Renewable and Sustainable Energy Reviews 137 (2021) 110611

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

On analytical tools for assessing the raindrop erosion of wind turbine blades

K. Pugh [a,*], J.W. Nash [a], G. Reaburn [b], M.M. Stack [a]

[a] Tribology group, Department of Mechanical Engineering, University of Strathclyde Glasgow, James Weir Building, 75 Montrose St, Glasgow, G1 1XJ, United Kingdom
[b] Centre for Renewables and Energy, Dundalk Institute of Technology, Co. Louth, A91 K584, Ireland

ARTICLE INFO

Keywords:
Wind
Energy
Turbine
Blade
Material
Rain
Erosion
Analysis
Profilometer
Renewable
Climate
Environment
Composites
Aerodynamic
Subsurface
Defects
Power
Damage
Mechanisms
Erosion maps

ABSTRACT

In renewable energy, wind capture has been expanding to now have one of the largest presences in the global green energy sector. With the drive to expand low carbon technologies; maintenance of the engineering components of wind turbines is crucial and in particular the monitoring of the leading edge of turbine blades which experience high impact velocities in service. Surface changes due to rain drop erosion can reduce energy conversion due to a loss of aerodynamic efficiency. This is one of the key areas of interest, as even small aerodynamic changes can lead to 2–3% loss in annual energy. Inspection methodologies of turbine blades are basic, involving an observation and high-definition photographs of the damage. Recent studies on the rain erosion of turbine blade materials show that this standard procedure often fails to characterise the loss of aerodynamic efficiency in these turbine blades in. 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. Presently there is little overlap in the analysis used in different studies. This review considers various techniques which may be used to inspect and characterise the materials performance following exposure to rain drop erosion. These techniques will be evaluated based on their potential 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.

1. Introduction

Now, more than ever, the world needs renewable energy to combat climate change and to reduce greenhouse gasses. 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 (i.e. blade lengths) to be larger and more efficient; however, the larger a turbine becomes, the greater the tip speeds at the leading edge, which is concussive to high erosion rates. In an industry where aerodynamics are crucial, high erosion rates are detrimental to the performance and the energy production [69]. The high tip speeds of the wind turbine blades which can now be up to 150ms-1 on the 220 m 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 to 25% depending on erosion severity, economics of operation 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 of 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].

Research has shown that, 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.

* Corresponding author.
E-mail address: kieran.pugh@strath.ac.uk (K. Pugh).

https://doi.org/10.1016/j.rser.2020.110611
Received 5 May 2020; Received in revised form 23 September 2020; Accepted 21 November 2020
Available online 1 December 2020

Nomenclature

n_{i_c}	Incubation period
S_{ec}	Coating strength
S	Material Strength
σ_{uc}	Ultimate tensile strength
b_c	Slope of the Wohler curve
ν_c	Poisson's ratio
k	Variable relating to the stress wave reflections
ψ_{sc}	Acoustic Impedance difference
P , σ^o	Impact Pressure
ρ_L	Density of liquid
C_L	Speed of sound in liquid
V	Velocity of impact
ρ_S	Density of substrate
C_S	Speed of sound in substrate
Z	Acoustic impedance
V_{DT}	Damage threshold velocity
K_{IC}	Fracture toughness
c_R	Rayleigh wave velocity
ρ_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 Polyethylene
DMA	Dynamic Mechanical Analysis
TBD	To Be Decided
SENT	Single Edge Notch Tensile
DVT	Damage Velocity Threshold
t	Time, Seconds (s)
mm	Millimetres
m	Meters
m/s	Meters per second
kg	Kilogram
kg/m^3	Kilograms per meter cubed to measure density
R_v	Maximum depth of valleys

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 predicting 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 occurs 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 method 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 makes reference to the work by Springer, in his widely regarded "Erosion by Liquid Impact" [4]. Presented here is one of the few mathematical models that has gained wider acceptance, seeking to provide a relationship between the lifetime estimation of a material, n, the material's strength, S and the pressure from a droplet impact, P. Although recent work from Eisenberg et al. [6] appears to show success in the application of this model to wind turbine blades in the field, the model itself has inherent flaws recognised by both Springer himself [4] and Adler in Treatise on Materials Science And Technologies Vol. 16 [71,72], which will be discussed throughout this section. Another model presented by Slot et al. [7,8], provides an alternative method for lifetime estimation, but as of yet is incomplete. In light of the associated limitations and to begin the process of standardising characterisation regimes, the Springer model will be used here as a basis. Therefore, the initial failure is assumed to be due to material fatigue.

Rain erosion applies to many materials and material/coating combinations, with the area of interest here being wind turbines. Wind turbine blades materials are primarily coated composites, but also composites and polymeric materials to a lesser extent. It is important understand that when considering coated materials, the model assumes that the coating fails before either the coating/substrate interface or the substrate itself. According to Springer [4], the model also has broad applicability to materials that follow ductile behaviour, with agreement for brittle materials too. Issues arise when applying the model to elastomers, as using traditional characterisation methods do not capture the material behaviour or response correctly under loading conditions. Therefore, a separate approach should be taken with these material types, either by adapting the model or the development of a new one.

