

# On Analytical Tools for Assessing the Raindrop Erosion of Wind Turbine Blades

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## Abstract

In renewable energy, the wind sector has been expanding to become one of the largest markets. With this increase in popularity, and drive to expand low carbon technologies, maintenance of wind turbines is crucial, especially the monitoring of the leading edge of turbine blades which see high impact velocities in service. Surface changes due to rain erosion can reduce energy conversion due to a reduction aerodynamic efficiency. This is one of the key areas of interest, as small aerodynamic changes can lead to 2-3% loss in annual energy. Inspection methodologies of turbine blades are very basic, involving an observation and high-definition photographs of the damage. Recent studies investigating the rain erosion of turbine blade materials show that this standard procedure fails to characterise the loss of aerodynamic efficiency in these turbine blades in service or evaluate their performance in an inter-study comparative approach. With the industry moving in the direction of leading edge profile samples, there is a consensus that whirling arm type test rigs are the most applicable testing regimes. There is little overlap in the analysis used in different studies. This review will consider the various techniques used to inspect and characterise the materials and performance used in rain erosion testing. The focus will be on their benefit to overall use within the industry. Findings conclude that a combination of techniques is optimal to analyse surface defects and that subsurface analysis is an important factor that must be considered in any investigation of long term blade integrity.

## Highlights

- Decline in energy production of wind turbines due to the degradation of the blades
- Analysing the materials of wind turbine blades tested in the laboratory
- Standardising the ways in which damage of the material is analysed
- Reviewing the most technologically advanced analytical tools for assessing erosion.
- Assessing erosion problems of turbine blades to combat uncertainty of output power

This is a peer reviewed, accepted author manuscript of the following in press research article: Pugh, K., Nash, J., Raeburn, G., & Stack, M. M. (Accepted/In press – September 2020). On analytical tools for assessing the raindrop erosion of wind turbine blades. *Renewable and Sustainable Energy Reviews* .

**Keywords:** wind, energy, turbine, blade, material, rain, erosion, analysis, profilometer, SEM, X-ray, microwave, renewable, climate, environment, experimental, polymers, composites, aerodynamic, efficiency, subsurface, defects, power, damage, mechanisms, erosion maps

**Word Count:** 7164

## Nomenclature

|                 |  |
|-----------------|--|
| $n_{i_c}$       | Incubation period                                |
| $S_{ec}$        | Coating strength                                 |
| S               | Material Strength                                |
| $\sigma_{uc}$   | Ultimate tensile strength                        |
| $b_c$           | Slope of the Wolher curve                        |
| $\nu_c$         | Poisson's ratio                                  |
| $k$             | Variable relating to the stress wave reflections |
| $\psi_{sc}$     | Aucostic Impediance difference                   |
| $P, \sigma^o$   | Impact Pressure                                  |
| $\rho_L$        | Density of liquid                                |
| $C_L$           | Speed of sound in liquid                         |
| $V$             | Velocity of impact                               |
| $\rho_S$        | Density of substrate                             |
| $C_S$           | Speed of sound in substrate                      |
| Z               | Aucostic impedance                               |
| $V_{DT}$        | Damage threshold velocity                        |
| $K_{IC}$        | Fracture toughness                               |
| $c_R$           | Rayleigh wave velocity                           |
| $\rho_w$        | Density of water                                 |
| $c_w$           | Acoustic velocity of water                       |
| $d_w$           | Droplet Diameter                                 |
| GFRP            | Glass Fibre Reinforced Polymer                   |
| CRP             | Carbon Reinforced Polymer                        |
| SEM             | Scanning Electron Microscope                     |
| CMM             | Co-Ordinate Measuring Machine                    |
| CLSM            | Confocal Laser Scanning Microscope               |
| NDT             | Non-Destructive Testing                          |
| HDPE            | High Density PolyEthelene                        |
| DMA             | Dynamic Mechanical Analysis                      |
| TBD             | To Be Decided                                    |
| SENT            | Single Edge Notch Tensile                        |
| DVT             | Damage Velocity Threshold                        |
| t               | time   |
| mm              | millimeters                                      |
| m               | meters   |
| m/s             | meters per second                                |
| kg              | kilogram   |
| $\text{kg/m}^3$ | Kilograms per meter cubed to measure density     |

# 1 Introduction

Now, more than ever, the world needs renewable energy to combat climate change and to reduce greenhouse gases. In an effort to produce more clean energy, there is a worldwide focus on wind energy. With this ever-growing popularity it has pushed the design of the wind turbine to be larger and more efficient; however, the larger a turbine becomes the greater the tip speeds at the leading edges, which is conducive to high erosion rates. In an industry where aerodynamics are crucial, high erosion rates are detrimental to the performance and the energy production. The high tip speeds of the wind turbine blades which can now be up to 150ms<sup>-1</sup> on the 220m diameter blades can create exponential forces when a droplet of water impacts on the leading edge. The erosion arising from these accumulated events is individually responsible for a drop in annual energy output ranging from 2-25% depending on erosion severity, costs operators and the environment of the wind turbine [1, 2]. To understand this interaction between the rain droplet and the fast moving turbine blade industry and academia have sought to investigate the rain erosion phenomenon using laboratory testing methods. Testing the rain erosion resistance of coatings and materials through various methods have concluded that the use of a whirling arm type rig is optimal [3, 4].

From the academic research into this type of erosion it was concluded that regardless of the turbine the erosion followed a general trend. Firstly, there is an incubation period during which there is no apparent damage. Initial damage then becomes measurable and progresses linearly with time in a steady state manner. Later, there is a final erosion state, where the processes become more complex with mixed degradation regimes likely.

The importance of this topic provides the necessity for clear and distinct methods to characterise the materials and coatings prior to rain erosion testing. Rain erosion resistance is contingent on clear and thorough documentation of material parameters. Poor documentation may also lead to incorrect or spurious conclusions by authors when trying to compare different studies.

The surface of a material and its characteristics are known to play a significant role in the damage evolution of wind turbine blade coatings and therefore a thorough characterisation of the surface is key to understanding what its influence is on rain erosion performance. If this is fully understood it can prove extremely beneficial when trying to predict the lifetime of the blades in order to schedule maintenance, repair and replacement at the optimum time in order to maximise energy production and generate the most income.

Subsurface damage or defects are thought propagate to the development of damage in coating layers. Damage below the surface is thought possible to occur prior to the presence of surface erosion, as noted by industrial standards agency DNVGL [5]. This is an area that has received little attention by the wider scientific community and to the authors knowledge, no methods have been used in any published material to investigate this phenomenon. This paper will aim to provide an insight into the possible methods available to researchers and industry.

Highlighted by DNVGL is the non-existence of a standardised methods to post process samples and compare results [5]. Therefore, this article is an overview of the appropriate materials characterisation methods, surface analysis techniques, subsurface analysis techniques and the

performance characterisation and comparison of rain erosion coatings. By standardising the way in which we analyse these features, researchers and industry can unite in their results to tackle the main issue of the degradation of energy production and build in robust structures to assess the reliability of the turbine blades.

