Rain droplet erosion behavior of a thermoplastic based leading edge protection system for wind turbine blades

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Abstract. This paper discusses the rain droplet erosion mechanisms of an acrylonitrile butadiene styrene (ABS). Rain droplet impingement was modeled based on a coupled smoothed particle hydrodynamics and finite element method (SPH/FEM). Using linear elastic material parameters at low strain rates, the dynamic stress behavior was studied and the location of damage initiation was predicted. Experiments using a pulsating jet erosion tester were performed and the resulting erosion behavior was analyzed using confocal microscopy. The damage was expected to initiate at the surface and remain superficial during propagation. It was shown that a pitting behavior occurred at the surface after the first few impacts. This pitting continued until 100,000 impacts. After this, the pits connected through a cracking mechanism and finally, at 300,000 impacts, cratering was observed which led to the onset of material loss. The depth of these craters was observed to be approximately 80µm, which was relatively low as compared to the material thickness of 4mm, indicating superficial damage. The resulting volume loss curve showed an initial period where no volume loss occurred, called the incubation period, followed by a linear relation between the volume loss and the number of impacts. This behavior agreed well with behavior found for other materials in literature. The surface roughness parameters were determined for each amount of impacts and the mean roughness value corresponded well to the volume loss behavior. Earlier stages of damage could be detected by analyzing the skewness value.

1. Introduction
Sustainable energy production is an important topic concerning society, economics and the environment. Wind energy is of vital importance to the energy transition and large investments in wind energy are made globally. Currently, a cumulative capacity of 205GW wind energy is installed in Europe, of which 22GW is offshore wind energy [1]. This offshore wind energy market is growing fast with an installed capacity of 3.6GW in 2019 only. Onshore turbines had an average power rating of 3.1MW while offshore turbines had an average power rating of 7.8MW with the largest being the 12MW GE Haliade-X prototype [2] which has a rotor diameter of 220m. Not only the size of the turbines increases, but also the tip speeds of the blades, currently exceeding 100ms⁻¹. These high tip speeds lead to interactions of the blade material with rain droplets causing high dynamic stresses in the blades, especially at the leading edge of the blade. These stresses cause surface fatigue damage, ultimately leading to a material loss [3]. The eroded surface of the leading edge has a negative effect on aerodynamics and might lead to structural failure of the blade, which is mainly made of glass fiber reinforced
thermosetting polymer composites. To prevent a possible failure of the leading edge of the blade, regular, expensive maintenance has to occur.

Currently, technologies to limit leading edge erosion consist of protective polyurethane coatings, tapes or shells as well as thermosetting gelcoats [4]. These are added on top of the blade structure, influencing the blade aerodynamics and reducing the erosion damage development. The research field on leading edge protection (LEP) systems is very active and currently involved with the influence of interphases between the LEP and the composite blade structure [5], the use of thermoplastic materials [6] and the optimization of (multilayer) microstructures of materials [7]. The recent research project InLEP (Integrated Leading Edge Protection for Offshore Wind Turbine Blades at High Speed) carried out in the Netherlands, focuses on an integrated leading edge protection concept based on thermoplastic materials to reduce the erosion mechanisms further without compromising aerodynamic efficiency of the blade. In order to design this InLEP concept, a fundamental understanding of the erosion and bonding mechanisms for different types of thermoplastics is required.

When looking at the erosion damage development, the intensity of the damage is often represented by the cumulative mass-loss and the time by either the cumulative number of impacts or exposure time. This results in a mass-loss curve such as in Figure 1. It can be seen that up to a certain number of impacts there exists no mass loss which is defined as the incubation period. Afterwards, a linear relation between mass-loss and exposure time is observed which is followed by a random behavior corresponding to a catastrophic failure of the blade. This relation is found to be similar for most LEP materials although the underlying damage mechanisms may differ. The end of incubation, which is the transition from the incubation period to the linear mass loss progression, is usually defined as the critical point for assessing the rain erosion performance of the LEP.

