



## Designing nickel coatings for water erosion performance: Optimisation of grain size and thickness

Nithin Chandra Gaddavalasa<sup>a</sup>, Arijit Lodh<sup>a,\*</sup>, Andrea Cini<sup>b</sup>, Vinodhen Saaran<sup>a</sup>, Ali Mehmanparast<sup>c</sup>, Andrew Starr<sup>a</sup>, Gustavo M. Castelluccio<sup>a</sup>

<sup>a</sup> Faculty of Engineering and Applied Sciences, Cranfield University, Cranfield, MK43 0AL, United Kingdom

<sup>b</sup> Department of Aerospace Engineering, Universidad Carlos III de Madrid, Leganes, Madrid, 28911, Spain

<sup>c</sup> Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, G1 1XQ, United Kingdom

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### ABSTRACT

Metallic coatings are gaining interest as an alternative to classical polymeric layers for erosion damage prevention due to their extended durability and sustainability. However, their implementation requires a thorough understanding of protective potential and reliability. This study explores the use of brush-plated nickel coatings on carbon-fibre reinforced composites to enhance their performance against water erosion. A combination of experimental analysis and computational modelling explores the effect of different coating thickness and properties to withstand water droplet erosion damage. Findings reveal a minimum critical coating thickness around 40  $\mu\text{m}$  can significantly improve the erosion resistance.

### 1. Introduction

Leading Edge Erosion (LEE) is one of the prominent degradation mechanisms for many applications such as wind turbine blades, aircraft wings and helicopter rotor blades [1–4]. Offshore wind turbines, in particular, are of specific concern since they have degraded faster than expected in recent years [5]. The impact of environmental elements such as sand, rain, and ice airborne particles results in wear and tear at the wind turbine blade leading edges [6]. This phenomenon poses a considerable concern for the efficiency, performance, and longevity of wind turbines, affecting their ability to convert wind energy into electrical power.

Wind turbine blades are commonly made of glass-fibre reinforced polymers (GFRP) rather than more resistant carbon-fibre reinforced polymers (CFRP) due to the higher costs of the latter. Hybrid composite laminates, which combine carbon fibres on top of glass fibres [7–10] have also been proposed for their increased strength and stiffness. However, the repair of LEE in any of these composites is still difficult, especially after being installed offshore.

A few protective technologies have been commercialised with various levels of success in preventing erosion or facilitating their adoption on in-service failure. Some manufacturers have developed protective tapes, paintings, and epoxy layering (e.g. engineered polyurethanes, multi-layer coatings, reinforced coatings [11]), which are relatively easy to install on site but do not entirely eliminate erosion [11,12]. On the contrary, nickel-cobalt metallic tiles are recognised as the most erosion-resistant solution given the high hardness of the alloy [12,13]. However, the use of harmful cobalt (> 40wt%) and the difficulty of installation prevent a wider adoption of this solution.

Metallic coating technology has emerged among the simplest and most sustainable solutions for the material extended life. A recent analysis on maintenance of materials [14], demonstrated that metallic coatings are among the best environmentally viable

\* Corresponding author.

E-mail address: [a.lodh@cranfield.ac.uk](mailto:a.lodh@cranfield.ac.uk) (A. Lodh).

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approaches for on-site as well as off-site production and repair. Moreover, nanostructured metallic materials have demonstrated exceptional hardness and good resistance against erosion [15–19]. Thus, it seems plausible that microstructural strengthening can replace solid solution hardening from cobalt tiles to result in an efficient erosion solution. Indeed, nanocrystalline nickel or nickel-tungsten coating shows similar hardness of nanocrystalline ni-cobalt (550HV at 20 nm grain size) [15–17,20]. Also, metallic coatings have superior electrical conductivity compared to reinforced polymers which can channel lightning strikes [21]. Hence, a thin layer of nanostructured metallic coatings can act both as an erosion resistor and lightning channelling without significantly increasing blade mass.

However, work remains to optimise microstructure, composition, integration with composites and coating deposition process. It is especially important to understand how metallic coatings perform when deposited on composites at an optimal thickness, ensuring that the coating does not add excess weight, which could affect the component's behaviour. The present work is focused to provide insights on how to design a nickel-based coating in terms of microstructure and thickness that can withstand water droplet erosion. For deposition of coatings, brush-plating is an emerging method with scalable technique. To the best possible knowledge of the authors, water erosion behaviour of brush-plated nickel is very rare [22]. We first evaluated the characteristics of nanostructured nickel electrodeposited on carbon fibre-reinforced composites by means of brush-plating. The results demonstrate that this technique not only provides excellent adhesion between the metal and composite but is also amenable to on-site repairs. We consider the effects of coating thicknesses and properties to improve erosion resistance through experimental and computational work. Overall, the excellent performance of nanostructured metallic materials over composites lay down the path to develop coated blades that can be repaired on-site.

## 2. Approach and methodology

We seek to develop solutions benchmarked to CFRP in resisting erosion but with better reparability. Hence, we consider electrodeposition of nanostructured nickel on a CFRP substrate, which enables conductivity. The concept can be further extended into conductive hybrid or GFRP composites. The next sections outline the experimental methodology for fabricating these composites, coating deposition, water droplet erosion testing, and subsequent characterisation and modelling of single droplet erosion.

### 2.1. Fabrication of composite plates

Unidirectional carbon fibre prepreg, MTC 510 - UD300 with an epoxy resin matrix from SHD Composites was selected to represent the composite structure [23]. Several 300 mm<sup>2</sup> laminates were cut and laid up in a [0,90]<sub>2s</sub> followed by a [90,0]<sub>2s</sub><sup>1</sup> resulting with 8 plies to account for a cured nominal thickness of 2.23 mm. The laid-up laminate stack was then placed on a polished platen to achieve the desired smooth surface finish. A layer of perforated release film was placed above the stack to control the flow of excess epoxy resin being released during the cure process, known as debulking. A breather cloth was then placed above it, before being covered with VACtite UltraP vacuum bagging film from Vac Innovation [25]. To ensure that the laminate stack was properly vacuum bagged and sealed, a vacuum bagging sealant tape was used to secure the film to the platen. Any remaining air was then vacuum pulled using a through bag connector, to eliminate the presence of air voids, increasing the fibre-to-epoxy ratio. The stacks were then cured in an autoclave for 2 h at 110 °C under 6 bar pressure with a 2 °C-min<sup>-1</sup> ramp rate, followed by a post cure of a 1 h dwell at 120 °C [23]. Specimens sized 100 mm × 70 mm were then cut from the cured composite plate for the brush plating procedure.

### 2.2. Brush plating setup

Brush plating is an electrodeposition technique that provide a mobile and highly productive solution to deposit metallic materials. The technique setup involves a rectifier and brush covered anode(s) soaked with surface preparatory/plating solution(s) (see Fig. 1(a)). A SIFCO model SPL-75 was used as rectifier [26], which is capable of being switched rapidly between cathodic and anodic modes. The anode was special heat-resistant graphite block, typically covered with white, particle-free non-abrasive 3M Scotch-brite® cloth. All solutions are industrial products manufactured by SIFCO ASC, which includes surface preparatory as well as plating solutions.

Early trials demonstrated that the smooth surface finish of the composite did not result in proper adhesion between the nickel and the substrate. Hence, the composite sample was mechanically polished using a 220-grit sanding tool to coarsen the surface finish. A fresh polishing with red 3M Scotch-brite® prior to deposition was performed to improve the adhesion of coatings. As part of surface cleaning and activation, a SIFCO process was followed which involves the following steps: a cathodic clean in alkaline solutions, an anodic etch in acid, followed by anodic smut removal in a weak acidic electrolyte. Cleaning of surfaces with deionised water in between the mentioned steps was performed as well. A thin layer (2 µm) of nickel was deposited in the pre-plating step using SIFCO Nickel Special™ while main electrodeposition was carried by SIFCO Nickel High Speed LHE™. Fig. 1(b) shows a typical example of nickel deposited on the composite plates following the mentioned procedure. The plating solutions and parameters are outlined in Table 1.

