O4.4-010

Recent developments in advanced materials tailored for enhancing the longevity and sustainability of hydroacoustic stations

Mounia Ticherfatine

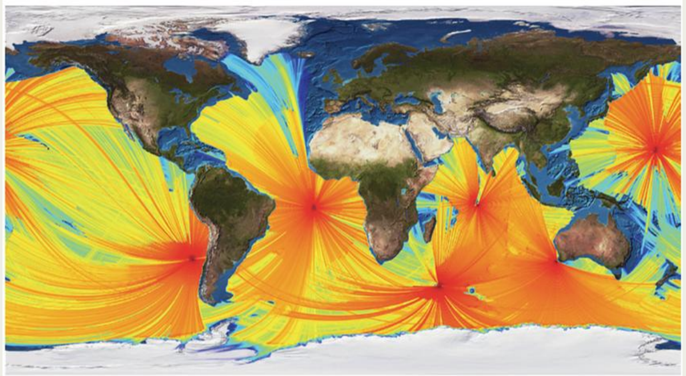
National School of Advanced Technologies, Algiers, Algeria

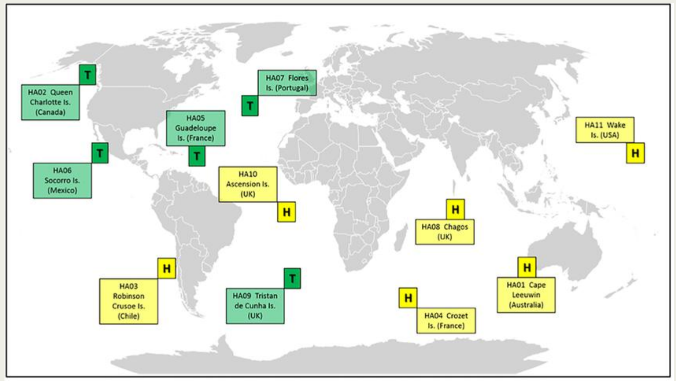
09 September 2025

Recent developments in advanced materials tailored for enhancing the longevity and sustainability of hydroacoustic stations

Mounia Ticherfatine

Introduction





The hydroacoustic stations of the CTBTO operate under some of the most extreme and challenging conditions on the planet. These stations are located in remote, deep-sea environments where they endure immense pressures, frigid temperatures, and corrosive saltwater.

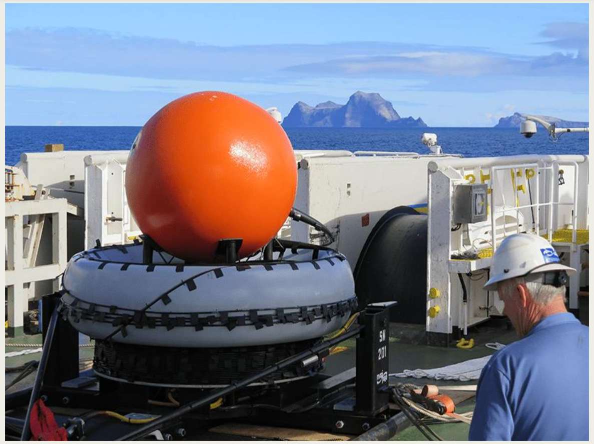
ENSTA

Mounia Ticherfatine

Importance of sustainmentt activities

Sustainment actions are crucial for preserving the operability of the CTBTO's hydroacoustic stations, which play a vital role in global nuclear test monitoring. ***Regular maintenance, timely repairs***, and ***technological upgrades*** ensure that these stations continue to function effectively, providing accurate and reliable data. By sustaining these stations, the CTBTO can maintain the integrity of its global monitoring system, ensuring continued compliance with the Comprehensive Nuclear-Test-Ban Treaty and contributing to international security.

