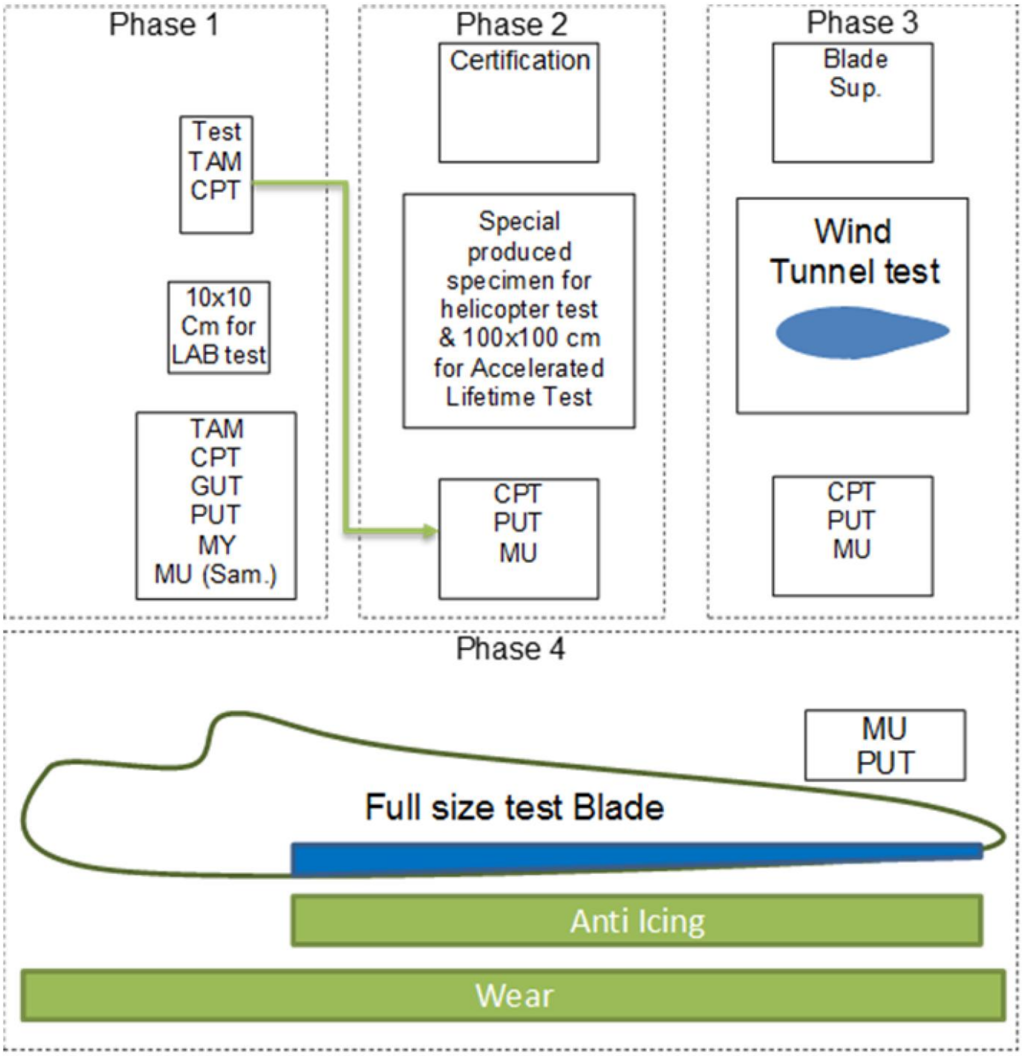


**FIGURE** 1: Scheme of Hydrobond project

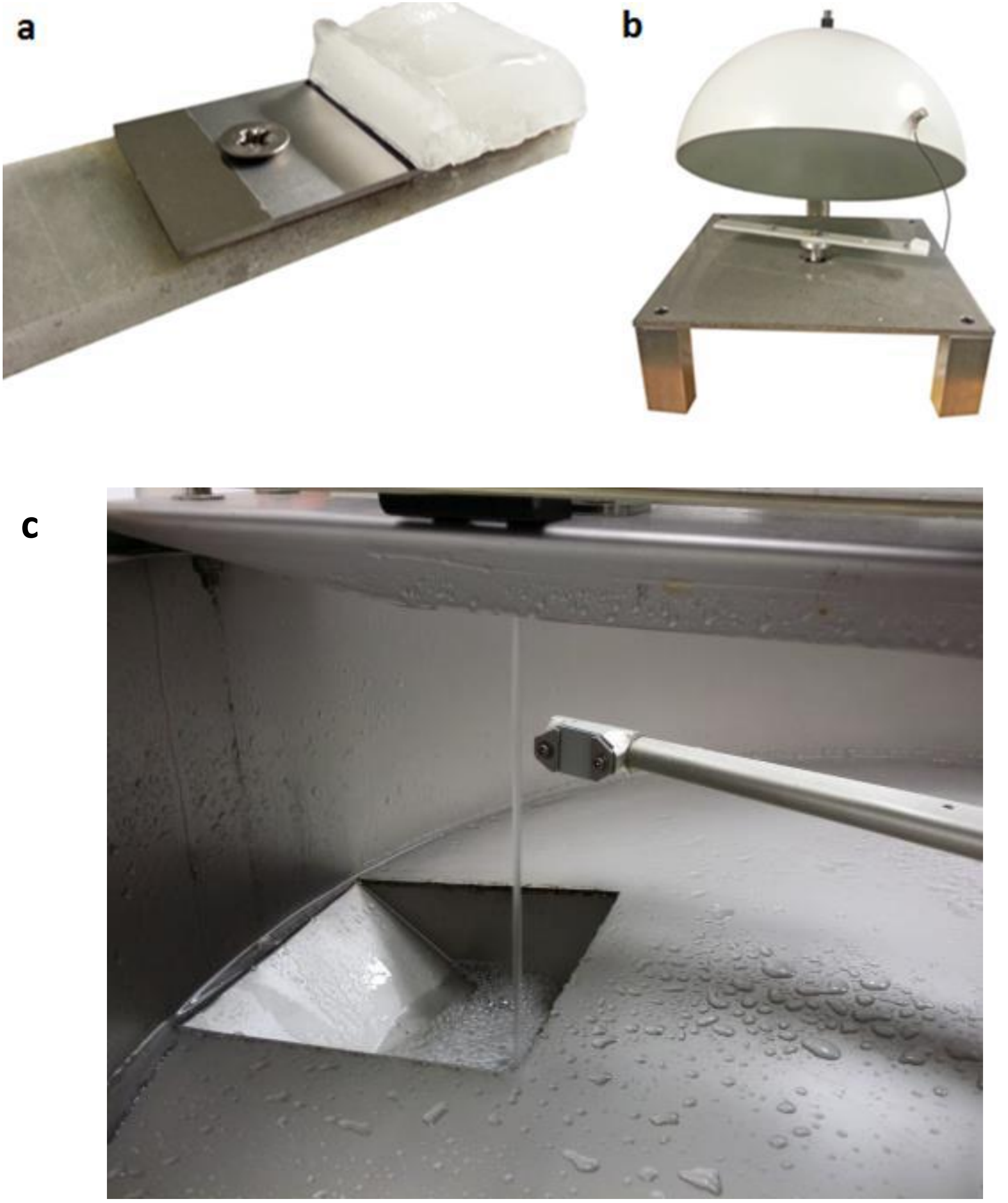


**FIGURE 2**: (a) Accreted ice on the sample; (b) centrifugal ice adhesion test equipment and (c) water jet erosion test

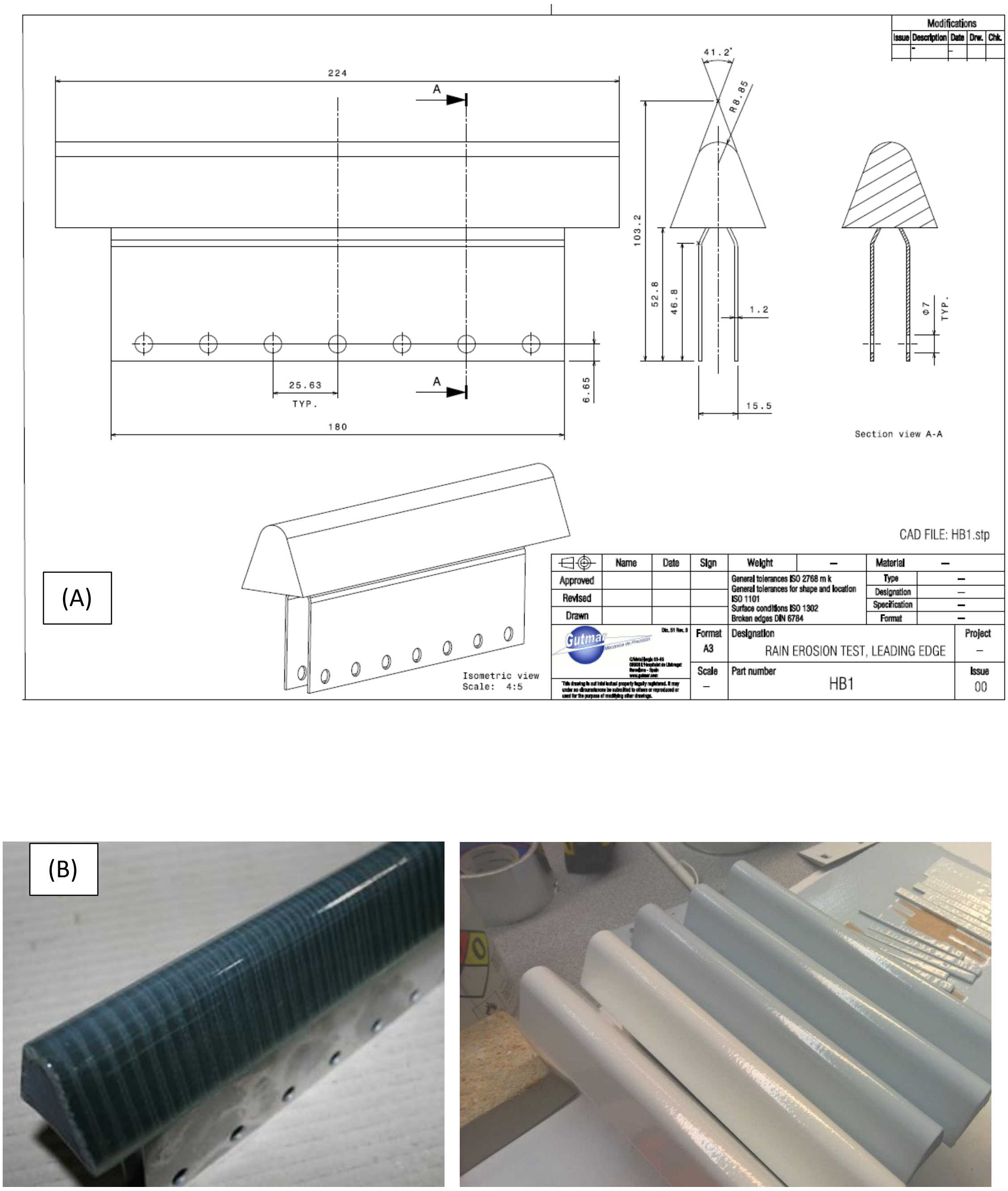