<sup>1</sup> The notation denote stacking pattern of the plies in the composite panel. Unidirectional layer fibre direction are parallel, 0°, or perpendicular, 90°, to the laminate direction. 2s represents number of consecutive stackings in the pattern mentioned and their symmetry with respect to the laminate mid plane. [24].

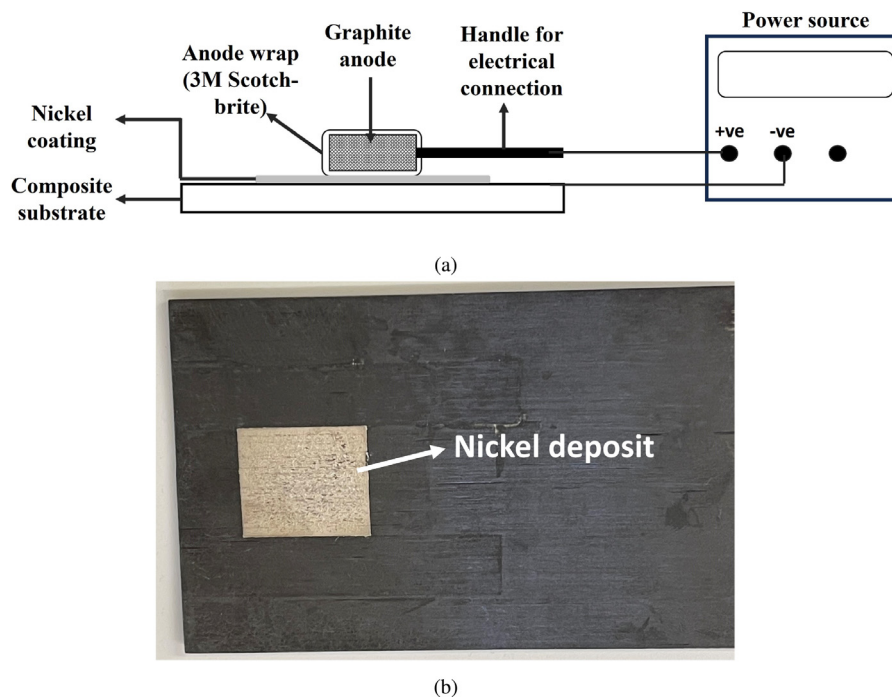


Fig. 1. Schematic of brush plating set up is shown in (a). An example of nickel deposit on composite plate is shown in (b).

**Table 1**  
Solutions involved in brush plating process with their application conditions.

| Step                | Solution              | Composition                                                                    | Condition                                                      |
|---------------------|-----------------------|--------------------------------------------------------------------------------|----------------------------------------------------------------|
| Surface preparation | Electrocleaning       | 3% Sodium Citrate<br>2% Sodium Hydroxide                                       | 13 V, cathodic, 120 s                                          |
|                     | Etching & desmutting  | 15% Sodium Citrate<br>3% Citric Acid<br>21% Nickel Sulfate                     | 15 V, anodic, 120 s                                            |
| Pre-plating         | Nickel Special        | 4% Citric Acid<br>2% Hydrochloric Acid<br>2% Acetic Acid<br>11% Nickel Sulfate | 15 V, cathodic,<br>300 s                                       |
| Plating             | Nickel High Speed LHE | 10% Ammonium Formate<br>5% Ammonium Citrate<br>4% Ammonia Hydroxide            | 15 V, cathodic,<br>35 °C, (900–1500 s)<br>46 A/dm <sup>2</sup> |

**Table 2**  
Time required to deposit coatings using brush-plating.

| Coating thickness (μm) | Time (Minutes) |
|------------------------|----------------|
| 25                     | ~ 65           |
| 50                     | ~ 150          |
| 100                    | ~ 280          |

The deposited areas were  $25 \times 25 \text{ mm}^2$  and masked with aluminium tape followed by vinyl tape. The current density for the plating process was on-average  $46 \text{ A/dm}^2$ . The deposited layer thickness was controlled by measuring the total current applied with the rectifier Ampere-hour counter. This Ampere-hour is calculated as follows,

$$AMP - HR = F \times A \times T \quad (1)$$

where  $F$  is a solution factor reported by the manufacturer on the technical data sheet [27],  $A$  is the surface area to be plated in  $\text{cm}^2$  and  $T$  is the thickness required in  $\mu\text{m}$ . Time required to deposit different thickness of coatings is mentioned in Table 2

**Table 3**  
Rain erosion test parameters in the test rig.

| Needle size (mm) | Volume of droplet (ml) | Flow rate (ml/min) | Impact angle (°) | Impact speed (m/s) |
|------------------|------------------------|--------------------|------------------|--------------------|
| 0.72             | 0.01461                | 46                 | 15               | 50                 |

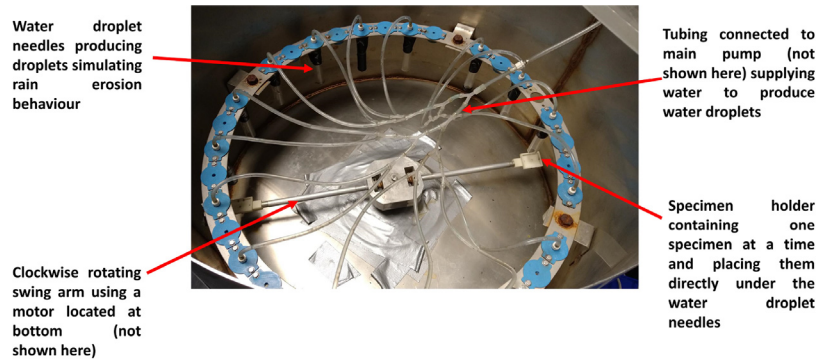


Fig. 2. Water droplet erosion rig at University of Strathclyde.

### 2.3. Nickel deposition characterisation

#### 2.3.1. X-ray diffraction & electron microscopy

X-ray diffraction (XRD) analysis was performed for quantitative analysis, such as grain size and textural development. A Siemens D5005 system, operated at 40 kV and 40 mA with  $\text{CuK}\alpha$  radiation ( $\lambda = 1.54 \text{ \AA}$ ), was used at a step size of  $0.04^\circ$  and 1 s time per step in the range of  $35\text{--}90^\circ$  to obtain the diffraction pattern. Grain size was calculated from the line broadening of diffraction patterns. Broadening due to grain size follows a  $1/\cos\theta$  dependence, known as Scherrer equation [28], and can be written as

$$D = k \frac{\lambda}{\beta \cos \theta} \quad (2)$$

where  $D$  is the grain size,  $\beta$  is the full-width-half-maximum (FWHM) of the analysed peak,  $\lambda$  is X-ray wavelength,  $\theta$  is bragg diffraction angle of the analysed peak,  $k$  is a constant (crystal shape factor, 0.9). Bruker Diffrac EVA software [29] was used to fit individual peaks using analytic peak profile analysis to obtain FWHM. All obtained diffraction peaks were analysed individually and an average grain size was calculated.

The deposited surface morphology was characterised with TESCAN VEGA 4 scanning electron microscope (SEM) using secondary electrons. All images were taken at 20 kV accelerating voltage with 10 mm working distance.

#### 2.3.2. Rain erosion test

Rain erosion tests were performed using a bespoke whirl arm erosion rig at the University of Strathclyde (Fig. 2). The design involves a motorised rotating swing arm which holds the specimen in the designed holder [30]. The specimens were trimmed down to  $35 \times 25 \text{ mm}$  to fit the test rig specimen holder. Care was taken for the coated area to remain unaffected during the cutting process. For comparison, we also evaluated uncoated carbon-fibre reinforced polymer (CFRP) and glass-fibre reinforced polymer (GFRP) (information about GFRP can be found here [31]). Rain behaviour was simulated using water droplet needles, which are supplied with water using a pump. Table 3 lists the parameters selected for the erosion tests.

One cycle of 8 h was considered for each specimen and a total run of 24 h was performed during erosion tests. Between each cycle, erosion was calculated by assessing mass loss. Mass measurements were taken, using a BM-252 analytical scale with 0.01 mg resolution, before and after each testing cycle. Specimens dried in air for a minimum of 3 days before their mass was measured to ensure that the measurements were not affected by water absorption. One specimen in each condition were tested as previous studies using the same erosion rig showed good repeatability in experimental conditions [32].