Sustainment activities are conducted in relation to the on-land outside plant equipment (e.g. cables, joints, splice pit, cathode, beach anchors, split pipes, conduits, etc.) and the underwater system (e.g. cables, joints, cathode, split pipes, stabilisation, etc.).



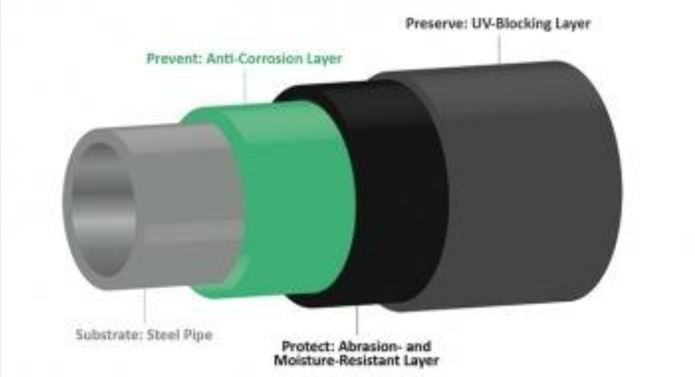
ENSTA

Mounia Ticherfatine

O4.4-010

Tackling Corrosion: The Primary Challenge for Hydroacoustic Stations

Corrosion remains the most challenging condition faced by the hydroacoustic stations. These critical monitoring installations, submerged in the unforgiving marine environment, are constantly exposed to corrosive elements, including saltwater, fluctuating temperatures, and intense pressures. The accelerated degradation caused by corrosion poses a severe threat to the structural integrity and operational reliability of the stations. Traditional materials and protective measures are proving insufficient in this hostile environment, making the development and implementation of ***advanced coating materials*** imperative. These cutting-edge coatings must be engineered to provide exceptional resistance to corrosion, ensuring the long-term durability of the stations. By addressing this challenge, we can secure the continued functionality and effectiveness of these vital components in global nuclear test monitoring.



ENSTA

Mounia Ticherfatine

Role of Superhydrophobic Coatings in Combatting Corrosion

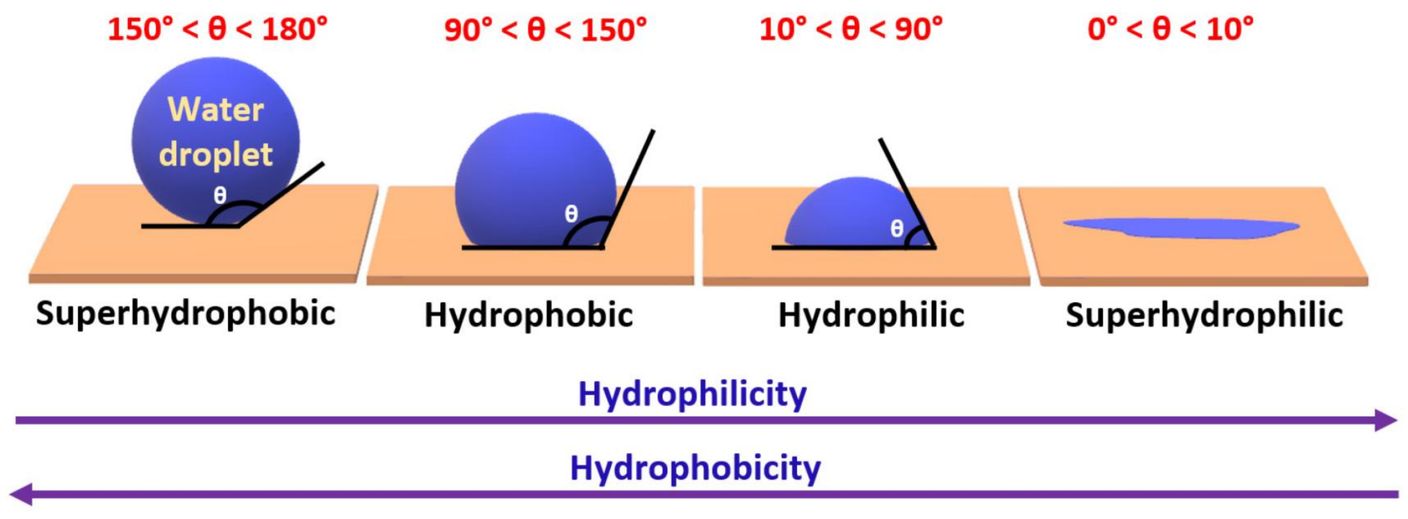
Superhydrophobic coatings, characterized by their extreme water-repellent properties, offer a promising solution to the pervasive corrosion issues in hydroacoustic stations. These coatings create a surface that *minimizes water contact* by causing water to bead up and roll off, significantly reducing the likelihood of corrosion-inducing moisture accumulation. This water-repellent behavior is crucial in marine environments, where constant exposure to saltwater accelerates the corrosion of submerged structures.

