Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT – DIEM

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SECTION 1: PROJECT DETAILS

Project Title	Drop Impact Erosion Mill (DIEM)
Lead Grantee (Organisation)	TU Dublin
Lead Grantee (Name)	Prof. Brendan Duffy
Final Report Prepared By	Dr Edmond Tobin, Dr Joseph Mohan & Mr Alistair Chambers
Report Submission Date	26/01/2024

	Name	**Organisation**
Project Partner(s)	Dr Edmond Tobin	South East Technological University (SETU)
Collaborators		

Project Summary (max 500 words)
Please provide an overview of your project, the context, objectives, key results and outcomes. **Context:** The most critical factor in efficient generation from the 4,600MW capacity of existing Irish wind farms is the quality of the laminar air flow. However, losses of up to 25% can occur due to poor leading edges surface quality. With aging infrastructure, wear on leading edges will now become a recurrent issue. Wind farm management must decide on the choice of coatings to be applied to existing assets. At present, the maintenance is carried out by a small number of companies, but the choice of coatings is broad and increasing over time as new products and technologies come to market. Large paint companies such as Akzo Nobel, Jotun & PPG dominate the market but smaller companies such as Belzona and Mankiewicz have specialised coatings for these applications, especially for on-site repair. The ESB operates wind farms using turbines supplied by 6 different OEMs, with an output of over 600MW. The ESB Wind Energy Team therefore need to better understand the coatings on existing turbines and coating options for maintenance.

Objectives: The main objective of this work is to develop a testing methodology to allow for rapid screening and testing of commercial leading edge protection systems. It is important that the ESB and SEAI can benchmark such available coatings under simulated conditions to maximise their operation lifetimes. Towards this end, TU Dublin & SETU have developed a methodology to evaluate the ability of leading edge protection systems to withstand rain erosion. A variety of coating systems were considered including two separate dual layer systems from PPG and Akzo Nobel. Both systems include an epoxy primer and polyurethane topcoat and are typically applied during the manufacturing process. Two systems, manufactured by Belzona and Mankiewicz, that were designed to be used for on-site repair were also evaluated.

Key Results: The coating systems were characterised using a variety of experimental techniques that included Taber abrasion, adhesion pull-off tests, ATR-FTIR & optical microscopy cross-sections. Results showed that the on-site repair systems are noticeable tougher and more abrasion resistant than those from PPG or Akzo Nobel. They are also significantly thicker systems than both the factory applied protective systems.

During design and commissioning of the DIEM test system, SETU performed a range of calibration tests using different designs of the Jet Cutting Disk, variable water pressures and rotating speeds. A range of test substrates were also tested for calibration purposes (i.e. aluminium, steel, PMMA and painted samples). High-speed photography was utilised to determine the morphology of the water drop prior to impact.

Outcomes: TU Dublin has evaluated a range of material combinations including various composite substrates and LEP Systems. A variety of experimental methods were used including FTIR spectroscopy, Taber wear tests and PAT adhesion tests.

In parallel, SETU designed and commissioned a DIEM test system that is capable of simulating in-service effects of rain on leading edges. The systems is capable of varying the size, speed and impact angle of the drops as well as test up to 30 samples at ones and is currently being used as part of a follow-on SEAI RDD project (SPOTBlade).

Keywords (min 3 and max 10)	Wind turbines; leading edge; coatings, laminar flow; erosion mill

SECTION 2: FINAL TECHNICAL REPORT

2.1 Executive Summary

The Drop Impact Erosion Mill (DIEM) project was focused on addressing the challenge faced by Irish wind farm operators. Specifically, the challenge in selecting the optimum leading edge protection system to mitigate losses in generating efficiency.

To achieve this goal, SETU designed and commissioned a DIEM test rig to simulate real-world rain drop impact conditions. This would enable rapid screening of commercial LEP systems. In parallel, TU Dublin performed a series on laboratory tests experimental tests to characterise the material and surface properties of the LEP systems.