**FIGURE 3**: *Scheme of rain erosion (RE) samples (A); Image of RE samples without coating and coated*

**FIGURE 4:** Wind blades placed in Bremerhaven (Denmark) to validate the Hydrobond process.

**FIGURE 5:** Wind blades painted with HBH070, Hydrobond solution

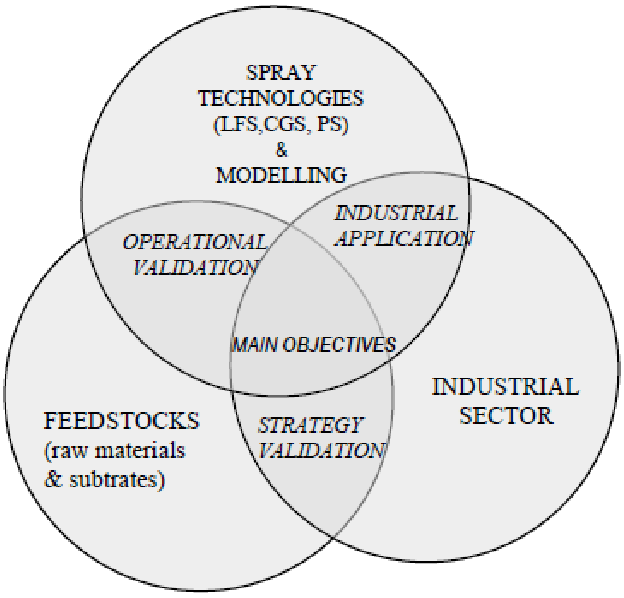


**FIGURE 6**: Strategy of Hydrobond project

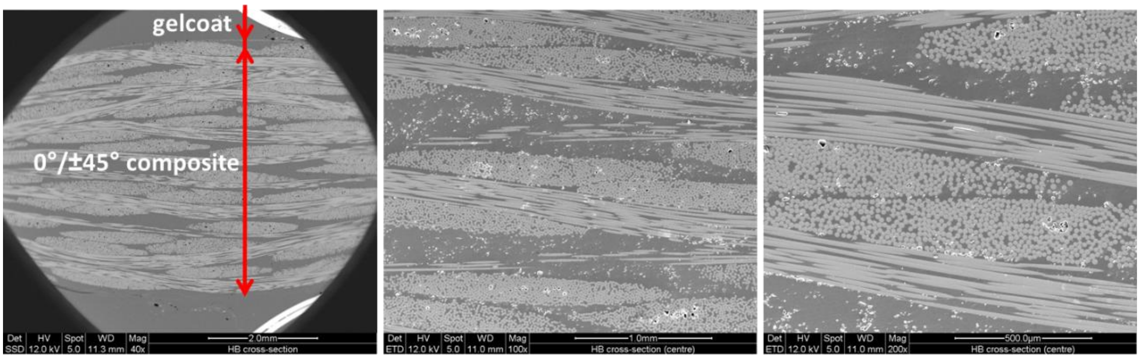


**FIGURE 7**: Microstructure of composite substrate

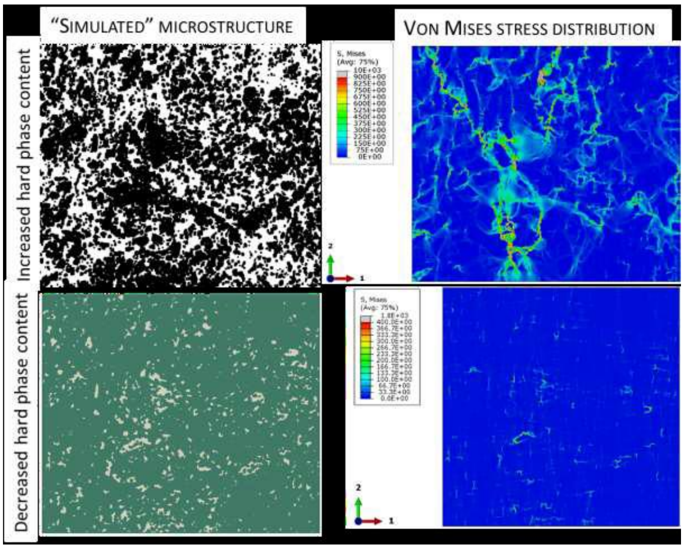


