An experimental approach to analysing rain droplet impingement on wind turbine blade materials

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Abstract

Leading edge erosion of wind turbine blades is an important issue within the industry and has been found to have a substantial impact on the annual energy output of generators. This forces operators to make blade repair a necessity, adding to the operation and maintenance costs of a project. A wind turbine's tip speed can in some cases have an upper limit based on the erosion exhibited on the leading edge.

This paper explores the variables of rainfall rate and impact velocity of the impinging droplets in an attempt to explore the recovery time of the tri-axial composite material used. It is shown that an increase in impact velocity results in a higher mass loss than an increase in the rainflow rate. Analysis using a scanning electron microscope reveals that pin holes in the laminate surface are exploited by the droplets, acting as initiation point for erosion of the composite. Overall the results suggest that the tip speed of the wind turbine blade is of greater importance when compared to the relevant rainfall conditions as to where the wind turbine is situated.

Keywords: Rain Erosion, Composites, Wind Turbine Blades

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1 Introduction

Leading edge erosion is an urgent and important issue in the wind turbine industry, and many examples of eroding blades have been observed in the past, an example of which can be seen in Figure 1. The issue is of the up-most importance as the energy yield from the turbine can be substantially reduced as shown by Sareen et al. [1]. In the study, the conditions of different types and severities of erosion were constructed as observed from damaged blades on actual wind farms which included pitting, gauging and delamination. Using the authors calculations, energy production losses were estimated to be between 3.5% and 23.5% with respect to the severity of the damage pattern present. Also, if left unattended the structural integrity of the blade could also be at risk. In reality however, this is not the case and wind turbine blades are regularly maintained to prevent any loss in energy capture/ potential revenue to the owner. Whilst onshore the issue is of lesser importance, offshore turbines suffer from considerably greater logistical constraints. This means that wind farm operators are incentivised to minimise the frequency and severity of maintenance on their turbines, in order to reduce costs.

Higher tip speeds are sought after due to the potential to reduce the overall loading on the drive-train at a given power output. A lack of constraint on acoustic emissions offshore also offers encouragement for greater tip speeds. Erosion on the leading edge of the blade is a major limiting factor for the operation of the wind turbine, but other constraints do also exist: effects on

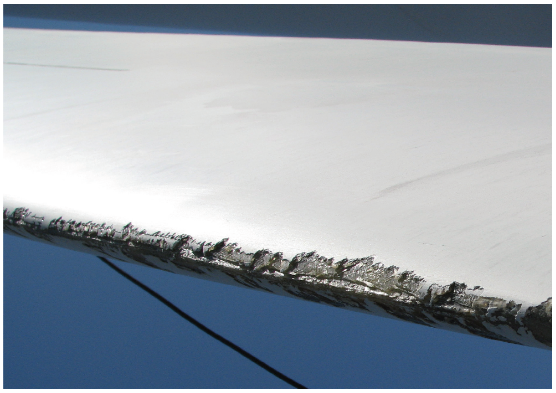

Figure 1: An example of leading edge erosion [2]

the rotor solidity by operating at a higher speed has an impact on the overall optimal rotor design and thus would need to be taken into consideration [3].

Literature reviews have been conducted in the area of leading edge erosion: Slot et al. [4] conducted a review and also produced a fatigue wear model for wind turbine coatings. It was recommended as a result of the work that developed coatings for the leading edge should be designed to have a low elastic modulus.

Keegan et al. [5] conducted a broader literature review in the area of leading edge erosion, as well as using explicit dynamics software to model the impact of rain droplets. The material modelled was an epoxy resin plate and was impacted by rain droplets at speeds varying from 40-140 m/s.

The work of Zhang [6] represents DTU's respective efforts to experimentally evaluate the erosion on wind turbine blades. For the work, a pulsed jet rig was constructed, the jet was produced by directing a straight jet through a slitted disk to produce small jet 'pellets'. These impacted upon a rotating flywheel which was used to cycle between a number of coating specimens. The results concluded that the water jet velocity as the most critical parameter, although a damage threshold velocity of around 167 m/s was observed.