## 2 Materials Characterisation

The issue of rain erosion is a complex one. Most current work is based on that of Springer, in his authoritative book "Erosion by Liquid Impact" [4]. Presented here is one of the few working models that provides a relationship between the life time estimation of a material,  $n$ , the material's strength,  $S$  and the pressure from a droplet impact,  $P$ . This model has proven its application to wind turbine blades as shown by Eisenberg et al. [6]. Another model presented by Slot et al. [7, 8], provides an alternative method for life time estimation, but as of yet is incomplete and has not seen widespread application. For these reasons, the Springer model will be considered here when appropriate. Rain erosion applies to many materials and material/coating combinations. The area of interest is wind energy production process typically through rotating a bladed configuration. The turbine blades materials are primarily coated composites, but also composites and polymeric materials to a lesser extent. It is important to note that this model has broad applicability to materials that follow ductile behaviour, with agreement for brittle materials too. Issues arise when applying the model to elastomers as these have different material properties. Therefore, a separate approach should be taken with these material types, either by adapting the Springer model or the development of a new version. The Springer model equations are outlined below for reference (equations 1, 2, 3). A thorough explanation of the model itself is beyond the scope of this paper and so for further reading, the authors would recommend referring to the original text.

$$n_{ic} = 7 \times 10^{-6} \left( \frac{S_{ec}}{\sigma_o} \right)^{5.7} \quad (1)$$

$$S_{ec} = \frac{4\sigma_{uc}(b_c - 1)}{(1 - 2\nu_c)(1 + k|\psi_{sc}|)} \quad (2)$$

$$P = \frac{\rho_L C_L V}{1 + \rho_L C_L / \rho_S C_S} \quad (3)$$

Although equation (1) only provides a value for the incubation period, the basis for the model of mass loss rate of the steady state erosion stage is reliant on the same strength and pressure parameters. The equations stated here also apply to pure materials without coatings, with the equations modified slightly. Importantly rain erosion is still reliant on the same material parameters and so the results follow the same trends in material parameters.

Equation (2) provides a value for the coating strength in terms of rain erosion resistance. As stated previously, the Springer model was developed for ductile materials, not elastomers and so the use of terms as the ultimate tensile strength,  $\sigma_{uc}$ , or endurance limit are not appropriate descriptors. At the present time, the authors do not have a replacement for this equation and instead just note the difficulties with applying the analysis to this problem. If the authors are investigating the use of brittle or ductile gelcoats, such as epoxy or polyester, the equations should apply as intended. The term  $b_c$  is the slope of the Wolher curve, a term related to the knee in the fatigue curve, the ultimate tensile strength and the endurance limit and the Poisson's ratio,  $\nu_c$ .

The combination of materials and coatings with different acoustic velocities and densities (usually combined into the term acoustic impedance,  $Z$ ) can have synergistic effects, with the coating potentially becoming an amplifier for the stress wave in magnitude [9]. If the thickness of a coating

is chosen incorrectly, it can lead to further problems in that it generates stress wave reflections, accelerating fatigue failure [10]. Note that the variable  $P$  has been exchanged for the variable  $\sigma^o$  in equation 1 to account for this and that the equation for strength includes the terms  $k$ , a variable relating to the stress wave reflections, and  $\psi_s c$  which relates to acoustic impedance differences [4]. A further explanation of how exactly  $P$  and  $\sigma^o$  relate can be found in [4].

The impact pressure,  $P$ , is typically approximated using a modified form of the water hammer equation (equation 3) [4, 7, 11]. The terms,  $\rho$ ,  $C$  and  $V$  are the density, speed of sound, impact velocity, respectively, with the subscripts L for liquid and S for substrate. The acoustic velocity is dependent on the stiffness properties of a material, whose definition can be found in Springer [4]. This equation provides a reasonable approximation for most materials, but begins to diverge from this equation for materials with particularly low stiffness properties upon which it underestimates the impact pressure. Elastomers such as polyurethane are an example of such materials and so the stiffness properties of a material or coating must be considered, as should their densities. It is important to note that the impact pressure cannot be accurately determined using this equation.

Whilst the model provides a good basis for rain erosion resistance, the influence of a number of parameters has not been mathematically deduced. These parameters include hardness, toughness, surface roughness, interfacial strength, with the addition of appropriate tensile and viscoelastic properties of elastomeric coatings. Some of these materials also have a noted temperature sensitivity around their operational range, with thermal aging also having the potential to influence their behaviour [12, 13, 14]. The application of the Springer model to a material and coating combination should either be linked to an appropriate temperature, with the respective material properties stated at that temperature or mathematical models of those material properties should be calculated and incorporated into the model.

To produce the model Springer made assumptions when considering incomplete data from rain erosion tests, also seen in more recent work. This insufficient documentation of material properties presents some difficulties in linking material parameters to performance [15, 3, 9, 8]. The requirement, therefore, for systematically documenting material properties that are thought to influence rain erosion performance is vital.

Currently, there are standardised documentation for testing of various properties of rain erosion coatings, although limited [16, 17]. These documents describe some minimum performance characteristics using standardised testing regimes that coatings should have. These documents define a number of tests some of which are listed in Table 1 and some of which have more applicable testing methods that are available.

## 2.1 Coating Adhesion Strength

A key indicator of coating performance is its ability to adhere to the substrate material. The 'Pull Off' test is the most widely used standardised method to test for coating adhesion [16, 18, 9, 3, 15], with its ease of use and proven applicability makes it the preferred choice of method for many analyses. The peel test is another method, but is used to a lesser extent. It cannot be used for all material coatings, as the material must be flexible and so works better for tape- type coatings [9]. There are reports of both the material flaking or delaminating in large pieces during rain erosion testing and a also concern of tape type coatings peeling away from the material, hence limiting their application.

## 2.2 Coating Layer Thickness

The coating layer thickness is significantly important too, with the performance inextricably linked to its performance. Defects such as “sagging” or coating delamination can be caused due to incorrect coating thicknesses [20]. Therefore it is not only important to apply the correct coating layer thickness, but also as discussed above the thickness should be selected in order to optimise the performance of the coating itself [4, 10].

