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Assessment of residual performances of Al/CFRP co-cured hybrid samples subjected to galvanic corrosion

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Abstract

Tartaric Sulfuric Anodizing (TSA) and γ -glycidoxypolytrimethoxysilane silanization (γ -GPS) were tested as treatments of Al-2024 and Al-2198 aluminum alloys for promoting adherence and corrosion protection of the Al/CFRP interface in CFRP/Al co-cured hybrid materials, and compared to Chromic Acid Anodizing (CAA). The corrosion resistance and the durability of the Al/CFRP interface was investigated and discussed. Polarization curves and Evans Diagrams were achieved in NaCl solution, and the adhesion and durability of the interface was evaluated by mechanical tensile test on single lap joint specimens before and after salt spray exposure. The results are discussed and compared to CAA in order to evaluate

the proposed treatments as CAA substitution candidate in the REACH European regulation. It was found that TSA and γ -GPS can provide as good adhesion as CAA before salt spray exposure, but a mechanical higher strength depletion of the interface is obtained after long term salt spray exposure compared to CAA. This depletion was attributed to an insufficient long term corrosion resistance of TSA or γ -GPS compared to CAA.

Keywords: Aluminium/composite hybrid structures; Durability; Galvanic corrosion; coatings; Manufacturing; co-curing

36 **Introduction**

37 In recent years, hybrid composite/metal structures are flourishing in the aerospace industry.
38 These hybrid structures are mainly made of composite materials, for their good performance-
39 to-weight ratio. Metal inserts are generally used to compensate for shortcomings in composite
40 performance, such as conductivity or joining capabilities. In addition, the global trend of
41 aerospace components and structures of gaining new functionalities, in combination with
42 weight reductions, will lead to an increase in the use of hybrid composite/metal,
43 composite/composite or metal/metal components in the near future. In this context, the use of
44 aluminium/CFRP structures is of significant interest in the aerospace industry, but the key
45 technological issues for such hybrid structures are its assembly and its mechanical properties
46 such as durability when subjected to corrosion.

47 The first point has been widely studied by researchers and engineers seeking the most
48 effective way to assemble dissimilar materials. Recently, one author presented an exhaustive
49 review of the various technologies available today (Martinsen et al. 2015). Among all of the
50 available technologies, the most efficient way to assemble a composite to metal appears to be
51 through co-curing composite and metal, by introducing a metallic part directly during the
52 manufacturing of the composite and by performing a direct, in-situ adhesion, following the
53 co-curing ideas of few authors (Gebhardt and Fleischer 2014, Schwennen et al. 2016, and
54 Ferret et al. 1998).

55 In Al/CFRP hybrid structures, where metal and composite are closely in contact, the strength
56 and durability of the interface between the metal and composite are fundamental to ensure the
57 load introduction from metal to composite. Moreover, due to the high corrosion potential gap
58 between aluminium and carbon, strong galvanic corrosion may occur and efficient corrosion
59 protection must be applied between the aluminium and the CFRP to avoid this destructive
60 phenomenon. Solutions have been developed to avoid direct contact between the aluminium
61 and carbon fibres, such as placing a dielectric layer in between the composite and metal