2 Methodology

2.1 Rain Erosion Rig

The University of Strathclyde possesses a rain droplet erosion rig for the purposes of testing the erosion performance of wind turbine blade materials. It is mounted on a vertical axis and is a "whirling arm" type rig, the impingement method is via syringes of which can be changed in order to modify the droplet diameter. The water is pressurised by a simple pump of which the flow rate can be modified to enable various rainfall rates for the experiment. The maximum operational speed of the rig is 60m/s, given that many modern turbines have an operational speed of around 80m/s it can only be stated that the testing speeds are less than adequate at this stage, however, liquid impingement wear was still present on the samples.

2.2 Samples

The samples used in the experiments would most ideally be coated specimens, however, the testing of uncoated specimens can shed light on the erosion behaviour of the underlying composite once the surface topcoat has degraded.

The two main constituents used in the composite was a standard epoxy matrix supported by e-glass fibres. The material was constructed by layering up ply sheets, each sheet had a stitched fibre orientation of 0°, 45° and -45° and a total of five sheets were used to form a 5mm thick laminate. The sample size used was 30x30mm and each sample was adhered to a backing material which was then attached via screws to the sample holder.

A 5kg Vickers hardness test was performed on one of the samples to gauge material response, three tests were performed resulting in an average of 28.1, with a standard deviation of 2.2.

SEM analysis was performed on one of the blank samples as shown in Figure 2. Pin holes of approximately 150-270μm in diameter can be seen- these pin-holes are an unavoidable consequence of infusion formation process and is the result of small air bubbles caught in the vacuum bag. The vacuum infusion process can minimised these defects compared to other formation

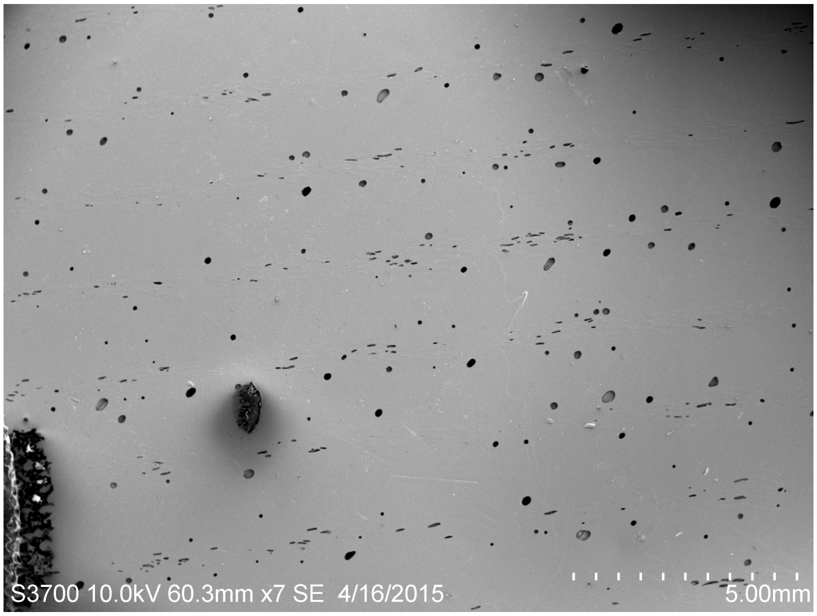

Figure 2: Presence of pre-existing pin holes in the untested sample

processes, but they can not be wholly avoided.

As explained further on, Figure 5 shows how these pin-holes are exploited as an initiation point for water droplet erosion.

3 Experimental Details

ASTM guidelines for "liquid impingement erosion using rotating apparatus" were used as a basic guideline where applicable; the standards have many guidelines and recommendations relating to composite material testing [7].

Experiments were carried out to map the erosion effects of the rainfall rate against tip velocity, This ranged from 40m/s to 60m/s at 5m/s steps and rain flow rate from 20mm/h to 40mm/h similarily at 5mm/h steps. The droplet diameter was held constant at approximately 2.5mm and each test lasted for a duration of 40 minutes. This was performed in order to gain an insight into the recovery time of the composite material used.

Polymer composite can be tested for liquid impact erosion in a fairly similar way to metals however, a key difference with composites is that they absorb moisture relative to the local humidity. This has significant impact on the weight loss measurements after the duration of the test, which has been selected as one of the main evaluation methods for erosion in this case [7]. This was resolved by measuring the weight loss 24 hours after the testing had finished, which was found to be an adequate resting period.

