

Innovation Foundation of Denmark

Project DURALEEDGE

Durable leading edges for high tip speed wind turbine blades

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Overview

- ❑ Duration: 3 years
- ❑ Start: November 1st, 2018
- ❑ Budget: 19.8 Mio kr



Workpackages:

WP1 **Understanding** the leading edge (LE) degradation.



WP2. Multiscale **computational modelling** and numerical simulation of LEE.



WP3. **Optimized protective solutions** with engineered coatings.



WP4 **Validation** for field applications, testing and exploitation.

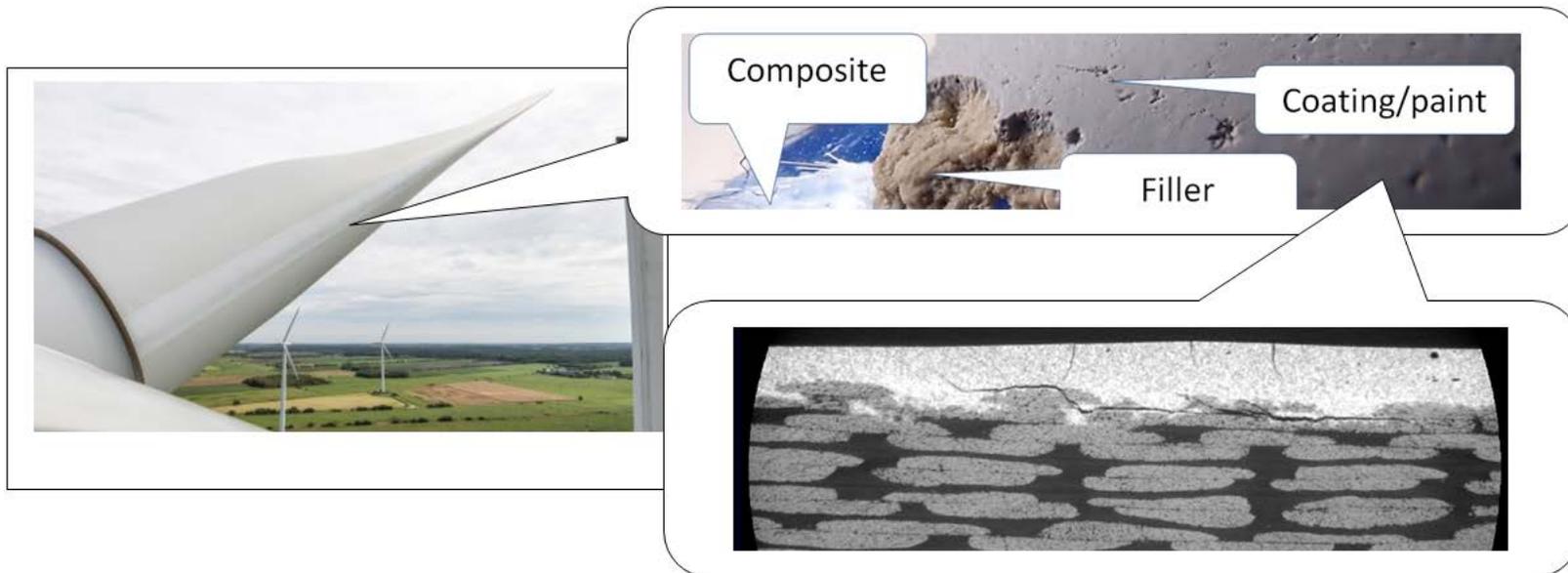


WP5. Dissemination and IPR

WP6. Management

Hypothesis

- ❑ Erosion of wind turbine blades occurs as **microscale cracking and debonding** of materials at surface.
- ❑ **Micro-architected protective coatings with optimized structures** can counteract and prevent the erosion and surface degradation of wind turbine blades.