Table 1: Outlining the preferred testing methods to obtain parameters thought/ known to be relevant to rain erosion

| Preferred Test Name/Equipment             | Property                         | Test Standard                    | Source             |
|---|----------------------------------|----------------------------------|--------------------|
| Pull Off Test                             | Adhesive/ Cohesive Strength      | ISO 4624                         | [3, 9, 15, 16, 18] |
| Peel Test                                 | Adhesive/ Cohesive Strength      |                                  | [9]                |
|   | Coating Layer Thickness          | ISO 2808-2007                    | [16]               |
| Tensile Test (Non-Viscoelastic Materials) | Stiffness                        |                                  | [12, 14]           |
| DMA(Viscoelastic Materials)               | Storage Modulus                  |                                  | [12, 14]           |
|   | Loss Modulus                     |                                  | [12, 14]           |
|   | Glass Transition Temperature (s) |                                  | [12, 14]           |
| Nanoindentation                           | Hardness                         |                                  | [9, 19]            |
| Tensile Test                              | Ultimate Tensile Strength        |                                  | [3, 12, 14, 16]    |
|   | Failure Strain                   | ISO 527-3 (specimen type 2)      | [3, 12, 14, 16]    |
|   | Max Strain Rate                  |                                  | [16]               |
|   | Poisson's ratio                  |                                  | [16]               |
| Tensile-Tensile Cyclic Loading            | Fatigue Performance              |                                  | [14]               |
| TBD                                       | Fracture Toughness               |                                  |                    |
|   | Density                          | BS EN ISO 1183-1:2012 (Method A) |                    |



## 2.3 Stiffness, storage modulus and loss modulus

In order to produce approximations for the impact pressure and evaluate the strength of a coating and subsequent substrate material combination (equations 2 and 3), the acoustic impedance is necessary and can be calculated using the material's stiffness [4]. For materials with limited viscoelasticity, simple methods like tensile testing as outlined in [16] provide values for the elastic modulus. However, for strongly viscoelastic materials, stiffness properties are more complex and dependent on temperature, frequency and loading regime. Therefore, the storage modulus can be used [9]. The stiffness of viscoelastic materials can be described by three properties; the storage modulus, the amount of elastic energy stored by the material, the loss modulus, the amount of energy dissipated through heating and viscous losses, and the tan delta value, the ratio of loss modulus to storage modulus. The importance of these parameters, with respect to their rain erosion performance has been investigated by O'Carroll et al. [19] using nanoindentation. These investigations established a negative correlation between storage modulus and rain erosion performance, but failed to do the same with loss modulus and rain erosion performance. As noted by O'Carroll et al., it may have been preferable to capture this information using nanoindentation. Such approaches can only typically measure these stiffness properties at one frequency and temperature. For this reason, dynamic mechanical analysis (DMA) machines would likely be the favoured method of testing LEP coatings. As mentioned above, several coatings of interest have temperature sensitivities around their operational range and so DMAs with their ability to run frequency and temperature sweeps are desired [14, 12].

## 2.4 Hardness

Rain erosion testing on materials have provided different conclusions regarding the relationship between rain erosion resistance and hardness. Different authors have claimed increasing hardness either improves or degrades rain erosion performance and there is conflict in the observed results. In metals, hardness appears to increase rain erosion resistance [21], but conversely the opposite appears to be true with respect to polymers [3, 19]. This is likely to be related, at least in part, to the way in which a material responds to an indentation test. One possible reason is explained by Shaw and DeSalvo [22]. They state that solids should be divided into two different classes when considering hardness, one for metals and one for glasses and polymers. This is based on their stiffness to uni-axial compression flow stress ratio. Metals typically have much higher stiffness to flow stress values than glasses and polymers. Hence, during indentation from a blunt indenter, glasses and polymers tend to distribute stresses in a more uniform manner over the indentation area, but metals typically produce Hertzian distributions. Indentation testing is also somewhat analogous to the impacts themselves, but at a slower rate and so it would be fair to assume a direct relationship. For high velocity impact erosion occurs at higher strain rates than at lower velocities and therefore conventional hardness measurements would be likely to not be applicable at such strain rates. One should note that indentation results are particularly dependent on the surface roughness, meaning that if performed on a rough surface anomalous results may be obtained.

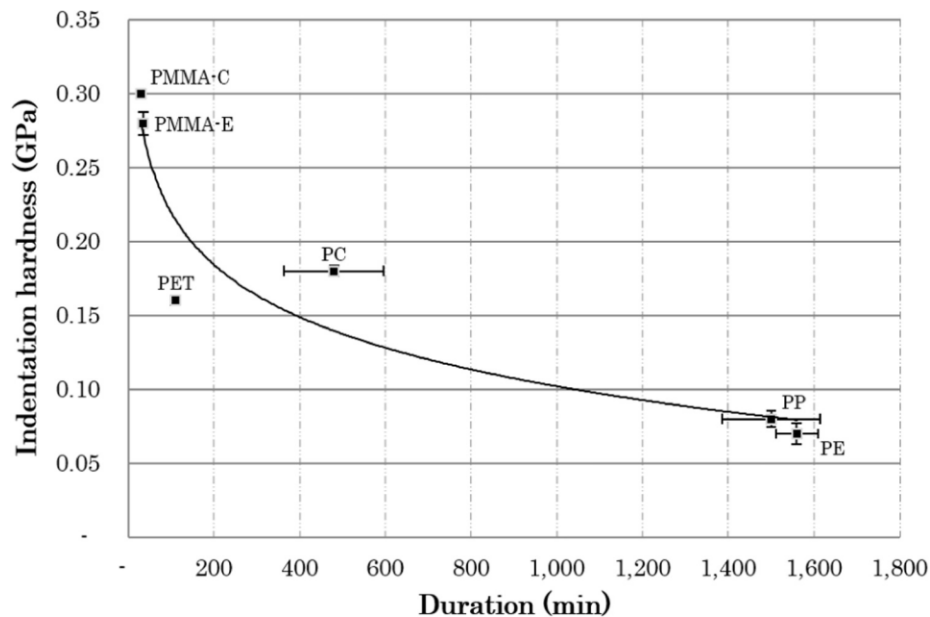


Figure 1: Hardness Vs. Rain Erosion Resistance of polymers. Figure from O’Carrol et al. [19] with permission from Elsevier.

The DIN EN 59 hardness test for coatings stated in the DNVGL standards documentation [16] for testing rain erosion protection coatings is designed for use with thicker coatings ( $\geq 0.5\text{mm}$ ). Coatings used on wind turbine blades are known to be thinner than this minimum thickness and thin films often display different properties to that of the bulk material as the close proximity to the interface can influence the result, so more appropriate testing regimes have been sought after [9]. Recent studies have shown the potential of nanoindentation testing, with favourable applicability to thin samples ( $\leq 0.5\text{mm}$ ), like those used in the multi-layer coating systems for wind turbine blades [23, 9, 19].

## 2.5 Tensile Properties

The Tensile properties as stated above can be found using the standard tensile test outlined in ISO 527-3, using specimen type 2 for flexible materials. As the strength model outlined by Springer [4] is intended for ductile materials, it is of value to investigate other properties aside from those outlined in the model. Elastomeric materials typically fail through fatigue, when exceeding a strain rate higher than the material can withstand or an elongation higher than the material can accept [7, 3, 14, 12]. More appropriate parameters may therefore be used to describe the material’s strength, S. Tensile-tensile cyclic loading testing should also be used to produce the Wohler curve as is necessary for the Springer model [14].