3.1 Outputting Cumulative Mass Loss Curves

As the weight loss could not be continuously measured at set intervals during the experiment due to the gained moisture content, an additional experiment was proposed. The weight loss relationship over time, a key erosion indicator as explained in Springer [8] would be determined in this case. In the test, a single sample was exposed for discrete 10 minute intervals in the rig, left to dry for 24 hours and then weighed before being exposed in the test chamber yet again. The scales used for weighing were accurate to +/- 0.1mg. This process was found to be adequate without the use of a high temperature desiccator, which could have caused damage on the material surface [9].

4 Results and Discussion

4.1 Cumulative Mass Loss

Figure 3 shows the wastage effects over the duration of a test for a sample. The test was stopped at regular intervals to allow for the sample to dry before the mass loss due to erosion could be measured. It can be seen that no incubation period is present at the beginning of the testing, meaning that damage resulting from liquid impingement is immediately reflected as material degradation on the sample.

The purpose of this test was to negate the wet-ability property of the composite, which on average accounted for twice the overall mass lost on the samples. This emphasises the importance of properly accounting for the wetability aspect of composites.

4.2 Erosion Mapping

Wear maps can help identify mechanistic changes on an eroded surface over a range of operating conditions. The development of erosion maps may assist in understanding the mechanisms involved in the material degradation and in some cases the chemical effects involved on the surface [10]. The erosion map presented here represents the total wastage and indicates potential safe operation conditions for the material.

The map shows the boundary conditions of the relationship between rainfall rate and impingement velocity, Table 1, sets out the boundary conditions for mass loss for each region. Approximate boundary lines have been drawn based on the experiments performed, represented by the gray points presented on the map.

As expected, a higher velocity impingement at higher rainfall rates produced the most severe erosion behaviour. A slight discrepancy can be observed at 35mm/h and 50m/s; however, this can be considered an anomaly as a general trend is present on the map.

Table 1: Classification of the parameters of mass loss for Figure 4.

Classification	Mass loss (mg)
Low	<2
Medium	2-5
High	5-15
Very high	10-100
Severe	>100

It can also be seen that the influence of velocity has a much greater effect on the severity of erosion than the rainfall rate.

Damage resulting from higher velocities can most simply described by the water hammer equation [11]:

$$P = \rho C v \tag{1}$$

Where ρ is the density of water, v is the velocity at which the droplet impacts the material and C is the acoustic shockwave velocity inside the droplet. The higher impact pressures associated with the increase velocity correlates to the greater amount of damage present of the material surface.

Conversely it can be seen that an increase in just the rainflow rates (i.e. The bottom right of the map) did not present as much damage on the sample compared to the velocity (i.e. The top left of the map). It can be deduced that the composite is far more sensitive to changes in the velocity (and thus impact pressure) of the impinging droplets rather than a specific increase in the number of impacts.

Severe erosion was present on the sample subjected to a velocity of 60m/s and a rainflow rate of 40mm/h as shown on the top right of the map. It was observed on the sample surface that large sections of epoxy had been eroded away exposing the fibres. On these sections fibre breakage was present, which accounted for a large proportion of the overall mass loss measurement.

4.3 SEM Analysis

Figure 5 represents the damaging effects of rain droplet erosion. This sample had a comparatively light exposure