Expected outputs

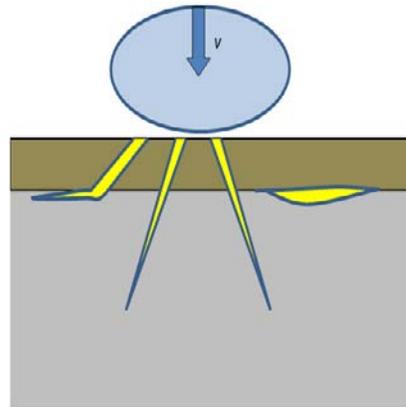
SOLUTION:

New protective coating with 5 times increased lifetime



KNOWLEDGE:

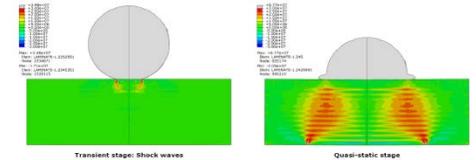
mechanisms of erosion



Strongly depend on considered polymer system

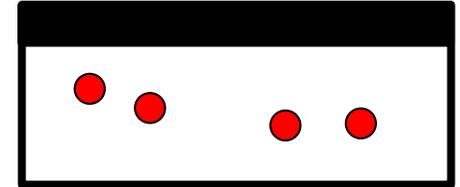
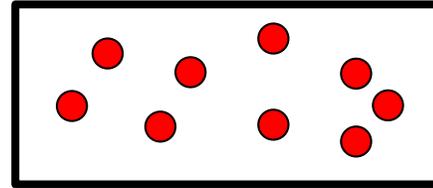
TOOL:

Computational model for numerical testing of new coatings

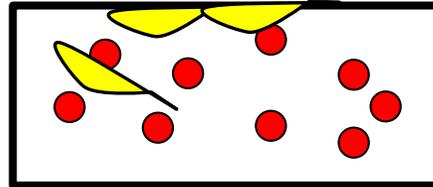


How we proceed

Defining which coatings we consider



Testing – which damage mechanisms control their degradation



Modelling – is this damage controlled by cracking?
Debonding?

Recommendations!

First step: Overview

what was done
before?



PROTECTIVE COATINGS against impact, fatigue, erosion loading

What are solutions by
other groups and in
neighbouring areas

?



Which polymer systems make best coatings against erosion?

Erosion rate is directly proportional to **high-frequency (10^7 MHz) loss modulus, and viscous modulus** (ability to dissipate energy).

G. Arena et al, 2015 eXPRESS Polymer Letters 9(3)

Polyurethane with **Cu(II) phthalocyanines organic filler**: weight loss of the CuPc/PU specimen after 500 cycles was 2 times lower than the neat PU

Youssef, et al, Int J Polymer Science, Vol 2015, Article ID 461390,

Polyurethane with **curable composition including aliphatic diisocyanate, cycloaliphatic diisocyanate and polyether polyol** Patent

EP3315526 Erosion-Resistant Polyurethane Coating, Fraunhofer Society

Polybutadiene polyurethane resins: robust materials for erosion protection, allows frequent heating, good adhesion

Golfman, Hybrid Anisotropic Materials for Wind Power Turbine Blades, CRC Press, 2012

Thermoplastic polymers with silica sands: Incubation behavior observed for PEEK, PPS, UHMWPE (not for PEI, PEK, PES, and PSU) at normal impact angle, and it decreases with an increase the particle velocity. **PEEK** shows best erosion resistance than the other polymers at oblique impact angles (15° , 30°). At higher impact angles (60° , 90°), **PPS** shows best erosion resistance.

Arjula, et al, J Mater Sci (2008) 43:1757–1768

Anti-impact coatings:

Not directly relevant but worth to look at

Polyureas elastomeric coatings, with viscoelastic phase transitions under impact, leading to large energy absorption, and also lateral spreading of the impact force

Roland et al. Philosophical Magazine Vol. 93, No. 5, 468–477

Adding **breakable spheres** in the protective coatings. Density gradient of graded polymeric hollow sphere agglomerates: “winning strategy in term of more absorbed energy with a low transmitted force could consist of placing the “hardest” layer as the first impacted layer and the “weakest” layer in contact with the protected structure to reduce the transmitted force”.

