Manufacturing issues which affect coating erosion performance in wind turbine blades

E.Cortés[1a)], F. Sánchez[2b)], L.Domenech[2c)], A.Olivares[2d)] ,T. M.Young[3e)], A.O'Carroll[3f)], F. Chinesta[4g)]

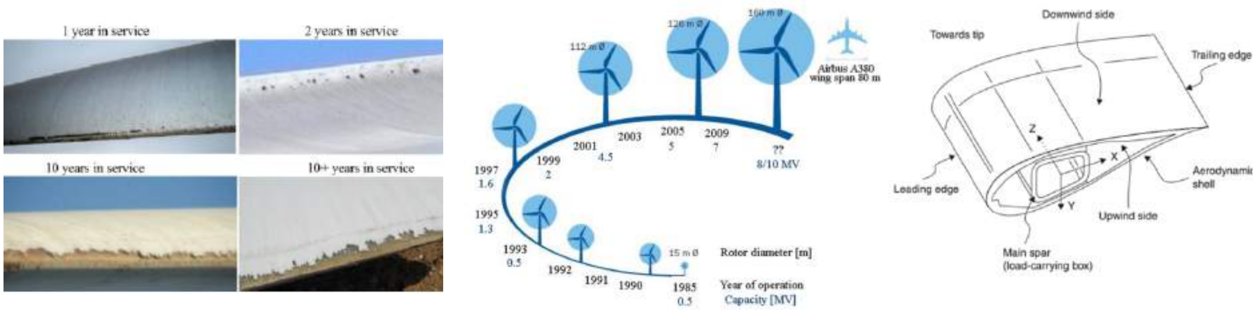
[1]*Aerox Advanced Polymers*
[2]*University CEU Cardenal Herrera, Moncada, Valencia (Spain)*
[3]*Irish Composites Centre, University of Limerick, Ireland*
[4]*Institut de Calcul Intensif, Ecole Centrale Nantes, France*

[a)] ecortes@aerox.es
[b)] Corresponding author: fernando.sanchez@uchceu.es
[c)] luis.domenech@uchceu.es
[d)] aurelio.olivares@uchceu.es
[e)] trevor.young@ul.ie
[f)] anthony.ocarroll@ul.ie
[g)] francisco.chinesta@ec-nantes.fr

Abstract. Erosion damage, caused by repeated rain droplet impact on the leading edges of wind turbine blades, is a major cause for cost concern. 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 coating is usually moulded, painted or sprayed onto the blade surface so adequate adhesion in the layers' characterization through the thickness is required for mechanical performance and durability reasons. In the current work, an investigation has been directed into the resulting rain erosion durability of the coating was undertaken through a combination of mass loss testing measurements with manufacturing processing parameter variations. The adhesion and erosion is affected by the shock wave caused by the collapsing water droplet on impact. The stress waves are transmitted to the substrate, so microestructural 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 to relate lifetime prediction and to identify suitable coating and composite substrate combinations and their potential stress reduction on the interface. In this research, the input parameters for the appropriate definition of the Cohesive Zone Modelling (CZM) of the coating-substrate interface are outlined by means of Pull off testing and Peeling testing results. It allowed one to optimize manufacturing and coating process for blades into a knowledge-based guidance for leading edge coating material development. It was achieved by investigating the erosion degradation process using both numerical and laboratory techniques (Pull off, Peeling and Rain Erosion Testing in a whirling arm rain erosion test facility).

INTRODUCTION, OBJECTIVES AND MOTIVATION

With the current EU objective to reduce gas emissions, and the 2016 COP21 Paris Agreement to keep a global temperature rise this century well below 2°C, the offshore wind renewable energy community is the biggest potential contributor to meeting these goals. The renewable energy sector has to be significantly expanded and the installation of very large wind turbines (10 MW and higher), standing in wind farms of several hundred megawatts will be required. It is anticipated that wind turbines with increased rotor diameters will be developed and installed within the next years. In this case, wind turbine blades of length of 80 m and more than likely up to 160 m in the near future, with increased tip speeds from 80 m/s to over 110 m/s, will be in operation. The tip speed is heavily dependent on turbine operational strategy and control. When considering the impact of rain, hailstones and other particulates on the leading edge, the tip speed is a key issue on material deterioration. The erosion of the forward facing leading edges of wind turbine blades has seen a dramatic increase in both occurrence, and the rate at which leading edges are eroding. This is particularly true on offshore wind turbines with large blades, high tip speeds and high wind speeds. Blade erosion is now the largest blade issue, affecting all wind turbine types and offshore operators [1]. It is therefore key to maximize the performance and reliability of the composites technologies, and lower the cost of the energy produced, to create a more efficient offshore wind sector. In order to achieve these goals, issues such as wind turbine blade leading edge erosion need to be urgently addressed. Due to the negative economic impact of blade erosion, all wind turbine Original Equipment Manufacturers (OEMs) are actively seeking solutions [2,3,4,5]. Up to now, the challenge has been approached by developing new coatings to mitigate this problem.