**FIGURE 8**: Modelling at the microscale level of the thermomechanical properties of the blade/coating system

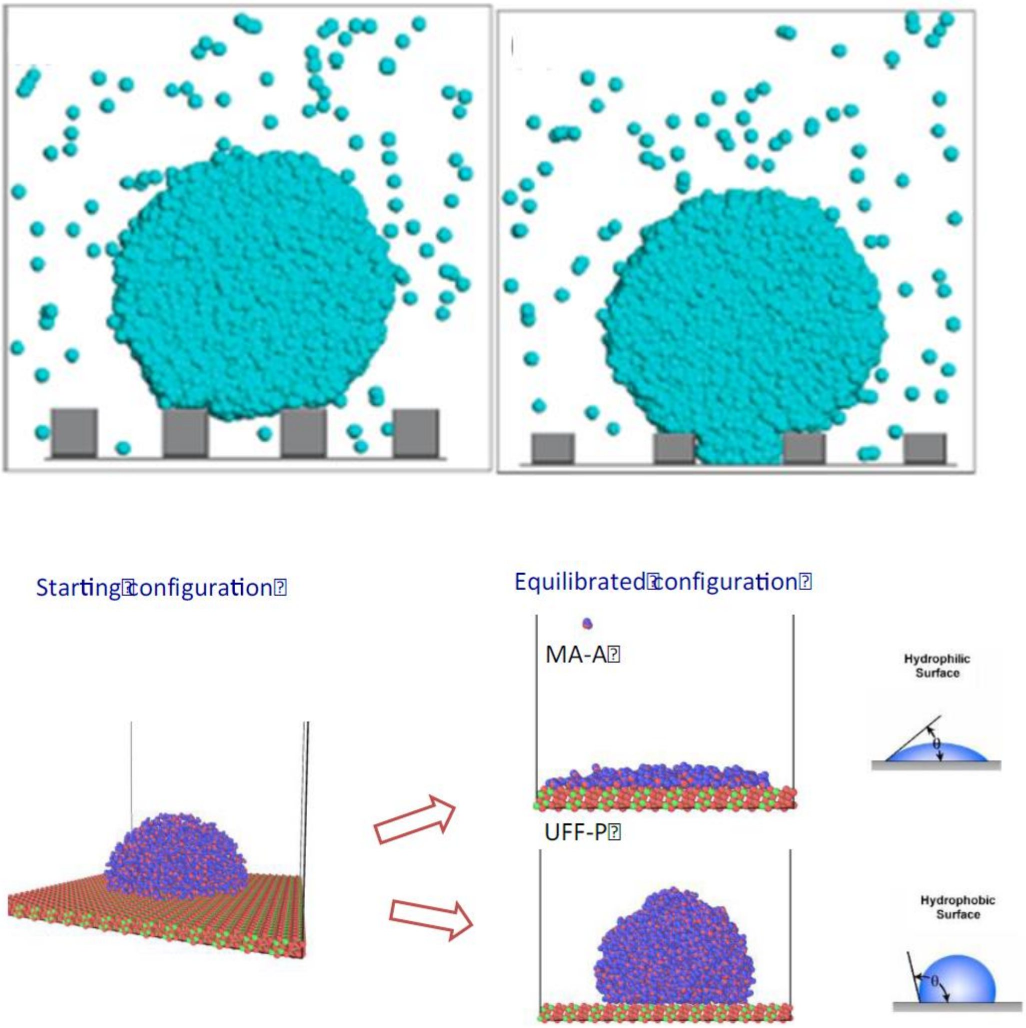


**Figure 9**: approach to increase the hydrophobicity is to reduce the surface density without increasing the surface porosity to the water molecules

