TOWARDS RAIN EROSION CHARACTERIZATION OF WIND TURBINE BLADE COATINGS: EFFECT OF THE IN-MOULD CURING CONDITIONS ON THE COATING-LAMINATE INTERPHASE

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Abstract

Resin Infusion (RI) is increasingly used in wind energy systems where low weight and high mechanical performance materials are demanded. The in-mould coating plays a key role in the manufacturing and performance of the product. The coating is usually painted or sprayed onto the mould tool before the dry preform is inserted, adequate adhesion in the coat-laminate interphase and good surface finish is often required for mechanical performance or durability reasons. Erosion damage, caused by repeated rain droplet impact on the leading edges of wind turbine blades, is a major cause for concern. In the current work, an investigation has been conducted into the curing of the coating. Test results are presented and discussed to relate the in-mould curing of the coating on the interphase coat-laminate mechanical properties and on the resulting rain erosion durability of the component. A mixed numerical/experimental technique based on artificial vision was used to estimate the induced effect of the surface coating curing in the laminate impregnation and the flow front advance during filling under controlled conditions. The experimental investigation focused on the effects of the curing of the coating on important mechanical performance parameters, which were assessed by pull-off testing, peeling-adhesion testing and rain erosion testing.

1. Introduction

The renewable energy sector has to be significantly expanded in order to reach the European Commission's target for the European Union (EU) to have 20% of its electricity supplied from renewable sources by 2020. The EU wind energy capacity should be extended by two orders of magnitude. To achieve this goal, the installation of very large wind turbines (10 MW and higher), standing in wind farms of several hundred megawatt will be required. In this case, wind turbine blades of length of 80 m and most than likely up to 110 m in the near future, with increased tip speeds from 80 m/s to over 100 m/s, will be in operation.

Average tip speeds around and in excess of 80 m/s are now common for many wind turbine designs. The tip speed is also heavily dependent on turbine operational strategy and control. A typical wind turbine may be expected to operate continuously for approximately 15 years over its service life. During this time, the materials of the blade are exposed to varied environmental conditions and fatigue loads. The erosion of wind turbine blade leading edges has seen a dramatic increase in both the frequency of occurrence (see Fig. 1) and the rate at which leading edges are eroding [11]. Erosion has been seen to be occurring within two years in off-shore blades and within a five year warranty period for onshore applications. The costs associated with erosion in terms of loss of power output and repair and downtime is significant and has a large impact on the LCoE (Levelized Cost of Energy) for wind. Solutions need to be developed to mitigate this problem, and the blade surface coating design is regarded as a key issue for the wind energy industry.

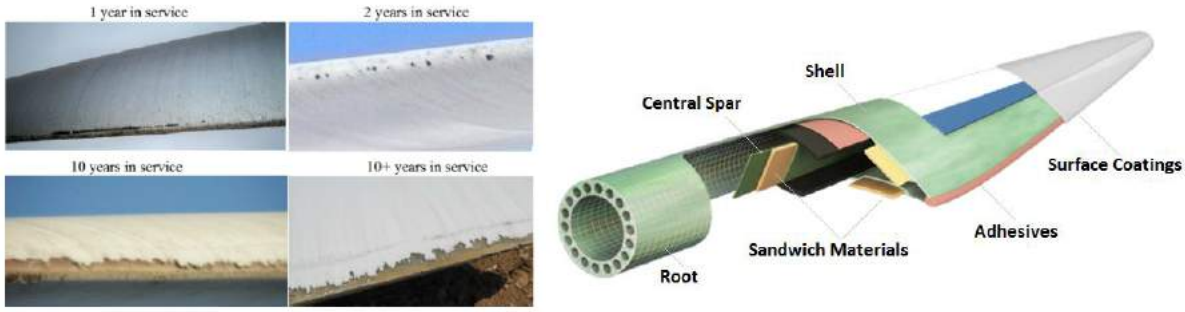

Figure 1. Examples of leading edge erosion across a range of years in service (left) [11]; and materials used in a typical blade cross section (right) [1]

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). Two most common technologies used are in-mould coatings (a moulded layer of a similar material to the matrix material used, i.e. epoxy/polyester) or a post-mould application (applied after moulding through painting or spraying, with different material choices) [11], [6].

The in-mould coating plays a key role in the product performance. An optimum interphase adhesion and surface finish is often required for mechanical performance or durability reasons [5], [7]. An important industrialization aspect due to the processing window requirements is to determine the effect of surface coating on the characterization of the process dynamical behaviour during mould filling in Liquid Resin Infusion [4], [6].