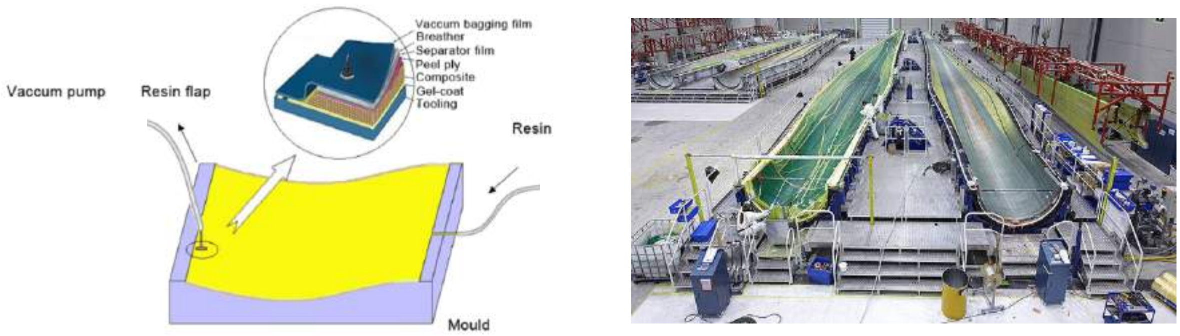
(a) (b) (c)

FIGURE 1. Examples of leading edge erosion across a range of years in service (a) from [6], size evolution for wind turbine blades (b) from [8] and blade section with leading edge location

Materials and Manufacturing issues

The large and ever-growing scale of modern blades has resulted in the widespread implementation of fibre reinforced thermosetting plastic composite technologies due to high specific strength and stiffness properties and fatigue performance. Composites perform poorly under transverse impact (i.e. perpendicular to the reinforcement direction) and are sensitive to environmental factors such as heat, moisture, salinity or UV. Blade manufacturers employ surface coatings to protect the composite structure (see Fig. 2). Each composite blade can be manufactured using vacuum resin infusion process. The principle of this moulding process involves initially applying a release demoulding film on the inner face of the mould, followed by a thin layer of gel coat. Next, is the application of dry fibre reinforcements over the coated area, followed by a peel ply, a separator film and a breather. Lastly, the whole system is enveloped in bagging film as shown in Fig 2. Thus, the plastic film will play the role of the top part of a mould. Under these conditions, the vacuum created in the closed cavity allows the resin to spread and impregnate the fibre reinforcements until complete saturation. Once the resin is cured, the plastic film, the peel ply, the separator film and the breather are removed and the upper or lower blade parts are easily demoulded and the part finished.

In wind turbine blades manufacturing, two most common technologies are used: (i) in-mould coatings (a moulded layer of a similar material to the matrix material used, i.e. epoxy/polyester) or (ii) a post-mould application (applied after moulding through painting or spraying, with different material choices). The in-mould coating plays a key role in the product performance of the whole part [8], [10]-[12], and post-mould application is typically used for the leading edge protection. In both cases, an optimum interface adhesion and surface finish is often required for mechanical performance or durability reasons [8], [13],[14]. Industrial process defines the Leading Edge Protection system on the blade surface, and several configurations can be outlined as a multilayered system with a high number of interfaces that tend to accelerate erosion by delamination (as it will be shown in next section).