**FIGURE 10**: Jet erosion test equipment

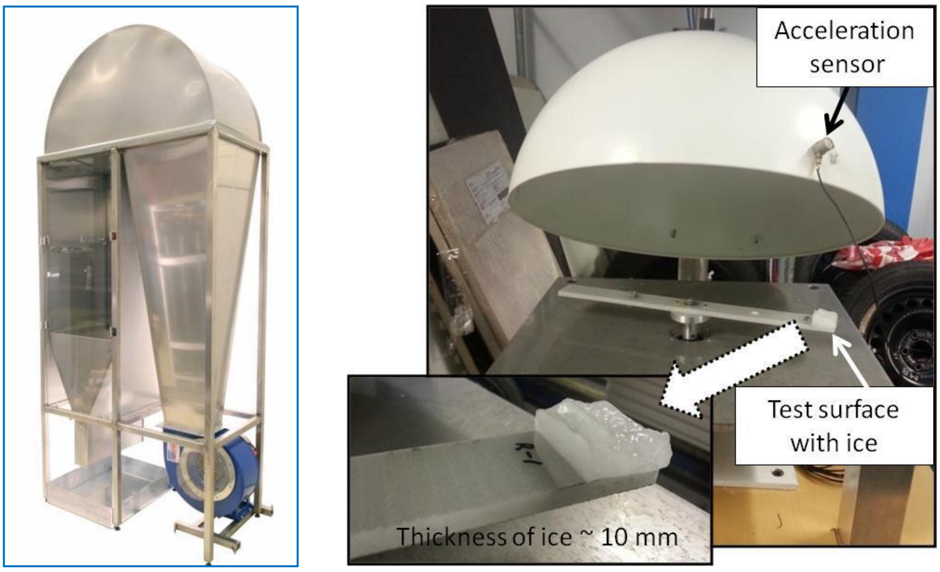


**FIGURE 11**: Icing wind tunnel at TUT and accreted ice on the sample and centrifugal ice adhesion test equipment

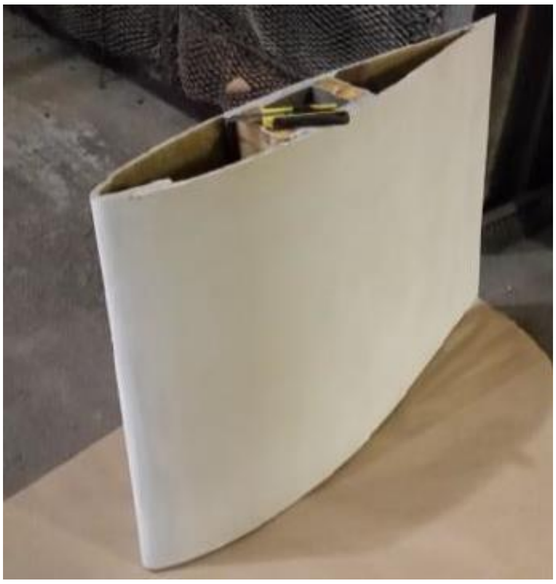


**FIGURE 12**: Part of a LM17.0 blade

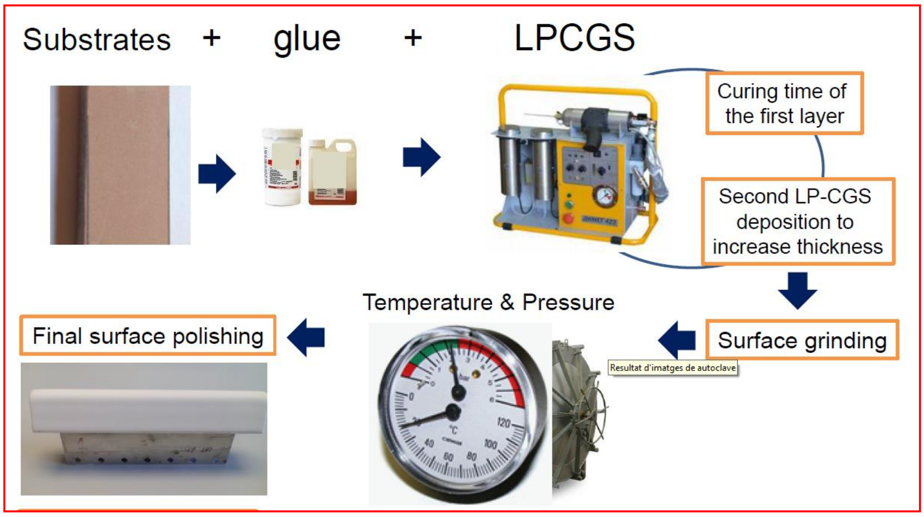
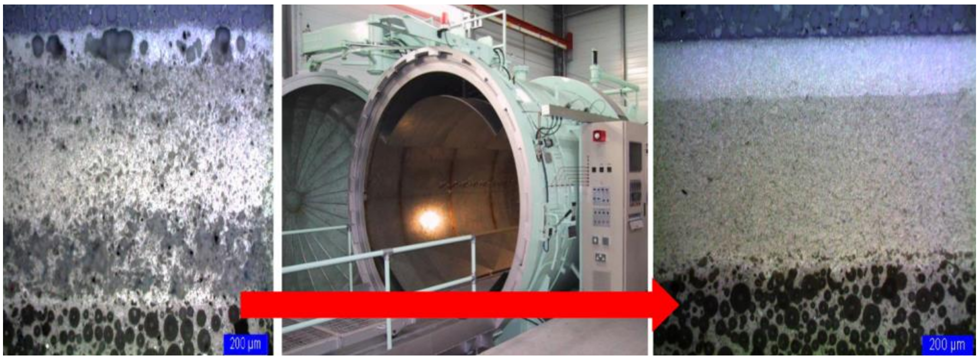


**FIGURE 13**: scheme of the global process



*Before* *AUTOCLAVE* *After P/T treatment*

**FIGURE 14:** Effect of the thermomechanical post-treatment on the coating microstructure (cross-section, optical microscopy, before and after P/T Treatment)

