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# Correlation of the rain erosion performance of polymers to mechanical and surface properties measured using nanoindentation

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## ABSTRACT

Rain erosion of leading edges of wind turbine blades is caused by repeated high speed liquid droplet impacts, which causes damage in the form of pitting or peeling over time and can lead to a significant reduction in performance if left untreated. Due to an increase in the tip speed of modern wind turbine blades, rain erosion is becoming an increasingly prominent issue. Currently, polymeric coatings are applied to the surface of the wind turbine during manufacture in order to mitigate the issue; however, it has been reported that these coatings are being eroded within the first 2–5 years of the 15–25 year life cycle of the blades. Rain erosion testing of polymer coatings requires prolonged characterisation using expensive bespoke apparatus. The focus of this study is to assess if nanoindentation can conveniently provide sufficient information to characterise the rain erosion resistance of polymeric materials. A range of polymeric materials were first tested in the Whirling Arm Rain Erosion Rig (WARER) to assess their ability to resist rain erosion, while a Nanoindenter G200 was also used to assess their stiffness, hardness, surface roughness, elastic and viscoelastic properties. The results indicated a number of correlations. A reduction in both storage modulus and hardness was seen to be beneficial for rain erosion resistance and materials that resist rain erosion can recover quickly to their original shape in time to resist subsequent impacts. Viscoelasticity was assessed through the fitting of a spring and dashpot model to the nanoindentation data, showing good correlation. This technique also has the potential to experimentally characterise the viscoelastic properties required to create analytical or numerical models to evaluate rain erosion performance. Scanning probe microscopy carried out at various stages of the erosion process showed that the roughness of the polymeric materials increases with erosion time up to critical roughness ($Sa_{\mathrm{CRIT}}$), before which no significant mass loss will occur. Furthermore, it was found that the rate at which a polymer is roughened during the incubation period is related to the rate at which it loses mass in the mass loss period, providing an empirical insight into the mechanics of the rain erosion of these materials.

## 1. Introduction

Rain erosion is caused when a surface is exposed to repeated rain droplets of water at impact speeds of greater than $50\ \mathrm{ms}^{1}$ [1]. In the early 1900 s, liquid drop impingement was a significant problem for steam turbines – this is a similar damage mechanism to rain erosion, albeit at a different droplet scale. Studies were restricted to metals, but by the 1950 s, rain erosion became an issue for composites; first noted as an issue for helicopter blades propeller and aircraft radomes [1]. Towards the end of the 1900 s, this damage type had become a considerable issue for the wind turbine industry. The size of wind turbines was continually increasing, meaning that the tip speed of the blades increased accordingly to a point where they are susceptible to rain erosion. Light pitting is the first stage of damage, beginning on the leading edge of the turbine blade tip. Over time the pitted areas will grow and coalesce, compromising larger sections of material. Fig. 1 illustrates typical leading edge erosion on a turbine blade [2,3].

The expected structural lifetime of the blades can range from 15 (for offshore) to 25 years (for onshore); however, accounts from inspection technicians and reports from, amongst others, Wood [4], Rempel [3] and Keegan et al. [5], indicate that leading edge erosion can require intervention within 5 years. Protection systems are applied to the leading edges of wind turbine blades in order to combat the effects of rain erosion. Paint or tape are most commonly used and the paint can be applied by brushing, rolling or spraying [5,6]. Polymeric materials are typically used as protection systems; epoxy is the most common polymer used as it is inexpensive and used extensively in the wind turbine blade structure. The coatings were made from epoxy or

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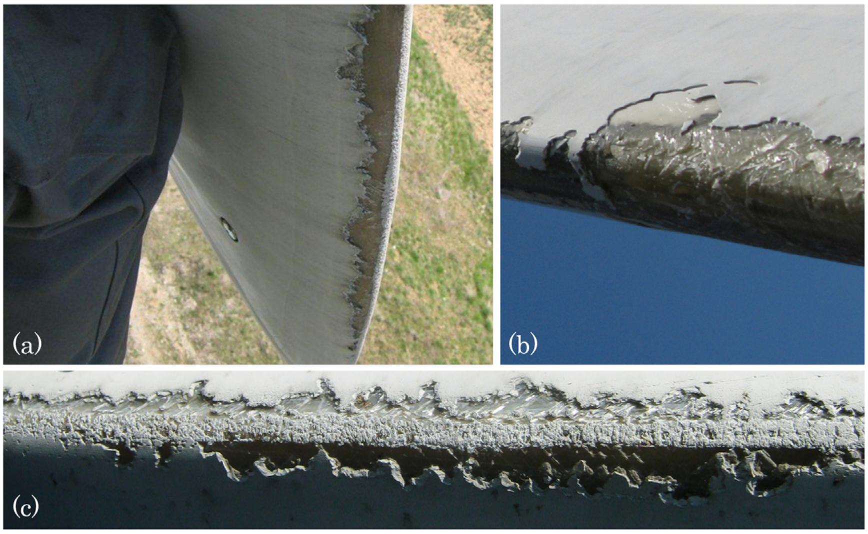

**Fig. 1.** (a) Eroded wind turbine blade tip [2], (b) detail of eroded leading edge [3] and (c) close-up of eroded leading edge [2].

polyester but over time, these rigid coatings were found to be inadequate and more ductile materials, such as polypropylene and polyurethane, were necessary. In recent years, manufacturers have moved towards multi-layered solutions, which can be designed to optimise performance and also, as a means of assessing the durability of the protection system.