Figure 2. Surface textile material application over the in-mould coating (left) [3]; and resin infusion process of a wind turbine blade [2]

2. Effect of surface coating on the characterization of the flow dynamical behaviour during Resin Infusion (RI) mould filling: estimation of material and manufacturing parameters

A mixed numerical/experimental technique based on artificial vision is used to estimate the induced effect of the surface coating curing in the laminate impregnation and the flow front advance during filling. The procedure iterates the value of the estimated local material parameters *M* in the physical numerical simulation until it matches the evolution of the experimentally measured flow front data (see Fig. 3). Computation of velocities at the flow front can be estimated by means of the distance and time between consecutive flow fronts. In this work [10] a level set approach is employed to compute the vent distance field. It can be observed so that the curing degree discontinuity of the coating areas can be identified by means of a deep change on the flow front velocity and hence *M* variation can be estimated and the flow behaviour characterised.

The experiments have been conducted by filling a 2D rectangular mould. Two different curing conditions for the gel coat were used in order to generate differences in the impregnation and flow advancement of the resin in the dry preform during filling. Coat 1 and Coat 2 are characterised previously by performing a measure of the degree of conversion of the polymerization reaction of the polymer matrix (see Fig. 4). The degree of conversion (α) is obtained by measuring the residual enthalpy DH (J/g) with a Differential Scanning Calorimetry (DSC). The samples are quantified and outlined in Fig. 3.

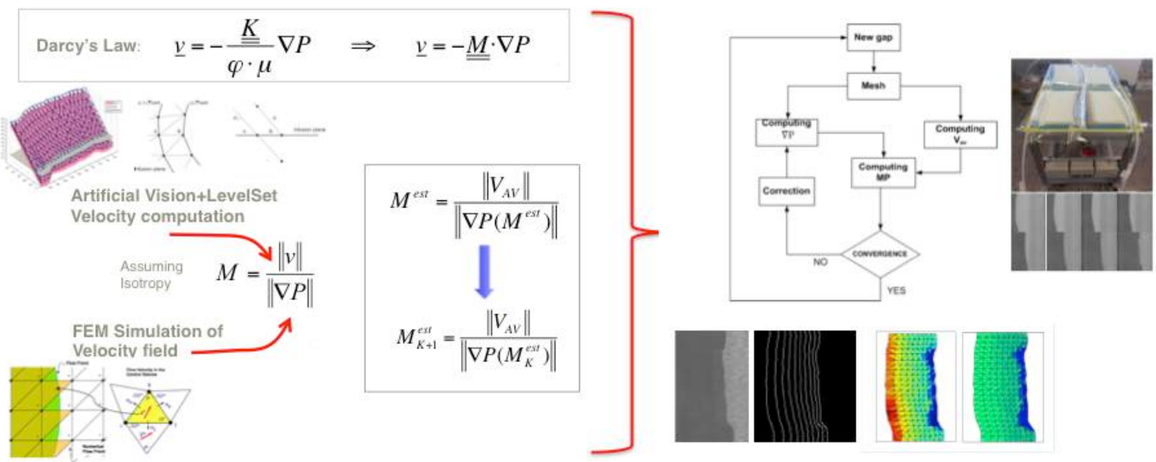

Figure 3. Estimation of the flow induced effect of the coating curing in the material characterization during filling: proposed algorithm (left) and experimental set up with results (right)

Coat	$\Delta H_{exothermic\ peak}$ (J/g)	α (%)
Total reaction enthalpy	329,296	0
Coat 2. 40' a 45 ºC	134,12	59,3
Coat 1. 24 horas a 25ºC	5,891	89,7

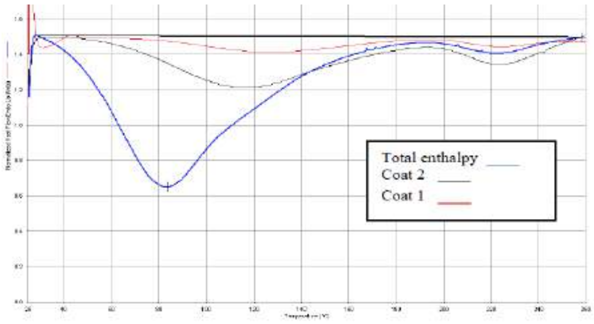

Figure 4. Degree of conversion (α) measured with DSC in the two experimental samples