**FIGURE 15**: Others applications

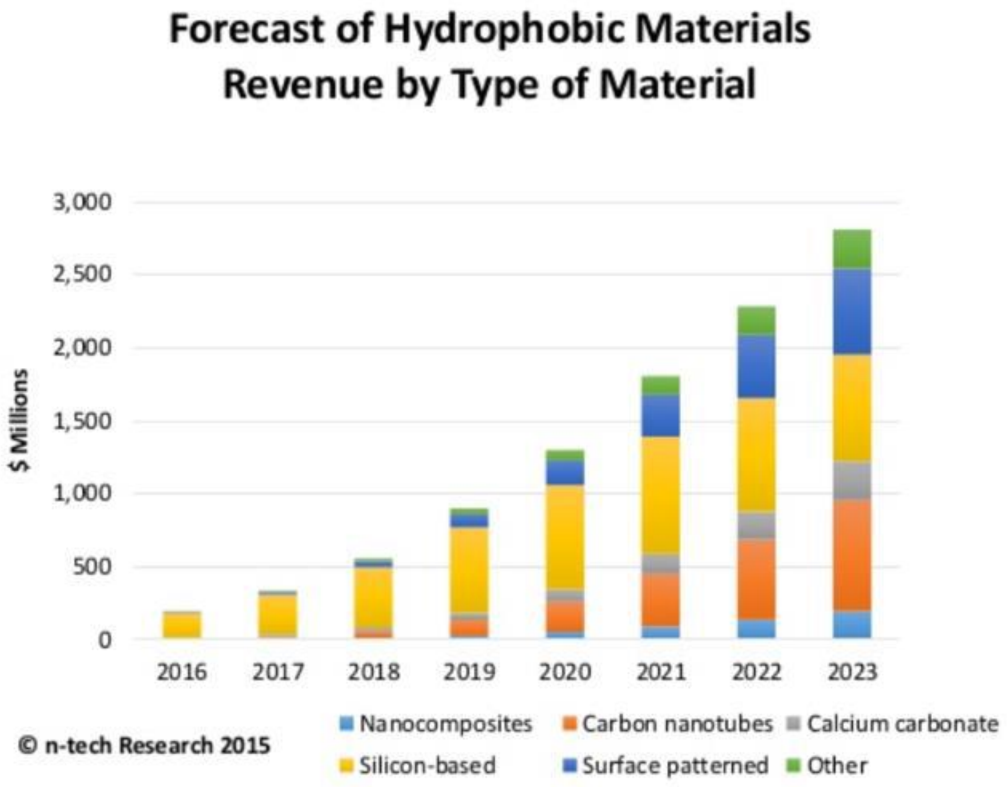


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**FIGURE 17**: Publicity of International workshop

**FIGURE 18:** Session in the International workshop

**Potential of icephobic coatings in wind turbine applications**

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**FIGURE 19:** Participation in Winterwind conference (6-8 February, 2017, Skellefteå, Sweden)

## HYDROBOND in IWAIS 2015

Heli Koivuluoto and Christian Stenroos from TUT participated in 16th International Workshop on Atmospheric Icing of Structures (IWAIS 2015) which was held in Uppsala (Sweden) 28 June – 3 July, 2015. Christian Stenroos presented the Hydrobond project in his presentation "Research on icing behavior and ice adhesion testing of icephobic surfaces". IWAIS conferences bring together leading researchers and industry representatives to facilitate exchange and interaction in view of finding practical and economical solutions to the disruptive effects of atmospheric icing. More information about the IWAIS2015: http://iwais.org/

# Research on icing behavior and ice adhesion testing of icephobic surfaces

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***Abstract*: Surface engineering shows potential to provide sustainable approach to icing problems. Currently several passive anti-ice mechanisms adoptable to coatings are known but further research is required to proceed for practical applications. Icing wind tunnel and centrifugal ice adhesion test equipment enable the evaluation and development of anti-ice and icephobic coatings for e.g., wind turbine applications but also other growing players in arctic environment e.g. oil, extractive and logistic industries. This research is focused on the evaluation of icing properties of various surfaces.**

***Keywords: ice adhesion, icing wind tunnel, ice accretion, coatings, surface properties***

### LEGEND AND ABBREVIATIONS

| | |
|---|---|
| *CA* | *Contact angle* |
| *F* | *Fluorine* |
| *FEP* | *Fluorinated ethylene propylene* |