The Springer model equations are outlined below for reference (equations (1)–(3)), where n_{i_c} is the number of impacts required to initiate damage at a specific location and is proportional to the ratio of the parameter S_{eC}, which is a term that represents the coating strength, to the average stress at the point of impact at the surface σ^o; σ_{uC} is the ultimate tensile strength of the coating; 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 of the coating; ν_C is the Poisson ratio of the coating; the terms k, ψ and γ are terms related to the stress wave reflections caused by acoustic impedance mismatches; ρ is the density; C is the acoustic impedance and V is the impact velocity. The subscripts S, C and L refer to substrate, coating and liquid respectively. The subscripts LC and SC refer to the liquid-coating and substrate-coating interfaces respectively. 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.

$$n_{i_c} = 7x10^{-6}\left(\frac{S_{eC}}{\sigma^o}\right)^{5.7} \quad (1)$$

$$S_{eC} = \frac{4\sigma_{uC}(b_C - 1)}{(1 - 2\nu_C)(1 + k|\psi_{SC}|)} \quad (2)$$

$$\sigma^o = \frac{\rho_L C_L V}{1 + \rho_L C_L / \rho_C C_C}\left[1 - \psi_{sc}\frac{1 + \psi_{LC}}{1 + \psi_{SC}}\frac{1 - \exp(-\gamma)}{\gamma}\right] \quad (3)$$

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, Springer assumes that the mass loss rate is still reliant on the same material parameters and so the results follow the same trends in material parameters.

As stated by Adler [72], there are four main damage modes associated with the material removal process. This is determined by the materials response to the droplet impact itself. As Adler states, although the interaction is complex it is likely that the dominant damage mode is through hydrostatic pressure, which would occur as a result of inconsistencies in the surface of the material/coating during the impact itself or during lateral jetting. This hypothesis on material removal is also supported by Field et al. [73]. Field at al. state that during the impact any water trapped inside a crack or pit would lead to a strong hydrodynamic effect increasing the level of damage.

Although the research by Field et al. focussed on brittle materials, their discussion on the process of surface damage exacerbation appears to have a broader implication. Another significant damage mode mentioned by Adler is the passage of stress waves throughout the surface and inside the material. If a surface stress wave is emitting from the impact location, it will pass over a crack. If it is of sufficient magnitude and duration, it will cause the stress intensity factor to reach its critical value, and so the crack will grow in length. This process is dependent on the material fracture toughness, the elastic wave velocity and the size distribution of the pre-existing surface flaws, as well as the water drops size and velocity. It would seem reasonable to attempt to apply the same condition to other material types with defects present on the surface, between coating layers and other subsurface defects. These two factors would suggest that the mass removal process is governed by a different set of equations, which is beyond the scope of this paper.

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 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 materials such as brittle or ductile gelcoats, such as epoxy or polyester, are being investigated the equations should apply as intended.

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 [4,9]. 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 [4,10,73].

The impact pressure, P, is typically approximated using a modified form of the water hammer equation [4,7,11]. The acoustic velocity is dependent on the stiffness properties of a material, whose definition can be found in Springer [4]. A different equation is presented here for the variable σ^o (equation (3)). This equation is an enhanced form of the modified water hammer equation and is used in order to account for stress wave reflections, if present. In the absence of reflections, for example in materials with no coatings, the equations simplify to equations (4)–(6).

$$n_i = 7x10^{-6}\left(\frac{S}{P}\right)^{5.7} \tag{4}$$

$$S = \frac{4\sigma_{uS}(b_S - 1)}{(1 - 2\nu_S)} \tag{5}$$

$$P = \frac{\rho_L C_L V}{1 + \rho_L C_L / \rho_S C_S} \tag{6}$$

Equation (4) 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 [4]. 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 polymeric and 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 [12–14]. Field et al. also discusses the possibility of frictional heating of the testing sample during rain erosion testing [73]. The studies discussed are conducted at much higher velocities than those concerned here, but still do show this to be a consideration. 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 several assumptions relating to material properties. The model is comprised of experimental results from studies that have insufficient data sets for the model itself. Springer therefore seeks to make assumptions for the values of several material properties, and as Adler [72] highlights, specifically the material property b, determined by the fatigue performance of the material. Springer simply assumes that b = 20 for all materials, except for magnesium and copper where b = 17.6. It is likely that Springer did not have values for b for the majority of the materials tested in their respective studies, as the values do not appear in literature, and that these studies did not conduct fatigue testing due to expense and complexity of testing for material fatigue. This insufficient documentation of material properties presents some difficulties in linking material parameters to performance [3,8,9,15]. 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 [3,9,15,16,18], 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 also a 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

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]
	Storage Modulus		[12,14]
DMA (Viscoelastic Materials)	Loss Modulus		[12,14]
	Glass Transition Temperature (s)		[12,14]
Nanoindentation	Hardness		[9,19]
Tensile Test	Ultimate Tensile Strength	ISO 527-3 (specimen type 2)	[3,12,14,16]
	Failure Strain		[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)	

should be selected in order to optimise the performance of the coating itself [4,10].

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 Ref. [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 [12,14].

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 with conflicting evidence. In metals, Heymann presented evidence to suggest that rain erosion resistance improves with increasing hardness [21], conversely others such as O'Carroll et al. (Fig. 1) presented evidence to suggest the opposite trend 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 uniaxial 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 (state number) 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.

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 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 mm), like those used in the multi-layer coating systems for wind turbine blades [9,19,23].