3. Mechanical characterization of the coat-laminate interphase

Wind turbine blade applications require an optimum interphase adhesion for mechanical performance and durability reasons. Distinctive mechanical testing are shown in order to assess the macroscopic behaviour of the laminates and its relation with the coating curing conditions. In Fig. 5 pull-off strength testing of the samples show the failure in the composite laminate and hence the capability of the coating to assure the required target strength. There is a lack of information regarding the curing effect on the interphase. Figure 6 shows a specially-developed peeling test for interphase coating-laminate adhesion response quantification. The samples are moulded over a rigid substrate, where the coating is bonded with a special adhesive and hence the differences on the adhesion laminate-coating depending on its curing can be measured. In Fig. 8 it can be observed in microscopy images how the less-cured coating (Coat 2) defines a broader interphase area due to a bigger chemical adhesion. Figure 7 shows the failure load for peeling interphase adhesion testing. Coat 1 (cured) has an average value 19.3 N and Coat 2 (tack) of 25.1 N.

Figure 5. Pull-off strength testing of composite laminates used for coating adhesion (left). Images of the failure in the laminate (right).

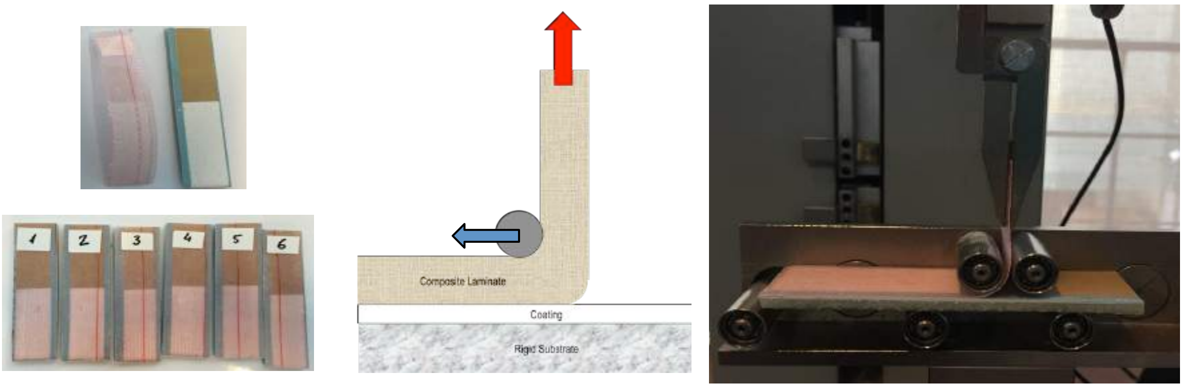

Figure 6. Developed peeling testing for interphase coating-laminate adhesion response quantification

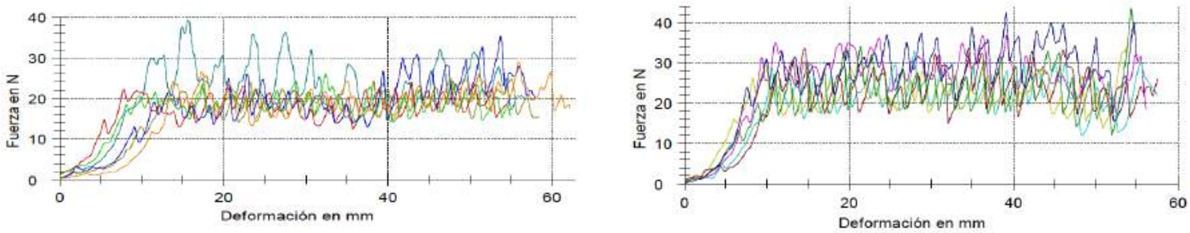

Figure 7. Force of failure for interphase adhesion testing: Coat 1 i.e. cured (left) and Coat 2, i.e. tack (right)