SETU demonstrated that the DIEM test rig can replicated the impact speeds of rain drops on the leading edge of wind turbine blades. The use of high-speed photography also provided insights into the influence of DIEM test rig operating parameters on the characteristics of the individual rain 'slugs'. TU Dublin's experimental tests showed that there was a noticeable difference in the performance of paint systems that were intended to be applied in a factory setting versus those that were specifically designed for on-site or in-situ repair.

The DIEM project led to TU Dublin and SETU forming a consortium with University of Galway and University of Limerick to successfully secure a further SEAI RD&D grant for the SPOTBlade project.

2.2 Introduction to Project

This project proposes to test commercially available coatings for Irish wind turbines and is highly aligned to the National Renewable Energy Action Plan. The plan places a strong emphasis on the generation of electrical energy from wind sources which Ireland has in abundance. From 1990 to 2016 Irelands share of electricity from renewable energy grew dramatically from 5.3% to 27.2%. Since 2000 the bulk of this increase has been from the wind energy sector, with national capacity standing at over 4,600 MW. In the December 2018 draft of the National Energy & Climate Plan, the Irish government has outlined targets on renewable energy contributions up to 2030. These targets have been adopted by the IWEA which has set a figure of 10,000MW but 2030, whereby wind energy is expected to account for 70% of all Irish electricity needs.

The project will expand upon the existing 3rd level infrastructure to develop a test bed for evaluation coating solutions for the Irish wind energy sector. The test bed can be used to aid wind farm operators to decide on new materials for future installations.

The test bed will enable Irish researchers to contribute to international research efforts in the area and improve their opportunities to join European H2020 and Horizon Europe consortia.

The proposal includes an opportunity to tailor an existing ESB training course delivered by CREST for wind energy engineers and operators.

2.3 Project Objectives

The project objectives as outlined in the original proposal are summarised in Table 1. The status of each objective is marked as largely complete. While the Covid-19 pandemic and associated recruitment challenges impacted on the ability of the DIEM team to go above and beyond the objectives, the core goals of the project were achieved.

Table 1: Summary of DIEM objectives and current status as per original submission.

No.	Objective Description	Status
1	Manage Project to achieve call aims	Complete
2	Review of Irish wind farm installations and existing coating systems	Complete
3	Survey coating suppliers for current systems available	Complete
4	Confirm design and order components for Erosion Rig	Complete
5	ISO TS 19392-1 Survey of materials started	Complete
6	Coating Course Outline (based on existing bespoke ESB course)	Complete
7	Complete assembly and trials of erosion rig	Complete
8	ISO TS 19392-1 Survey of materials complete	Complete
9	Complete Ranking and generate a technical report for dissemination	Complete

2.4 Summary of Key Findings/Outcomes

Describe how your project has furthered the current state-of-the-art, current knowledge or current practice. Clearly highlight the degree of novelty and innovation demonstrated by your project.

Furthering of current state-of-the-art, knowledge and practice

The DIEM project made several advancements in terms of state-of-the-art, knowledge and practice within both SETU and TU Dublin. In terms of state-of-the-art, SETU developed a novel drop impact erosion mill (DIEM) to satisfy the requirements of ISO/TS 19392-1. Current knowledge was enhanced by providing insights into the wear characteristics and adhesion performance of various commercially available paint systems that are typically evaluated individually by the companies themselves. Finally, the outputs from this DIEM project have informed the inputs to the SEAI SPOTBlade project that will result in best practices for off-shore wind turbine operators.

DIEM Test Rig

The droplet impact erosion mill was designed and fabricated in SETU. Figure 1 shows the design process from initial sketch and conceptualisation, through to computer-aided design, fabrication and final assembly. Off-the-shelf parts (e.g. motors and pumps) were used where applicable and custom parts were manufactured in-house in SETU.