Rain droplet impacts cause elastic waves in the material. These highly dynamic waves interact with interfaces, defects and each other leading to complex stress situations. Understanding how these waves propagate as a function of not only material parameters but also geometric and impact parameters is therefore of vital importance when designing LEP systems. Initially, analytic models using the (modified) waterhammer pressure were proposed [8]. These models are still widely used and adapted to more advanced materials. Recent developments have been made in numerical modeling to obtain a more accurate description of the stresses. Often, a smoothed particle hydrodynamics (SPH) approach for the fluid is used in combination with a finite element method (FEM) approach for the solid [3, 9]. Some work has used a combined Eulerian/Lagrangian mesh for the fluid structure interaction and the results corresponded
well with SPH/FEM approach [10]. Simulation of damage is very challenging due to the dynamic waves and microstructures of the materials. Combining SPH/FEM simulations with experimental observations can be useful to understand damage initiation and development [11]. More difficulties lie in predicting the long term performance based on these stress wave fields. So far, fitting of experimental results to a fatigue model is still required [12, 13].

Understanding the rain erosion behavior and validating the models requires methods to do accelerated testing of material coupons. Generally, two different types of experiments exist, being rotating arm and jet based erosion tests [14]. In rotating arm rigs, a material coupon or small leading edge section is rotated through an artificial rain field at high velocity [15]. During the test, the mass loss can be evaluated by drying and weighing the specimen at set intervals and the end of incubation and breakthrough points are identified. With this data, the Wöhler curve can be made and the Springer model can be fitted [8]. These tests provide a fast method to characterize different materials for long term erosion behavior, however the insight gained in the stress and damage development under rain droplet impact is limited. To overcome this, jet based systems are generally used [16]. In these systems, a stationary sample is impacted by a high velocity jet or jet segments. Because the sample is stationary, it is easier to perform measurements on the sample and the number of impacts is controlled in a better way. The material damage due to rain droplet impact however is very local in jet based setups, therefore a validation of these tests based on erosion behavior observed in the field is relatively difficult. Some efforts have been made to correlate both test methods [17], including surface topology parameters after damage [18]. A third test method using elastomeric balls as projectiles is also under development [19] and shows high potential for accelerated testing of coating systems. The visco-elastic effects in the balls do however differ from the compressive effects in the water droplets.

In this paper, a pulsating jet erosion test (PJET) is performed on an acrylonitrile butadiene styrene (ABS) material. The rain droplet erosion damage initiation and propagation are studied and compared with modeling results. A novel method to determine the volume loss of material after the PJET is discussed and the results are compared with the surface roughness parameters.

2. Model

A coupled SPH/FEM method was used to model the dynamic fluid structure interaction between the water droplet and the ABS LEP system. The model was interpreted in ABAQUS and solved for a linear elastic material. The results gave insight in stress locations and magnitudes as a function of time. This was used to predict damage initiation locations. The model was solved using the parameters in Table 1.

| Property | Density [kg/m³] | E [GPa] | ν | C_p [m/s] | µ [Pas] | V [m/s] | Diameter [mm] |
|----------|-----------------|---------|---|----------|--------|--------|--------------|
| Droplet  | 997             | -       | - | 1481     | 8.9e-4 | 160    | 2            |
| LEP      | 1050            | 2.45    | 0.408 | -        | -      | -      | -            |