## 2.6 Damage Resistance

For materials to be resistant to rain erosion, their ability to resist damage initiation and limit its propagation should be important factors. The importance of fracture toughness as outlined in the literature reviews of Keegan et al. [11] and Gouhardani [24] is the relation of fracture toughness to the damage evolution in the rain erosion phenomenon. Springer [4] speculated that fracture toughness would influence rain erosion performance, which has been supported by Busch et al. [25] with their investigation into the notch sensitivity of various polymers and rain erosion. Previous work by Evans et al., sought to relate the erosion of brittle materials from solid projectiles to their fracture toughness with good agreement (equation 4) [26]. Keegan [11] used this equation to show the significant effect this could have on epoxy coatings with different fracture toughnesses. Zhang et al. [3] investigated the impact resistance of various coatings and their rain erosion performance; however, the experimental work in this regard was limited and a fracture toughness value was not produced. The results showed that the coating with a poor rain erosion performance also failed during the impact test by detaching from the surface, compared with the two that performed significantly better in both. Another damage resistance characteristic investigated by Zhang et al. was the abrasion resistance, which showed a correlation in abrasion resistance and rain erosion resistance. This indicates that the abrasion and erosion process may follow similar trends, and therefore could occur through the same or similar mechanisms.

$$V_{DT} \approx 1.41 \left( \frac{K_{IC}^2 c_R}{\rho_w^2 c_w^2 d_w} \right)^{1/3} \quad (4)$$

$V_{DT}$  is the damage threshold velocity, above which the material damage will occur. The definition of this damage is not stated.  $K_{IC}$  is the fracture toughness,  $c_R$  is the Rayleigh wave velocity,  $\rho_w$  is the density of water,  $c_w$  is the speed of sound in water and  $d_w$  is the droplet diameter.

The link between damage resistance characteristics and rain erosion is not clear with the limited data available, and so the selection of an appropriate toughness parameter is not possible. Furthermore, an in depth discussion and selection of appropriate fracture toughness testing methods and model is complex and is far beyond the scope of this paper. Instead, presented here are some thoughts on how one should approach the selection of an appropriate test configuration. During rain erosion, a material or coating is continuously degraded. Damage can be initiated through direct failure, surface fatigue or through the presence of a defect. In the majority of situations, failure develops from the exposed side of the coating or material. Fracture toughness analysis should therefore use single edge notch tensile (SENT) testing [12]. Currently the most appropriate methodology reverts to the use of bulk materials testing regimes. Rain erosion in itself is not a steady state or quasi static situation; it involves the repeated impulses from droplet impacts. Therefore a cyclic or transient testing format would be most applicable.

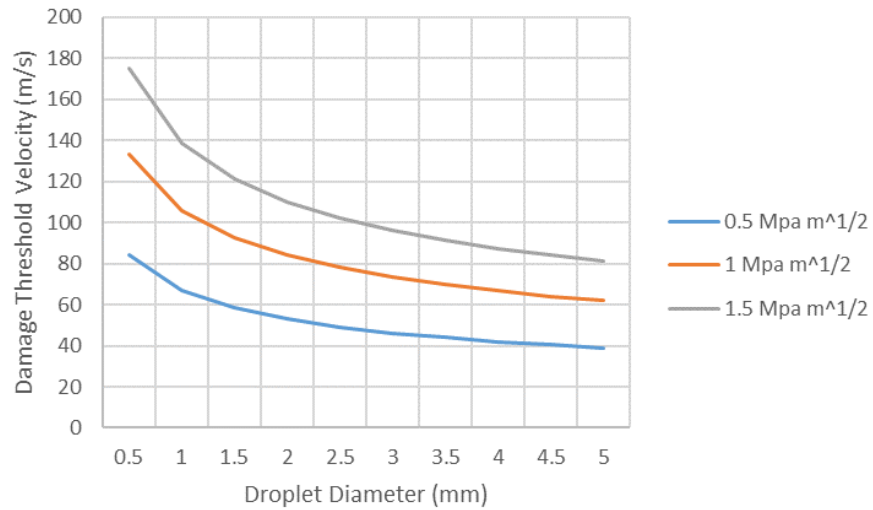


Figure 2: Damage Threshold Velocity (DVT) Vs. droplet diameter using 4 from [26] for epoxy coatings with different fracture toughnesses. Figure adapted from [11]. Rayleigh wave velocity,  $c_R = 942\text{m/s}$ , Density of water,  $\rho_w = 1000\text{kg/m}^3$ , Acoustic velocity of water,  $c_w = 1490\text{ m/s}$ .

### 3 Surface analysis

Surface analysis is a diverse topic and is the most commonly used for investigating erosion mechanisms. There are many techniques that are utilised in surface analysis and many categories depending on the scale of the subject, for liquid impact erosion the test samples are usually inspected on the micro scale. During analysis, the features that are of interest include pits, gouges and delamination. These features are used in some studies as the three stages of erosion in GFRP/CRP (Glass Fibre Reinforced Polymer/ Carbon Reinforced Polymer) and coatings [2]. However, the depth and diameter of each feature is determined for each study.

Due to the various analytical techniques available in surface analysis many studies will use multiple techniques in order to confirm their results or to obtain a different perspective with a different analytical tool. This allows for direct comparison between methodologies and an insight on tools that are used symbiotically.

There has always been a desire to use optical microscopes in order to provide an assessment of the surface prior to/post testing. Unfortunately, this method fundamentally really only provides limited detail of the surface of a material and whilst yes, it may be possible to view larger scratches and grooves, details relating to surface roughness, defect sizing and locations may be missed as this method is reliant on the skill and ability of the individual operating the tool [27].

### 3.1 SEM

The Scanning Electron Microscope (SEM)(Figure 3) is a common analytical tool for assessing morphological features on a surface. In order to analyse glass fibres, which is the most commonly used material for constructing wind turbine blades, the sample requires a gold plating in order to obtain an image. This is to create a conductive surface for the flow of electrons. The images obtained from analysing GFRP can range from a low magnification in order to observe pits in the surface (Figure 4) [28] (visible by the human eye) to a very high magnification in order to observe the surface texture of a single glass fibre (Figure 5). This large range in magnification is very beneficial as it allows many of the features obtained during rain erosion to be analysed under one machine in one operation.

