MANUFACTURING AND SERVICE APPLICATION CONCERNS THAT INFLUENCE LEADING EDGE PROTECTION RAIN EROSION PERFORMANCE IN WIND TURBINE BLADES

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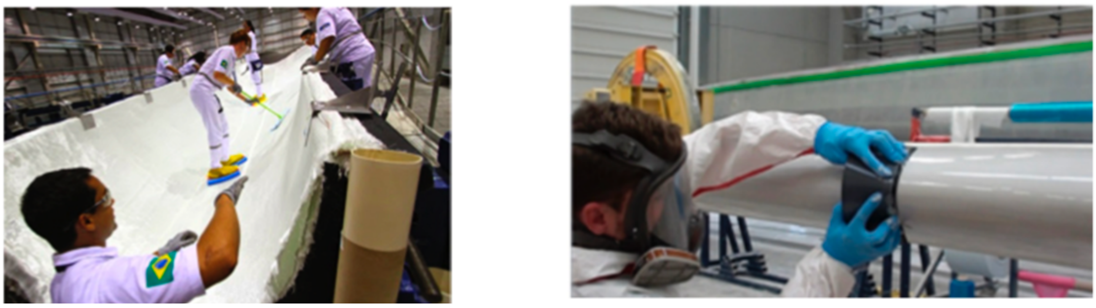
Abstract
Erosion damage, caused by repeated rain droplet impact on the leading edges of wind turbine blades, is a key cause for maintenance and reliability issues. Resin Infusion (RI) is used in wind energy blades where low weight and high mechanical performance materials are demanded. The surface coating plays a crucial role in the manufacturing and performance response. The Leading Edge Protection coating is usually moulded, painted or sprayed onto the blade surface during manufacture or during a repair in-field, often in a number of layers. Adequate adhesion between these layers is required for mechanical performance and durability reasons. In the current work, an investigation into the rain erosion durability of various coatings has been undertaken. Mass loss measurements are used as the key metric in an effort to assess the response of changing manufacturing processing parameters. The adhesion and erosion is affected by a number of shock waves caused by the collapsing water droplet on impact [2]. The stress waves are transmitted to the substrate, so microstructural discontinuities in coating layers and interfaces play a key role on its degradation. Standard industrial systems are based on a multilayer system, with a high number of interfaces that tend to accelerate erosion by delamination. Analytical and numerical models are commonly used for lifetime prediction and to identify suitable coating and composite substrate combinations and their potential to reduce stress on the interface. In this research, the material parameters for the appropriate characterization of the coating-substrate interface are outlined by several laboratory tests, including Differential Scanning Calorimetry (DSC), pull-off testing, peeling–adhesion testing and nanoindentation testing. The rain erosion performance is assessed using an accelerated testing technique, whereby the test material is repeatedly impacted at high speed with water droplets in a Whirling Arm Rain Erosion Rig (WARER) [3,4].

1. Introduction

Rain erosion damage on wind turbine blades, is a major cause for maintenance cost concern, see Fig.1. The problem has been approached by developing new coating systems to diminish the erosion drawback. In this research, two main coating technologies have been considered: In-mould coatings (Gel Coat) applied during moulding on the entire blade surface and the Post-mould coatings specifically developed for the Leading Edge Protection (LEP) and usually moulded, painted or sprayed on the frontward facing leading edges of the wind turbine blades, see Fig.2.

(a) (b)

Figure 1 (a) Examples of leading edge erosion across a range of years in service; (b) blade section with leading edge location where the rain erosion protection is critical.



(a) (b)

Figure 2. (a) Surface textile material application over the in-mould coating before the resin infusion process of a large turbine blade. Depending on the curing conditions of the coated area, its chemical and adhesion relation with the later infused resin is different. (b) Leading Edge Protection application with trowel.