### 2.4. Erosion modelling

Finite Element (FE) simulations were developed to investigate the effects of different nickel thickness and microstructure on coating erosion resistance and delamination from the substrate. The commercial software Abaqus [33] was used as FE solver leveraging its explicit integration capability to efficiently simulate dynamic damage and degradation mechanisms. To accurately model the fluid–structure interaction and the sample damage mechanics, the simulation implements Coupled Eulerian–Lagrangian (CEL) model, supplemented by the Johnson–Cook damage model and cohesive elements [33]. Fig. 3 shows the water erosion Finite element model highlighting different materials regions and mesh structure. The model, representative of a  $25 \times 25 \text{ mm}$  sample, comprises five different components (Fig. 3). The underlying 2.3 mm thick, CFRP composite substrate is topped by a variable

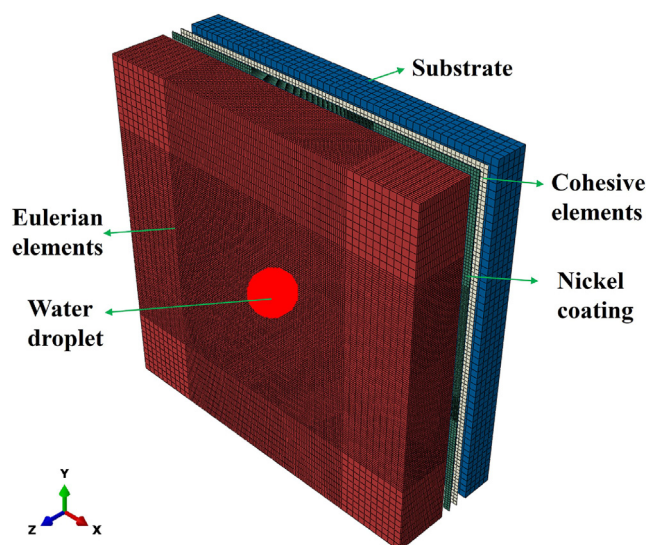


**Fig. 3.** Finite element model for water erosion. The water droplet was modelled as Eulerian elements while the interface between coating and substrate was modelled as cohesive elements. Delamination of the coating was estimated when scalar stiffness degradation value reached 1.

**Table 4**  
Properties of pure nickel used in simulation [35].

| Density<br>(kg/m <sup>3</sup> ) | Young's Modulus<br>(GPa) | Poisson's ratio |
|---------------------------------|--------------------------|-----------------|
| 8880                            | 207                      | 0.33            |

thickness nickel coating, directly facing the rainwater droplets impact. The nickel deposit is a typical “cauliflower” microstructure, however the model did not consider that and assumed a homogeneous microstructure without any textural input. A 20  $\mu\text{m}$  thick cohesive layer, is included at the composite substrate/nickel interface to simulate the coating delamination process. The impact of a droplet 2.7 mm in diameter is simulated by defining a 4 mm thick Eulerian region (Fig. 3) above the sample discretised by 3D linear Eulerian elements with reduced integration (EC3D8R). Water is modelled as nearly incompressible Newtonian fluid using the linear Us – Up Hugoniot form of the Mie-Grüneisen equation of state. It has a density of 1  $\text{gm}/\text{cm}^3$  and dynamic viscosity of 1  $\text{mPa s}$ . The Eulerian volume is divided into an initial region occupied by the droplet water using Abaqus volume fraction capability [33]. The remaining Eulerian volume is filled with air. The water impact is simulated by imposing an initial velocity of 103  $\text{m/s}$  to the droplet volume fraction and enforcing a friction-less contact between the Eulerian region and the Lagrangian sample. The assumption is compatible with having a water boundary layer considerably smaller than the Eulerian element size.

The sample substrate and the coating are meshed by 3D linear reduce-integrated Lagrangian element (C3D8R), whereas the coating/substrate interface employs COH3D8 cohesive elements implementing a traction–separation constitutive equation [33]. A regular structured mesh of 481224 elements in total, showing refined elements size of 0.05 mm around the droplet impact area is generated, for both Eulerian and coating Lagrangian areas (Fig. 3). Eulerian far-field elements had a 0.5 mm planar square section whereas a 0.05 mm seed was used throughout the whole region thickness. The nickel coating thickness was discretised by 10  $\mu\text{m}$  thick elements and tied to a cohesive region with 0.25 mm mesh seed. A course cubic mesh of 0.5 mm was applied to the composite substrate. The element size was selected as results of mesh sensitivity studies to obtain the best compromise between computational time and damage prediction accuracy. The sample was assumed to be fixed on its whole lower surface and the droplet impact transient dynamics was simulated for a time of 40  $\mu\text{s}$ . Tables 4 and 5 list the nickel and CFRP material properties. Table 6 lists the properties for cohesive layer used in the simulation. Initiation of damage is assumed when maximum nominal stress ratio reaches a value of one. We used fracture energy based damage evolution criterion with linear softening behaviour. Table 7 list the Johnson–Cook model parameters implemented in the simulation, respectively. A detailed description of the FE model and analysis parameters can be found in [34].

### 3. Results and discussion

#### 3.1. Characterisation of deposited nickel coatings

The morphology of brush-plated Nickel High Speed shows the typical globular structure [38] for all deposited thicknesses. Fig. 4 shows representative SEM images of the coating at different magnifications.

**Table 5**  
Properties of CFRP used in simulation.

| Density<br>(kg/m <sup>3</sup> ) | Young's Modulus<br>(GPa)                       | Poisson's ratio                                            |
|---------------------------------|------------------------------------------------|------------------------------------------------------------|
| 1500                            | $E_{11} = 79$<br>$E_{22} = 79$<br>$E_{33} = 8$ | $\nu_{11} = 0.03$<br>$\nu_{22} = 0.03$<br>$\nu_{33} = 0.4$ |

**Table 6**  
Properties of cohesive bond used in simulation. [36].

| $E/E_{nn}$<br>(GPa) | $G1/E_{ss}$<br>(GPa) | $G2/E_{tt}$<br>(GPa) | $\sigma_n$<br>(MPa) | $\sigma_s$<br>(MPa) | $\sigma_t$<br>(MPa) | Fracture energy<br>(mJ/mm <sup>2</sup> ) |
|---------------------|----------------------|----------------------|---------------------|---------------------|---------------------|------------------------------------------|
| 15                  | 15                   | 15                   | 0.5                 | 0.5                 | 0.5                 | 48.3                                     |

**Table 7**  
Johnson–Cook model parameters of pure nickel with different grain sizes [35,37]. Only yield strength (A) varied with grain size while other parameters are constant for all simulations with  $T_{ref}$  (K) = 293 and strain rate ( $m^{-1}$ ) = 0.002.

| Grain size (nm) | A (MPa) | B (MPa) | C       | n    | m    |
|-----------------|---------|---------|---------|------|------|
| 45              | 820     | 648     | 0.00006 | 0.33 | 1.44 |
| 56              | 823     | 648     | 0.00006 | 0.33 | 1.44 |
| 80              | 660     | 648     | 0.00006 | 0.33 | 1.44 |
| 140             | 405     | 648     | 0.00006 | 0.33 | 1.44 |

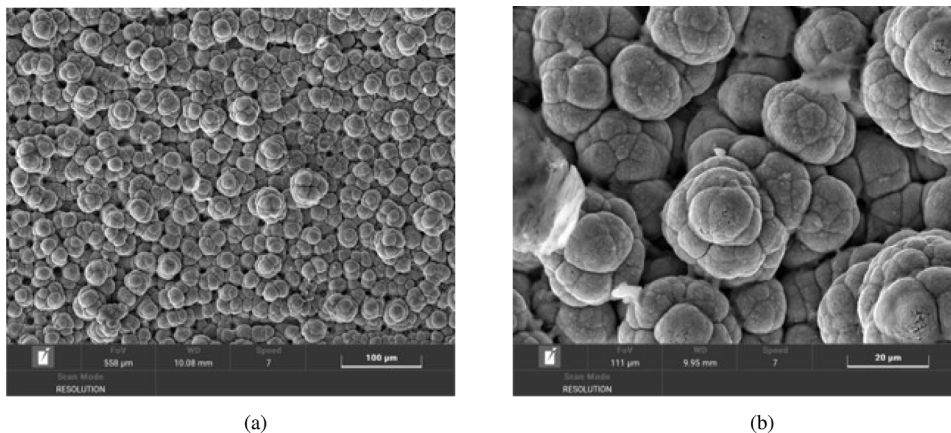


**Fig. 4.** Typical microstructure of the as-deposited nickel coating observed as SEM image with secondary detector. (b) displays an enlarged view of (a), revealing the magnified image of “cauliflower” structure.