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 important 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 [3,7,12,14]. More appropriate parameters may therefore be used to describe

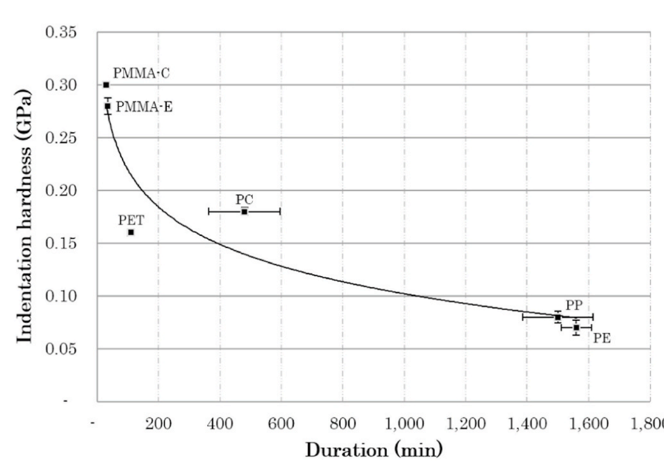

Fig. 1. Hardness Vs. Duration of incubation period for various polymers tested in whirling arm type rig. Figure from O'Carroll et al. [19] with permission from Elsevier.

the material 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 crack 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 (7)) [26]. Keegan [11] used this equation to show the significant effect this could have on epoxy coatings with different fracture toughness's (Fig. 2). 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 samples that performed significantly better in both. Another damage resistance characteristic investigated by Zhang et al. was the abrasion resistance. Zhang et al. conducted Taber abrasion resistance testing with coatings lasting longer in the abrasion rig, also lasting longer in the whirling arm test rig. This indicates that the abrasion and erosion processes may be governed by at least some of the same materials characteristics.

$$V_{DT} \approx 1.41\left(\frac{K_{Ic}^2 c_R}{\rho_w^2 c_w^2 d_w}\right)^{1/3} \tag{7}$$

where 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, ρ_w is the density of water, c_w is the speed of sound in water and d_w is the droplet diameter.

As noted by Field [73], most rain erosion literature appears to suggest that, provided there are enough impacts, a material can fail at any velocity. This would infer that a damage threshold velocity does not exist for any material per se as there are many other parameters which affect the erosion process. Hence, if one was to assume the rain erosion process is a fatigue process, it may instead be likely that there is an effective damage threshold velocity where the number of impacts to

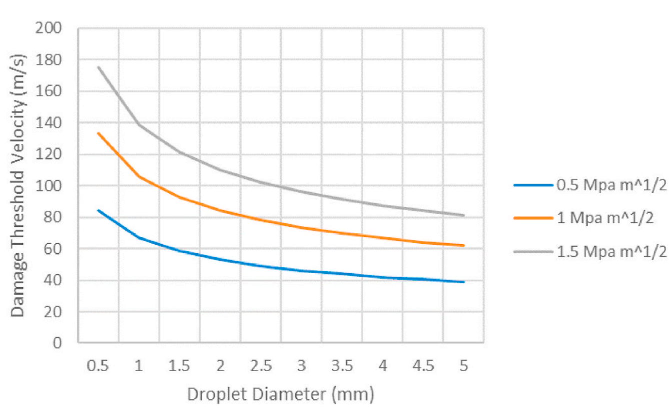

Fig. 2. Damage Threshold Velocity (DVT) Vs. droplet diameter using 4 from Ref. [26] for epoxy coatings with different fracture toughness's. Figure adapted from Refs. [11]. Rayleigh wave velocity, c_R, = 942m/s, Density of water, ρ_w, = $1000kg/m^3$, Acoustic velocity of water, c_w, = 1490 m/s.

initiate a failure exceeds the life of a wind turbine. Therefore, the use of such a term is justified. 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.

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 before and after testing due to their flexibility and quickness. Unfortunately, this method provides limited detail of a material surface and whilst 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) [29] is a common analytical tool for assessing morphological features on a surface [70]. 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 (Fig. 3) [28] (visible by the human eye) to a very high magnification in order to observe the surface texture of a single glass fibre (Fig. 4). 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.

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

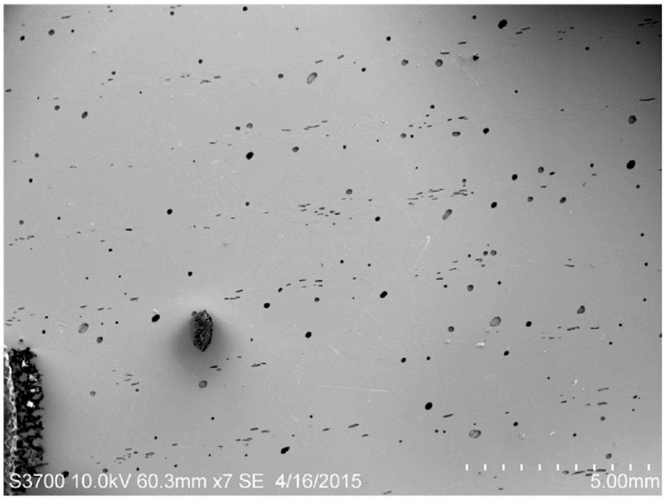

Fig. 3. SEM image of pinholes on GFRP [28].