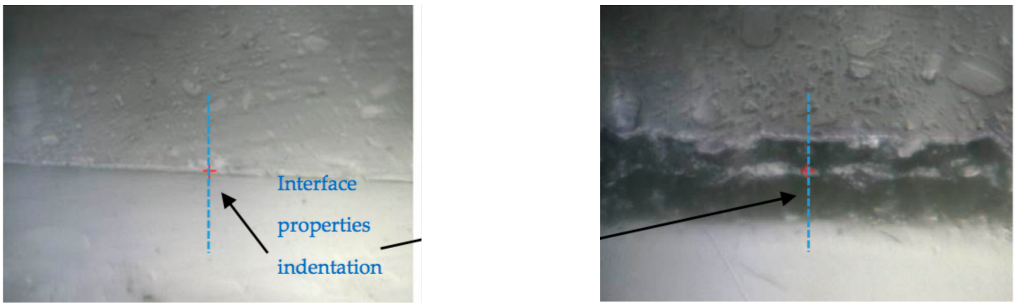
The coating adhesion and erosion is affected by a shock wave caused by the collapsing water droplet on impact. The stress waves are reflected and transmitted to the laminate substrate depending on their relative acoustic properties [2]. It is necessary to optimize the contact adhesion resistance of the multi-layered system interface boundaries in order to avoid failure by delamination. The experimental investigation has been directed into the resulting rain erosion testing performance depending on the coating-laminate interphase adhesion characterization, which was assessed by pull-off testing, peeling-adhesion testing and nanoindentation testing. The work considers distinctive coating configurations as study cases [1]: A first case analyses the effects of the in-mould Gel Coat curing, and a second one ponders the inclusion of a primer layer and a filler layer on a LEP configuration system. The rain erosion performance is assessed using an accelerated testing technique, whereby the test material is repeatedly impacted at high speed with water droplets in a Whirling Arm Rain Erosion Rig (WARER) [3,4]. The results are shown to analyse manufacturing and coating processes for blades into knowledge-based guidelines for leading edge coating material development.

2. Effect of Curing Conditions of In-Mould Blade Coatings on Erosion Performance

In this section, the in-mould curing conditions are studied with a view to assessing how they affect erosion performance. Two different curing conditions for the in-mould gel-coat EPOLIT GC are used in order to generate differences in the impregnation and flow advancement of the epoxy resin in the dry laminate preform during filling. The whole part is completely cured in both cases before demoulding. The substrate laminate of the testing coupons used in this work were manufactured in both cases with two-layer biaxial glass fibre (1.4 mm thick) and the in-mould coating layer was defined as 0.3 mm, as in the previous case. Coat 1 and Coat 2 were previously characterised by performing a measure of the degree of conversion of the polymerisation reaction of the polymer matrix. The degree of conversion (α) is obtained by measuring the residual enthalpy ΔH (J/g) using Differential Scanning Calorimetry (DSC). Coat 1 is cured for 24 h at 25 °C, which is considered to be a full cure (89.7% cured), whereas Coat 2 is cured for 40 min at 45 °C, which is considered to be semi-cured (59.3% cured). The typical mechanical testing used in the wind turbine industry for material qualification is shown in order to assess the macroscopic behaviour of the laminates and how it is influenced by the coating curing conditions. Pull-off strength testing of the samples showed different cases in which the failure is in the composite laminate, and hence the ability of the coating to assure the required target strength. No information regarding the interphase strength is given in cases where the failure does not take place in the coating or in the interphase, but it does indicate a limit value. Moreover, there is a lack of information in the literature regarding the curing effect on the interphase. A specially developed peeling test for interphase coating–laminate adhesion response quantification showed the differences on the adhesion laminate-coating depending on its curing. The failure load for peeling interphase adhesion testing. Coat 1 (Cured) had an average value 19.3 N and Coat 2 (Semi-cured,) of 25.1 N.