(Vermeeren 1991), or using a protective pre-treatment on Aluminium (Higgins 2000, Petrie 2007). Moreover, many pre-treatments of aluminium alloys have been developed to ensure good adhesion between Al and polymers and are, for example, commonly used in painted aluminium structures or aluminium adhesive bonding in the aerospace industry (Higgins 2000, Petrie 2007). These processes are based on a passive and protective alumina scale responsible for the corrosion protection and the adhesion. However, most of them use CrVI compounds to protect the aluminium against corrosion, whereas CrVI compounds are known to be detrimental to human health and the environment, so the European REACH regulation tends to encourage their substitution in industrial products. Park et al. (Park et al. 2010) published a review of surface pre-treatments for aerospace applications suitable for the substitution of CrVI pre-treatments. According to the authors, non-chromate anodizing, silane, sol-gel, laser, plasma, and ion-beam-enhanced deposition processes could be suitable candidates. This choice of processes has been confirmed by Sinmazcelik et al. (Sinmazcelik et al. 2011) in the case of high interface performances in Fibre Metal Laminate applications. There are many publications concerning the aluminium CrVI free pre-treatments and their adhesion or corrosion properties, but very few publications concern metal/composite joining dealing with both mechanical and corrosion performances. It is therefore of great interest to study the influence of aluminium treatments on interface corrosion properties in such materials and to assess the durability of the joint after exposure to a humid or corrosive environment. In a previous work, several surface pre-treatments of aluminium plates, bonded by an epoxy based film adhesive were screened (Agogu et al., unpublished report 2014). Higher strengths were obtained through Chromic Acid Anodizing (CAA), Tartaric Sulfuric Anodizing (TSA) or γ -glycidoxypropyltrimethoxysilane silanization (γ -GPS). For that reason, only CAA, TSA and γ -GPS were considered in this work.

Material and methods

88 **Sample preparation**

89 The materials selected for this study are an Al-2024-T3 aluminium alloy (composition in
90 wt.%: 4.4% Cu, 1.50% Mg, 0.6% Mn, Al bal.), an Al-2198-T3 aluminium alloy (Composition
91 in wt.%: 3.2% Cu, 0.95% Li, 0.53% Mg, 0.3% Ag, 0.11% Zr) and a CFRP quasi-isotropic UD
92 laminate (T700GC/M21, Hexcel Composites) made from prepreg. The chosen stacking
93 sequence for the composite is [45/90/-45/0]_{2s}.

94 For galvanic corrosion measurements, 10 x 10 x 4 mm coupons were from a 4 mm thick sheet
95 for both Al-2024 and Al-2198. One 10 x 10 x 4 mm coupon was cut from the CFRP plate, in
96 order to expose the XY face in contact with the aluminium alloy in the co-cured material, as
97 shown in Fig. 1. All the coupons were cut with an Isomet 4000 precision cutter from Buehler.

98 For single lap joint tensile tests, 125 x 156 x 8 mm hybrid plates, made of two overlapping Al
99 and CFRP plates, were prepared by a co-curing process. The first plate was made of
100 composite, whereas the second one was made of aluminium. Each plate had the same size of
101 125 x 90 x 4 mm. The overlapping area was set to 125 x 24 mm². The thickness of the test
102 specimens was designed to avoid any plasticity effect in the aluminium plate during the
103 mechanical tests.

104 Before manufacturing hybrid materials, the aluminium samples were prepared as follows: (i)
105 the surface of the aluminium plates was cleaned with ethanol and deionized water; (ii) an
106 alkaline cleaning was performed using a 10% NaOH solution for 3 min at 60°C; (iii) after
107 rinsing with deionized water, the samples were etched in a 30% nitric acid solution for 10 min
108 at room temperature; (iv) the samples were rinsed with deionized water and dried for 30 min
109 at 80°C.

110 After this preparation sequence, CAA, TSA and γ -GPS were finally applied as shown in
111 Table 1. The treated aluminium samples were co-cured within one hour after this surface
112 treatment sequence.

The following steps were carried out for the co-curing process of Al/CFRP specimens: (i) the treated aluminium plate was placed in the mould; (ii) the prepreg plies were placed according to the chosen stacking sequence and the overlapping area; (iii) a two-hour dwell at 180°C was performed to consolidate the composite. In addition, a pressure of 6 bars was applied to the composite during curing. The Al/CFRP interface was generated before gelation of the polymer, when the resin flows from prepreg to the interface; (iv) Finally, four 156x24x8 mm SJL specimens were machined from the co-cured plate (Fig. 2).