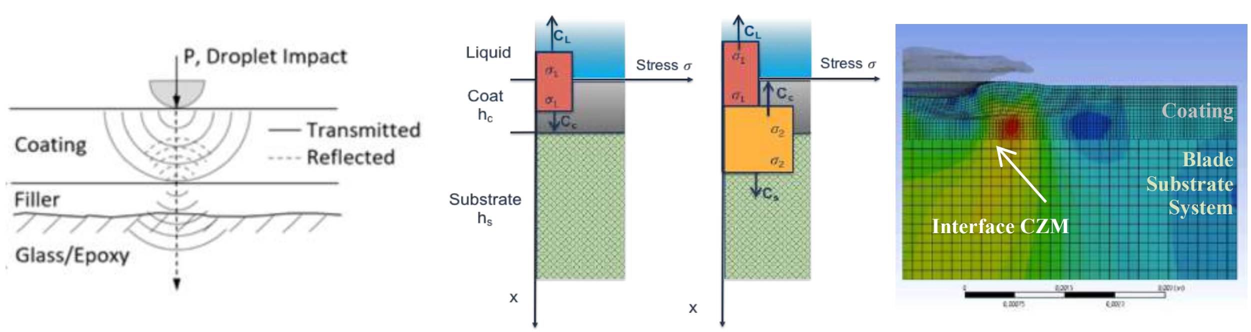
(a) (b)

FIGURE 2. (a) Coated mould area and tooling materials used [9], (b) resin infusion process of a wind turbine blade from [7]

FIGURE 3. Industrial process with a fewer number of coating layers are recommendable because of the robustness of the process and the reduction of interfaces. The coating application during processing is a major concern on erosion performance

On the modelling of the rain drop impact on Wind Turbine blades

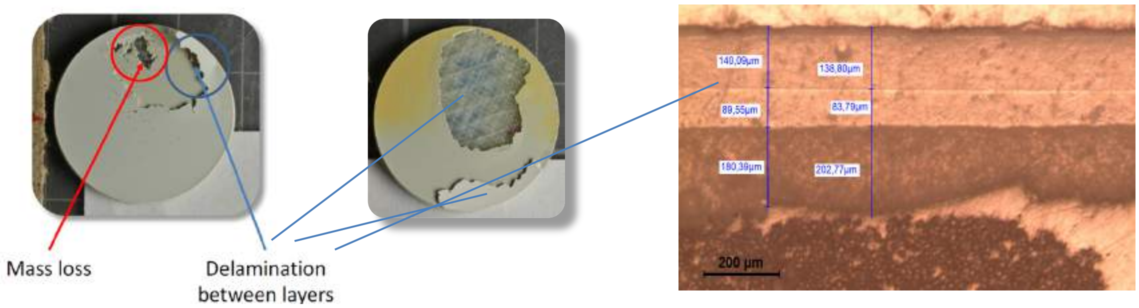
The analysis of the behaviour of a single waterdrop impact is a meaningful point for investigating the multiple impact sequences that produce leading edge erosion. The blade composite structure is affected by the shock wave caused by the collapsing water droplet on impact, and the elastic and viscoelastic responses of the materials, surface preparation and coating application and the interactions between them (see Fig. 4). The understanding of these interactions through the numerical modelling is limited but thought to be of key significance.



(a) (b) (c)

FIGURE 4. (a) Standard multilayered blade structure, (b) Shockwave propagation depending on acoustic impedances, (c) Numerical modelling of Normal Stress due to rain droplet impact. Interface CZM defines failure resistance between layers.

Upon impingement on the coating two different wave fronts travel into the liquid and coating respectively, as shown in Fig. 4 (a) and Fig.4 (b). The wave front in the coating further advances towards the coating-substrate interface, where a portion of the stress wave is reflected back into the coating and the remaining part is transmitted to the blade substrate system. Due to this reflection a new wave is now advancing in the coating with a different amplitude depending on the acoustic impedances of the coating and substrate [14]. This shock wave is reflected wherever the acoustic impedance properties differ locally, so microestructural defects, such as voids and lack of adhesion at the interfaces play a key role on the degradation of the blade leading edge (delamination may occur at the interface between material layers), as shown in Figs. 5 (a) and (b).