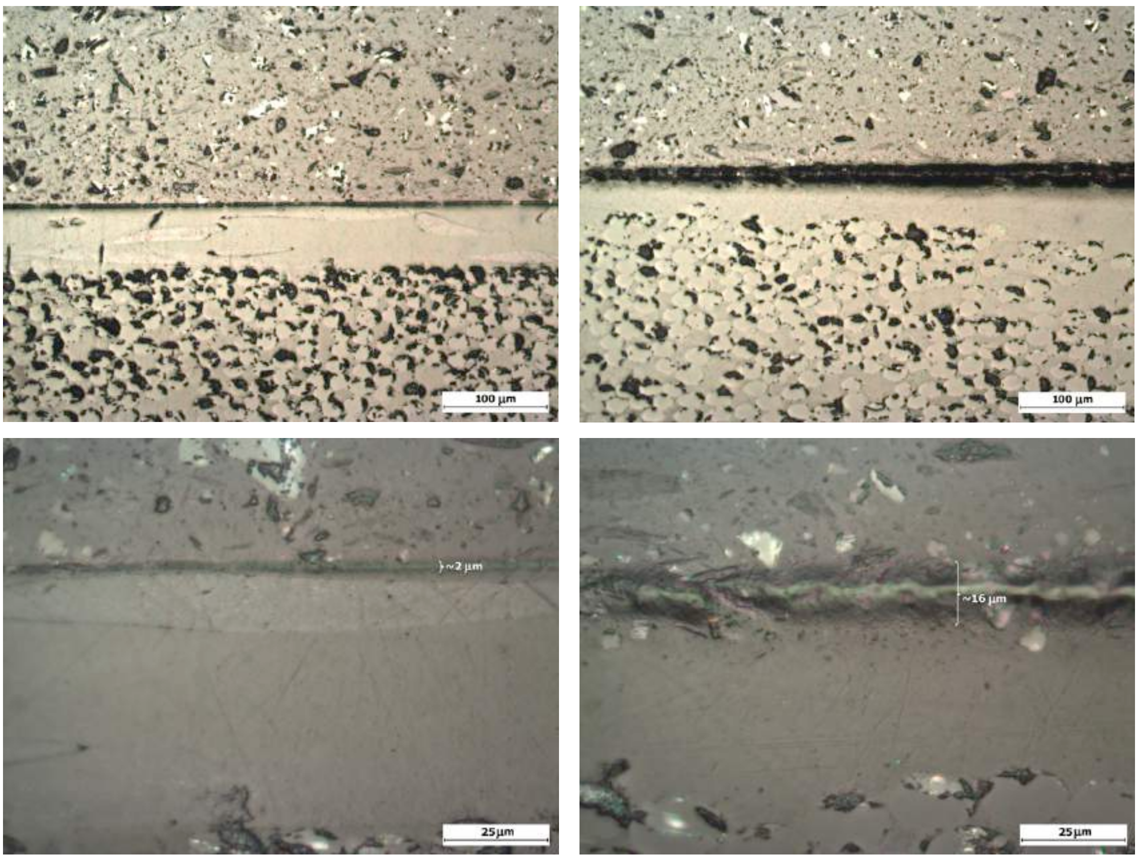

Figure 8. Microscopy samples for interphase chemical adhesion: Coat 1, i.e. cured (left) and Coat 2, i.e. tack (right) (zooming: x100 upper images and x400 lower images)

4. Rain erosion testing for laminates with different curing conditions affecting interphase

Due to the absence of suitable rain erosion testing standards within the wind sector, the industry looked to the aerospace sector [11]. Evaluations are typically performed using a rotating arm rain erosion test to ASTM G73-10 (Liquid impingement erosion using rotating apparatus) [12]. Assessment is normally undertaken through a combination of mass loss measurements and surface characterisation. Interpretation of mass loss data can be difficult as it does not distinguish between erosion depth and area losses. Another difficulty concerns the inability to directly correlate laboratory testing and in-service erosion. Surface topography of test coupons (measured using a confocal laser scanning microscope) has also been used as a means to characterise damage and to provide a partial correlation between different test facilities [13]. Despite the inherent complexities of simulating real-life erosion in a laboratory environment, such testing has been shown to be very helpful in rating rain erosion resistance of different materials and in characterizing the induced damage. The objective of the current research is to assess the relationship between the coating-laminate interphase and the material's resistance to erosion damage, through mass loss measurements.

The rain erosion testing was conducted in the University of Limerick's whirling arm rain erosion facility (WARER), which is described by Tobin *et al*. [14], [15]. The test procedure, which is based on ASTM G73-10 [12], evaluated the two coatings at impact speeds up 135 m/s in an artificially generated rainfall with a rate of 25.4 mm/h. The evolution of damage was monitored through mass loss and visual examination of the specimen surfaces. The results were obtained from samples of laminate substrate with two layer biaxial epoxy-GF, 0.7 mm thick and a gel coat layer of 0.3 mm. The circular coupons had a diameter of 27 mm, with an overall thickness of approximately 1.7 mm.

The eroded samples are shown in Fig. 10. It is evident that the samples manufactured with a higher degree of cure performed worse in regard to erosion compared to those that had a lower degree of cure.