Upon final assembly, the DIEM test system was commissioned. The commissioning process can be seen in Figure 2 and Figure 3. In Figure 2 (left), painted samples (white and green) provided by TU Dublin / CREST can be seen mounted in the rotary holder. The high-speed camera (Figure 2 (right)) is positioned on the outside of the DIEM test chamber and setup to capture the impacts of the individual rain drops on the painted coupons. Various designs of the water jet disrupter disc were tested to produce an optimum drop shape that represented real world conditions (see Figure 3 (left)). In parallel, a calibration curve was produced by performing tests at various water pressures and comparing to the specifications of the nozzle (see Figure 3 (right)). The real-world velocities achieved were slightly less than the theoretical values expected from the specifications. However, a similar trend was observed, and it was possible to achieve the necessary speed to replicate the impacts of rain drops under real-world conditions. Calibration tests were completed on 3 mm Perspex samples to use as a control for all further testing. The impact crater produced after 3 hours of testing is shown in Figure 4.

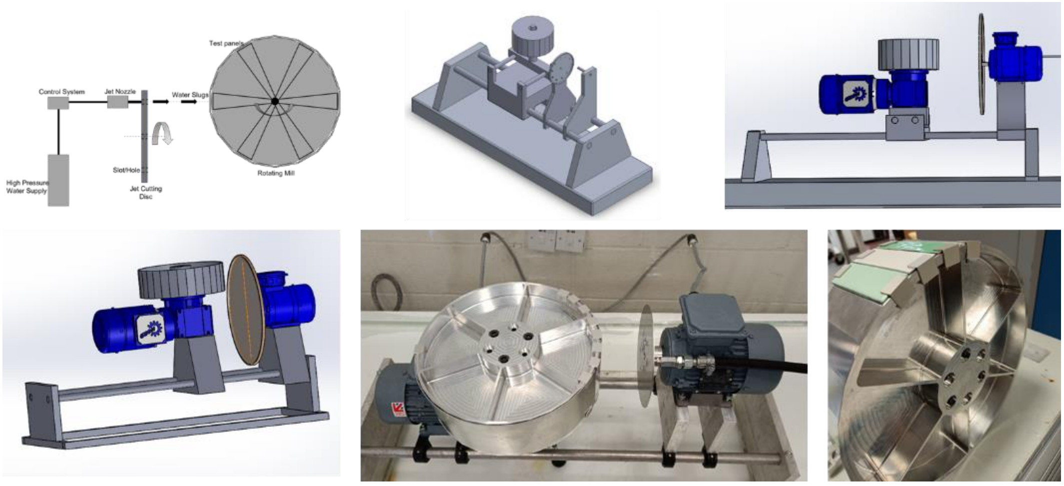

Figure 1: Design and fabrication of drop impact erosion mill.

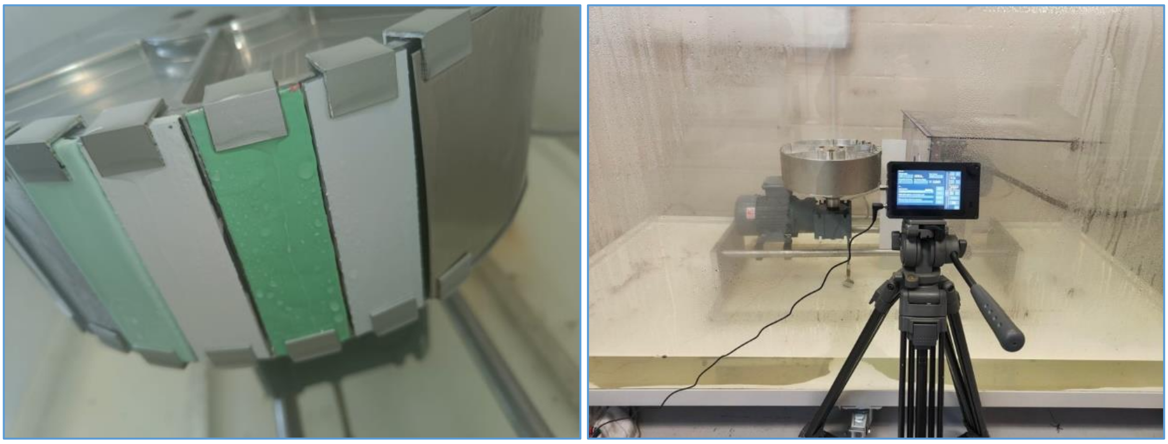

Figure 2: Drop impact erosion mill experimental setup with samples mounted in holder (left) and high-speed camera (right) that captures the drop impacts.