| *IA* | *Ice adhesion* |
| *LWC* | *Liquid Water Content* |
| *PTFE* | *Polytetrafluoroethylene* |
| *PU* | *Polyurethane* |
| *VMD* | *Volume median diameter* |

### INTRODUCTION

On-going climate change, opening of new logistic routes, energy and mineral resources as well as increasing tourism feed the growing activity in cold climate regions. One of the major challenges for operations in these areas is ice and snow accretion. Icing reduces safety, operational tempo, productivity and reliability of logistics, industry and infrastructure. Figure 1 shows examples of an ice accretion on the problematic parts such as on wind turbine blade leading edge and on vessel.

**Figure 1**: Ice accretion a) on wind turbine blade leading edge [1] and b) on vessel [2].

Surface engineering shows potential to sustainable approach to icing problems. Passive anti-ice coatings can hinder ice formation and icephobic surfaces reduce the adhesion of accreted ice. Current commercial coatings with icephobic characteristics rely on hydrophobicity, releasing of lubricant or melting point depressants and ablation. Currently, research is additionally carried out on icephobic potential of superhydrophobic surfaces [3], phase change materials [4], slippery liquid infused surfaces [5], anti-freeze proteins [6] and surface morphology [3,7]. All these anti-ice mechanisms show promising results in reducing ice accretion and adhesion. Nevertheless, so far these are functional only in specific icing conditions for a limited amount of time. However, the wear resistance of these coatings is poor and thus, the current coatings are practical only in limited applications or the icephobic effect is insufficiently significant [8]. Ideal icephobic surface should have also anti-ice characteristics. It should work in three different stages of ice formation. Ideal icephobic surface should 1) minimize accumulation of water on the surface by reducing interactions of the surface and incoming water, 2) inhibit heterogeneous ice nucleation and 3) weaken the adhesion of ice on the surface [9].