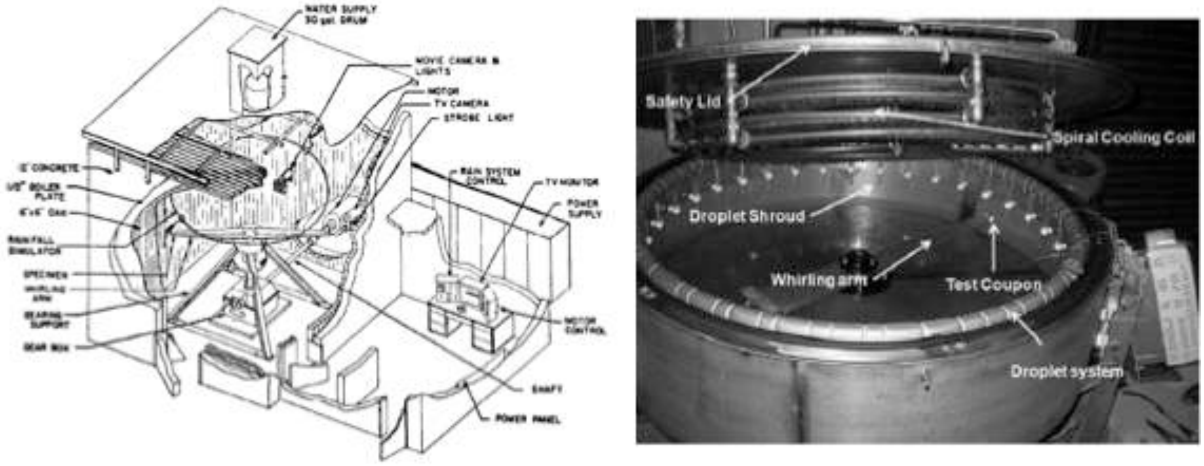

Figure 9. Rain test facility at University of Dayton Research Institute, developed for aerospace applications (left) [11] . WARER at University of Limerick (right) [14].

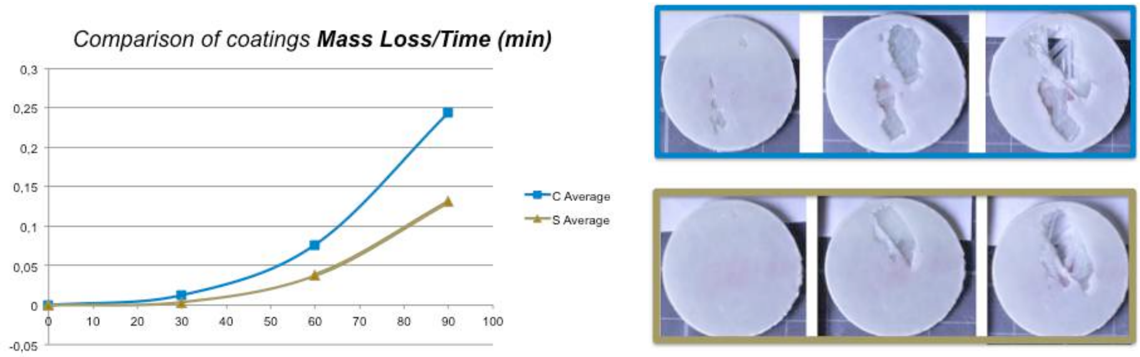

Figure 10. Average mass loss versus time for two different coatings: Coat 1 i.e. Cured (C in blue) and Coat 2 with tack (S in Green) (left). Images of surface damage after 30, 60 and 90 minutes of testing.

5. Conclusions and future work

In this work, the mechanical characterization of coat-laminate interphase, which depends on processing (curing) conditions, has been investigated. The rain erosion testing indicated that samples manufactured with a higher degree of cure (as determined using DSC), performed worse in regard to erosion compared to those that had a lower degree of cure. These results correlate with the peeling tests where the moulded coating had a lower value of the force of failure for interphase adhesion testing.

In future research, the determination of coating factors that affect erosion performance will be investigated. It will be accomplished by evaluating various aspects of the system, these include; mechanical characterization, coating application method and curing, adhesion to substrate, coating film thickness and the effect of coating defects on the erosion degradation process. Optimization guidelines for coatings will then be developed and confirmed using both laboratory techniques and rain erosion testing. Moreover, 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, and the mechanical response of the blade structure, surface preparation and coating application and the interactions between them. The understanding of these interactions through the numerical modelling is limited but thought to be of key significance.

Acknowledgments

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