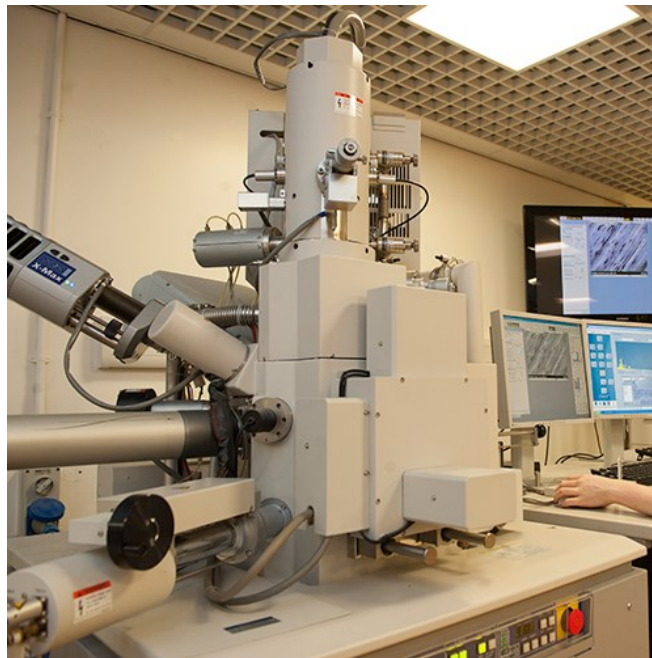


Figure 3: SEM at the University of Strathclyde within the Advanced Materials Research Laboratory [29]

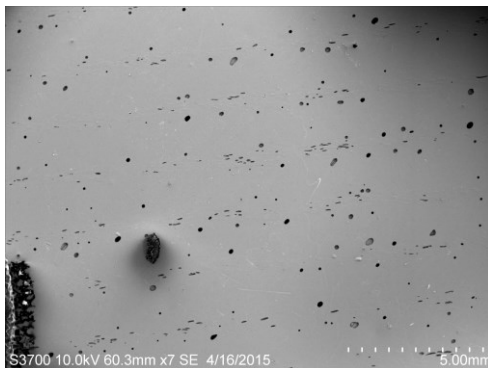


Figure 4: SEM image of pinholes on GFRP [28]

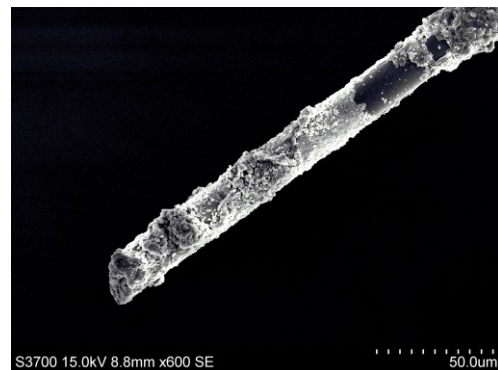


Figure 5: SEM image of glass fibre [30]

SEM analysis whilst a powerful tool may present some issues. Confusion can occur when there are misleading shadows that create an optical illusion, this can lead to the uncertainty between peaks and troughs. When investigating the erosion of metals using a SEM the sample can be analysed at different stages throughout testing as the surface is already conductive. This method has been used to visualise the surface damage at different known number of impacts [31]. This is not possible to do when investigating the erosion of GFRP as it requires a gold plating. This means that the analysis is only applicable at the end of the investigation, this is very common within studies [32, 27, 28, 33, 34]. Arguably this is the biggest issue with SEM analysis as the information which is gathered during the investigation is of great importance as it describes the process of erosion and the rate at which it occurs. For the specific investigation of erosion of wind turbine blades where the blades are mainly manufactured from GFRP the SEM analysis serves as a perfect tool for an end of investigation analysis however for looking into the rate of erosion there are more appropriate tools.

### **3.2 Optical**

In comparison to the SEM, optical analysis has a greater variance in equipment. Optical analysis can include anything from high resolution images of erosion from a camera used on the field all the way to microscope images taken in the laboratory. Relatively speaking optical analysis is more affordable and portable. However, the resolution of the image produced by the SEM is very difficult to match using optical equivalents.

A very popular method of recording erosion of the surface topography for comparative blade analysis is conventional photography with no magnification [35, 36, 2, 11, 18, 37, 38] as this is an extremely easy and repeatable method; however, the level of detail captured is minimal. This type of recording data is useful for comparing experimental data to the pictures captured within the field as the images recorded from services teams are unable to conduct high detail scans due to time issues. The images however only show large features once the blade has undergone considerable erosion; it would be impossible to detect the microscopic pitting from the initial stages of erosion using this method.

For laboratory analysis, a high magnification optical microscope can be used to detect all the stages of erosion of GFRP. It can also be repeated during the experiment as the sample requires no treatment in order to be analysed, this allows for the progression of erosion to be recorded on a single sample at different stages of the experiment. This is highly admirable as the rate and mechanisms of erosion are more likely observed and measured. This methodology has been used by Zhang [3] to investigate the progression of erosion between two coatings for wind turbine blades. The results show two different mechanisms of erosion, one being a failure of the epoxy matrix and the other by defects which caused cracks and loss of material.

Optical analysis can be used in conjunction with SEM analysis as seen in the literature [30, 39]. This allows for a direct comparison between the two types of surface analysis. In a recent study [30] which assessed the effect of stress on the material while being subject to rain erosion, the topography analysis used both SEM and an optical microscope. The two images presented different features. The SEM images showed the fibres in high detail and the loss of material whereas the optical microscope displayed the plastic deformation of the top epoxy layer which

was missed in the SEM. This could have been user error. However it could be argued that the optical microscope allowed for a different perspective on the specimen. Another study which compared SEM and optical microscope images directly was carried out by Thomason [39]. This research investigated natural fibres and obtained images from the SEM and optical microscope both in the same magnification observing the same feature. Having such images creates an opportunity to accurately compare the detail obtained from both pieces of equipment. The results show more detail from the SEM. However it could be argued that some features are only seen from the optical microscope.

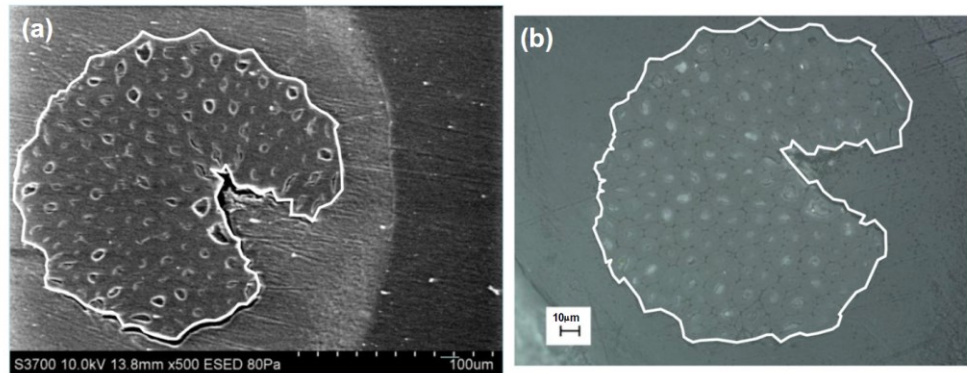


Figure 6: Comparison between SEM imaging and Optical imaging [39]

### 3.3 Profilometer Analysis

One form of topography analysis which is becoming more popular for inspection is the use of a profilometer to image and also measure the material surface. This is a form of measurement device that evaluates the changes in surface height to a very small scale and outlines a profile, from these measurements an image can be created illustrating the topography. From the literature there are two variants of profilometer; stylus, that uses a tactile probe that physically moves along the surface and optical, which is a device that uses a laser to scan the surface. These devices are designed to calculate the surface roughness of a material which is essential when investigating the erosion of wind turbine blades as it can help determine the aerodynamic efficiency of the blade and hence the overall efficiency of the turbine.