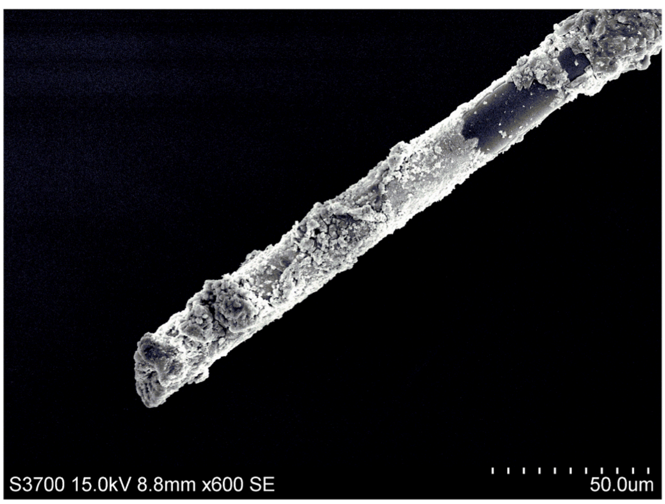

Fig. 4. SEM image of glass fibre [30].

gold plating. This means that the analysis is only applicable at the end of the investigation, this is very common within studies [27,28,32–34]. 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 highly appropriate tool for an end of investigation analysis; however, for assessment of 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 high resolution images of erosion from a camera used on the field to microscopic 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 [2,11,18,35–38] 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 (Fig. 5). 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 of the larger features are more visible from the optical microscope.

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 the measurements of surface height variation an image can be created illustrating the topography. From the literature there are two variants of profilometer; stylus figure (7), that uses a tactile probe that physically moves along the surface and optical figure (6), 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.

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 GFRP sample used in a simulated wind turbine environment subject to saltwater erosion [27]. This figure describes the surface profile in a 3D image that can be used to evaluate the distance between the highest peak to the deepest valley.

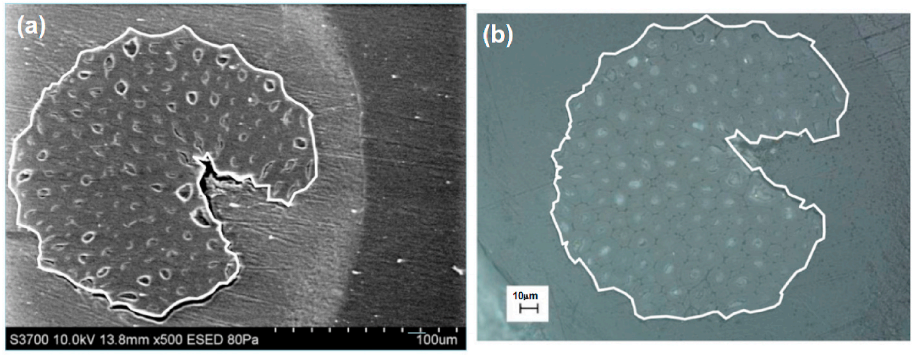

Fig. 5. Comparison between SEM imaging and Optical imaging [39].

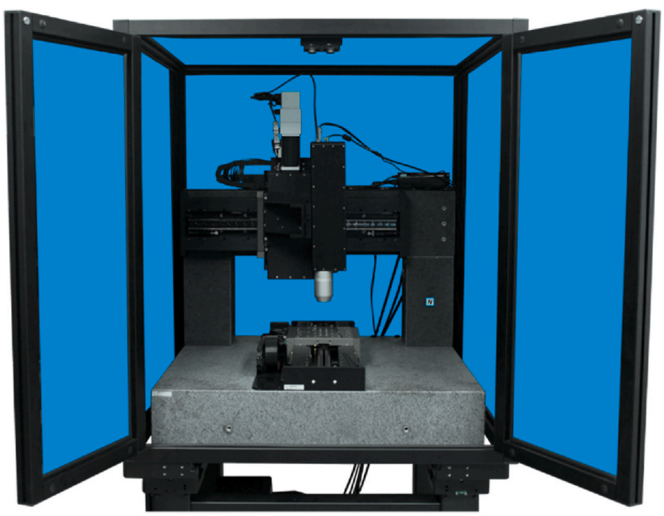

Fig. 6. Optical profilometer: Nanovea HS2000, ultilses white light to measure flat surfaces with a resloution of 1 nm [28,66].

Recent research has used this technology to investigate the topic of rain erosion on wind turbine blades [35,36,41,42]. Ins recent work by Tobin and Young 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 testing procedures. 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 [18,43–45]. 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 [3,46]. 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 wavelength of the frequency used [48]. Although it is currently not be possible to measure the wavelength 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.

Fig. 7. Stylus profilometer: Mitutoyo Crysta Apex S, ultilises a stylus of radius 0.3 mm to measure flat surfaces with a resolution of 0.1 μm [30,67].

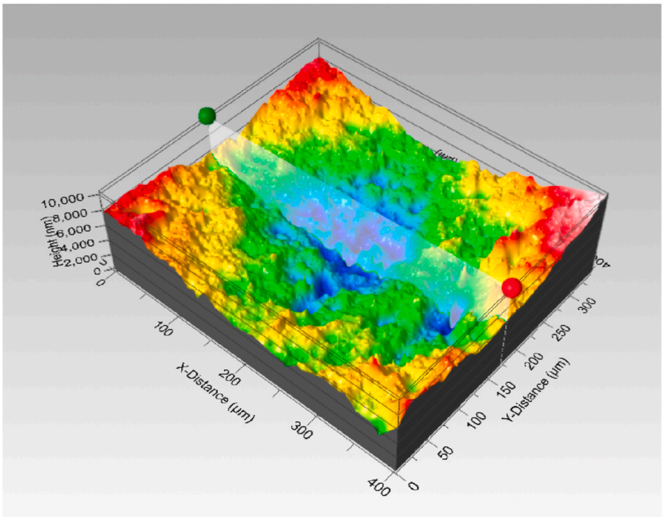

Fig. 8. CLSM scan of sample subject to saltwater erosion [39].