The process of repetitive droplet impact will initially roughen the surface, creating depressions. Over time, prone surfaces are created and up to a certain point, no observable mass loss occurs – this is considered to be the incubation period [7,8]. In an impact event, the outward flowing water jet can travel at speeds of, at least, three times the impact speed, caused by the high pressures produced on impact [9]. Prone material is effectively pushed by the jetted liquid, opening crack(s) or causing shear failure [10–13]. Over time, these cracks can propagate and coalesce with other cracks, resulting in the removal of small pieces of material [1]. The incubation period ends when larger pieces of material begin to be removed and the second period, the steady mass loss period, begins. During the steady mass loss period, the mass loss rate will typically be constant with time as the material is progressively eroded [14]. The removal of material reveals a roughened surface and the cycle continues [5].

Early attempts to improve erosion resistance focussed on increasing the surface hardness, where studies showed that harder metallaic materials perform better [15–17,1]. However, this relationship has been refuted by Bowden and Brunton [12] and also by Beal and Wahl [18] who found that softer materials worked better. As there are conflicting reports on the influence of hardness there are also very few studies focusing on polymeric materials – most studies focus on metallic materials. A test undertaken by Busch et al. [15] showed, for a range of polymers, that harder materials exhibited greater mass loss than softer material of the same type.

There is also disagreement regarding how elastic modulus influences erosion resistance. The stiffness of the material governs the speed of sound in the material, which is key for this damage mechanism [19]. The speed of sound regulates the speed of the stress waves travelling through the material and it also has an effect on the water hammer pressure [20]. The water hammer pressure is the pressure generated on impact based on relative acoustic impedances of the target material and the impacting substance. Acoustic impedance is calculated by multiplying the speed of sound of a material by its density. Slot et al. [17] and Thiruvengadam [21] demonstrated in their studies, that by using materials with low elastic moduli, the pressures, and ultimately the magnitude of the stresses on the surface, would not be as great. Hobbs [16] and Garcia and Hammitt [22] have created equations for predicting erosion resistance, and these indicate that a reduction in stiffness is desirable. In addition, the stiffness can be broken down into storage and loss components – the storage modulus is the material's ability to store energy following a loading event, and the loss modulus is the material's ability to dissipate energy. The tan delta is the ratio of the storage modulus to the loss modulus of a particular material. A large tan delta would indicate that a material could dissipate the energy from an impact event instead of storing it, which would be very desirable [1,19].

A material's ability to recover following an impact event, according to a number of authors [23,10], is an important factor in being able to resist progressive damage. Engel [24] indicates that a material should be soft and rubbery in order to resist rain erosion. Thomas and Brunton [25] and Busch et al. [15] insisted it is critical that a material can recover quick enough to return to its original shape prior to a subsequent impact event. If the material can quickly return to its original shape in advance of a subsequent impact it should last longer before the surface begins to fail [15].

Polymers respond viscoelastically and exhibit time-dependant behaviour termed *creep*, *relaxation* and *recovery* [26]. A material that can damp out impact energy and recovers quickly is deemed to be most suitable for erosion resistance [15,24]. The viscoelastic response of a material to an impact event can be idealised in terms of springs and dashpots. There are a number of spring-dashpot models, as shown in Fig. 2, each with their own advantages and disadvantages. The

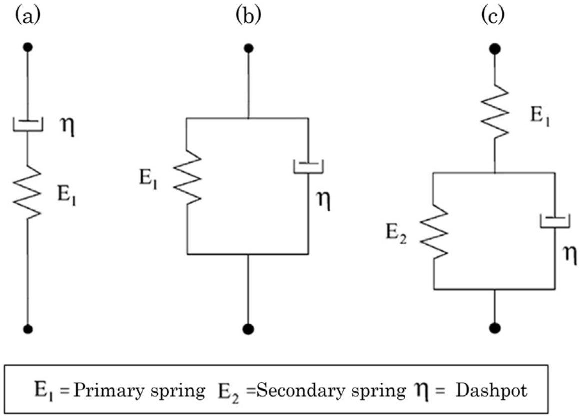

**Fig. 2.** Spring and dashpot models: (a) Two-element Maxwell, (b) two-element Voigt and (c) three-element Maxwell-Voigt. Redrawn after [26].