Corrosion and mechanical tests

The galvanic coupling was evaluated by the Evans method using polarization curves of the aluminium alloys and CFRP specimen. The polarization curves were measured using a model 273A potentiostat in a neutral 3.5% NaCl solution at room temperature (20°C). The potential scanning rate was 1 mV.s⁻¹. A saturated Ag/AgCl electrode was used as the reference electrode, and the counter electrode was a 1 mm diameter platinum wire. Before the CAA, TSA, and γ-GPS treatments and measurements, the Aluminium and CFRP specimen were embedded in an isolating resin and polished, leaving an area exposed to the solution during the electrochemical measurements. In order to evaluate the direct galvanic coupling between Al and carbon fibres, a non-impregnated carbon fibre yarn was directly embedded in isolating resin and polished as described before. The carbon fibre area was evaluated according to the number of fibres in the non-impregnated yarn and their diameter. The current densities presented in this paper were obtained after normalization of the measured current by this calculated area.

The salt spray ageing was conducted for 240h at 35°C in neutral 5% NaCl salt spray according to ASTM B117 with a S120T Salt Spray Chamber from Ascott. During the salt spray test, the cut edges of the specimens were protected with a 1263 ADR3 VGII varnish from Blaser Malter.

The mechanical properties of the co-cured interface were measured using a single lap joint (SLJ) test. The jaws clamp the sample and are tightened by means of wedges and screws (measured tightening torque). Tensile tests were carried out at a constant velocity of 1 mm.min⁻¹ until the ultimate load was reached. In order to characterize the experimental dispersion, at least 3 samples of each configuration were tested. Each sample for each configuration was machined from the same plate. The experimental dispersion presented in this work corresponds to the standard deviation over the specimens.

Results and discussion

In this paper, results are divided into 3 main parts. First, the galvanic corrosion behaviour of Aluminium alloys Al-2024 and Al-2198 with composite T700/M21 [45/90/-45/0]2S is presented. Secondly, a general investigation of the effect of surface pre-treatments on interfacial strength is performed. The last part is focused on the effect of corrosion on the residual properties of the interface. For this deeper investigation, only Al-2024 is considered. The global test matrix for the characterization of the interface properties is presented in Table 2.

Analysis of the Al/CFRP co-cured specimens

Two kinds of defects were analysed on produced samples: (i.) the porosity, since Park et al. (Park et al. 2010) observed a premature failure of GLARE laminates due to the porosity located at the interface; and (ii.) the shape distortion due to residual stress, since some authors have observed geometrical distortions due to the difference in the coefficient of thermal expansion of the composite and the aluminium layer in hybrid composite/metal structures (Kim et al. 2006). The assessment of the porosity rate was performed using cross-sectional observations of the samples. As shown in Fig. 3, no porosity was found on micrographs at the Al/CFRP interface for the characterized samples. Moreover, the thickness of the interface could also be estimated: a polymeric layer of 5 µm to 20 µm over a 5 µm protective alumina scale was observed for TSA samples (Fig. 3 b), whereas the polymeric layer is thinner

without any visible protective alumina scale for samples with no treatment, where direct contact between the carbon fibres and aluminium can consequently be observed in some locations (Fig. 3 a).

The curvature of the specimens was measured and found to be very small in comparison to the sample typical length. Consequently, the effect of residual stress and residual strain was neglected in this paper.

Galvanic corrosion measurements

Fig. 4 and Fig. 5 show the polarization curves of Al-2024 and Al-2198 specimens in a 3.5% NaCl solution.