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 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 particular temperature sensitive materials, such as those discussed previously. To achieve a high resolution, it will be necessary to use high frequency ultrasound. It is 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 t frequency selected will be dependent on the materials tested (See Fig. 9). The main benefit of using ultrasound would be that the price would be significantly less than X-ray [48,51]. 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].

4.2. Radiolographic methods

Radiographic methods are desirable with their significantly higher resolving power, they can provide a much higher level of detail (individual fibres) then 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 a 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 [44,51–53].

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 1.5 mm in diameter and a thickness of 0.5 mm 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 [54–56]. 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. Airgaps of 0.25 mm are also possible to image (ideally larger at 0.4 mm), which essentially constitute delamination. To mimic delamination, laboratory testing of thin slithers of Teflon sandwiched between rubber has been tested with good levels of accuracy (Table 2). Disbonds of 0.03 mm can be imaged. Microwave NDT can also provide information on the state of cure as well as moisture ingress [52].

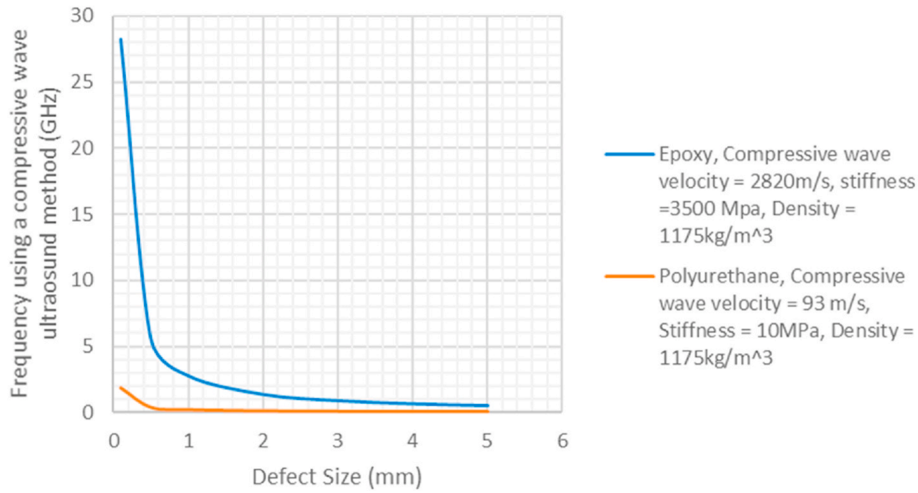

Fig. 9. Displayed here is a graph showing defect size vs. approximate frequency required to detect it. Materials data was sourced from Slot et al. [7]. Wave speed was calculated using the equation provided by Springer [4]. Frequency was calculated using the standard wave equation $c = \lambda f$, where c is the speed of sound, f is the frequency and λ is the wavelength.

Table 2
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].

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	

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 [9,18,25,27,28,30,35,37,41,42,57–59]. 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 [4,28,37,41,42,59]; 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 (Fig. 10).

If the investigation involves more than one range of variables an appropriate format 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 (Fig. 11).

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

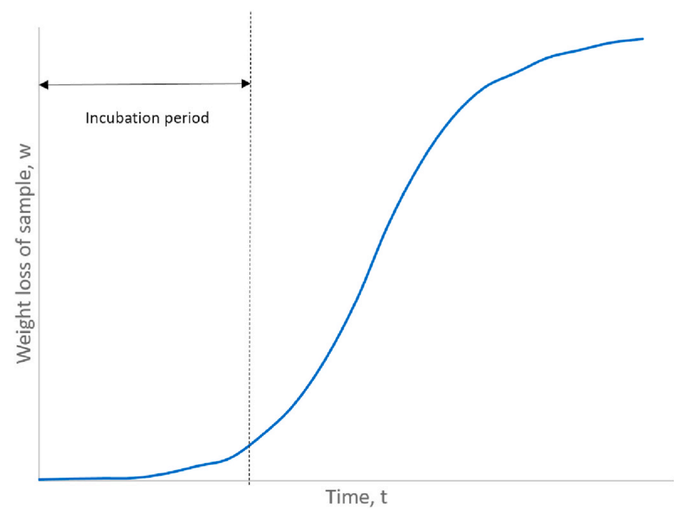

Fig. 10. Line graph displaying weight loss against time [4].

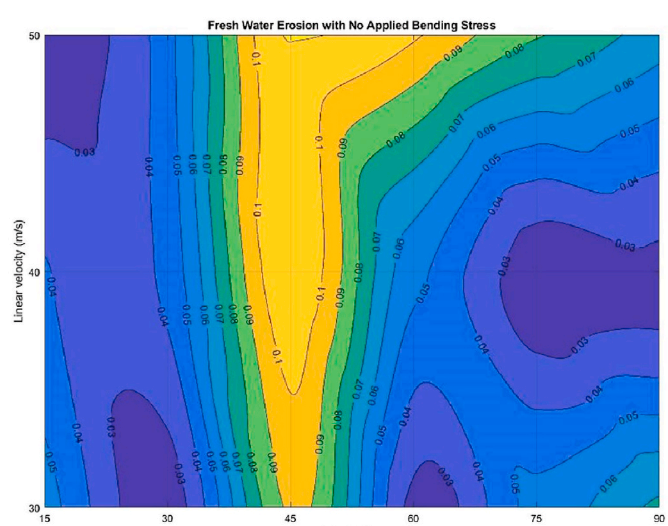

Fig. 11. Wear-map showing mass loss with respect to impact velocity and angle [30].