Rösler, et al(1997). Farbe und Lack. 103. 50-54.

H.Zeng, et al, Impact behaviour of hollow sphere agglomerates with density gradient. 9 pages. 2009. <hal-00443066>

Polymer–metal laminates (with thin polyethylene coating): For a thin layer, the impact resistance is highest for the blunt projectile. As the thickness of the polymer coating approaches the projectile radius, the failure mode for all three nose shapes converge. Polyethylene with the high degree of strain hardening at high strain rates (i.e. UHMWPE) ensure best protection.

Mohagheghian et al, IJ Solids and Structures Vol.88–89, 2016, Pages 337-353

Ultrathin **polymeric microlattices** (impact protection is ensured by sideways buckling of the microlattice trusses).

Lai, C. Daraio, IJ Impact Engineering, 120, 2018



Wind turbine blade coatings:

Recent developments of other groups

Polycarbonatediol-polyurethane based coating (hybrid **polyurethane-urea technology**) for erosion protection of wind turbines. Samples manufactured with a higher degree of cure performed worse in regard to erosion compared to those that had a lower degree of cure.

Project "AEI-010500-2015-373 ...new polycarbonatediol-polyurethane based coating to protect the leading edge of wind turbine blades", founded by MINECO (Ministerio de Industria, Energía y Turismo), <http://www.aerox.es/projects/>

Cortés et al, AIP Conference Proceedings 1896, 030023 (2017); <https://doi.org/10.1063/1.5008010>

Carbon nanofiber paper based coatings, with embedded nickel nanostrands. Damping ratio increased by 40..100% (for different modes). Conductivity and lightning strike protection

Gou et al. 2010Composites Part B Engineering 41(2):192-198

Epoxy coatings with ceramic nanoparticles, surface teated. SiC modified by polysiloxane and functionalized. Hybrid organic/inorganic

FunzioNano particles prepared by sol-gel method. Higher roughness in unmodified epoxy. Erosion resistance clearly increases with increasing the nanoparticles content (both for FunzioNano and SiC).

Armada, <https://www.sintef.no/projectweb/nowitech/>, 2010

Adding **Diels–Alder additives (ionomeric coatings)** to improve rheology and enhanced viscosity of coatings and the clay addition to improve impingement.

Wouters, et al, Tuneable adhesion through novel binder technologies, Progress in Organic Coatings 2011 72 (1-2) Wouters, Wind blade coatings: Challenges in impingement protection of wind turbines, TNO

PU 100% , and FN (FunzioNano) and SiC reinforced industrial coating (IC) and tape (IT). 6.6 times less material loss that IC. SiC/PU: 10 less materials loss than IC. FN/PU 6.9 less materials loss than IC.

Valaker et al, Energy Procedia 80 (2015, 263 – 275

Multifunctional carbon nanofiber (CNF) paper-based nanocomposite coating. CNF with grafted Polyhedral Oligomeric Silsesquioxane/POSS.

Damping ratio of the nanocomposite increased by 300% compared to the baseline composite. improved the blockage of water as superhydrophobic material.

Fei L. et al, J Smart and Nano Materials, Volume 2, 2011 - Issue 3, pp. 120-133

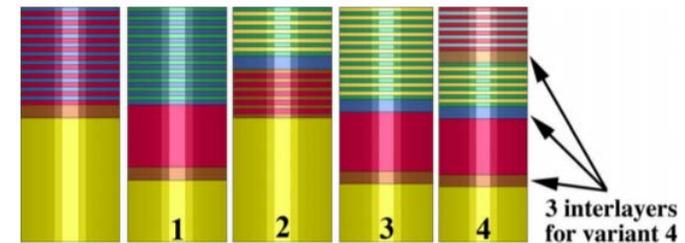
Coating based on sol-gel technique and adding CNTs and graphene