It can be seen that, for any given potential and alloy, the lowest anodic current density is obtained by far for CAA, confirming its excellent corrosion behaviour. The anodic current density decreases with TSA and silanization on Al-2024, but the effect is weaker than that obtained with CAA and is only relevant for low anodic potentials (between -0.5 and -0.35 V/NHE). For the Al-2198 alloy, the effect of TSA on the anodic current density reduction is only relevant for potentials between -0.5 and -0.3 V/NHE. At higher potentials, the current density is higher than for the unprotected alloy. With regard to the silanization treatment on the Al-2198 alloy, the reduction of the anodic current density is very weak compared to the TSA treatment and is only effective in a potential window between -0.5 and 0 V/NHE. At higher potentials, no protection effect can be observed. These results confirm the results obtained by Zhang et al. where CAA on Al-2024 induced a better corrosion resistance than other anodizing processes like Phosphoric Acid Anodising, Boric Acid Anodising or Boric Acid/Sulfuric Acid Anodising in Aluminium/Aluminium adhesive bonding (Sheng Zhang et al., 2008).

The Fig. 6 shows the polarization curves of the CFRP specimens in an aerated 3.5% NaCl solution measured on the XY faces of the specimen (Fig. 1). The polarization curve of non-impregnated carbon fibre yarn in the same solution is also presented in Fig. 6.

It can be seen that the zero current potential of the XY face of the CFRP specimen and the non-impregnated carbon fibre yarn are similar, with about -0.06 V/NHE and -0.16 V/NHE respectively. On the other hand, the current density values obtained when the potential varies from the zero current potential to more cathodic potentials are very different. It can effectively be seen that the measured current density is about ten times higher for the non-impregnated carbon fibre yarn than for the XY face for a same overpotential. This difference in cathodic current density is due to the orientation of the carbon fibres in both specimens. In the non-impregnated carbon fibre yarn specimen, the carbon fibres are orthogonal to the measured surface, so the current can directly flow through the carbon fibre length with very low electrical resistance, allowing high current density at high overpotential. Conversely, in the XY face of the CFRP specimen, the stacking sequence induces discontinuity in the current flow between carbon fibres and plies through the specimen's thickness, so the current can only flow due to local contact between fibres and plies, inducing a higher electrical resistance and a lower current density compared to non-impregnated carbon fibres when the overpotential increases. However, despite the relatively low contact between carbon fibres in the CFRP specimen, it can be seen that the cathodic current density is not negligible and that the CFRP behaves as a conductive material, confirming the possibility of galvanic corrosion, when assembled to metallic parts and exposed to corrosive environment. It can also be noticed that, despite the low cathodic current densities measured on the XY face of the CFRP specimen, the local current density obtained at the surface on the carbon fibre in contact with the corrosive solution can reach the same value as that obtained on the non-impregnated carbon fibre specimen, so the local galvanic corrosion can be high and destructive.

The galvanic current and potential determination was carried out using the Evans method. This method consists in measuring the polarization curve of the two constitutive materials in the corrosive media (Figures 4 to 6) and in constructing the galvanic coupling by representing on the same graph, the anodic part of the aluminium polarization curve and the absolute value

of the cathodic part of the composite curve. Fig. 7 shows the Evans diagrams of the unprotected and protected Al-2024 and Al-2198 alloys coupled with the XY face of the CFRP and the non-impregnated carbon fibre yarn. For each coupling configuration, the respective coupling potential and coupling current density have been determined and summarized in Table 3.

It can be seen that, whatever the treatment, a decrease in the galvanic corrosion current density can be observed for both tested alloys when compared with the unprotected coupons. The efficiency of the treatment in a galvanic coupling situation is similar to what has previously been observed in polarization curves. The CAA treatment is identified as the best treatment. The galvanic current is divided by about 2 to 5 for Al-2024, and divided by 2 to 7 for Al-2198, depending on the CFRP configuration.

The efficiency of TSA or γ -GPS silanization is different depending of the considered alloy: for Al-2024 alloy, the γ -GPS silanization is better than TSA and its performance is equivalent to that of the CAA treatment. When compared with the untreated alloy case, the galvanic current is divided by a factor 2 to 3 for γ -GPS, whereas it is only divided by a factor 1.5 to 2 for TSA; for the Al-2198 alloy, TSA is better than γ -GPS. The galvanic current is divided by a factor 2 to 2.7 for TSA, whereas there is almost no effect of the γ -GPS treatment on the galvanic current density on Al-2198.