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 method by which surface roughness is classified is by measuring the variation in height on the samples surface including the depth of valleys and height of peaks which form during erosion. There are multiple ways to classify the roughness [68]; however, the maximum depth of valleys, R_v will provide the most information in this scenario as larger valleys are concurrent with loss of material. This measurement can be taken by a profilometer as mentioned before in the previous section. This parameter, R_v, can help define the aerodynamic properties of the material if it were to be used in a wind turbine blade as the larger valleys on the leading edge of the blade will create a more turbulent airflow resulting in flow separation from the blade and decreased efficiency from the turbine.

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 blade's microstructures and the development of pits, gouges, valleys, peaks 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 rain drop 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. There are various research and industrial projects on a global scale tackling this issue but there is still a wide variety of techniques used in measurement. 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 which has been neglected to date 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 it is less economic than other methods and take a long period of time for an evaluation. 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 1 mm 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 are promising and viable solutions and these have arisen from the testing and analysis of materials within the laboratory. Such innovations include a 'swim cap' as a protective engineering structure that is fitted to the leading edge to reduce the erosion and extend the lifetime of the blades overall increasing energy production [65]. Such protection systems need to be verified with experimental conditions which accurately simulate the environmental conditions. Hence, the future direction for this research is further testing in the laboratory and careful analysis of the blades in the field to have a real time monitor of the degradation rates in the environment and to ensure the window of conditions in the laboratory are appropriately scaled to those in the field.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to gratefully 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)".

References

[1] Han W, Kim J, Kim B. Effects of contamination and erosion at the leading edge of blade tip airfoils on the annual energy production of wind turbines. Renew Energy 2018;115:817–23.
[2] Sareen C A Sapre, Selig MS. Effects of leading edge erosion on wind turbine blade performance. Wind Energy 2014;17(10):1531–42.