Further, these specimens were characterised with XRD for bulk microstructural characterisation. The results show typical diffraction pattern of nickel without additional peaks suggesting absence of any other phases Fig. 5. The most intense peak in all conditions corresponds to (111). Compared with other peak intensities ((200) and (220)), it is evident that brush-plating has not caused any textural development. Further, average crystallite size was calculated for each condition and presented in Table 8. Similar crystallite sizes across different thicknesses confirm a nearly identical bulk microstructure.

### 3.2. Erosion behaviour of electrodeposited nickel at varying thickness

Fig. 6 shows progression of erosion for different deposited conditions after each 8 h of test cycle. The uncoated carbon fibre specimens did not show clear surface damage (fibres having de-bonded from the surrounding epoxy). 25 μm thick coated specimen

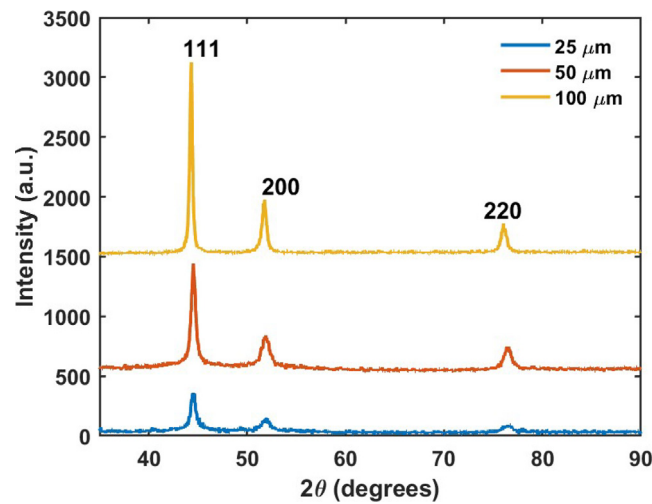


Fig. 5. X-ray peak profile data of the deposited coatings.

Table 8

Average crystallite size of the deposited coatings. Three maximum peak intensities were used to estimate the average crystallite size for all conditions.

| Coating thickness (μm) | Average crystallite size (nm) |
|------------------------|-------------------------------|
| 25                     | 139.4                         |
| 50                     | 140                           |
| 100                    | 140.2                         |

starts showing visible damages as loss of coating after second cycle of testing which deteriorates further with increase in time of tests. On contrary, 50 μm and 100 μm specimens do not show any visible damage as observed with 25 μm specimen.

Mass losses are plotted in Fig. 7 to quantify the damage of coatings. The uncoated carbon fibre specimen outperformed the glass fibre specimen with the former having 0.33 mg of cumulative erosion across 3 cycles and the latter having 1.18 mg (~3.6 times higher). The overall experimental results reveals that 100 μm coating performed the best among all coated conditions. The 25 μm coating shows comparable erosion resistance trend as of 50 or 100 μm coating for the first 8 h of cycle of testing. However, it was experiencing higher erosion in further cycles, observed as a sharp increase in mass loss (Fig. 6). Significant studies have been carried out to understand the mechanisms of erosion damage initiation and progression for coatings undergoing water droplet impact [39–42]. The initiation of damage is considered as a series of events that leads to mass loss. A typical erosion curve (denoted by mass loss vs exposure time) is represented by five stages [43,44] First is incubation stage where only surface roughness increases but no mass loss happens. This is followed by acceleration stage where mass loss starts, and micro-cracks start to generate. Towards end of this stage, cracks grow, and coating material removal starts in form of pitting, delamination or flaking. A constant erosion rate is then observed where the coating degrades progressively. This is followed by deceleration stage of erosion rate and finally terminal stage, where erosion rate is constant again (but lower than stage three) and the coating can be considered as failed to serve the purpose. Visually, the incubation stage shows minor pitting in the coating. At stage three, patches of the underlying epoxy are visible in random areas, but the coating remains partially intact. In further stages, coating gets completely removed and epoxy gets exposed. Among all the stages, incubation and constant erosion rate stage are most critical. The coating can be considered to have superior erosion resistance either by extending incubation stage or lowering the constant erosion rate by changing microstructural and/or mechanical properties. Since, erosion damage begins beyond a threshold impact velocity, a single droplet can initiate the damage. Thus, a single droplet model beyond that threshold velocity can simulate qualitatively erosion damage. The mass loss plot combined with photographs indicates beyond the first cycle, 25 μm coating reached the breakthrough phase. For 50 and 100 μm coating, the test cycles are at stage three showing a steady rate of mass loss, [43] (see Fig. 7).

Since we compare the erosion behaviour of composites (non-coated) and metallic coating with different densities, volumetric loss appears a more appropriate metric than mass loss. We calculated volume loss by following equation

$$\text{Volume loss} = \frac{\text{Mass loss in each incremental step of erosion test}}{\text{Density of coatings}} \quad (3)$$

Hence, Fig. 8(a) presents the volumetric loss during erosion tests, computed using a density of 1.2 g/cm<sup>3</sup> for epoxy resins of composites (since epoxy resin is being eroded in laminates) and 8.9 g/cm<sup>3</sup> for nickel coating. Non-coated carbon fibres show similar volumetric loss as 100 μm coated composites while glass fibres follow similar trend as 25 μm coating. Following this, erosion rate

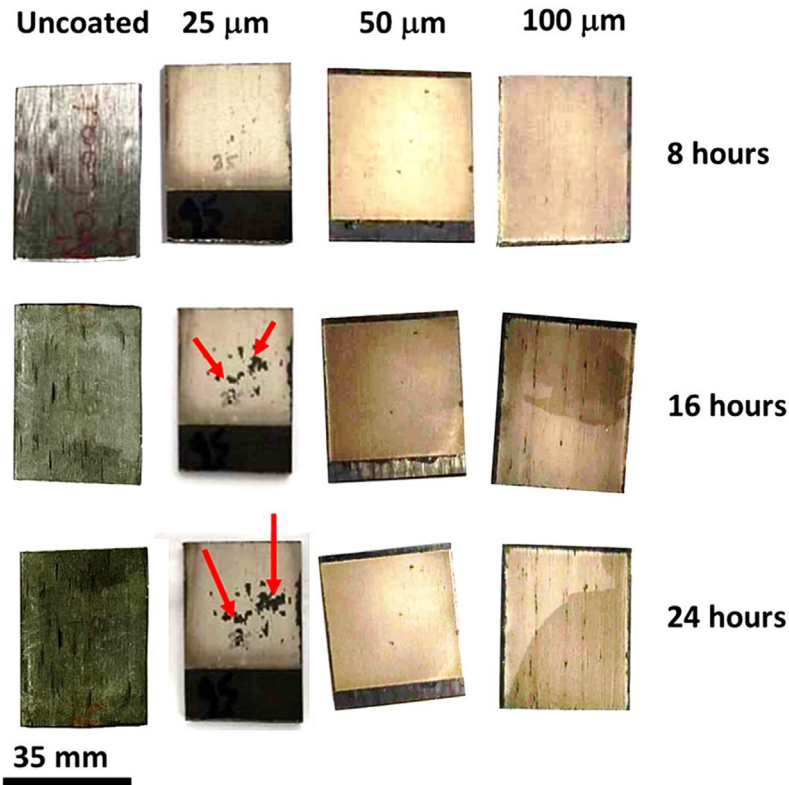


Fig. 6. Photograph of the uncoated CFRP, 25 μm, 50 μm and 100 μm coated specimens (from left to right) after 8 h, 16 h and 24 h of testing. Red arrows show loss of coating due to erosion.