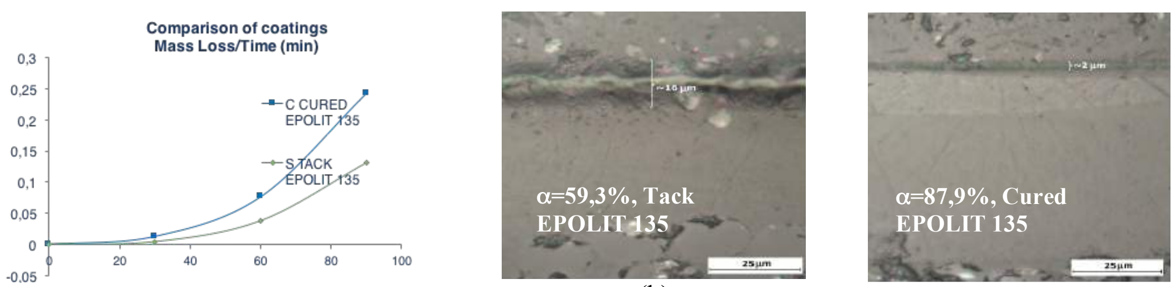


(a) (b)

FIGURE 5. (a) Rain erosion testing specimens. Erosion failure due to mass loss on surface and interface delamination. (b) Multilayer system microscopy. Two coating layers define an interface that tend to delaminate upon impingement.

The capability of the coating to transfer wave energy can influence the erosion damage. Stress reflections oscillate repeatedly through the coating and structure until damped by the material properties to reduce the energy of the initial shockwave. By matching delamination resistance between the coating and the blade structure, coating life time under repeated impacts can be extended. Owing to the need for the system to lower its total free energy and depending on the activation rates and available relaxation mechanisms, micro cracking takes place as a major high rate mechanism of recovery. The cracks nucleate and propagate by the usual fatigue characteristics.

In previous research of the authors, the mechanical characterization of coat-laminate interface, which depends on processing curing conditions, has been investigated for in-mould coatings. In [15] the processing window requirements were investigated. In [16] rain erosion testing conducted in the University of Limerick's whirling arm rain erosion facility (WARER) [17], indicated that samples manufactured with a higher coating degree of cure (as determined using DSC), performed worse in regard to erosion compared to those that had a lower degree of cure, see Fig.6. It can be observed how the less-cured coating (curing conversion a=59,3% instead of a=87,9% for the same epoxy based polymer, EPOLIT) defines a broader interface area with the infused GF laminate with epoxy resin due to a higher chemical adhesion.



(a) (b) (c)

FIGURE 5. (a) Rain erosion testing results. Average mass loss versus time for two different coatings: Coat 1 i.e. Cured (C in blue) and Coat 2 with tack (S in Green). (b) and (c) and microscopy interface characterization for two different coating curing.

Destructive mechanical testing was also undertaken in [16]. Pull-off strength testing of the samples showed the failure in the composite laminate and hence the capability of the coating to assure the required target strength. A specially-developed peeling test for interface coating-laminate adhesion response quantification showed that the cured coating had an average peeling force value of 19.3 N and the less-cured coating a value of 25.1 N. These results correlated with the rain erosion tests, as shown in Fig. 5 (a). The objective of the current research is to assess the coating-laminate interface through numerical modelling, correlating the manufacturing coating application factors (curing, sanding, spray, roller, trowel, etc.) with the material's resistance to rain erosion damage (through mass loss measurements in the WARER).

MANUFACTURING FACTORS AFFECTING EROSION BY MEANS THE COHESIVE ZONE MODELLING OF INTERFACE DELAMINATION

The appropriate development of numerical rain erosion prediction models could yield a tool for effective leading edge coating design. The coating-laminate adhesion and erosion is affected by the repetitive shock wave caused by the collapsing water droplet on impact. In order to assess the mechanical response of the multilayer interfaces, it is proposed to define the cohesive zone modelling (CZM) between layers to be incorporated in the numerical modelling of the rain droplet impact, and hence, the related erosion lifetime prediction models as described in [14] (see Fig.6). The proposed methodology states the CZM input parameters with both physical Peeling testing of manufactured specimens and their numerical modelling [18][19][20][21][22]. Once CZM has been defined, it can be used for the interface delamination modelling computed in the droplet impact analysis. The approach allows one to account for the effect of the surface preparation and coating application and the interactions between them with the multilayer system.