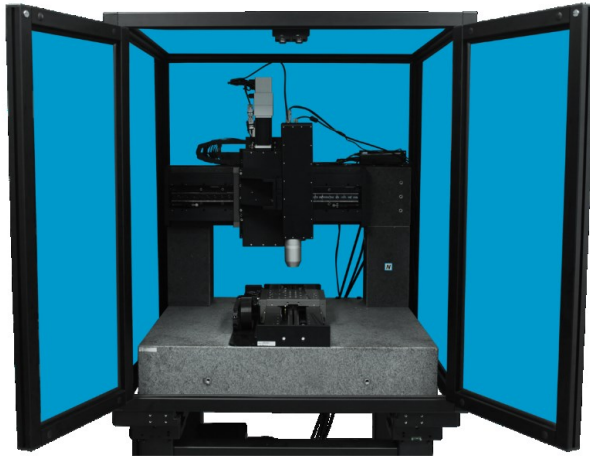


Figure 7: Optical profilometer [28] Figure



Figure 8: Stylus profilometer [30]

The Stylus profilometer is not as commonly used for measuring rain erosion. This could be due to the reduced resolution however it would be useful for larger samples including a leading edge of a blade as the CMM has a larger range of depth it can scan within one analysis. This is because the CMM is not limited by the field of view limit that exists in the CLSM (confocal laser scanning microscope) due to the use of lenses.

The technology behind the CLSM is developing since its creation in the mid-1970s [40] and the use within tribology research is becoming more popular. The qualities of this type of analysis are ideal when investigating micro level defects on a materials surface and the effect that the surface morphology has on the roughness and hence the drag. Figure (8) is a CLSM scan of a sample used in [27] subject to salt water erosion. This figure describes the surface profile in a 3D image that can be used to evaluate the distance between the highest trough to the deepest groove.

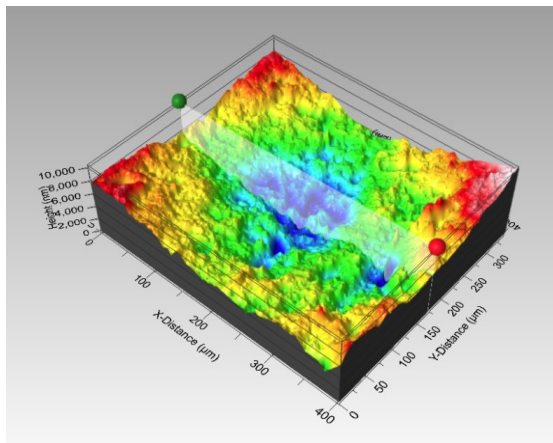


Figure 9: CLSM scan of sample subject to salt water erosion [39]



Recent research has used this technology to consider 1 into the topic of rain erosion on wind turbine blades [35, 36, 41, 42]. In Tobin's recent work he looks into the analysis of the incubation period in rain erosion using a CLSM. In the investigation, scans of the material were carried out at different time stages which allowed for various measurements to be taken during the investigation. This this includes parameters describing the surface roughness and mass loss [42].

## 4 Subsurface analysis

When considering rain erosion, little attention has been given to the presence of subsurface features or damage initiation inside the coating layers. The presence of defects in composites, such as voids or porosity has been well documented [43, 44, 45, 18]. When coatings and multi layer coating systems are then introduced into composite manufacture, this presents further possible sites for defects to exist [20]. Given the size of wind turbine blades, manufacturing structures such as these without the presence of defects is not possible. When also considering the cost of discarding blades with defects or coating defects, especially as coatings are non structural, subsurface defects are likely to be fairly common blades.

During rain erosion testing, subsurface defects are one possible reason for inconsistent results, in situations where there appears to be a smooth and otherwise good surface [46, 3]. There are two reasons as to why defects are of concern; firstly is their ability to affect material/ coating performance and secondly, their ability to cause stress wave reflections. The defect size of interest, that is likely to lead to interfacial failure includes those that are of comparable size to the coating layer thickness and larger [47]. The defect size of interest with respect to stress wave reflections is dependent on the wavelength of stress waves emitted during impact. Acoustic waves only interact with defects of comparable size to their wavelength and larger. In ultrasound Non-Destructive Testing (NDT), to obtain good wave reflections to allow defect detection, the defect should be at least about half of the wave length of the frequency used [48]. Although it is currently not be possible to measure the wave length of the wave emitted through the coating during droplet impacts, the time period of the waves generated will be related to the impact velocity. Higher velocity impacts should cause higher coating particle velocity during impact, which would generate higher frequency waves inside the material. This would lead to smaller wave lengths and so will therefore interact with smaller defects. The penetration of acoustic wave reduces with increased frequency. Therefore, smaller defects will likely only influence damage propagation due to reflections close to the surface, but as distance increases only larger defects will likely be of importance.

Currently this topic is yet to be properly investigated, so the true influence is unknown. The ability of different methods to detect various defect types will be discussed, with comments on the considerations for designing a test setup and some other considerations will be addressed. The aim of this discussion is to provide some insight into the available methods of imaging defects within coated composites. The methods found to be applicable fall into three main categories; ultrasound, radiology and microwave methods.

## 4.1 Ultrasound

Ultrasound is one of the most common NDT methods, with its application widespread. It works on the basis of generating mechanical vibrations within a material, typically propagated in compressive or shear wave form through the material. When these waves are introduced to interfaces between materials of differing acoustic impedances, liquids or gases, they are reflected back and the signal is received and processed. There are two possible configurations; the first is a combined transmitter and receiver probe, called transceiver and the second is a separate transmitter and receiver probe. The data is typically generated into B- and C-scan forms, which give you cross sectional views of the specimen and plan views, respectively. With modern developments of phased array probes, robotic scanning arms or Gantry systems and computers 3D scans of samples can be generated. Due to inherent limitations with the near field effect in contact probes, they cannot be used for thin samples like those used in rain erosion testing. It could be possible to use an immersion probe, which would require submerging the whole or part of uneroded and eroded components into water. Any investigator should consider whether this is feasible to do and whether or not submerging components inside water for periods of time may affect the material's properties through absorption. An alternative method would be to use a laser ultrasound generation method. This method has been shown to work and achieve reasonable results in carbon fibre composites, but no such studies investigating glass fibre composites were found by the authors [49, 50]. This method would enable eroded specimens to be analysed without immersion inside a tank, but importantly the laser impulse on the surface could affect the material properties of any particularly temperature sensitive materials, such as those discussed previously. To achieve a high resolution, it will be necessary to use high frequency ultrasound. It's likely that a scanning rig would need to be set up to automate the inspection of the specimens and produce a 3D model of the subsurface. The exact form of data that will be collected will still need to be determined, both pulse echo and time of flight diffraction have their individual merits and it appears possible to collect both and use them in a complimentary fashion. The exact frequency selected will be dependent on the materials tested. The main benefit of using ultrasound would be that the price would be significantly less than X-ray [51, 48]. One of the main concerns surrounding Ultrasound and its use in testing composite components is due to the high attenuation, caused by scattering from the fibres [52]. It can also be difficult distinguishing between the initial impulse and reflections caused by defects in thin samples [49].