The aluminium alloy treatments can therefore be ranked with regard to the anti-corrosive effect from these measurements. For the Al-2024 alloy, the ranking is the following: CAA is slightly better than γ -GPS, which is better than TSA. For the Al-2198 alloy, the ranking is the following: CAA is better than TSA, which is better than γ -GPS.

Mechanical properties of the interface of the co-cured specimens

The interface strength of manufactured samples was assessed using a single lap joint tensile test. In order to characterize damage kinetics, the acoustic emission (AE) was recorded during one test of each series using a piezoelectric sensor held on the aluminium plate. Three tests

were performed for each aluminium pre-treatment series and were similar to each other. The stress is the ratio between the applied force and the interface area (24x24 mm²), and the displacement used is that of the tensile machine. Fig. 8 and Fig. 9 show stress/displacement curves, respectively, for Al-2024 and Al-2198, and only for one test by pre-treatment series. For both aluminium alloys, the linear behaviour was observed from 3 MPa up to the ultimate load with a brittle failure. Under 3 MPa, the nonlinear behaviour is due to the positioning of the jaw clearances. A brittle failure mode at the composite/aluminium interface was observed for all specimens, which was confirmed by the morphology of the fracture surface.

The lap-shear ultimate strength of the samples is presented in Fig. 10. In this figure, error bars represent the standard deviation of the measurements. The obtained values, between 14 and 17 MPa, are similar with ultimate strength obtained in Al/CFRP co-cured interface without any chemical pre-treatment of the aluminium (Park et al., 2006) and comparable with values obtained in classical adhesive joints by few authors in Al/CFRP adhesive joints with different surface finish of the aluminium (Arenas et al., 2013), or in Al/Al adhesive joints with different anodising pre-treatments of the aluminium, including CAA (Sheng Zhang et al., 2008). The co-cured Al/CFRP interface has therefore a similar strength than equivalent assemblies produced with more classical adhesives.

It can be seen in Fig. 10 that TSA and γ -GPS treatments provide a higher interface strength after co-curing in comparison to the CAA treatment for Al-2024 (respectively +11% and +9%). For Al-2198, the interface strength is very slightly higher with the TSA and γ -GPS treatments than with the CAA treatment (respectively +3% and +2%), but in the end the relative standard deviations show similar strength when considering the three specimens. Given that CAA is well known to provide high interface strength in aluminium adhesive joints (Sheng Zhang et al. 2008), this result indicates that TSA and γ -GPS provide an equivalent or even better adhesion between aluminium and CFRP just after co-curing. These

two pre-treatments seem to be good candidates for the replacement of CAA for both aluminium grades.

The acoustic data are recorded in order to detect the first occurrence of damage, by means of the cumulated absolute energy, which is the integral of the squared signal amplitude over the hit duration. The first rise of this energy is around 106 aJ and is considered as the damage threshold. For both aluminium materials, the damage initiation with the CAA pre-treatment occurs before the two other cases. The TSA and γ -GPS pre-treatment delay the damage initiation stress, respectively, of +32% and +24% for the Al-2024 and of +42% and +48% for the Al-2198 (Fig. 11).

For the Al-2024/CFRP, the damage seems progressive whatever the pre-treatment performed, meaning that the damage starts at between 50% and 66% of the maximal loading. It can be added that the γ -GPS pre-treatment shows many more high-energy events than the CAA and TSA and thus a better interface resistance for the Al-2024. For the Al-2198/CFRP, the damage still seems progressive and with many damage events for the CAA pre-treatment (starting from half of the maximal loading), but seems to be instantaneous for the other pre-treatments, as the damage initiates during the last quarter of the curve and with less damage events. In this Al-2198 case, the CAA pre-treatment presents a good interface resistance as it bears the numerous high-energy events, despite an early damage initiation.