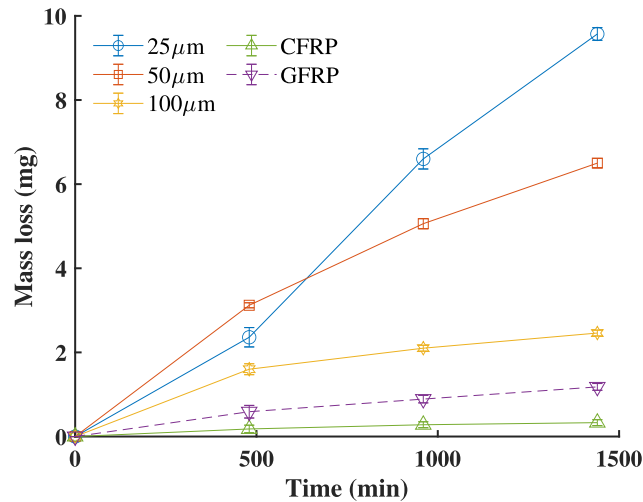


Fig. 7. Weight loss of coatings and uncoated composite specimens during water erosion tests.

was calculated as volumetric loss per incremental time in experiments as per the formulation below

$$\text{Erosion Rate at time}_{(i+1)} = \frac{\text{Volume loss at time}_{(i+1)} - \text{Volume loss at time}_{(i)}}{\text{erosion test at time}_{(i+1)} - \text{erosion test at time}_{(i)}} \quad (4)$$

The results show that, for all conditions (bare and coated CFRPs), incubation stages 2 and 3 results in a change in volumetric loss rate for 25 μm (see Fig. 8(b)). The 50 μm coating shows comparable volumetric loss to non-coated glass fibres, whereas 100 μm coating is almost identical to non-coated carbon fibres. For 50 and 100 μm coating, the extended erosion tests (including additional

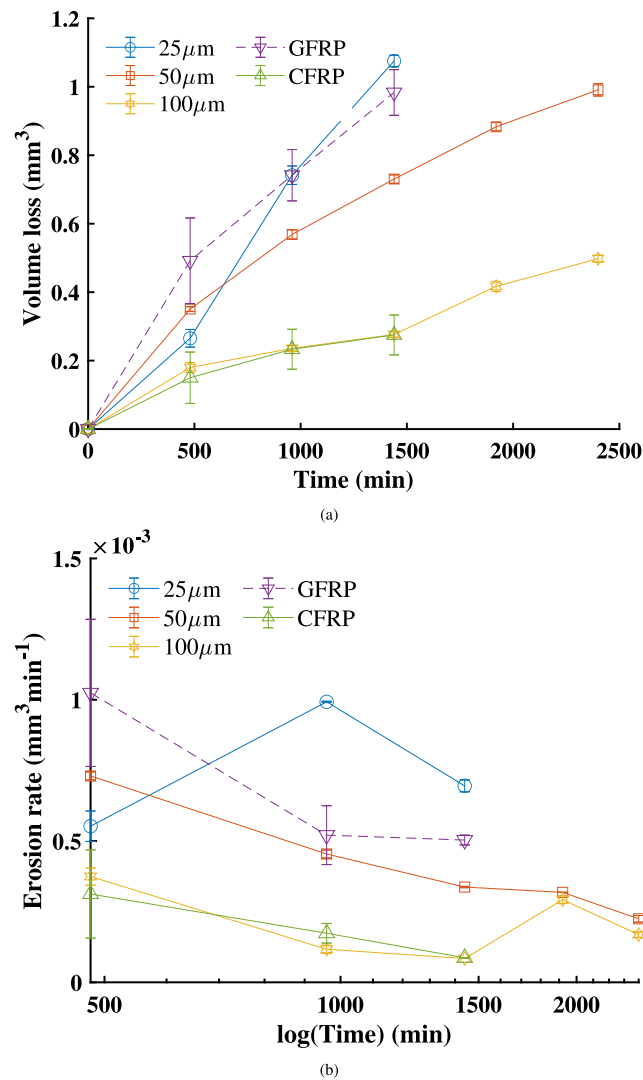


Fig. 8. (a) Volumetric loss of coatings and uncoated composite specimens during water erosion tests. (b) Erosion rate as observed for different coating thicknesses and bare GFRP and CFRP.

datapoints in Fig. 8 related to 32 and 40 h testing) show a steady state loss and no visible coating failure. The rate of mass loss was increased after 32 h erosion testing, which gave a higher erosion rate for 100 μm coating. These results indicate that 50 - 100 μm coating can absorb the impact energy from water droplets and protects the substrate. The constant erosion rate for 50 μm coating, comparable with glass fibres, demonstrate decohesion is not occurring due to impact. Bare CFRP shows less erosion rate than GFRPs due to high stiffness and tensile strength. However, with gel coat as protective layer, volume loss (or erosion rate) increases compared to bare CFRP/GFRPs (~ 2 times) [45]. In our study, we observe 25 μm coating deteriorates the erosion property of CFRPs. But with increase in coating thickness, the adverse effect gets diminished. As shown in previous researches [19,46], a nickel coating of 30 μm thickness applied to copper-cladded GFRPs exhibited nearly 20 times greater impact resistance compared to bare GFRPs, with approximately 80% of the deposited coating thickness remaining intact. No significant visible damage to either the coating or substrate was observed, which aligns with the findings of our study. The comparable erosion rate of bare CFRP and 100 μm thick coating suggests nickel coating is as strong as CFRPs. Based on these observations, we find that a coating thickness of at least 40 μm is necessary to withstand liquid droplet impact for a microstructure with 140 nm grain size.

Fig. 9 shows post eroded surface of different coating thicknesses. Comparing to the as-deposited surface (see Fig. 4), 25 μm coating shows the crystallites are no longer in “cauliflower” morphology and changed to globular or spherical shape. Prominent cracks have started to appear on the surface and coating loss exposed the composite underneath. A closer look reveals two distinct regions (Fig. 10): early signs of damage where part of metal coating was eroded and still signs of initial layers are visible. On contrary, there are areas where coating was completely removed exposing the bare composite and upon further erosion, the resin was actually eroding, similar to bare composite erosion. This also shows lack to adhesion of nickel to composite surface due to repeated impact of water