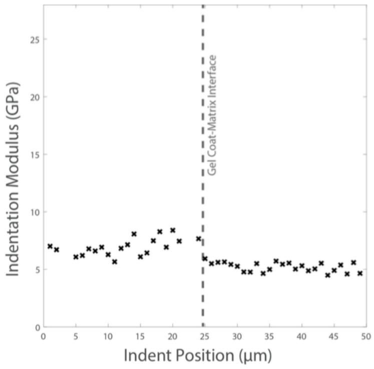
In order to explore a local variation of the acoustic impedances due to the interface layer in both cases, nanoindentation testing was done. Lines of indents were carried out across these interfaces through the thickness; see Fig.3. For sample Coat 1 (Cured), a distinct interface is detected where the indentation modulus for the EPOLIT GC gel coating is slightly larger than that of the GFRP composite epoxy-based matrix material; see Fig. 4 (a). However, for the Coat 2 (Semi-cured) sample, a clear interphase is present between the materials, where the interphase has a much larger stiffness than either material, see Fig.4 (b).

These results correlate well with the erosion testing and also with the acoustic impedance variation due to the interphase. A very interesting result concerns the improved acoustic effect of the Coat 2 interphase, i.e., Semi-cured. It can be reasoned how the relative impedances from the Gel Coat–Coat 2 interphase layers may generate and attenuate the reflected and transmitted waves from the coating to the first substrate layer and even larger from this one to the GFRP laminate. It can be appreciated the delayed incubation time obtained from the erosion testing and observed in Fig. 5.

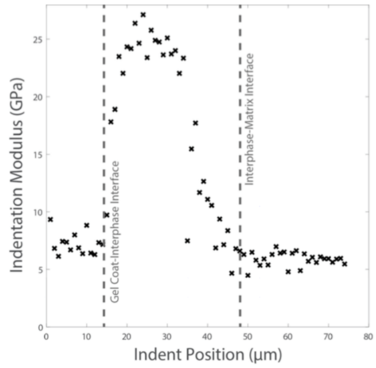


(a) (b)

Figure 3. Layout of the indentation for Gel Coat and interphase properties of the two cases of curing. (a) Coat 1, i.e. Cured and (b) Coat 2, i.e. Semi-cured.

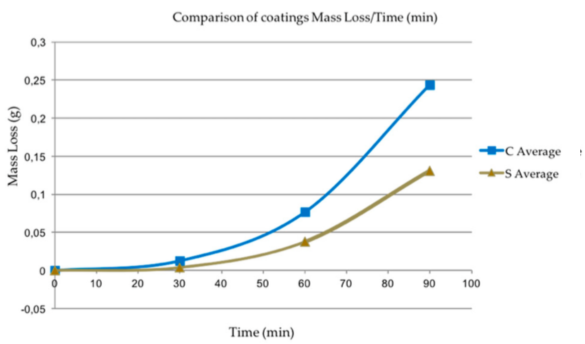


(a)

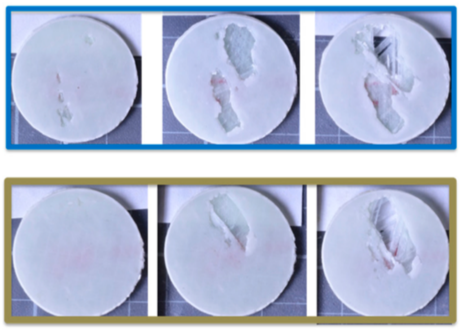


(b)

Figure 4. Two series of indents across the interface for the two samples of in-mould Gel Coat and the epoxy based matrix of the GFRP laminate with different curing conditions (a) Coat 1, i.e. Cured and (b) Coat 2, i.e. . Semi-cured. A clear interphase is present between the materials, where the interphase has a much larger stiffness than either material.



(a)



(b)

FIGURE 5. (a) Average mass loss versus time for two different coatings: Coat 1 i.e. Cured (C in blue) and (b) Coat 2 Semi-cured, (S in Green). (b) Images of surface and delamination damage at 30, 60 and 90 min.

The key points to take from this case study are that the adhesion of the coating to the substrate is of paramount importance for the rain erosion resistance of the material. The coating, which was only partially cured before the fibre reinforcement was inserted, out-performed the coating, which was fully cured, in all aspects of the test.