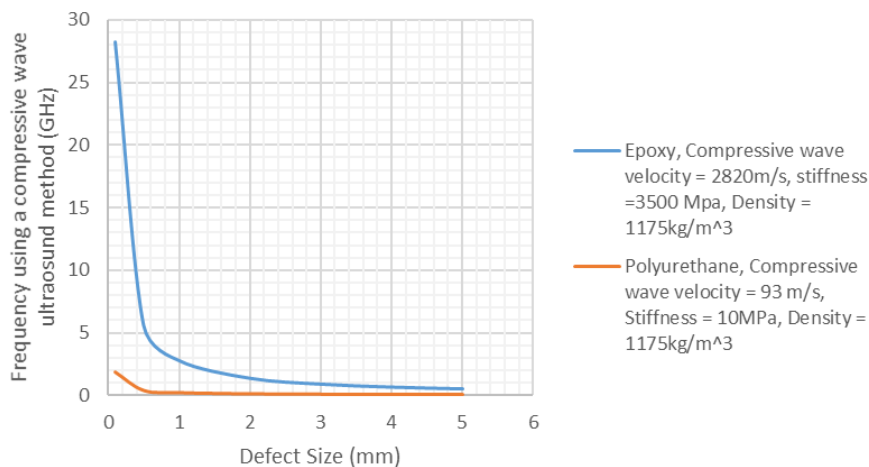


Figure 10: Displayed here is a graph showing defect size vs. approximate frequency required to detect it. Materials data was sourced from Slot et al. [7]. Wave speed was calculated using the equation provided by Springer [4]. Frequency was calculated using the standard wave equation  $c = \lambda f$ , where  $c$  is the speed of sound,  $f$  is the frequency and  $\lambda$  is the wavelength.

## 4.2 Radiographic methods

Radiographic methods are desirable with their significantly higher resolving power, they can provide a much higher level of detail (individual fibres) than other techniques. There are a few different methods for radiology: gamma radiology, x-ray radiology and neutron radiology (although this is different in operational principle). Gamma radiology and x-ray radiology follow the same principles, but their difference is the source of photon energy and how it is generated. They operate on the principle of irradiating a sample, with different materials and defects having different absorption properties. The transmitted radiation is then detected, more commonly these days, using a detector. The result is a 2D image of the specimen and so the orientation of the component can be key in detecting defects. The absorption of a material is dependent on the density of the specimen and its thickness [51, 53]. This presents a problem for polymeric materials, due to their low density, which gives a poor contrast [52]. With the development of computers, computed tomography has become available allowing a series of 2D X-ray images to be compiled into 3D scans which can help to reduce problems with orienting the specimen properly. Although this is desirable in most cases, X-ray gamma ray imaging begins to become very costly and x-ray imaging is also a slow process. Typically, with this in mind its ability to detect very fine defects such as pores, voids or cracks can make it more favourable compared with other NDT methods. The possibility of using X-ray opaque coatings could provide a possibility for investigating the effect of defects [52, 51, 44, 53].

## 4.3 Microwave Imaging

Microwave imaging relies on passing microwaves through a specimen using a transducer and receiving the signal either in the sample probe, or using a separate probe. Microwaves are reflected at interfaces between materials with different dielectric properties. It therefore has significant potential in the testing for defects in polymer coated composites. It has advantages over traditional inspection techniques such as x-ray, being that it is significantly cheaper and safer, and Ultrasound, in that it can detect stacked defects within samples. It is well suited to the testing of high porosity composites (>2%) and less attenuation occurs whilst scanning GFRP composites, which typically make Ultrasound methods challenging. Currently, defects of approximately 1.5mm in diameter and a thickness of 0.5mm can be detected with reasonable visibility. The technology is a relatively immature, largely being developed at the National Physics Laboratory. The main application is the investigation of butt welds in HDPE pipes and as well as some composite components [54, 55, 56]. It should be noted that microwave NDT cannot be used to image carbon fibre or graphite composites, due to the carbon fibre's high conductivity which attenuates most of the microwave signal. Air-gaps of 0.25mm are also possible to image (ideally larger at 0.4mm), which essentially constitute delaminations. Disbonds of 0.03mm can be imaged. Microwave NDT can also provide information on the state of cure as well as moisture ingress [52].

| Layer  | Relative complex permittivity | Thickness (mm) | Estimated thickness (mm) |
|--------|-------------------------------|----------------|--------------------------|
| Rubber | 4.80-j0.17                    | 3.175          |                          |
| Teflon | 2.00-j6E-4                    | 0.381          | 0.385                    |
| Rubber | 5.31-j0.22                    | 6.35           |                          |
| Teflon | 2.00-j6E-4                    | 0.508          | 0.518                    |
| Rubber | 4.80-j0.17                    | 3.175          |                          |

Table 11: Thin sandwich structures of Teflon and rubber have been imaged, alternating in material to mimic delamination. The layers of Teflon were estimated using microwave imaging techniques respectively. Adapted from [52].

## 5 Standardised methods for assessing damage

### 5.1 Mass Loss/ Volume Loss and Erosion maps

The most common characterisation of wear and erosion and in most cases the easiest to measure is mass loss. This is simply by comparing the mass of the sample before and after testing. This methodology has been used in many research papers considering the erosion of wind turbine blade materials [57, 18, 35, 27, 30, 9, 42, 25, 28, 58, 59, 41, 37]. The measurement of mass loss is a very blunt measurement as it does not describe the erosion mechanisms in any detail, however it does allow for a direct comparison between investigations.

The mass loss is displayed differently within different investigations ranging from a table of results [38] to wear maps [27, 30]. The most common format is a cumulative mass loss line graph [37, 4, 41, 59, 28, 42]; this displays the mass loss of the sample at different periods during testing. When the information is displayed in such a manner the rate of erosion becomes more apparent and the stages in which the material degrades can be observed. The most apparent of these stages is the incubation period where very little mass is lost from the sample (Figure 11).

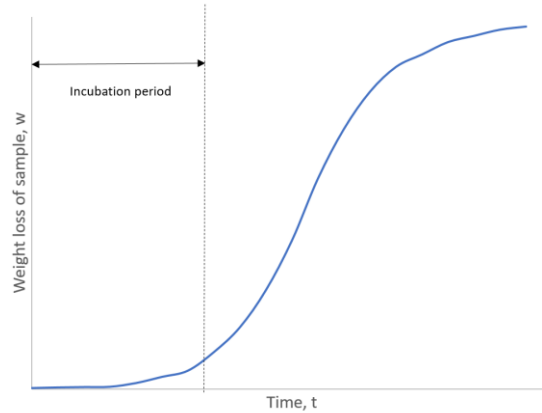


Figure 11: Line graph displaying weight loss against time [4]

If the investigation involves more than one range of variables an appropriate mechanism to display the mass loss information would be through a wear map. For example if the investigation is considering impact angle and velocity as previously carried out [30] the mass loss results are set in a matrix form to produce a wear map (Figure 12).