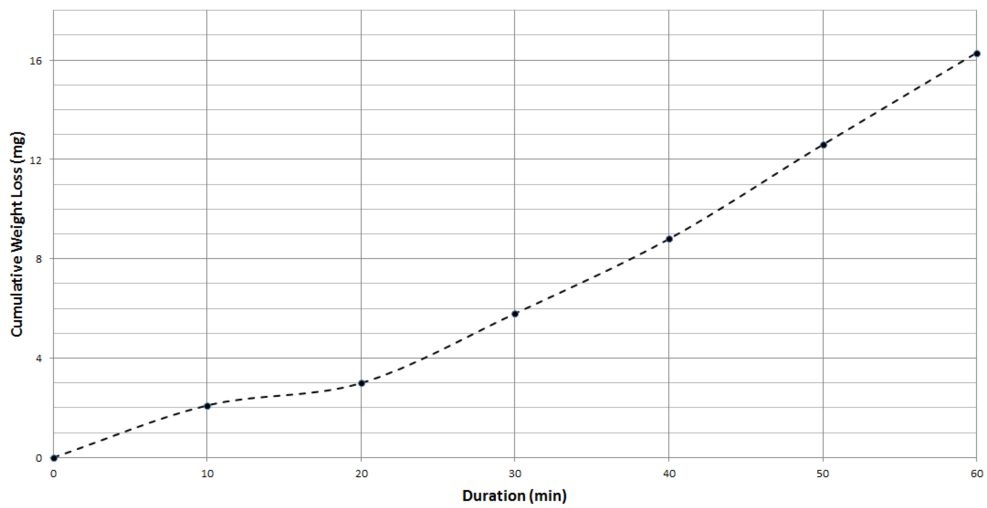

Figure 3: Mass loss- time relationship of a sample subject to a droplet diameter of 2.5mm, at 60 m/s through a rainfall rate of 25 mm/h.

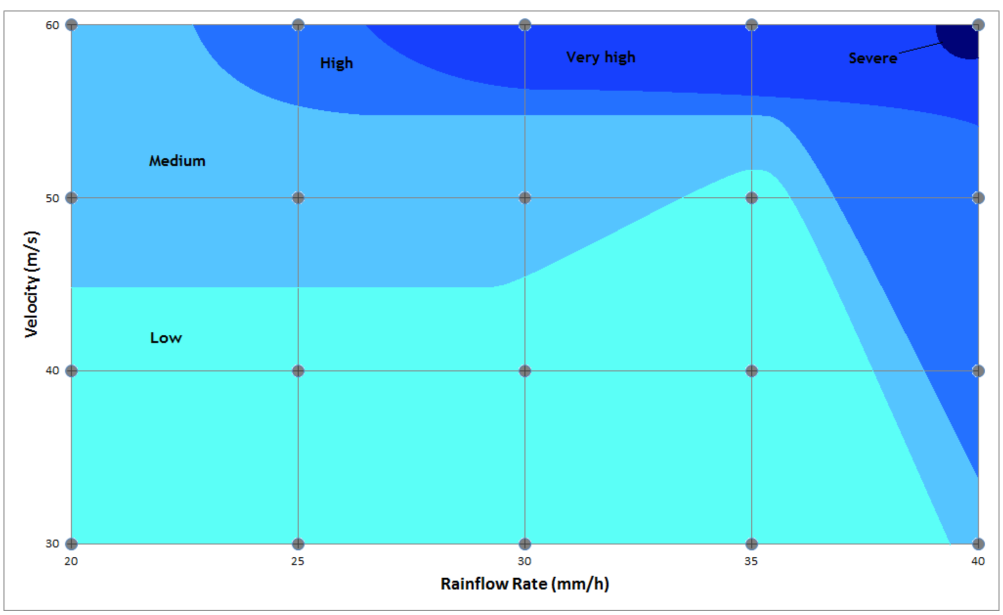

Figure 4: Wastage map showing the measured mass loss varying the impingement velocity against rainfall rate. The duration of each test was 40 minutes and the droplet diameter was 2.5mm

at a velocity of 30m/s for 40 minutes through a rainfall rate of 30mm/h. Most notably the surface morphology as shown in Figure 5, did not show any evidence of pin-holes, as previously mentioned in Section 2.2- it can therefore be deduced that it was quite likely the erosion initiated from these surface defects. Fibre exposure was present on the sample; however, the top layer of fibres remained predominantly aligned, suggesting that at this stage only the surface epoxy was affected.

Another sample as seen in Figure 6 was exposed for 40 minutes at a rainfall rate of 25mm/h at a velocity of 60m/s. It can be seen in the image that the 20μm diameter fibres sustained breakage after a period of time. Whether the damage occurred before or after the surface epoxy had eroded away is difficult to determine, and may be key to analysing the damage mechanisms in the overall composite.

If fibre fracture had occurred following erosion of the epoxy, then it is more likely that the fibres experienced hydraulic loading as a result of the compression region of the droplet being constricted amongst the fibres. Comparatively high impact forces and pressures can be produced in this process.

Further work will assess the effects of other parameters, such as droplet size, on the erosion performance of such materials in order to ascertain whether similar patterns are present in the results.