3. Effect of Primer on the Performance of Leading Edge Protection (LEP) Coatings

Post-mould application is typically used to apply Leading Edge Protection (LEP) in locations where the threat of rain erosion arises. Industrial processes state that LEP systems can be outlined as a multi-layered system, where some manufacturers include a putty layer between the laminate and the coating. Some manufacturers also include a primer layer under the coating and over the putty to improve adhesion. The coating application procedure is designed with the final material properties in mind (i.e., thickness, number of coating layers, surface roughness, temperature, humidity, viscosity, processing time, curing time, etc.). Specific post-mould application methods and materials are similarly employed when repairing a damaged area, during a service or as part of a prevention maintenance programme. The repair of the LEP damage is most frequently achieved through the unsophisticated application of a primer-based layer and putty materials, smoothed over, and then cured to generate a new uniform and smooth surface finished to the affected blade zone—see Fig. 6.

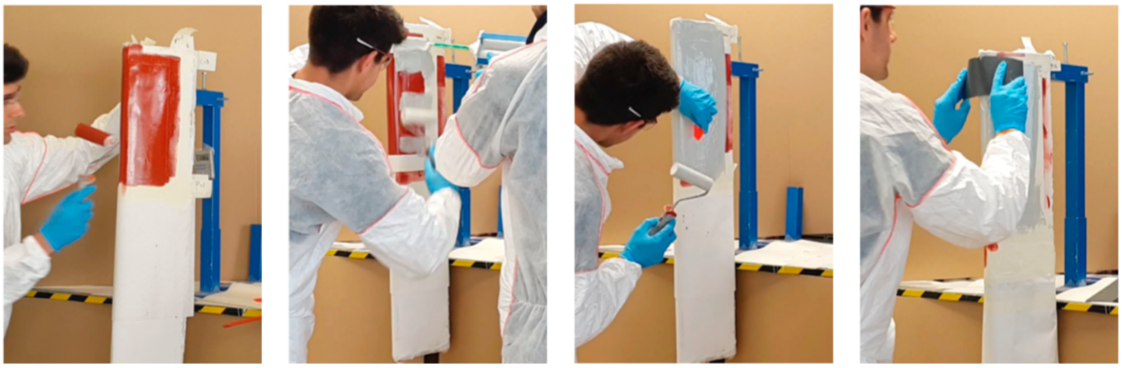
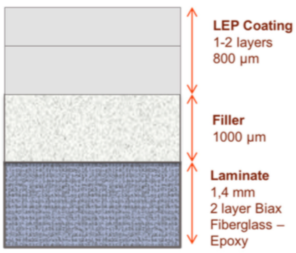
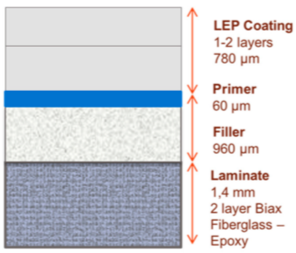


Figure 6. Leading Edge Protection Service application with different techniques, from left to right: application of the primer layer, the putty/filler/LEP material, thickness needs to be monitored closely, the surface is screened down to ensure a flat, smooth surface following the blade contour

In this section, a post-mould coating system configuration that includes a filler layer between the surface coating and the composite laminate is assessed. The performance of this configuration was compared to a comparable system that includes an additional primer layer to improve the contact adhesion of the coating to the substrate, as depicted in Figure 7. The two configurations of the testing coupons make use of a similar prototype LEP material (AEROX AHP LEP900, a range of products) with the substrate defined by an intermediate filler layer prototype (EPOPUR MS900, a range of products). The substrate (from the EPOPUR MS range), and the composite laminate, in both cases, is a two-layer biaxial Glass Fibre laminate (1.4 mm. thick). The primer layer included in one of the configurations is based on a prototype material (EPOLIT PR100, range of products). This configuration is not optimised to perform for an extended period of time – rapid testing and delamination failure analysis are the focus of this experiment.