Residual properties of the interface after salt-spray ageing

In order to evaluate the galvanic corrosion damage with regard to the Al/CFRP interface strength and to assess the durability of CAA, TSA and γ -GPS in a corrosive environment, SLJ tensile tests were carried out on Al-2024/CFRP co-cured specimens after aging in a neutral salt spray chamber for 240h at 35°C and compared to previous results obtained after co-curing. The lap-shear ultimate stresses of the samples obtained before and after aging in a neutral salt spray chamber are presented in Fig. 12.

It can be seen from results obtained after salt spray exposure that a strength reduction of about 20% occurs with TSA and γ -GPS, whereas no reduction is observed with the CAA treatment, indicating that the protection obtained with TSA or γ -GPS is not as efficient as that obtained with the CAA treatment.

Ranking of the aluminium alloys treatments regarding the residual strength after ageing: CAA is better than TSA and γ -GPS. TSA and γ -GPS provide similar performances.

Examination of the fracture surface

In this subsection, fracture images of samples before and after salt spray testing are presented.

It can be seen from the fracture surfaces of co-cured Al-2024/CFRP SLJ specimens before salt spray tests (Fig. 13), that the aluminium part contains CFRP materials and resin, showing that the fracture occurs at different interfaces between the alumina surface and the inner part of the CFRP.

This behaviour, already shown in co-cured Al/CFRP materials (Park et al., 2006) is consistent with mixed adhesive/cohesive failure mode, indicating a good adhesion between the aluminium part and the CFRP because of a non-negligible part of cohesive failure in the CFRP material. The morphology of the different samples is very similar, indicating a similar behaviour of the interface whatever the aluminium treatment, thus confirming the SLJ tensile test results discussed before.

Fig. 14 shows the fracture surfaces of an Al-2024/CFRP co-cured SLJ specimen after salt spray testing and tensile testing. Fig. 15 shows the Al-2024 SEM fractography of the same specimens in back-scattered electrons, in order to better identify the chemical nature of the fracture surface.

It can be seen from Fig. 14 and Fig.15 that the morphology of the interface is different for each aluminium pre-treatment.

In the case of γ -GPS pre-treated Al-2024, corrosion evidence can be identified at the edges of the fracture surface of the aluminium part. This corrosion is probably responsible of the decrease in the interface strength observed after salt spray exposure.

With regard to the TSA treated aluminium, the interface morphology does not show any corrosion evidence, but the very low fraction of remaining CFRP material on the fracture surface of the aluminium part indicates a relatively high rate of adhesive failure mode of the interface. Indeed, a large alumina area can be seen on the aluminium surface after tensile testing compared to other samples. The presence of alumina revealed the failure of the resin/alumina interface characteristic of this adhesive failure.

CAA treated aluminium samples show the best behaviour with no evidence of corrosion and the lowest area of adhesive failure compared to other samples. A high failure area can indeed be seen in the CFRP itself, which is characteristic of a good adhesion, even after long-time exposure in a corrosive environment.

The analysis of fracture surfaces after salt spray exposure and tensile testing thus confirms the results obtained with corrosion measurements. The CAA-treated aluminium sample shows the best behaviour because of a good adhesion combined with an excellent corrosion resistance. TSA treated aluminium samples show a slight degradation of the interface strength, mainly due to a lower adhesion at the oxide/CFRP interface than in the CAA case. Finally, γ -GPS treated aluminium samples show deficient durability because of the poor durability of the γ -GPS coating when subjected to a corrosive environment, reducing the loaded area of the interface, producing a large decrease in the interface strength after exposure to a corrosive environment.