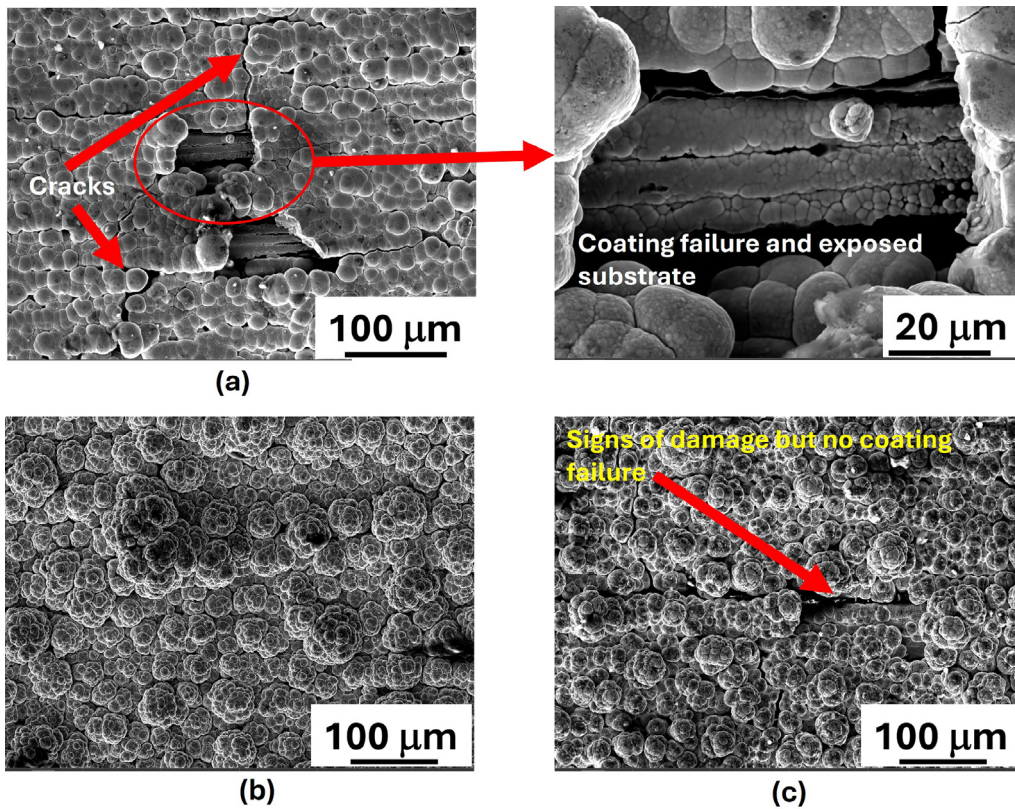


**Fig. 9.** Post-mortem analysis of eroded surface using scanning electron microscopy for (a) 25  $\mu\text{m}$  (b) 50  $\mu\text{m}$  and (c) 100  $\mu\text{m}$  coating thickness. For 25  $\mu\text{m}$  thick coating, the cauliflower morphology is changed to globular/spherical shape while 50 and 100  $\mu\text{m}$  thick coatings still retain the as-deposited morphology.

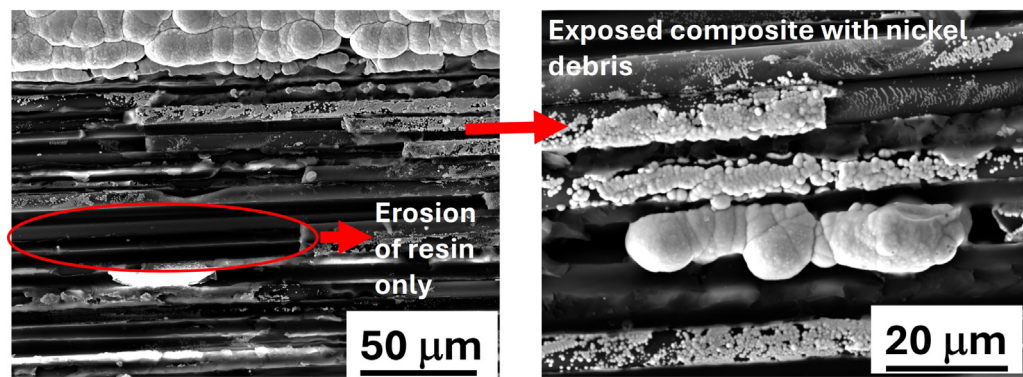


**Fig. 10.** Detailed view of 25  $\mu\text{m}$  thick coating showing different regions of damage.

droplets on the coating. On other hand, 50 and 100  $\mu\text{m}$  coatings show the structure is still comparable to cauliflower morphology. Though partial “crater” type appearances are visible but no signs of long cracks or exposed composite surface due to coating loss. This strengthens the hypothesis that below 50  $\mu\text{m}$  thickness, the coating quality is insufficient to droplet impact and decohesion starts from the interface leading to coating failure.

### 3.3. Modelling analysis

The finite element model was developed to assess the damage morphology as a function of the coating thickness and properties. The FE-based damage simulation procedure based on coating erosion damage and decohesion prediction was already validated against literature data for polymeric gel coat [36]. Moreover, Johnson–Cook damage mechanism already proved its effectiveness in

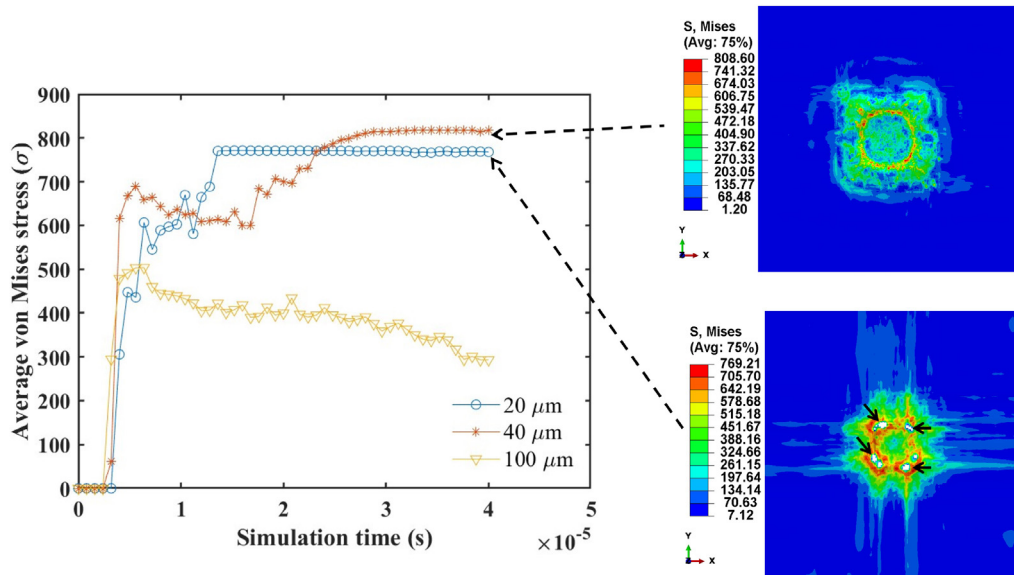


Fig. 11. Average von Mises stress for different coating thickness with 140 nm grain size. The data was averaged for the ten elements with maximum stress value in each simulation time. The solid arrows denotes failure of coating as seen by element deletion in simulation.

predicting ductile damage caused by water droplet erosion [47,48]. The surface damage obtained by the FE model was validated against sample visual inspection, proving good correlation. Fig. 11 presents the time evolution during the droplet impact of the von Mises stress, averaged among ten most stressed elements. Since the failure stress is dependent on element locations, the average value of stress was used to avoid bias. Within this range, the 20  $\mu\text{m}$  coatings exhibited subpar performance, indicating insufficient resilience. Conversely, notable observations emerged for the 40 and 100  $\mu\text{m}$  coatings: doubling the thickness (from 20 to 40  $\mu\text{m}$ ) did not significantly change the average von Mises stress in coating layer ( $\sim 780$ – $810$  MPa). But the coating failure did not happen (as seen from element removal in Fig. 11). Increasing the thickness further to 100  $\mu\text{m}$  shows almost 2 times decrease in stress value ( $\sim 400$  MPa). The results imply that 40  $\mu\text{m}$  coating is just enough to resist the impact from water droplets — similar observation from experiments. Increment in thickness reduces the stress significantly increasing the integrity of the coating.

Further, the simulations reveal the coating failure happens due to debonding between coating and substrate, see Fig. 12. Though the average von Mises stress in coating is comparable in 20 and 40  $\mu\text{m}$  coatings, the thinner nickel coating dissipates the droplet impact energy by debonding from the substrate and local surface erosion. Damage mechanism limits the coating strain energy and consequently the averaged von Mises stress. Since we have used a single droplet model, we captured qualitative behaviour of erosion damage from simulations. By combining the cohesive delaminated area from simulations and the erosion experimental observations, we can conclude multiple droplet erosion model, similar to experimental scenario, can produce a complete coating erosion. Since experiments were performed under multiple droplet impact, almost complete coating erosion was observed below 25  $\mu\text{m}$  coatings indicating clear insufficient tolerance to water droplet impact due to coating thickness.

In case of rain erosion, stress distribution in the coating layer, generated by the water droplet impact is the main cause of erosion damage initiation and evolution. Considering the ductile nature of the nickel coating, local plastic deformations, quantified by the equivalent plastic strain in the numerical damage simulations, and the consequent void coalescence are assumed to cause erosion damage. The presence of a rigid composite substrate, with no plastic capability, affects the stress distribution and plastic energy absorbed by the tens of  $\mu\text{m}$  deep coating. In fact, the coating/substrate interface exerting a stiffening constraint on the nickel layer reduces its permanent deformation capabilities, concentrating plasticity in specific zones (Fig. 11) and limiting the amount of stored plastic energy. This increases the interface normal and shear stresses, resulting in large interface decohesion (Fig. 12(a)). Thicker layers, being less constrained by the substrate, have the possibility of free plastic deformation, showing smaller von Mises stress and equivalent plastic strain distributions and consequent limited erosion intra-layer and interface damage (Fig. 11).