(a)

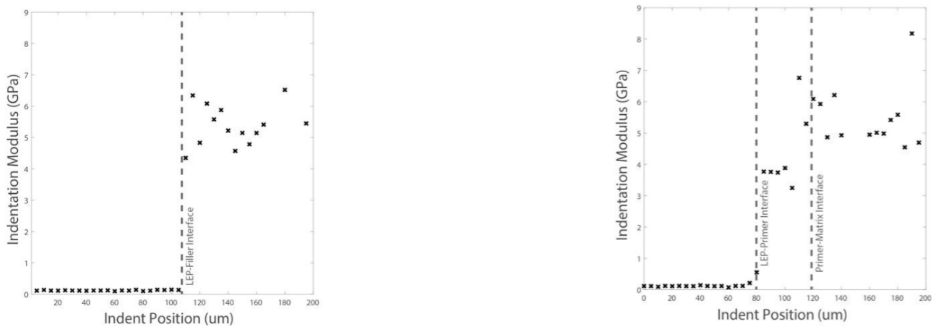


(b)

Figure 7. (a) Leading Edge Protection Coating configuration with an intermediate filler layer. (b) Additional primer layer included to improve adhesion to substrate.

Pull-off testing of the samples achieved the adhesive failure for the no-primer configuration (with a value of 5.6 MPa) and the cohesive failure (6.77 MPa) of the specimens that included the primer layer. Peeling testing demonstrated the improved interphase coating–laminate adhesion response when the primer layer is included, with a force load for peeling with a value of 29.3 N (averaged across five samples), versus a value of 9.45 N for the no-primer configuration. It was clear that the primer significantly improves the adhesion of the LEP to the filler. Complementary nanoindentation tests were carried out on the primer application configuration for more precise local interface discontinuities characterisation, see Fig.8. While a distinct change in modulus is apparent for the LEP–primer interface, the slightly lower modulus of the thin primer layer (compared with the filler) can be seen for the primer–

filler interface, see Fig. 8 (b). This result reveals a similar acoustic impedance on the primer–filler interface and also shows how the primer matches the filler acoustic impedance without pronounced discontinuities.



(a) (b)

Figure 8. Two series of indents reveals (a) a similar acoustic impedance on Primer-Filler interface and (b) shows also how the primer matches the filler acoustic impedance without pronounced discontinuities

These testing results correlate with the rain erosion tests, as shown in Fig. 9. It can be observed in both cases how the erosion failure advances from the surface through the multilayer system thickness until it reaches the laminate. The incubation time (start of perceptible erosion) is outlined and can be quantified similarly in the pictures. The inclusion of the primer layer avoids delamination owing to the increase in fracture energy revealed by the peeling testing values. Delamination occurs only in the first configuration where no primer is included and hence, worse chemical bonding is achieved.

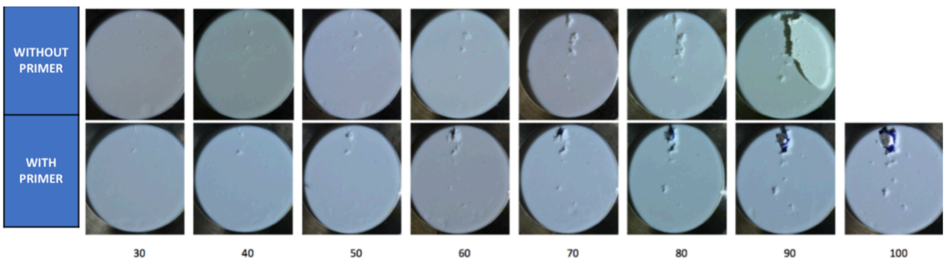


Figure 9. Images of surface and delamination damage after time intervals (in minutes) of testing. (upper) LEP coating with No-primer application. (lower) LEP with intermediate primer layer. These results correlate well with the similar erosion incubation time observed in both configurations (with and without primer) in the rain erosion testing. The primer layer avoids delamination but no affect erosion incubation time

The key result is that the inclusion of a primer layer, in this case, does not negatively influence the rain erosion performance of the coating systems. The adhesion of the coating to the substrate has been significantly improved, which, in turn, reduces the opportunities for delamination to initiate, offering a more reliable solution. Further optimisation of the primer material could improve the rain erosion performance of the entire system.