Conclusions

The adhesion and durability of the interface of hybrid aluminium/CFRP co-cured specimens was compared using three different surface treatments applied on either Al-2024 or Al-2198 aluminium alloys before the co-curing process: Chromic Acid Anodizing (CAA), tartaric-

Sulfuric Anodizing (TSA) and γ -GlycidoxyPropyltrimethoxySilane (γ -GPS). Galvanic corrosion was studied with potentiodynamic analysis and the Evans method, showing that CAA provides the best protection against corrosion, with a corrosion current divided by a factor 2 to 7 compared with TSA or γ -GPS, depending on the aluminium alloy and the CFRP direction. Mechanical tests on SLJ Al/CFRP co-cured samples showed that CAA, TSA or γ -GPS lead to good interface properties, showing a mixed cohesive/adhesive fracture and similar tensile strength of the interface after the co-curing step, thereby confirming that TSA or γ -GPS treatments provide good adhesion properties compared to CAA after manufacturing. However, the mechanical tests performed on similar samples after 240h salt spray tests lead to a 20% reduction of the tensile strength of the interface for TSA and γ -GPS. The analysis of the fracture surface showing corrosion of the aluminium at the interface was identified as the main reason of this interface strength reduction for the γ -GPS treatment, whereas an adhesive failure was identified for the TSA treatment. With regard to the CAA treatment, no reduction of the interface strength was identified after corrosive environment exposure, showing the excellent corrosion resistance of CAA even in a galvanic corrosion situation with carbon fibres.

This study thus showed that either TSA or γ -GPS can produce a satisfying adhesion between aluminium alloys and CFRP in co-cured parts, but that the corrosion resistance is too weak compared to the CAA treatment to obtain a good durability of the interface in galvanic corrosion situations, particularly for γ -GPS treatment where the corrosion of the aluminium was clearly identified as the cause of the interface strength reduction.

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Table 1. Surface preparation of the aluminium samples before corrosion tests or co-curing of Al/CFRP hybrid material specimens

Process	Composition		Conditions
1- Chromic Acid Anodizing	CrO ₃	50 g/L	Anodizing at 40°C, 40V for 20 min, then 50V for 10 min
2- Tartaric Sulfuric Anodizing	C ₄ H ₆ O ₆	80 g/L	Anodizing at 35°C, 15V for 30 min
	H ₂ SO ₄	45 g/L	
3- γ-GPS silanization	γ-GPS	1% vol.	Dipping for 10 min, air drying, condensation for 60 min at 80°C

Table 2. Experimental test matrix for the characterization of the interface properties

Aluminum alloy	Pre-treatment	Mechanical performances		Fracture surface	Galvanic coupling
		After manufacturing	After ageing		
Al-2024	Untreated				●
Al-2024	CAA	●	●	●	●
Al-2024	TSA	●	●	●	●
Al-2024	γ-GPS	●	●	●	●
Al-2198	Untreated				●
Al-2198	CAA	●			●
Al-2198	TSA	●			●
Al-2198	γ-GPS	●			●

Table 3. Corrosion potentials E_{corr} and coupling current densities I_{corr} for coupling between untreated and treated Al-2024 and Al-2198 alloys and for two CFRP configurations.

Alloy	CFRP, XY face		Isolated carbon fibers	
	E_{corr} (V/NHE)	i_{corr} (A/cm ²)	E_{corr} (V/NHE)	i_{corr} (A/cm ²)
Al-2024	-0.529	3.09E-06	-0.519	1.13E-04
Al-2024 + CAA	-0.444	1.61E-06	-0.362	1.98E-05
Al-2024 + TSA	-0.476	2.11E-06	-0.442	5.32E-05
Al-2024 + γ -GPS	-0.423	1.30E-06	-0.409	3.61E-05
Al-2198	-0.523	2.98E-06	-0.501	9.63E-05
Al-2198 + CAA	-0.440	1.55E-06	-0.334	1.35E-05
Al-2198 + TSA	-0.433	1.44E-06	-0.409	3.61E-05
Al-2198 + γ -GPS	-0.507	2.68E-06	-0.495	9.08E-05

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