Hadavinia group, Kingston University

Geometrical effects-1

Multilayered coatings

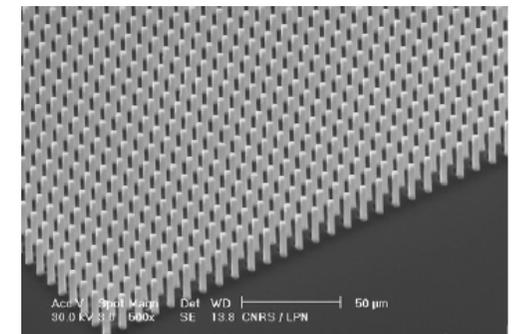
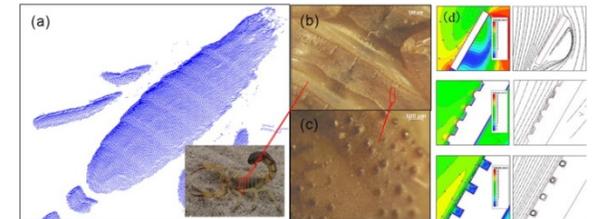
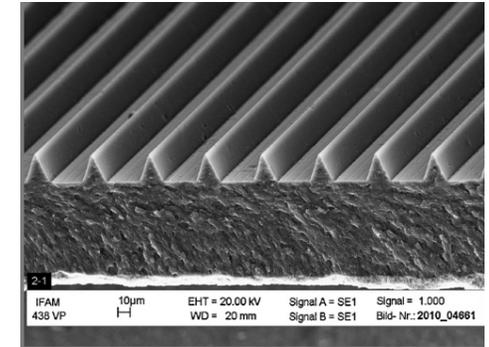
- ❑ **Multilayer polyurethane/PUR coatings** ensure at least better erosion protection than 2 layer PUR coatings, which in turn ensure at least better and protection that single coatings [Engel et al, Naval Air Systems Commands, 1974, Florida Atlantic University].
- ❑ Superposition of **ductile and stiff layers**, where ductile layers act as dampers and absorb shocks [Anti-Erosion Structure For Aircrafts, US Patent 20160046370
- ❑ Multiple polymer **foam interlayers** between stiff plates drastically reduces the average stress in the multilayer material [Tasdemirci Hall, Mater. Des. 30 (2009) p.1533]
- ❑ **Soft rubber elastic layer** can minimize the interfacial shear stress at the multilayer coating, but can also lead to high tensile stresses on the surface [Jayachandran et al, I Computer-Aided Materials Design, 1995]



Geometrical effects-2

Surface roughness modified

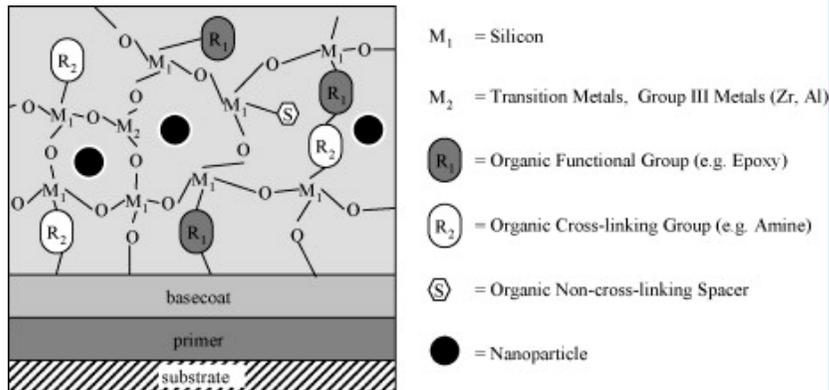
- ❑ **Structured back surfaces of polyurethane-coated laminates** [Kusano, et al, Materials Letters Volume: 221 2018].
- ❑ **Riblet-technology (micro-structured paint on large surfaces)** [Stenzel, et al, Conference EWEA 2014At: Barcelona, Spain; Stenzel et al, Progress in Organic Coatings, Volume 70,4]
- ❑ **Grooved surface Bionic functional surfaces** inspired by desert scorpions (who sustain permanent sand impact in desert) shows best erosion protection, as compared to smooth and convex surfaces. Han, et al, J Bionic Engineering, Volume 7, 2010.
- ❑ **Micropillar pattern and nano-grass** (an array of nano-sized randomly distributed nano-needles) (Lotus effect), ensures ice-cleaning and water-repellent structures on the surface [Okulova et al, Aerodynamic effect of icing/rain impacts on super-hydrophobic surfaces (in print)]