[3] Zhang S, Dam-Johansen K, Norkjaer S, Bernad PL, Kiil S. Erosion of wind turbine blade coatings " design and analysis of jet-based laboratory equipment for performance evaluation. Prog Org Coating 2015;78:103–15.
[4] Springer GS. Erosion by liquid impact. A Halsted Press book. Scripta Publishing Company; 1976.
[5] DNVGL. DNVGL-RP-0171: testing of rotor blade erosion protection systems. Recommended Practice; 2018.
[6] Eisenberg D, Laustsen S, Stege J. Wind turbine blade coating leading edge rain erosion model: development and validation. Wind Energy 2018;21(10):942–51.
[7] Slot HM, Gelinck ERM, Rentrop C, Van Der Heide E. Leading edge erosion of coated wind turbine blades: review of coating life models. Renew Energy 2015;80:837–48.
[8] Slot HM, IJzerman RM, le Feber M, Nord-Varhaug K, van der Heide E. Rain erosion resistance of injection moulded and compression moulded polybutylene terephthalate pbt. Wear 2018;414:234–42.
[9] Cortés E, Sánchez F, O'Carroll A, Madramany B, Hardiman M, Young T. On the material characterisation of wind turbine blade coatings: the effect of interphase coating–laminate adhesion on rain erosion performance. Materials 2017;10(10):1146.
[10] Lee MK, Kim WW, Rhee CK, Lee WJ. Liquid impact erosion mechanism and theoretical impact stress analysis in tin-coated steam turbine blade materials. Metall Mater Trans 1999;30(4):961–8.
[11] Keegan MH, Nash DH, Stack MM. On erosion issues associated with the leading edge of wind turbine blades. J Phys Appl Phys 2013;46(38):383001.
[12] Sankarasubramanian M, Torabizadeh M, Putnam ZA, Moosbrugger JC, Huang MY, Krishnan S. Enhanced elastomer toughness and fracture properties imparted by chemically reactive flat nanoparticles. Polymer Testing; 2019. p. 105932.
[13] Persson BNJ, Brener EA. Crack propagation in viscoelastic solids. Phys Rev 2005;71(3):036123.
[14] Tcharkhtchi A, Farzaneh S, Abdallah-Elhirtsi S, Esmaeillou B, Nony F, Baron A. Thermal aging effect on mechanical properties of polyurethane. Int J Polym Anal Char 2014;19(7):571–84.
[15] Zhang S, Dam-Johansen K, Bernad PL, Kiil S. Rain erosion of wind turbine blade coatings using discrete water jets: effects of water cushioning, substrate geometry, impact distance, and coating properties. Wear 2015;328:140–8.
[16] DNVGL. DNVGL-CP-0424. Coatings for protection of FRP structures with heavy rain erosion loads. Class Programme; 2016.
[17] ISO. Pd iso/ts 193921:2018 paints and varnishes coating systems for wind-turbine rotor blades. part 1: minimum requirements and weathering. 2018.
[18] Valaker EA, Armada S, Wilson S. Droplet erosion protection coatings for offshore wind turbine blades. Energy Procedia 2015;80:263–75.
[19] O'Carroll A, Hardiman M, Tobin EF, Young TM. Correlation of the rain erosion performance of polymers to mechanical and surface properties measured using nanoindentation. Wear 2018;412:38–48.
[20] Pomázi Á, Toldy A. Multifunctional gelcoats for fiber reinforced composites. Coatings 2019;9(3):173.
[21] Heymann FJ. Erosion by liquids. Mach Des 1970;10:118–24.
[22] Shaw MC, DeSalvo GJ. The role of elasticity in hardness testing. Metallogr Microstruct Anal 2012;1(6):310–7.
[23] Grundwürmer M, Nuyken O, Meyer M, Wehr J, Schupp N. Sol–gel derived erosion protection coatings against damage caused by liquid impact. Wear 2007;263(1–6):318–29.
[24] Gohardani O. Impact of erosion testing aspects on current and future flight conditions. Prog Aero Sci 2011;47(4):280–303.
[25] Busch H, Hoff G, Langbein G, Taylor G, Jenkins DC, Taunton MA, Fyall AA, Jones RF, Harper TW. Rain erosion properties of materials. Phil Trans Roy Soc Lond Math Phys Sci 1966:168–81.
[26] Evans AG, Gulden ME, Eggum GE, Rosenblatt M. Impact damage in brittle materials in the plastic response regime. Technical report. ROCKWELL INTERNATIONAL THOUSAND OAKS CALIF SCIENCE CENTER; 1976.
[27] Pugh K, Rasool G, Stack MM. Some thoughts on mapping tribological issues of wind turbine blades due to effects of onshore and offshore raindrop erosion. J Bio-and Tribo-Corrosion 2018;4(3):50.
[28] Siddons C, Macleod C, Yang L, Stack MM. An experimental approach to analysing rain droplet impingement on wind turbine blade materials. In: EWEA 2015 annual event; 2015.
[29] Strath.ac.uk. Scanning electron microscopes | university of strathclyde.
[30] Pugh K, Rasool G, Stack MM. Raindrop erosion of composite materials: some views on the effect of bending stress on erosion mechanisms. J Bio-and Tribo-Corrosion 2019;5(2):45.
[31] J. Foldyna, J. Klich, P. Hlaváček, M. Zeleňák, and journal=Tehnički vjesnik volume=19 number=2 pages=381–386 year=2012 publisher=Strojarski fakultet u Slavonskom Brodu, Elektrotehnički fakultet u Osijeku Ščučka, J Eros Metals Pulsating Water Jet.
[32] Lammel P, Rafailovic LD, Kolb M, Pohl K, Whitehead AH, Grundmeier G, Gollas B. Analysis of rain erosion resistance of electroplated nickel–tungsten alloy coatings. Surf Coating Technol 2012;206(8–9):2545–51.
[33] Davis A, Yeong YH, Steele A, Loth E, Bayer IS. Nanocomposite coating superhydrophobicity recovery after prolonged high-impact simulated rain. RSC Adv 2014;4(88):47222–6.
[34] Bowden FP, Brunton JH. The deformation of solids by liquid impact at supersonic speeds. Proc Roy Soc Lond Math Phys Sci 1961;263(1315):433–50.
[35] Tobin EF, Rohr O, Raps D, Willemse W, Norman P, Young TM. Surface topography parameters as a correlation factor for liquid droplet erosion test facilities. Wear 2015;328:318–28.
[36] Tobin EF, Young TM, Raps D, Rohr O. Comparison of liquid impingement results from whirling arm and water-jet rain erosion test facilities. Wear 2011;271(9–10):2625–31.
[37] Bartolomé L, Teuwen J. Prospective challenges in the experimentation of the rain erosion on the leading edge of wind turbine blades. Wind Energy 2019;22(1):140–51.
[38] Zhang S, Kiil S, Dam-Johansen K, Bernad Jr PL. Accelerated rain erosion of wind turbine blade coatings. Danmarks Tekniske Universitet (DTU); 2014.