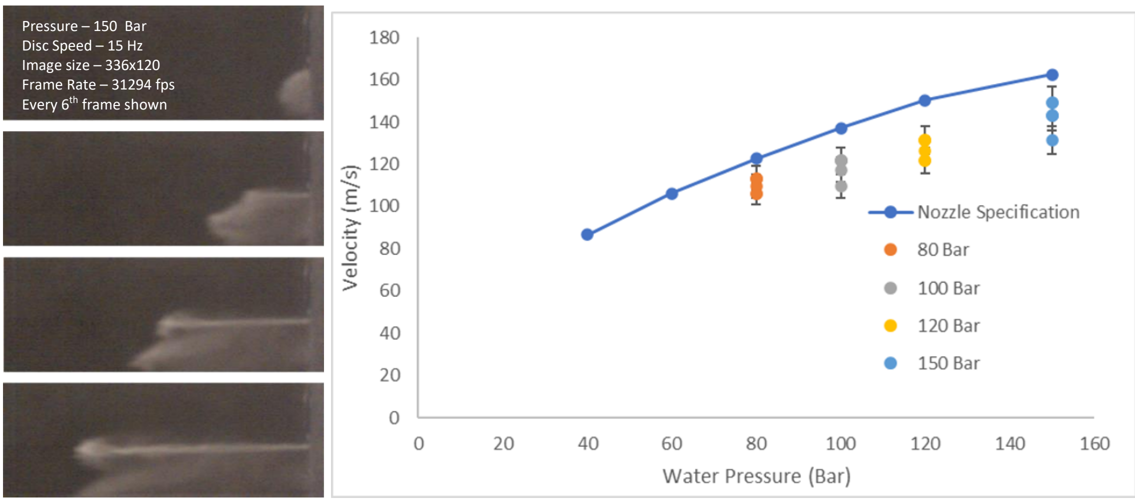

Figure 3: High-speed photography showing evolution of water jet (left) and calibration curve (right).