3. Experiments

The experimental setup shown in Figure 2 was based on a pulsating jet erosion test and developed in house at the University of Twente, The Netherlands. A high pressure pump ejected water from a reservoir through a nozzle. The resulting continuous jet was sliced using a slotted rotating disk resulting in jet segments that impacted a stationary sample. The water was captured and filtered and flowed back into the reservoir. The setup could reach pressures of 180bar and flow
rates of 19l/min. This allowed for jet velocities of up to 190ms$^{-1}$ at nozzle diameters of up to 1.4mm. At larger nozzle diameters, the maximum velocity decreased, as expected. For the tests described in this report, a jet velocity of 160ms$^{-1}$ was used with a nozzle diameter of 1mm. The jet length was determined by the width of the slots in the rotating disk and the angular velocity. The latter was set to a constant value of 600rpm and the used slot width theoretically resulted in a jet length of 47mm. The used disk had 20 slots and therefore the impact frequency was 200Hz. For ABS, this frequency did not result in heating of the specimen and the resulting impact waves of two consecutive impacts did not interact with each other as proofed by piezoelectric sensors.

| Parameter           | Value          |
|---------------------|----------------|
| Nozzle diameter     | 0.6 – 1.6mm    |
| Jet velocity        | 0 – 190m/s     |
| Impact frequency    | ≤ 200Hz        |
| Impact angle        | 90 – 15deg     |

**Figure 2.** Overview of the pulsating jet erosion tester at the University of Twente.

The material used was a 4mm thick ABS plate which was clamped between two aluminum plates with a round hole of 55mm diameter. The impacts occurred in the center of this plate. The spread of the droplet impact locations was found to be smaller than the droplet diameter confirmed by the damage pattern and location sensing using piezo electric sensors. Several tests were performed with increasing numbers of impacts. Confocal microscopy was performed after testing to visualize the damaged area and determine the volume loss and roughness parameters.

A Keyence VK-9700 laser scanning confocal microscope with a 10× lens was used to obtain the 3D height data of the surface. A single image was used to determine the roughness parameters. A stitched image was made to obtain an overview of the damaged area. From this overview image, it was possible to determine the volume loss. To gain more detailed information of the damage mechanisms, lenses with higher zooms (50×, 100× and 150×) could be used. These lenses however did not give an image with a representative surface and could therefore not be used for roughness studies. The measured data was stored as a height profile and post-processed by using MATLAB.

To determine the volume loss, the height profile was extracted from the microscope as shown in Figure 3 (a). A reference surface was fitted with respect to the undamaged material at the sides of the image (red regions). The total deviation of the height profile with respect to this reference surface was taken as the volume loss in the distance to mean method. This method was improved by reducing the noise using the standard deviation (STD) of the surface roughness. A second plane was defined as the reference plane lowered by the standard deviation. Only the points beneath this plane were considered for the volume loss with respect to the initial reference plane. This improved method considered only the dark regions in Figure 3(a) and reduced the influence of noisy measurements. It could also be seen that the considered region for the volume loss corresponded well with the microscopic image in Figure 3 (b). It was therefore expected that the STD corrected method resulted in a higher accuracy compared with the distance to mean method.
4. Results

The results from the coupled SPH/FEM model are shown in Figure 4 for two different time instances. It can be seen that the regions with the highest stresses were very small and remained superficial. These locations were expected to also be the locations where damage initiated during testing. The high stresses were observed only during the initial stages of the rain droplet impact, which emphasized the importance of the compressive effects in the fluid. After 0.9µs lateral jetting occurred and the compressive pressure in the droplet was released which led to reduced contact pressures.

The surfaces of the eroded ABS specimens for different amounts of impacts are given in Figure 5. It can be seen that the damage intensity increased with a higher number of impacts. It started with the creation of small pits at the surface that were connected by cracks at 200,000 impacts. Material loss occurred in the form of cratering after 300,000 impacts. According to the analyzed surface roughness height, the depth of these craters was less than 0.1mm, which was found to be low as compared to the material thickness of 4mm.

Figure 6 shows a more detailed view of the pitting, cracking and cratering mechanisms. It can be seen that with increasing pitting densities, the pits started to connect by the cracking mechanism. This appeared between 150,000 and 200,000 impacts. Later, these cracks connected and this resulted in craters which led to the material loss. As seen in Figure 6(c), the cracks
Figure 5. Confocal microscopy (10× lens) images of eroded ABS specimens with increasing numbers of impacts.

extended from the craters and more material was released which expanded the crater size or connected multiple craters together.