Shear stresses are known to be driving factors of the water droplet erosion mechanism [11] in particular the one generating by the lateral jetting. While lateral jetting and water shear layer friction are correctly simulated by the numerical model, the Johnson–Cook damage model, based on ductility fracture by void coalescences, considers the equivalent plastic strain as damage state variable [33]. Therefore, the effect of the total deviatoric deformation and not only of specific shear stress or strain components are included into the damage model, representing the standard for ductile material damage [33]. For the sake of completeness, Fig. 13 show the  $\tau_{12}$  stress distribution on the specimen surface under the droplet impact area at  $8.0 \cdot 10^{-6}$  s from the impact onset for (a) 20  $\mu\text{m}$ , (b) 40  $\mu\text{m}$  and (c) 100  $\mu\text{m}$  coating with 140 nm grain size. In plane shear stresses distributions reaching their peaks along  $\pm 45^\circ$  directions as expected from the problem symmetry, show a repetitive pattern highlighting the circular shock waves generated by the droplet impact and lateral jetting ( Fig. 13)

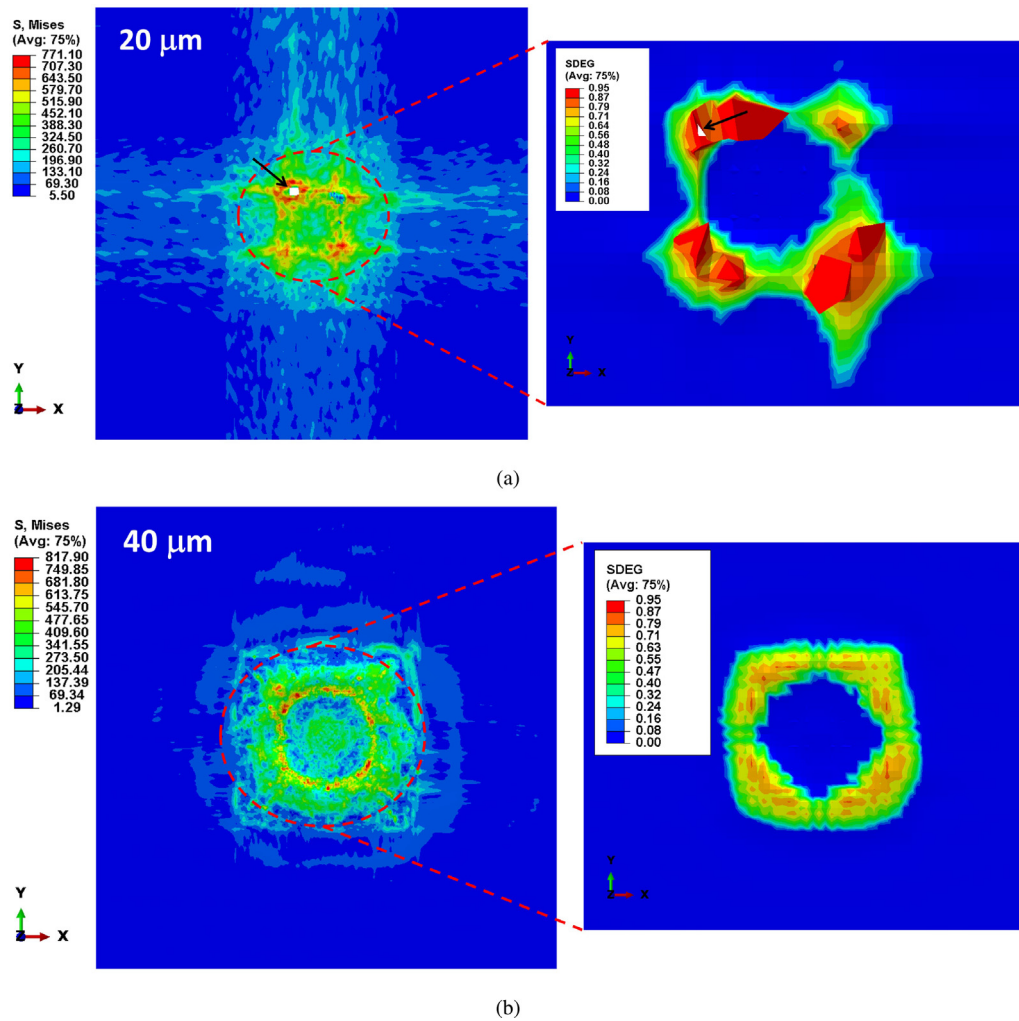


**Fig. 12.** von Mises stress at coating layer (left) and debonding criterion (right) for (a) 20 μm coating and (b) 40 μm coating at peak values of average von Mises stress as obtained in Fig. 11. The black solid lines indicate the initiation of failure.

To comprehend the microstructural fluctuations affecting coating thickness, we varied the Johnson–Cook parameters to represent different grain sizes (45 nm, 55 nm, 80 nm and 140 nm) keeping the coating thickness constant (20, 40 and 100 μm). This variation was transferred to the model by changing the yield stress with grain size as shown by Table 7. A grain size reduction results in a smaller coating plastic zone although maximum equivalent plastic strain magnitude is obtained for 80 nm large grain, see Fig. 14. The strain peak is thought to be caused by a mesh-driven numerical issue owing to the lack of symmetry and its localised nature.

The resistance to water impact comes primarily from the strength of the coating material. For Ti/TiN multilayer coating [49], it was shown a minimum coatings of about 50 μm performed better for rain water erosion and avoided poor adhesion between coating and substrate.

The computational model predicted the critical combination of thickness and grain size that can maintain the coating integrity, see Fig. 15. As grain size variation comes from experimental condition to deposit the coating (current density is the primary variable for this), thickness cannot be considered as the only parameter influencing the impact resistance. Therefore, using our model, we can design the deposition conditions (e.g. current density) of a well-performing coating. Fig. 15 shows the maximum von Mises stress developed in coatings as function of its thickness and grain size. For 20 μm coatings, even with reduction in grain size, the coating still fails indicating poor resilience to droplet impact. All the grain sizes show impact resistance for coating thicker than 40 μm thick. Reducing the grain size enhances the maximum stress (or reduction in plastically deformed zone) that the coating can withstand. Hence, a 40 μm coating with 45 nm grain size is a promising solution. However, the deposition conditions can restrict in having such small grain size. Therefore, minimum coating condition could be 40 μm thick coating with grain size of 80–140 nm.

Prediction of erosion behaviour of metallic coatings is more complex than general tribological behaviour due to factors like bond strength, residual stresses, defects and thickness. Coating defects and insufficient thickness are primary causes of failure in coated steam turbine vanes and blades [50]. Brush-plating or electrodeposition methods may show different microstructure than