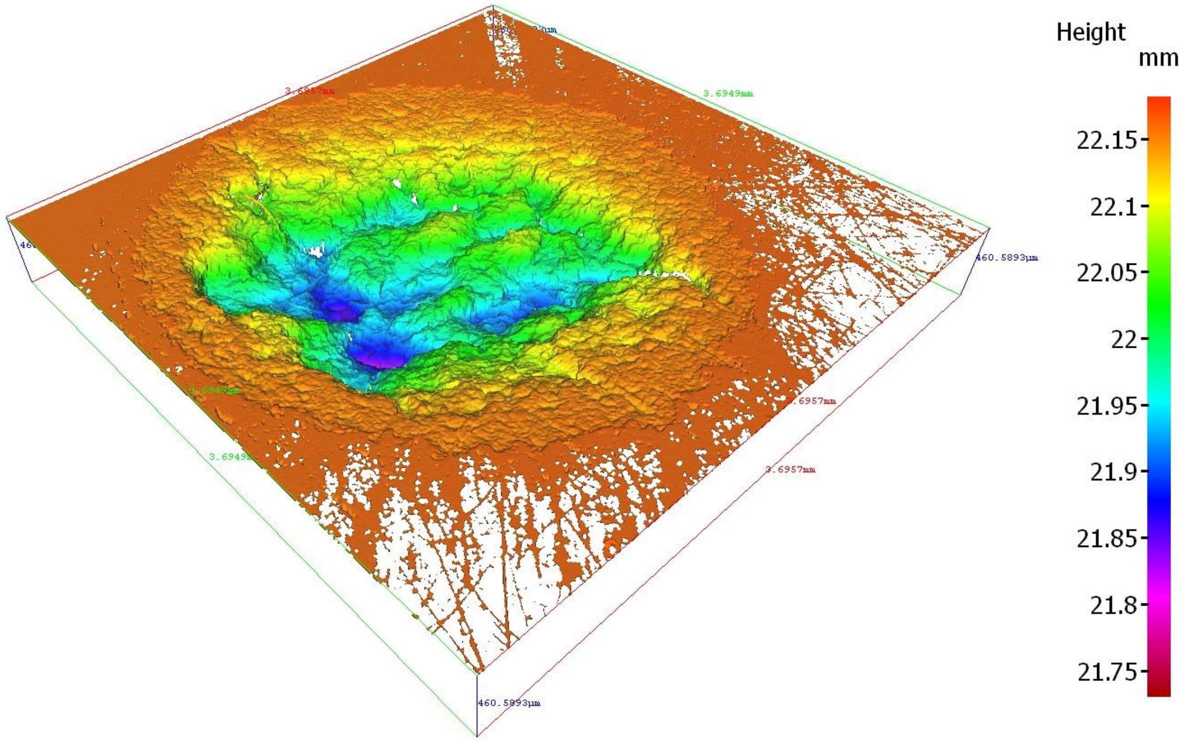

Figure 4: Erosion scar on a Perspex panel imaged using a Alicona InfiniteFocus G5+

Insights into LEP Coating Systems

Four commercially available marine and leading-edge protection paint systems were used:

- Akzo Nobel: Interplus 356 Primer & Interthane 870 Topcoat
- Alexit: Blade Rep 9
- Belzona: Beltech 5721
- PPG: Sigmacover 280 Primer & Sigmadur 520 Topcoat

The Akzo Nobel and PPG systems are typically designed to be applied in a factory setting while the Alexit and Belzona systems are intended for on-site repair. As a result, the factory systems were less viscous with the two repair systems having thixotropic-like properties. An FTIR spectra of each polyurethane topcoat can be seen in Figure 5 and would be typical of most polyurethane systems.

In addition, two composite substrate laminates were considered. In both cases, the fibre reinforcement was a +45/-45 layup of non-crimped (i.e. non-woven) glass-fibre. Two resin matrices of polyester and epoxy were used to manufacture the laminates in-house at TU Dublin. A typical optical and scanning electron microscopy cross-section can be seen in Figure 6 left and right respectively.

The painted samples were tested for adhesive to the substrate via a Pneumatic Adhesion Tensile (PAT) test and for wear resistance via a TABER test. A photograph of a sample after PAT testing can be seen in Figure 7 (left) and the resulting experimental data can be seen in Figure 7 (right). In general, adhesion was significantly better to composite laminates manufactured with an epoxy matrix rather than a polyester resin.

Figure 8 shows a photograph (left) of a painted sample after TABER testing with a visible wear track. The measured weight loss for each paint system is presented in Figure 8 (right). The two repair systems had reduced weight loss (i.e. better wear performance) compared to the Akzo Noble or PPG systems. Further insights were gained in the wear tracks by performing optical profilometry on the resultant surfaces after testing that can be seen in Figure 9.

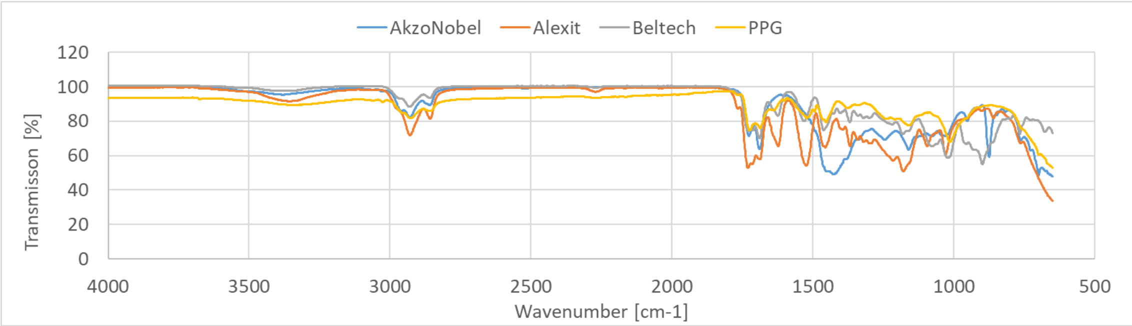

Figure 5: FTIR spectra for each polyurethane topcoat under examination.

