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Mishnaevsky Jr., Leon ; Fæster, Søren; Doagou Rad, Saeed

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Mechanisms and computational analysis of leading edge erosion of wind turbine blades

Leon Mishnaevsky Jr.¹, Søren Fæster¹ and Saeed Doagou Rad¹

¹Department of Wind Energy, Technical University of Denmark, Roskilde, Denmark
lemi@dtu.dk

Abstract. Microstructural characterization and computational simulations are combined to study the micromechanisms of leading edge erosion of two different coating systems. Scanning electron microscopy (SEM) and X-ray tomography investigations were performed and micromechanical models of the two coatings were developed which take their micro- and nanoscale structures into account. The computational unit cell models are compared to the microscopy studies and both show that the heterogeneities, particles and voids in the protective coatings have critical effect on the crack initiation in the coatings under multiple liquid impact.

1. Introduction
Leading edge erosion of wind turbine blades is one of the most common reasons of reduction of power generation by wind turbines [1]. Leading edge erosion is responsible for more than 5% reduction of annual energy production for a utility-scale wind turbines [1], [2]. The erosion of wind turbines leads also to an increase in drag coefficient by 80-200% [3], and decrease in lift coefficient for higher angles of attack [4]. In this paper, the damage mechanisms of leading edge erosion, methods of computational modelling of the erosion and possibilities of development of new protection coatings are discussed.

2. Damage mechanisms
In order to develop the blade protection against erosion, understanding the microscale erosion mechanisms is necessary. Two different industrially used leading edge coating systems were investigated by electron microscopy and X-ray tomography after a rain erosion test performed on an R&D rain erosion tester [5]. Two typical coatings were investigated, provided by leading companies in this area, one with relatively thin (coating A, thickness of top layer ~100 µm, filler layer ~240 µm) and another two times thicker (coating B, thickness of top layer ~200 µm, filler layer ~400 µm). The tested specimens were 3-mm thick, flat and U-shaped, consisting of a coating on a glass fibre reinforced polymer laminate manufactured by vacuum infusion. The two coating systems were tested in an R&D rain erosion tester with a drop size of 3.5mm and a max speed of 168.9 m/s until erosion was observed. Figures 1 and 2 are scanning electron microscopy (SEM) images that show typical structures of coating system A and B respectively. The figures show the heterogeneity of the coating and putty layers. Voids, heterogeneities, particles can be seen on images. Large round Si particles and large elongated particles of Al, Si and K were observed. It can be seen that the manufactures have used completely different coating systems, which also lead to completely different damage mechanisms when subjected to a rain erosion test.

Coating system A contain many elongated particles which mainly is oriented parallel to the surface. One can see the cracks along these elongated particles close to the surface, see Figure 3, supposedly due
to a difference in stiffness between the elongated particle and the matrix. This type of cracks are not observed in coating system B. Coating system B contain a lot of bubbles both in the top coat and in the putty, see Figure 2 and Figure 3. X-ray tomography was performed on coating system B after testing using a Zeiss Xradia 520 Versa. The scanning was carried out with a polychromatic X-ray beam with energies up to 40 kV originating from a tungsten target. The sample was rotated ±180° while 1601 projections were acquired. Reconstruction was performed using a Feldkamp cone beam reconstruction algorithm. The voxel size in the reconstruction is 2.0 μm which is sufficient to resolve cracks within the material. Figure 3 show two different virtual slices through the reconstruction. Cracks can be observed between the surface and the bubbles in the top coat and the cracks extend from these bubbles further into the putty.

The electron microscopy investigations and X-ray tomography showed that the leading edge erosion is controlled to a large degree by heterogeneities of the coating systems and manufacturing defects. Voids and weak interfaces heterogeneities trigger therefore damage mechanisms (cracks from voids, debonding particles, debonding between layers etc.). So, one of the keys to the improvement of anti-erosion coating lies in improving the coating manufacturing technology and better quality control.

Figure 1. SEM images of a cross sections through the coating systems A. (a) Overview image and (b) close up of the top coating and the putty after testing showing dark cracks close to elongated white filler particles.

Figure 2. SEM images of a cross sections through the coating systems B. (a) Overview made as a collage of SEM images (b) Close up of the top coating and the putty showing air bubbles before testing.
Figure 3. Virtual slice through a tomographic reconstruction of coating system B after testing showing cracks between the surface and bubbles within the top coat.

3. Computational modelling: Drop/Surface interaction

In order to develop the required protective coatings against rain erosion, predictive computational models of the material degradation under erosion are required. Main steps of leading edge erosion modelling include the evaluation of loading (rain density, droplet size distribution, dust, flow velocity), modelling of impact contact between droplet/particle and surface (pressure on the surface, time, deformation and damage initiation; wave distribution, Rayleigh waves), modelling of materials degradation over time (coating cracking, debonding, cracks in composite fatigue, material loss, roughening of surface, estimation of lifetime). The schema of the rain erosion modelling is presented on Figure 4.

Figure 4. Schema of the rain erosion modelling.

Numerical models of surface erosion of wind turbine blades are expected to provide both predictions of performance, lifetime and maintenance requirements of repaired structures, and serve as a tool for the optimization of the protection and repair technologies. A number of quite complex multiscale and multiphysical models have been developed, from good phenomenological formulas (water hammer, damage threshold velocity, see [9]) to complex multistep models [6], including the full model chain from turbulent flow, real rain statistics via the liquid impact [6], up to the fatigue damage studies [7].
A new research project “DURALEDGE - Durable leading edges for high tip speed wind turbine blades” has started at the Technical University of Denmark, to optimize the structure of protective coatings of wind turbine blades on the basis of computational models [10]. Figures 5 - 7 show some computational models and results of the numerical modelling of rain droplet impact, obtained in the framework of Duraledge project.