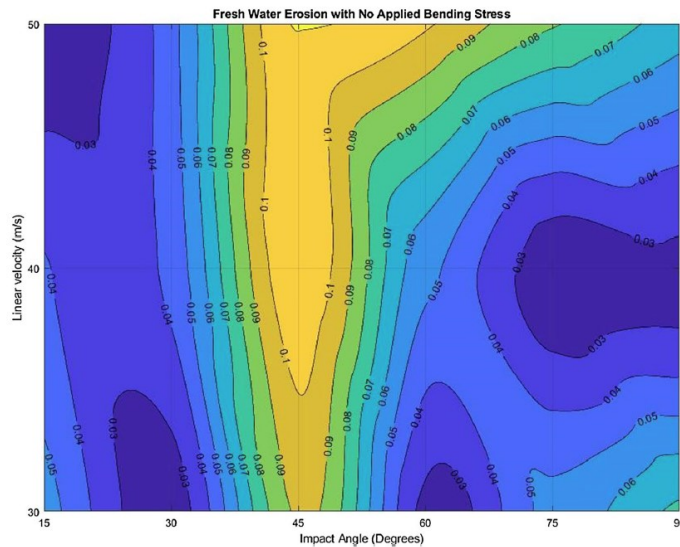


Figure 12: Wear-map showing mass loss with respect to impact velocity and angle [30].

Due to the blunt nature of mass loss analysis in terms of measuring erosion it is almost always accompanied by surface analysis to determine the mechanisms of erosion and also to highlight the locations of mass loss to confirm the results. The accompanying analysis can also be from a profilometer, if a scan of the sample is taken before and after testing the volume loss can be measured. With this technology it is possible to locate exactly the locations where materials suffered the highest degradation. This analysis is useful when testing new materials for wind turbine blades and understanding their weak points.

## 5.2 Surface Roughness

Surface roughness has been a parameter investigated thoroughly. An early study by Boermans and Selen [60] was carried out on sailplanes where adhesive backed polyester film was wrapped around the wings to collect insects during flight. These insects were then removed from the sailplane and inserted onto a test aerofoil in a wind tunnel to test the changed aerodynamic properties of the compromised wing that would now have a different surface roughness.

When investigating the erosion on wind turbine blade materials a measurement of surface roughness is required in order to evaluate the change in surface parameters [61, 62]. The way in which surface roughness is classified is by measuring the variation in height on the samples surface including the depth of pits which form during erosion. This measurement can be taken by a profilometer as mentioned before in the previous section. This parameter can help define the aerodynamic properties of the material if it were to be used in a wind turbine blade. The development of surface roughness initiated by erosion can provide a good indication of the more resistant materials to rain erosion.

In recent studies [63] the effect of increased surface roughness from erosion on the leading edge was studied by looking into the lift coefficient of various aerofoils at three stages of surface roughness. This provided real data that can easily be transferred to the output efficiency of a turbine generator. In a study by Pechlivanoglou [64] the initial surface roughness of a newly manufactured blade is observed and it is clear that before the blade is put into commission it has a substantially rough surface. This can result in multiple initiation points for erosion, and within this study sand build up.

Overall surface roughness provides in depth knowledge of the blades micro structures and the development of pits, gauges and cracks within the material and after erosion. The measurements can be carried out at different stages of experimentation and can provide rates of erosion.

## 6 Discussion and Conclusions

The understanding of erosion on wind turbine blades by liquid impact is crucial in solving the problem to the loss in energy production of a wind turbine due to its degrading blades. From the literature it can be argued that standardization techniques are required to evaluate properties. d. There are various research and industrial projects around the world tackling this issue with very few collaborating and fewer who are discussing how they formulate their results with regard to their material. There are preferred methods (table 1) however these are not widely used.

Within this review, the possibility of various analytical techniques has been discussed and the methods for investigation of various parameters within the topic of rain erosion on wind turbine blades has been scrutinised. A parameter about which there has been little work is subsurface analysis of the material and the various methods of analysing the damage caused by the water impact. Even so, some points can be addressed. X-ray scans have the ability to provide very detailed scans, but ultimately is less economic than other methods, take a long period of time and health and safety procedure is long and cumbersome. It is also possible that due to the low density of polymeric materials, the contrast of any image may be limited and so the distinction of defects

may prove difficult. Ultrasound may provide a possibility for imaging using immersion techniques and high frequencies, but authors need to consider whether allowing the samples to be submerged is possible. It may also prove difficult to image samples due to the complexity of the composite structure causing attenuation and noise and imaging stacked defects may not be possible. Microwave methods have shown real potential, but their application has been limited. Individuals seeking to investigate the phenomenon further should test these methods in a comparative manner and critically assess the application and results of each.

The most popular use of analysis when investigating rain erosion on wind turbine blades is surface analysis. As little as a 1mm defect in the surface can lead to major annual energy losses up to 5% [2]; therefore it is vital that during testing in the laboratory every pin hole, crack and loss of material is documented properly as these defects will lead to a decrease in aerodynamic efficiency resulting in less energy production and then ultimately a loss in annual revenue from the wind turbine owner. Due to the need for surface analysis the technology is evolving and changing, producing new and exciting techniques for describing, analysing and evaluating a materials surface. It is clear from the literature that multiple analytical tools are utilised in evaluating a sample working in harmony to accurately define the surface parameters and monitor the changes when subject to erosion. It is impossible to determine whether one technique has any advantage over another due to the infinite situations possible. However when considering rain erosion on wind turbine blades which primarily investigates GFRP a profilometer is an important tool to provide the most extensive data as it produces analytical data of the samples along with detailed images. In a research project this analysis would be required to combine with other analysis including SEM or Optical Microscopy consistent with the literature and to confirm results.

The first form of analysis when investigating erosion is normally mass loss as it stands as a simplistic correlation to the magnitude of wear. It provides a relatively simple methodology that requires little input and it serves as an excellent tool for an initial experiment to warrant a further investigation using more time intensive analysis.

Within the field of erosion on wind turbine blades there is promise into viable solutions and there have arose from the testing and analysing of materials within the laboratory. Such innovations include a 'swim cap' device that is fitted to the leading edge to reduce the erosion and extend the life time of the blades overall increasing energy production [65]. These protection systems will still have to be legitimised within experimental conditions and analysed using the same techniques. The future direction for this research is further testing in the laboratory and analysing the blades in the field to have a real time monitor of the degradation rates of the blade.

## Acknowledgements

The authors would like to acknowledge the support of the Interreg (Northern Ireland – Ireland – Scotland) Special EU Programmes Grant No SPIRE2\_INT – VA – 049 “Storage Platform for the Integration of Renewable Energy (SPIRE 2)”.

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