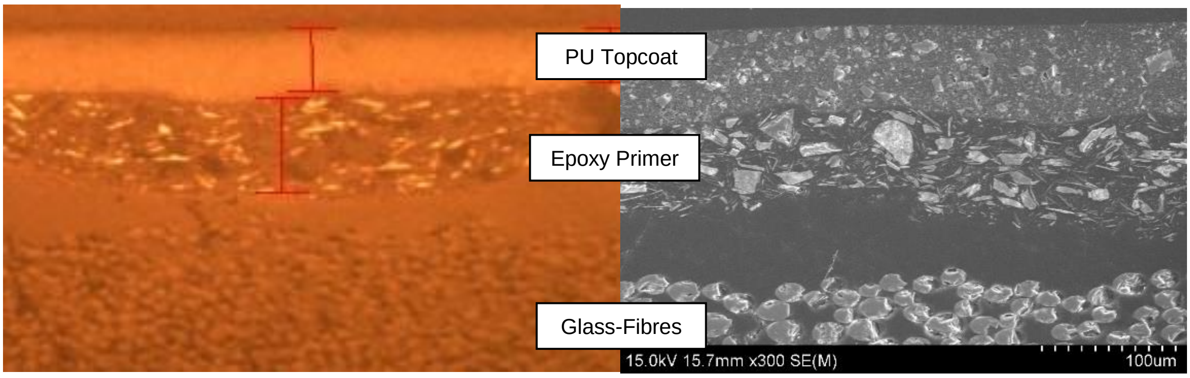

Figure 6: Optical micrograph of painted composite sample (left) and equivalent cross-section from a scanning electron microscope (right).

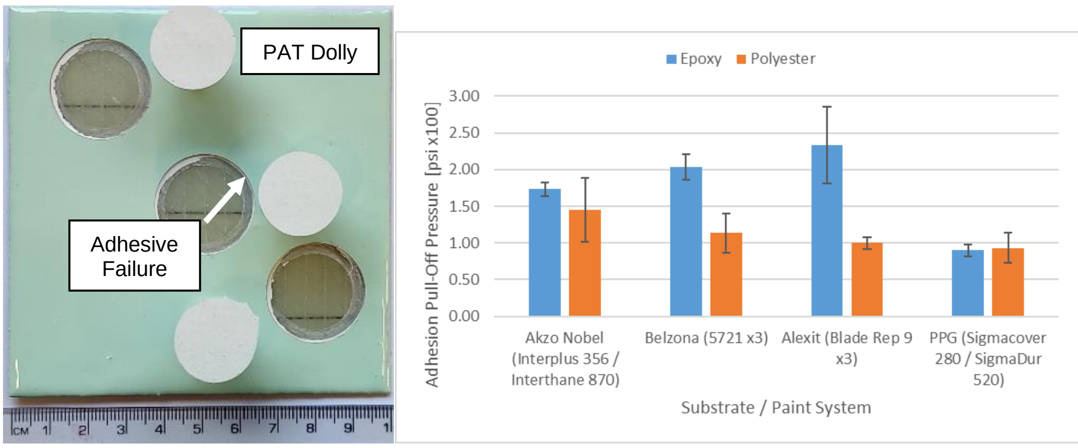

Figure 7: Pneumatic Adhesion Pull (PAT) test experiment test (left) and results (right). Note that higher is better and indicates a stronger adhesive bond.