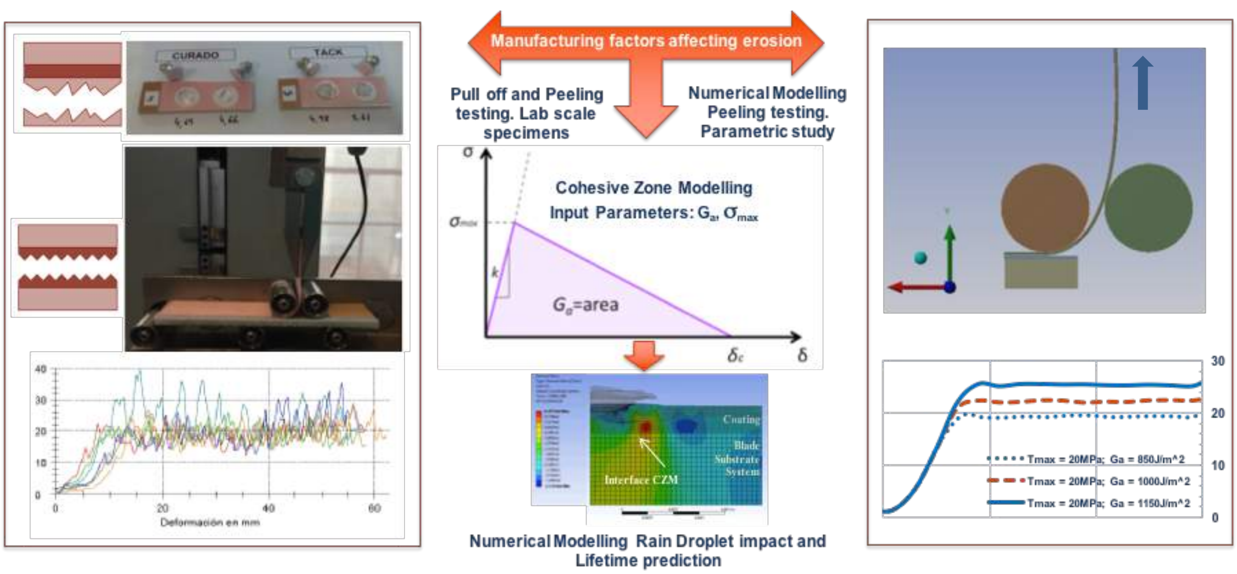


FIGURE 6. Proposed methodology for the modelling of manufacturing factors that affect erosion. Input parameters for Cohesive Zone Modelling are determined with Peeling testing and its simulation.

The present work has considered the Peeling testing numerical simulation of the coating-laminate interface fracture for two specimens configurations with different coating curing (as described in previous section and in [16]). The model is based on a cohesive zone formulation were knowing the experimental peeling force value (of 19.3 N for the cured specimen and the less-cured coating with a value of 25.1 N.), it is related numerically to the fracture energy, G_a necessary for the interface failure. Its value is ascertained from an energy-balance approach [20, 21] and requires the stress versus strain curve of the peel arm to be inputted into the analysis. This can be achieved via a bilinear model, as shown in Fig. 6. Since here the peel energy, G_{input} is experimentally measured with the peeling testing and the energy associated with the bending, G_{bend}, of the peel arm may be considered constant in both cases (since the curing only affects the interface and not the arm), we then have a first approximation for the fracture energy based on simulation results as $G_a = G_{input} - G_{bend}$ G_a =850 J/m^2 for the cured coating and a value of G_a=1150 J/m^2 for the tack coating. In all the simulations, it is related as a parameter value the normal traction, σ, to the normal opening displacement, δ, across the crack surface since fracture was assumed to be predominantly via a Mode I (tensile) failure. Moreover, the parametric value of σ_{max} can be also limited by the experimental value obtained from the Pull-off testing.

CONCLUSIONS AND ACKNOWLEDGEMENTS

In order to state the complete numerical analysis of the rain droplet impact and its corresponding physical rain erosion testing, it is necessary to characterize the failure resistance of the multilayered system interfaces. In this work, the input parameters for the interface Cohesive Zone Modelling (CZM) are defined by means of both physical Pull-off and Peeling testing of manufactured specimens and their numerical modelling. This methodology has been studied with the coating curing conditions, but can be extended to any other coating surface application process like sanding, spray, roller, trowel, primer, etc. (further work is on its development).

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