5 Conclusion

Erosion of the leading edge of the blade occurs with far greater severity for increasing velocity and rainflow rates, it can be seen from the wastage map produced that an increase in impact velocity results in a higher mass loss than an increase in the rainflow rate. suggesting that the velocity of the impact has a greater mass loss than an increase in the rainflow rate. This suggests that the tip speed of the wind turbine blade is of greater importance compared to the relevant environmental conditions to which the wind turbine is exposed.

It also follows that the recovery rate of the material is not as significant as previously thought compared to impingement velocity. SEM analysis show that erosion can initiate via small pin-holes already present on the epoxy surface.

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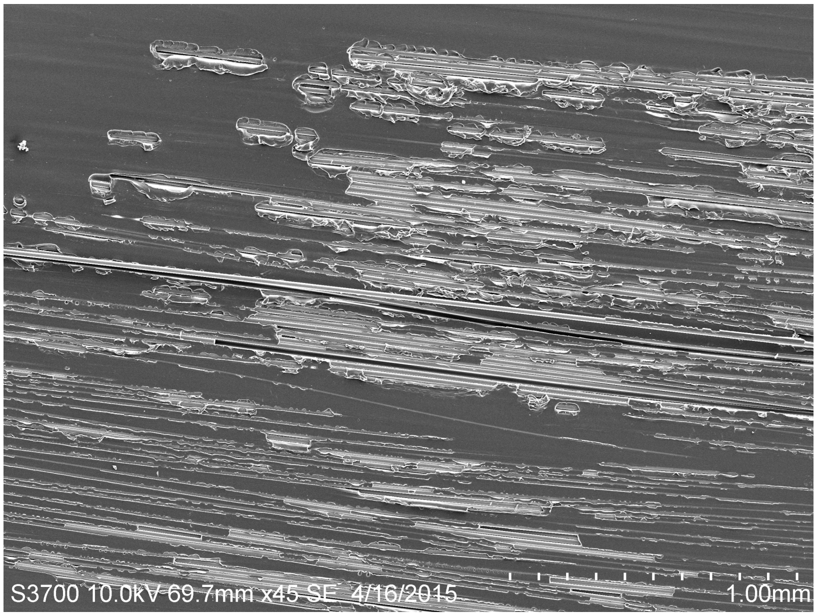

Figure 5: SEM image showing a sample exposed to an impact speed of 30m/s though 30mm/h of rainfall for 40 minutes using droplets of approximately 2.5mm in diameter.

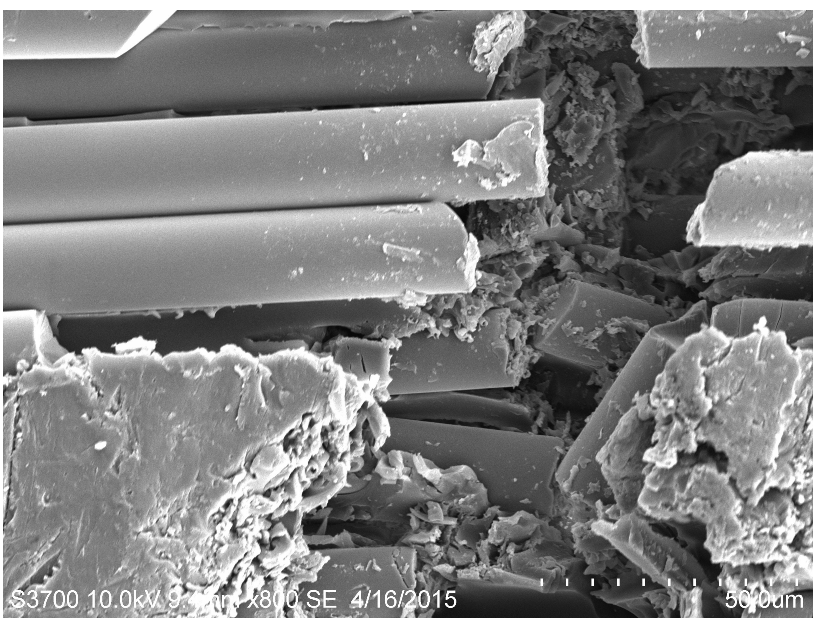

Figure 6: SEM image showing a sample exposed to an impact speed of 60m/s though 25mm/h of rainfall for 40 minutes using droplets of approximately 2.5mm in diameter.