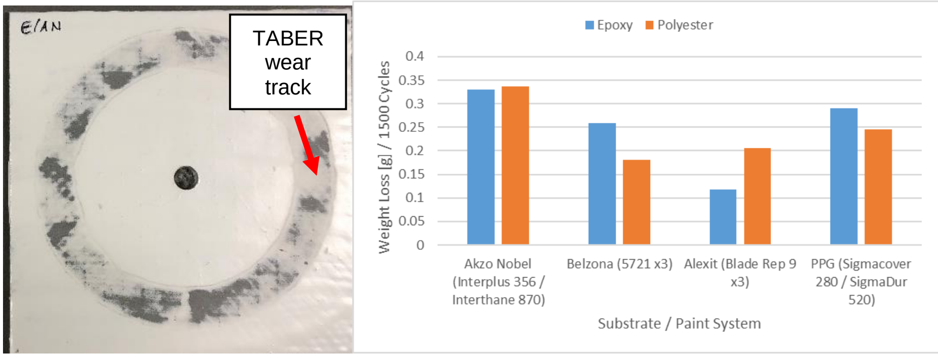

Figure 8: TABER wear test sample after testing (left) and weight loss results for each paint system examined. Note that lower is better (i.e. less material wear).

Parameters	Unit	Hole	Peak
Projected area	µm²	3.005e+07	7207399.678
Volume	µm³	2.239e+09	6.266e+07
Max. depth/height	µm	113.056	27.531
Mean depth/height	µm	74.515	8.694

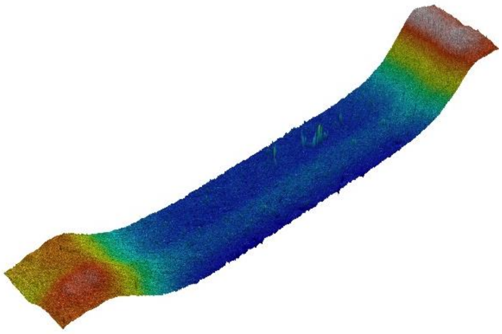

Figure 9: Hole volume analysis of a section of the TABER wear track (left) with corresponding 3D map (right).

Several insights were obtained from the experimental work. For example, the paint systems generally adhered better to epoxy matrices compared to polyester ones as evident by the PAT tests. While polyester is a cheaper resin to use in the manufacture of wind turbine blades, there is potential that it may negatively impact on the service life of leading-edge protection systems.

It was interesting to note that two paint systems designed for on-site repair had noticeably better performance under TABER testing. The TABER results also suggests that the factory-applied systems may struggle during the harsh conditions experienced by wind turbines.

Novelty and Innovation

Address each innovation in a bullet point below. Add as many bullet points as you need:

- *Innovation 1: Novel Composite Laminates and Protective Systems*

  With the acquisition & commissioning of a composite manufacturing suite, CREST now has the capability to fabricate novel materials and coating systems. In future, this will allow the design novel composite and coating systems from a range of innovative.

- *Innovation 2: Rain Erosion Test System*

  The DIEM system provides for the efficient and cost-effective testing of wind turbine materials for both development and qualification needs. The system provides a novel procedure to allow various impact angles to replicate in-service conditions to a superior level.

2.5 Project Impact

Clearly position the impact of your project with reference to the needs of the Irish Energy Sector, national and international policy objectives, and SEAI's remit.

Discuss the key impacts of your project: societal, economic, technological or otherwise. Clearly identify and highlight the value of your project in the wider context.

Main Impacts for Irish Energy Sector

The increasing use of wind turbines is a key element of the Irish Energy Sector's strategy to move away from fossil fuel as its main source of energy. However, as the wind-turbine grid matures, the issues of maintenance, repair and overhaul (MRO) will become an increasing challenge. Operators of wind turbine farms need guidance and expertise in the performance, application and selection of leading-edge protection systems. The DIEM project has established a novel test setup for the rapid development, screening and testing of leading-edge protection paint systems that will be invaluable to the Irish Energy Sector going forward.