[39] Thomason JL, Carruthers J, Kelly J, Johnson G. Fibre cross-section determination and variability in sisal and flax and its effects on fibre performance characterisation. Compos Sci Technol 2011;71(7):1008–15.
[40] Sheppard CJR, Choudhury A. Image formation in the scanning microscope. Opt Acta: Int J Optics 1977;24(10):1051–73.
[41] Tobin EF, Young TM, Raps D. Evaluation and correlation of inter-laboratory results from a rain erosion test campaign. In: Proceedings of 28th international congress of the aeronautical sciences; 2012.
[42] Tobin EF, Young TM. Analysis of incubation period versus surface topographical parameters in liquid droplet erosion tests. Mater Perform Char 2017;6(2):144–64.
[43] Selmi A. Void effect on carbon fiber epoxy composites. In: Second international conference on emerging trends in engineering and technology (ICETET), London, May; 2014. p. 30–1.
[44] Di Landro L, Montalto A, Bettini P, Guerra S, Montagnoli F, Rigamonti M. Detection of voids in carbon/epoxy laminates and their influence on mechanical properties. Polym Polym Compos 2017;25(5):371–80.
[45] Katnam KB, Comer AJ, Roy D, Da Silva LFM, Young TM. Composite repair in wind turbine blades: an overview. J Adhes 2015;91(1–2):113–39.
[46] Keegan MH, Nash D, Stack M. Modelling rain drop impact on offshore wind turbine blades. ASME Turbo Expo 2012. Article–GT, 2012.
[47] Chen J, Bull SJ. Approaches to investigate delamination and interfacial toughness in coated systems: an overview. J Phys Appl Phys 2010;44(3):034001.
[48] Collaboration for NDT Education. Wavelength defect detection. NDT Resource Center; 2001.
[49] Vandenrijt JF, Languy F, Thizy C, Georges M. Laser ultrasound flexible system for non-contact inspection of medium size and complex shaped composite structures made of carbon fiber reinforced polymer. In: Multidisciplinary digital publishing institute proceedings. vol. 2; 2018. p. 455.
[50] Focke O, Kalms M, Kopylow CV, Jueptner W. Ndt of free formed cfrp composites with laser ultrasonic. In: 12th asia pacific conference on NDT; 2006.
[51] Halmshaw R. Non-destructive testing. second ed., vol. 323. Sevenoaks, Kent TN 13 2 YA, UK: Edward Arnold, Mill Rd, Dunton Green; 1991. p. 1991.
[52] Pethrick RA. Non-destructive evaluation (nde) of composites: dielectric techniques for testing partially or non-conducting composite materials. In: Non-Destructive evaluation (NDE) of polymer matrix composites. Elsevier; 2013. p. 116–35.
[53] Ehrhart B, Valeske B, Bockenheimer C. Non-destructive evaluation (nde) of aerospace composites: methods for testing adhesively bonded composites. In: Non-destructive evaluation (NDE) of polymer matrix composites. Elsevier; 2013. p. 220–37.
[54] Stakenborghs B. Evisivescan microwave scanning ndt. NPL Project VITCEA; 2015.
[55] Gower M, Lodeiro M, Aktas A, Shaw R. Validated inspection techniques for composites in energy applications. NPL Project VITCEA; 2015.
[56] Microwave NPL. Ndt for composites explained. NPL E-Training Course; 2019.
[57] ASTM International. ASTM G73-10(2017) standard test method for liquid impingement erosion using rotating apparatus. ASTM International; 2017.
[58] Springer GS, Yang CI, Larsen PS. Analysis of rain erosion of coated materials. J Compos Mater 1974;8(3):229–52.
[59] Chiu KY, Cheng FT, Man HC. Evolution of surface roughness of some metallic materials in cavitation erosion. Ultrasonics 2005;43(9):713–6.
[60] Boermans L, Selen H. On the design of some airfoils for sailplane application. Technical Soaring 1981;7(1):13–35.
[61] Ehrmann RS. Effect of surface roughness on wind turbine performance. PhD thesis. 2014.
[62] Sagol E, Reggio M, Ilinca A. Issues concerning roughness on wind turbine blades. Renew Sustain Energy Rev 2013;23:514–25.
[63] Zidane IF, Saqr KM, Swadener G, Ma X, Shehadeh MF. On the role of surface roughness in the aerodynamic performance and energy conversion of horizontal wind turbine blades: a review. Int J Energy Res 2016;40(15):2054–77.
[64] Pechlivanoglou G, Fuehr S, Nayeri CN, Paschereit CO. The effect of distributed roughness on the power performance of wind turbines. In: ASME turbo expo 2010: power for land, sea, and air. American Society of Mechanical Engineers; 2010. p. 845–55.
[65] How a 'swim cap' could extend the life of wind turbine blades. 2020. Retrieved 3 March 2020, from, https://www.greentechmedia.com/articles/read/swim-cap-extend-the-life-of-wind-turbine-blades.
[66] Surface profilers from Nanovea | non-contact profilometry [Internet]. Mi-net.co.uk. 2020 [cited 14 September 2020]. Available from: http://www.mi-net.co.uk/surface-profilers.php.
[67] [Internet]. Mitutoyo.co.uk. 2020 [cited 14 September 2020]. Available from: https://www.mitutoyo.co.uk/application/files/3415/5888/3870/E16004.pdf.
[68] Gadelmawla ES, Koura MM, Maksoud TMA, Elewa IM, Soliman HH. Roughness parameters. J Mater Process Technol 2002;123(1):133–45.
[69] Wood Robert JK. Liquid impingement erosion, friction, lubrication, and wear technology. In: Totten George E, editor. ASM handbook, vol. 18. ASM International; 2017. p. 302–12. https://doi-org.proxy.lib.strath.ac.uk/10.31399/asm.hb.v18.a0006378.
[70] Qian Linmao, Chen Lei, Jiang Liang. Wear measurement, *friction, lubrication, and wear technology*. In: Totten George E, editor. ASM handbook, vol. 18. ASM

International; 2017. p. 225–32. https://doi-org.proxy.lib.strath.ac.uk/10.31399/asm.hb.v18.a0006387.
[71] Preece CM, editor. Treatise on materials science and technology, vol. 16. Erosion: Academic Press; 1979.
[72] Adler WF. In: Erosion CM Preece, editor. The mechanics of liquid impact, treatise on materials science and technology, vol. 16. Academic Press; 1979. p. 127–83.
[73] Seward C, Pickles C, Coad E, Watt M, Field J. Studies of rain erosion mechanisms in a range of IR transmitting cermaics - including coated samples (final report). Defense Technical Information Center; 1994. p. 1–233.