As an example, there are three main icing mechanisms for wind turbine applications: 1) in-cloud icing, 2) precipitation icing (wet snow, freezing rain) and 3) frost formation [10]. The first two mechanisms include supercooled liquid water and the third one condensing water vapor. In-cloud icing is the most detrimental icing mechanism for wind turbines [11]. It occurs when supercooled water droplets, contained in cloud or fog, hit a surface below 0 °C and freeze upon impact. In-cloud icing can be divided in two sub-mechanisms based on the macrostructure of resulting ice: rime (soft and hard) icing and glaze icing. In rime icing, water droplets freeze immediately upon impact contact with the surface and form porous ice with white appearance [12]. Soft rime has a feathery appearance, it is formed at cold temperatures, from small droplets, low liquid water content (LWC) and its adhesion is low. Hard rime has more icy appearance but it has still high porosity. Hard rime has higher adhesion and it is formed after slower freezing which, in turn, is due to larger droplets, higher liquid water content, or higher temperature. On the other hand, in glaze icing, part of the water droplets freeze upon impact and the remainder run along the surface before freezing and form smooth and non-porous clear ice.

In order to develop anti-ice or icephobic coatings, test equipment was designed and constructed. Several icing tests have been introduced in literature [13-15]. However, often these tests either include heavy wind tunnels used by aerospace and automotive industry or the tests are extremely simplified and far from practical conditions. Even more, icing tests are not standardized. To make affordable and compact but truthful test facilities for evaluation of icing, it was decided that a small scale icing wind tunnel and an ice adhesion test apparatus be constructed. Both of these items are placed in a climatic room to guarantee constant atmospheric conditions throughout testing.

**FIGURE 20**: participation in International Workshop on Atmospheric Icing Structures (28June-3July, Uppsala, Sweden, 2015)

TABLE I: Characterization results of  final candidates to INDUSTRALIZATION stage (WP8)

| Recipes | | | | Coatings | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample name | Powder provider/Technology | | Composition | Contact Angle (>90o) | | | | | | Ice-adhesion (<80kPa) | | | | Adhesion | | Taber test | UV treatment: IR spectral changes x = change 0 = no change | UV treatment x=color changes o=no changes | jet erosion (>2h) | Sand erosion (>BM), Carboline, 1.52 | Thickness (µm) |
| | | | | Before UV | | | | After UV | | Before UV | | After UV | | Pull-off adhesion (>4MPa) | Cross Cut | <20 microns | | | | | |
| | | | | Static CA (as sprayed) | Static CA (treated surf) | Dynamic CA | Hysteresis (<30) | Static CA (as sprayed) | Static CA (treated surf) | as sprayed | treated surf | as sprayed | treated surf | | | | | | | | |
| HBP059 | MY | CGS | CeO2 + 25% PVDF | 134 | 82 | 152/20 | | 144 | 117 | 349 | 247 | 274 | 170 | 3 | | 6 | 0/x | 0/x | 1 | 0,48 | 800 |
| HBP064 | MY | CGS | CeO2 + 15% PVDF | 139 | 92 | 141/20 | | 142 | 116 | 370 | 116 | 345 | 148 | 3 | | 14 | 0/x | 0/x | 0,5 | 2,01 | 300 |
| HBP065 | MY | CGS | ZrO2 + 25% PVDF | 134 | 95 | 140/110 | 30 | 140 | 116 | 230* | 81** | 224* | 75** | 6 | | 5 | 0/x | 0 | 6,5 | 0,68 | 520 |
| HBP067 | MY | CGS | ZrO2 + 35% PVDF | 135 | 89 | 149/115 | 34 | 144 | 118 | 360* | 81** | 346* | 110** | 3 | | 17 | 0/x | 0 | 0,5 | 0,36 | 450 |

**TABLE II:** tests prior the RE test:

| Test method | Standard | Acceptance value | # of replicates |
|---|---|---|---|
| Pull-off test | ISO 4624 | >5MPa | 3 |
| Repairability (pull-off test after recoat) | ISO 4624 | >5MPa | 3 |
| Ice-adhesion |  | <80KPa | 3 |
| Thickness reduction[1] |  | >30% | 1 |

[1] Only applicable for CGS samples