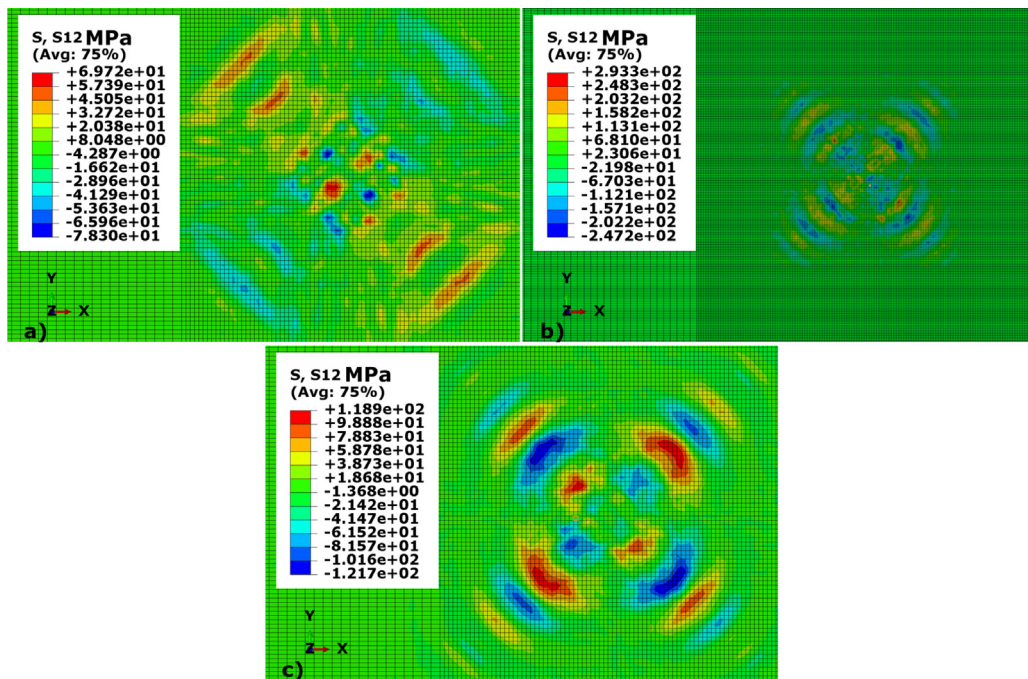


Fig. 13. In plane shear stress ( $\tau_{12}$ ) distribution on the droplet impact area after  $8.0 \cdot 10^{-6}$  s from the water/sample contact for (a) 20  $\mu\text{m}$ , (b) 40  $\mu\text{m}$  and (c) 100  $\mu\text{m}$  coating with 140 nm grain size.

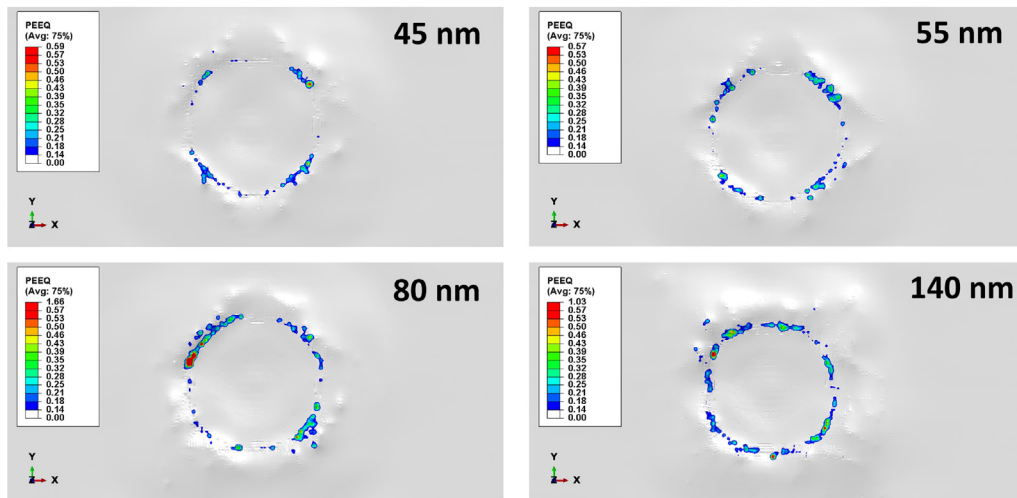


Fig. 14. Plastic strain distribution in the area of impact for 40  $\mu\text{m}$  thick coating. Lowering the grain size decreases the area of deformed zone.

conventional cast and thermomechanically treated conditions. The microstructure in this work appears as typical “cauliflower” microstructure which can be considered as a compact structure. With increase in current, the diffusion-controlled growth responsible for “cauliflower” microstructure can shift towards activation-controlled growth and increased hydrogen evolution creating pores [51]. As we have optimised the deposition conditions first, these porosities were not observed in the final conditions. However, porosity is unavoidable in any processing condition and can be considered as stochastic variable impacting the optimisation considered in this study. Increased porosity can promote more random damage nucleation points, while these additional stress concentration regions help to reduce maximum stress in the coating. Since crack initiation is accelerated with stress concentration, porous coatings tend to show poor performance than their less porous counterpart in water droplet impact behaviour.

On other hand, common practice to reduce erosion is increasing hardness and/or thickness of coating. Hardness improvements can be achieved through crystallite size reduction or solid solution hardening. However, a critical thickness is necessary for coating integrity. For example, sand erosion rate decreases by a factor 18 when diamond like carbon coating (DLC) thickness increases from

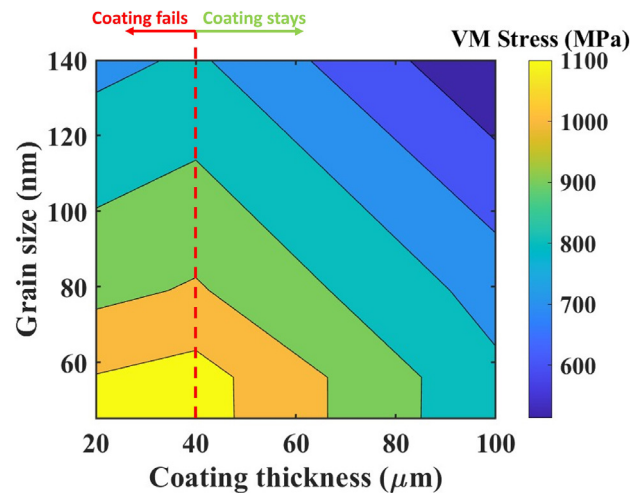


Fig. 15. Optimisation of coating thickness and grain size based on maximum stress experienced in simulation elements. The colorbar represents maximum von Mises stress in MPa.

3  $\mu\text{m}$  to 16  $\mu\text{m}$  with minimal improvement further to 50  $\mu\text{m}$  thickness. Beyond 16  $\mu\text{m}$ , erosion damages were observed without any cracking or coating failure [52]. Other studies also suggest that crack initiation is mainly related to the thickness and hardness of the coating [53–57]. The increased thickness improves the fracture toughness, reducing the formation of cracks [58]. In our experimental results, 25  $\mu\text{m}$  coatings developed cracks exposing substrate with debris of coating left, similar to sand erosion tests [52]. On further increase in thickness of coating, damages are observed but not led to cracking and coating failure. From modelling, even we have increased the hardness of coating through reduction in crystallite size, it was found to be insufficient to withstand erosion, emphasising the dominant effect of coating thickness over hardness due to fracture toughness.

#### 4. Conclusion

This study evaluated the performance of brush-plated pure nickel coatings on CFRPs against water droplet erosion. Between different thicknesses deposited, we obtained nanocrystalline size of grains ( $\sim 140$  nm) indicating microstructural invariability. Nevertheless, when absorbing impact energy from water droplets, a coating with a thickness of 25  $\mu\text{m}$  proves insufficient in providing adequate protection to the substrate. The experiments and modelling both confirmed that a functional reliable coating thickness typically ranges between 40 to 100  $\mu\text{m}$ . Exploring the microstructural and physical variables, we suggest a feasible design space for coatings. This further validates the successful adhesion achieved between carbon fibres and metallic coatings. Results indicate metallic coatings as a promising potential solution to protect composite panels from water droplet erosion as well as repair maintenance, similar conditions observed for wind turbine blades and aeronautic structures.

#### CRediT authorship contribution statement

**Nithin Chandra Gaddavalasa:** Software, Investigation. **Arijit Lodh:** Writing – original draft, Validation, Methodology, Formal analysis. **Andrea Cini:** Writing – review & editing, Supervision, Software. **Vinodhen Saaran:** Investigation. **Ali Mehmanparast:** Writing – review & editing, Methodology. **Andrew Starr:** Project administration, Funding acquisition. **Gustavo M. Castelluccio:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrew Starr reports financial support was provided by Henry Royce Institute. One of the Co-authors (Prof A Mehmanparast) is Subject Editor for Energy Engineering. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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## **Designing nickel coatings for water erosion performance: optimisation of grain size and thickness**

**Gaddavalasa, Nithin Chandra; Lodh, Arijit; Cini, Andrea; Saaran, Vinodhen; Mehmanparast, Ali ...**

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