4. Conclusions

The development of new coating systems, with an aim to diminish the rain erosion damage in wind turbine blades, requires knowledge-based tools to identify suitable coating and composite substrate combinations. This research has been directed into the coating–laminate interphase adhesion characterisation in order to effectively predict rain erosion performance. The experimental work involved accelerated rain erosion testing, pull-off testing, peeling–adhesion testing and nanoindentation testing of individual coating configuration cases. The rain erosion testing results correlated well with the mechanical adhesion characterisation in the two cases.

This study has focused on characterising the failure resistance of the system interfaces in order to create complete analytical or numerical models of rain droplet impact and corresponding physical rain erosion testing. A more precise and complete analysis, which is the focus of future work, requires the use of appropriate numerical models that account for stress–strain behaviour and the accurate acoustic propagation of shock wave in the multi-layered composite.

In ongoing research, it is necessary to implement ultrasonic testing to accurately measure the impedance of materials and take into account improved models for the stress–strain behaviour in order to evaluate the viscoelastic properties of a LEP system. Nanoindentation is a very convenient testing method to characterise such behaviour on the interface and surface boundaries at the microscopic scale. Moreover, it can allows for the creation of more accurate numerical models. Cohesive Zone Modelling (CZM) between layers is planned to be incorporated into the numerical modelling of the droplet impact. The input parameters for the interface CZM can be defined by means of the adhesion characterisation methodology employed in this work as it is shown in Fig.10.

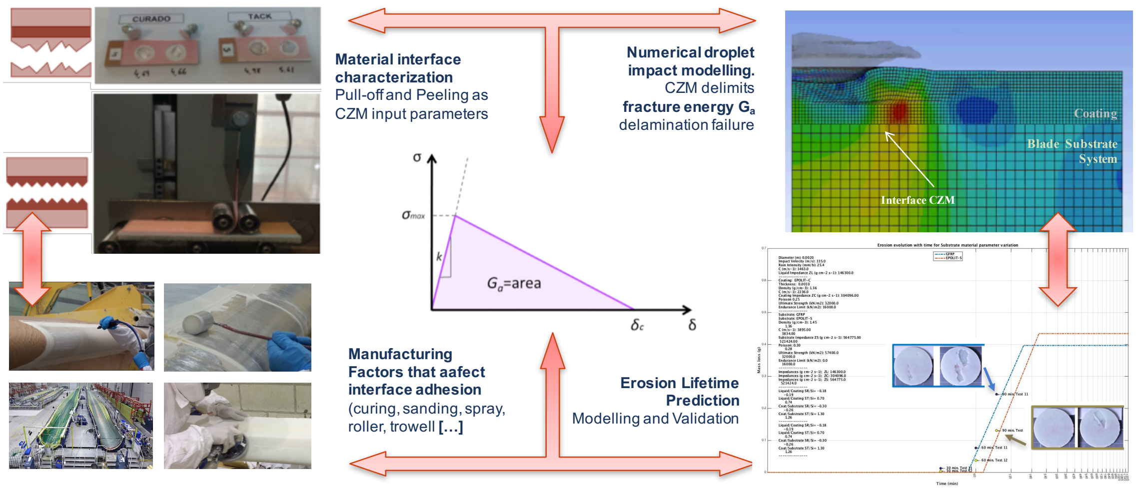


Figure 10. Proposed methodology for the modelling of manufacturing factors that affect erosion performance. The processing conditions may vary interface adhesion capabilities and hence delamination failure. In order to compute the Stress-Strain behaviour of the multi-layered system under impingement, the Input parameters for Cohesive Zone Modelling are determined with Peeling and Pull off testing., etc. Moreover, the erosion lifetime prediction can be modelled considering premature delamination (further work is on its development).

Acknowledgments

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