Figure 6. Detailed confocal microscopy images of the damage (50× lens).

Figure 7 shows the roughness values and the volume loss for increasing numbers of impacts for the ABS specimen. It can be seen from both the roughness and the volume loss curves that a transition region was found to be present between 300,000 and 400,000 impacts. Other observations were the increase of the skewness value in the early stages and the small differences between the volume loss calculated by using the distance to the mean and the standard deviation corrected methods.

5. Discussion
As seen from the model results, the highest stresses were very local and remained superficial. When the damage patterns were observed, it was found that damage initiated locally and at the surface. This indicated a good correlation between the model and the experiments. The depth of the craters was around 80µm, indicating that damage did not penetrate far into the material and a thin layer could be studied for LEP applications. It should however be noted that in this case, interfaces between the LEP and the blade structure start to play an important role. The
**Figure 7.** Roughness values and volume loss of eroded ABS specimens for increasing numbers of impacts.

A combined method of modeling and experiments could be used to study multiple materials and predict their erosion behavior as a function of not only material parameters, but also impact and geometric parameters. Incorporation of damage in the model is very challenging due to the high strain rates for which material parameters are generally not known. To solve this, it is recommended to test promising materials at high strain rates or to fit a damage model with rain erosion experiments (e.g. elasto-viscoplasticity).

As seen from the volume loss graph, a higher number of impacts resulted in more volume loss. For lower numbers of impacts, surface pitting and cracking was observed indicating that damage was accumulated during the incubation stage but no volume loss was measured. Traditionally, the end of incubation point (start of volume loss) is considered when lifetime predictions are made, however damage might occur earlier as seen from these results. In order to develop new materials for LEP systems, it is important to understand what happens during the incubation stage. In order to quantify this, the surface roughness parameters were analyzed.

It was seen that the skewness showed a high dependency on the pitting intensity. A positive skewness value indicated that a small amount of pits was present, a negative skewness indicated that a lot of pits or craters were present and a zero skewness indicated that there was as much high as low points or the surface was undamaged. Because of these characteristics, the skewness could be used to describe the surface during incubation. After incubation, the mean roughness seemed to increase significantly following the same trend as the volume loss which corresponded to literature for other materials [20]. This showed that using the skewness and arithmetic mean roughness values, the damage progression during incubation as well as the volume loss after incubation could be described.

The two methods that were used to determine the volume loss showed a minor deviation, this has to do with a small amount of noise on the measurements. By looking at the surface roughness development and the initiation of craters, it could be seen that it was likely that volume loss occurred after 300,000 impacts. This indicated that the STD corrected method was slightly more accurate than the distance to mean method.

**6. Conclusions**

ABS specimens were eroded by consecutive water droplet impacts using a pulsating jet erosion tester. The resulting samples were analyzed using a Keyence VK9700 laser confocal microscope.
A novel method for the determination of volume loss using the height profile was developed and successfully used to identify the end of incubation point. This method can be used to compare jet based erosion tests to whirling arm based erosion tests in terms of mass loss and volume loss.

It was seen that initial damage for this particular material occurred during incubation in the form of pitting at the surface. It was shown that this could be analyzed using the skewness parameter. The damage initiation at the surface was also in agreement with the model, that showed high local superficial stresses. The pitting density increased with prevailing impacts to the point at which they were connected by cracks. After this, loss of material occurred in the form of cratering. The observed material loss could be measured by using the arithmetic mean surface roughness parameter as well as the developed volume loss algorithms. It is of vital importance to understand the combination of these damage mechanisms and how they develop in order to study rain erosion resistance of materials and develop sophisticated leading edge protection systems.

Future work includes testing of ABS at lower velocities to verify the damage mechanisms and establish the Wöhler curve for comparison to other LEP materials as well as development of a sophisticated damage model using high strain rate material parameters to predict long term erosion performance.

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