüss, 2008. Available online at https://warwick.ac.uk/fac/cross_fac/sciencecity/programmes/internal/themes/am2/booking/dropshapeanalyser/practical_contact_angle_measurement_2.pdf (accessed on 03 Feb. 2021)
- [5] Trapuzzano, M., Crane, N.B., Guldiken, R. *et al.* Wetting metamorphosis of hydrophobic fluoropolymer coatings submerged in water and ultrasonically vibrated. *J Coat Technol Res* **17**, 633–642 (2020). <https://doi.org/10.1007/s11998-019-00250-1>