Collaboration outside DIEM

Aside from the technical impacts, the DIEM project has resulted in significantly increased collaborative research between two new technological universities, TU Dublin and SETU. This has resulted in several publications and members of the DIEM project are highlighted in bold:

- Hegde, M., Kavanagh, Y., **Duffy, B. and Tobin, E.F.** (2020). Multifunctional hybrid sol-gel coatings for Marine Renewable Energy Applications: Synthesis, Characterization and Comparative Analysis with Organically Modified Silicon Precursor Coatings. MRS Advances, 5(33-34), pp.1757–1764. doi:https://doi.org/10.1557/adv.2020.157.
- Hegde, M., Kavanagh, Y., **Duffy, B. and Tobin, E.F.** (2022). Abrasion and Cavitation Erosion Resistance of Multi-Layer Dip Coated Sol-Gel Coatings on AA2024-T3. Corrosion and Materials Degradation, 3(4), pp.661-671.
- Hegde, M., **Mohan, J.**, Warraich, M.Q.M., Kavanagh, Y., **Duffy, B. and Tobin, E.F.** (2023). Cavitation erosion and corrosion resistance of superhydrophobic sol-gel coatings on aluminium alloy. Wear, p.204766.

Leveraging further funding with SEAI

While external events negatively impacted on the progress and on-time delivery of the DIEM project, the resulting technical and collaborative achievements previously outlined resulted in the formation of a strong consortium (together with University of Limerick and University of Galway) that successfully secured an RD&D SEAI grant for the SPOTBlade project. A high-level overview of the SPOTBlade project can be seen in Figure 10. The major output from DIEM project has been the development of internal capabilities within SETU and TU Dublin that have directly feed into SPOTBlade and accelerated the progress of that project.

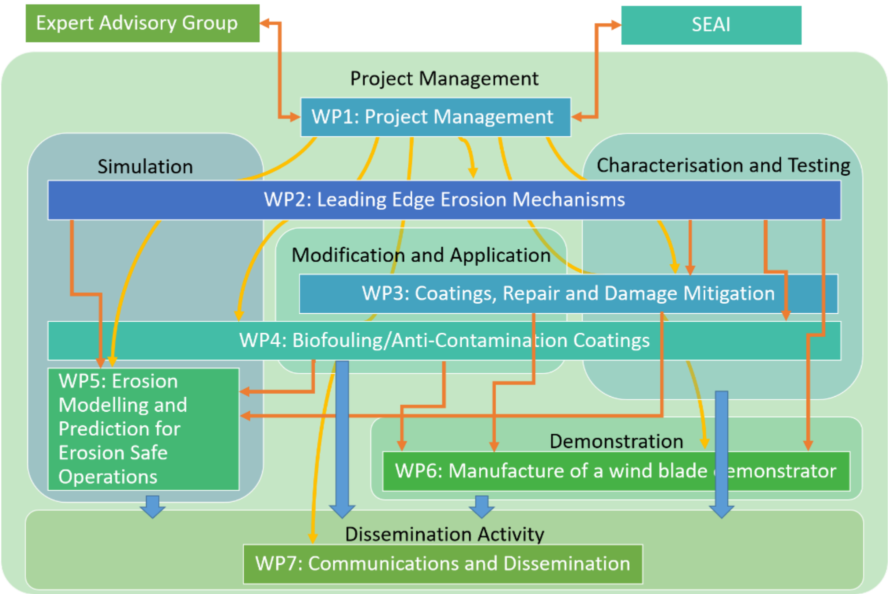

Figure 10: High level overview of the SPOTBlade RD&D SEAI project.

2.6 Recommendations

Please highlight any implications/opportunities/recommendations for Ireland (e.g., for policy makers, for the research community, for industry) based on the work carried out in the project.

Based on the outputs from the DIEM project, there is an apparent need for a leading-edge protection system that combines the workability of the factory-applied polyurethane paint systems with the wear resistance of the repair-type protection systems. There is an opportunity for CREST to leverage its expertise to develop novel wear resistant paint systems that can be rapidly evaluated using the DIEM system that was commissioned in SETU.

2.7 Conclusions and Next Steps

The impact of the Covid-19 pandemic and resultant recruitment challenges can not be ignored. Despite this, the DIEM project successfully delivered on commissioning a novel test rig that is currently being utilised withing SETU. The capabilities and expertise within CREST have been enhanced by working with the LEP systems and have been leveraged for other projects. The DIEM project also served as a precursor for future collaboration between SETU and TU Dublin via the SEAI funded SPOTBlade project. The next and final step for the DIEM project will be to publish the experimental outputs from this work in a peer-reviewed journal article.