Other interesting coatings solution

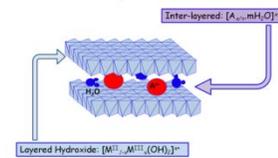
Organic-inorganic hybrid coatings sintesized with sol-gel technology and with added ZrO2 nanoparticles ensure the same protection with up to 23 times lower thickness than commercial PUR. Silica- and silica-alumina based network, cross-linked and non-cross-linked organic groups in the network. Ceramic oxide and non-oxide particles of 10-50 nm uniformly distributed in the coating. Flexible organic groups ensures best erosion protection (40 times higher than commercial PUR solution). Nanoparticles can increase the liquid impact resistance up to factor 4. Erosion protection coatings of 80–300 μm the layer thickness is reduced to $\sim 10 \mu\text{m}$ using the sol-gel technology.

Grundwürmer, et al 2007, Wear 263(1): 318-329

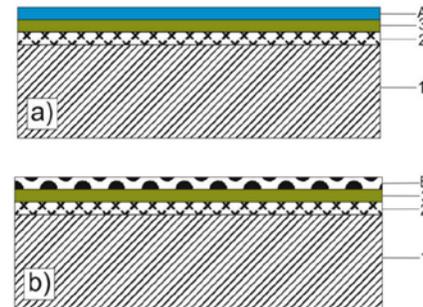


Textured composite coatings with platelets (LDH – layered double hydroxides) aligned parallel to substrate surface. Porous structure at the lower part of primer layer. Hintze-Bruening and F. Leroux

(2012). Nanocomposite Based Multifunctional Coatings, IntechOpen, DOI: 10.5772/48567.



Three-layered epoxy-polyurethane coatings (epoxy, interlayer epoxy, modified polyurethane with 3.5 wt% alumina nanoparticles or silica nanoparticles). Kotnarowska, et al, J Materials Science Research; Vol. 3, No. 2; 2014.



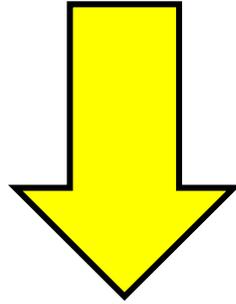
1 – steel substrate, 2 – primer layer (epoxy), 3 – interlayer (epoxy), A – unmodified polyurethane surface layer, B – nanofiller modified polyurethane surface layer

Conclusions:

There exist several **new promising technologies**

- ❑ Particle and **nanoparticle reinforcements** (silica, fumed silica, ceramics)
- ❑ Hybrid **sol-gel** produced coatings
- ❑ Hybrid **PUR-urea** technology or **PUR-epoxy** multilayers
- ❑ Multilayered coatings with **alternating stiff/soft** layers,
- ❑ **Nanoforests** or grooved surfaces,
- ❑ Properties: Controlling high-frequency (107mHz) loss modulus, and viscous modulus; Stiffness

Next steps



- choose promising and practicable protective solutions,
- Testing and understanding damage mechanisms,
- Computational modelling and optimization....

**Project DURALEEDGE started
at November 1st**

Comments? Suggestions?