A parametric 3D model of raindrop hitting the coated laminate has been developed in [11]. For the simulation of rain drop fluid behavior, both Smoothed Particle Hydrodynamics (SPH) and Coupled Eulerian Lagrangian (CEL) were used and compared. It was observed that both methods tend to predict similar trends of stress evolution during the full period of contact. The coupled Eulerian-Lagrangian method is more accurate in capturing the details, but more computationally expensive.

![Figure 5. Simulated stress field under impact and droplet simulated with SPH. (Reprinted from [11] with kind permission from Springer)](image1)

A crucial element in erosion behavior of the coatings protecting wind turbine blades is the surface characteristics of the applied coatings, in particular, roughness. Figure 6 (b) shows the model to investigate the influence of surface roughness on the stress fields within the coating. The surface is dented randomly with half-spheres with the various radii of 5-20 μm. The results showed that the high stress concentration sites around the surface irregularities, that could lead to crack initiation.

![Figure 6. Finite element rough surface model. Stress fields at (c) smooth versus (d) rough surface. Reprinted from [11] with kind permission from Springer](image2)
Manufacturing defects have also strong influence on the erosion. One of the common manufacturing
defects are bubble [5], [12]. In order to investigate the sensitivity of the erosion behavior to the presence
of the bubbles, bubbles with different sizes were included within the coatings [11]. The simulation
results on these defected coatings showed that even minuscule bubbles could aggravate the coating
erosion resistance. While presence of 40 µm bubbles within the coating intensified the initial peak stress,
larger sizes of bubbles increased the initial stress and heightened the stress levels afterwards. Even
presence of 100 µm bubbles could lead to at least 10 % shortening of the lifetime of the coatings. For
the analysis of the fatigue degradation of the coatings, software, based on the critical plane models (I.e.,
assuming that fatigue damage accumulates on a specific plane in the material, denoted “critical
plane”), Miner-Palmer fatigue rule and the rainflow counting was developed [13]. The critical plane
model allows simulation of multiaxial fatigue. Figure 7 shows the output of this software code [13] in
which the load cycles are presented and rainflow histogramm is shown.

Figure 7. (a) Principal stress cycles, and (b) rainflow histogram.

4. Directions of optimization of coatings
As a first evaluation of the materials potential for erosion protection, various predictors for the erosion
resistance of coatings were proposed, an easily tested value. Among them, resistance against abrasive
wear: [14], viscoelastic moduli at given frequency [14], fracture energy in tensile tests [15], rebound
resilience [16], reduction of storage modulus of coating [17], recovery of material after impact [17],
[18] are considered.

Multilayer coatings is a promising option to enhance the protection of laminates, since they allow
combining advantages of various materials in different layers, and exploiting interfaces for wave
reflection. The multi-layered coatings with alternating stiff and ductile layers found applications in many
protective systems. Engel et al [19] demonstrated that multilayer polyurethane/PUR coatings ensure at
least better, and more stable erosion protection than two layer PUR coatings, which in turn ensure at
least better and more stable protection than single coatings. Cortes and colleagues [20], [21] studied
carbodiimide-polyurethane based coating (hybrid polyurethane-urea technology) for erosion
protection of wind turbines, and reported good performance of these coatings. In-mould coatings were
painted or sprayed onto the mould tool. Mohagheghian and colleagues [22] considered the polymer–
metal laminates (with thin polyethylene coating). Also, in British project Leading Edge for Turbines
(LEFT), the integration of electroformed metallic leading-edge protection solutions (nickel cobalt
alloys) into the erosion protection systems is investigated. Herring, Dyer et al. [23] proposed electroformed nickel shields, located in higher speed regions of the wind blades and thermoplastic coatings (which are lighter and cheaper) located at the intermediate, closer to roots areas. Another mechanisms of wave dissipation is the scattering on inclusions. An interesting type of materials is the materials with interpenetrating polymer networks/IPN. For instance, damping properties of polyurethane can be improved by introducing epoxy to form polyurethane/epoxy interpenetrating polymer network [27]. The advantages of IPN as compared with pure polyurethane include better heat resistance, higher strength, and extend the temperature range with sufficiently high damping peaks [28], [29]. In a number of works, particle (microscale and nanoscale) reinforcements in the polymer coatings have been studied. Armada et al. [31] developed epoxy coatings with surface treated ceramic nanoparticles, prepared by sol-gel method. They observed that the erosion resistance clearly increases with increasing the nanoparticles content (both for FunzioNano and SiC). Gou et al. [32] developed carbon nanofiber paper based coatings, with embedded nickel nanostrands. As with other applications of nanoengineering, the positive (or negative) output of nanomodification strongly depends on specific technology: manufacturing and distribution of nanoparticles, functionalization, surface modification, etc. [33], [34]-[37]. For instance, Gohardani et al. [38] explored the effect of CNT (carbon nanotube) reinforcement in resins on the erosion under multiple liquid impact and did not observe sufficient improvement of CNT reinforced resin as compared with pure resin.

5. Conclusions
Micromechanisms of leading edge erosion of coated wind turbine blades are studied with the use of scanning electron microscopy and X-ray tomography and computational micromechanics simulations. Heterogeneities of the coating systems and manufacturing defects such as air bubbles are found to initiate leading edge erosion. In the improvement process of anti-erosion coatings it is therefore vital to improve the coating manufacturing technology and to ensure a better quality control

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