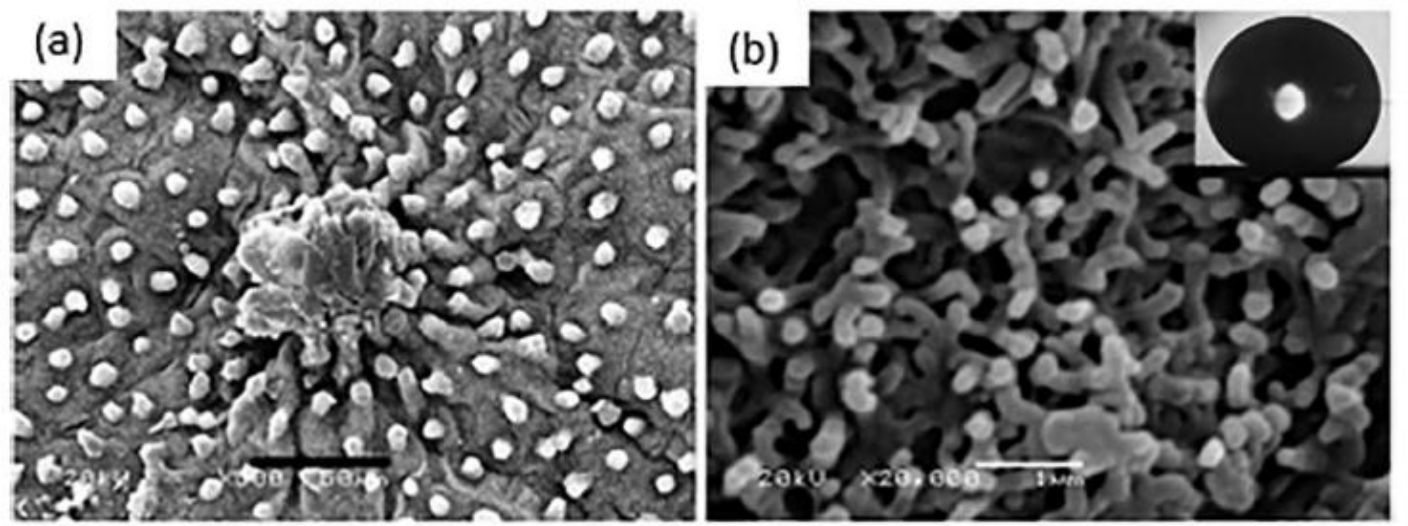
In addition to water resistance, superhydrophobic coatings can also ***reduce the adhesion of marine organisms***, such as algae and barnacles, which contribute to biofouling and further exacerbate corrosion. By preventing both water ingress and biofouling, these coatings can enhance the durability of hydroacoustic stations, extending their operational life and reducing maintenance costs.

Mounia Ticherfatine

What is superhydrophobicity ?

O4.4-010





SEM images of superhydrophobic surfaces at low and high magnification. (a) and (b) lotus leaf with a 162° water contact angle

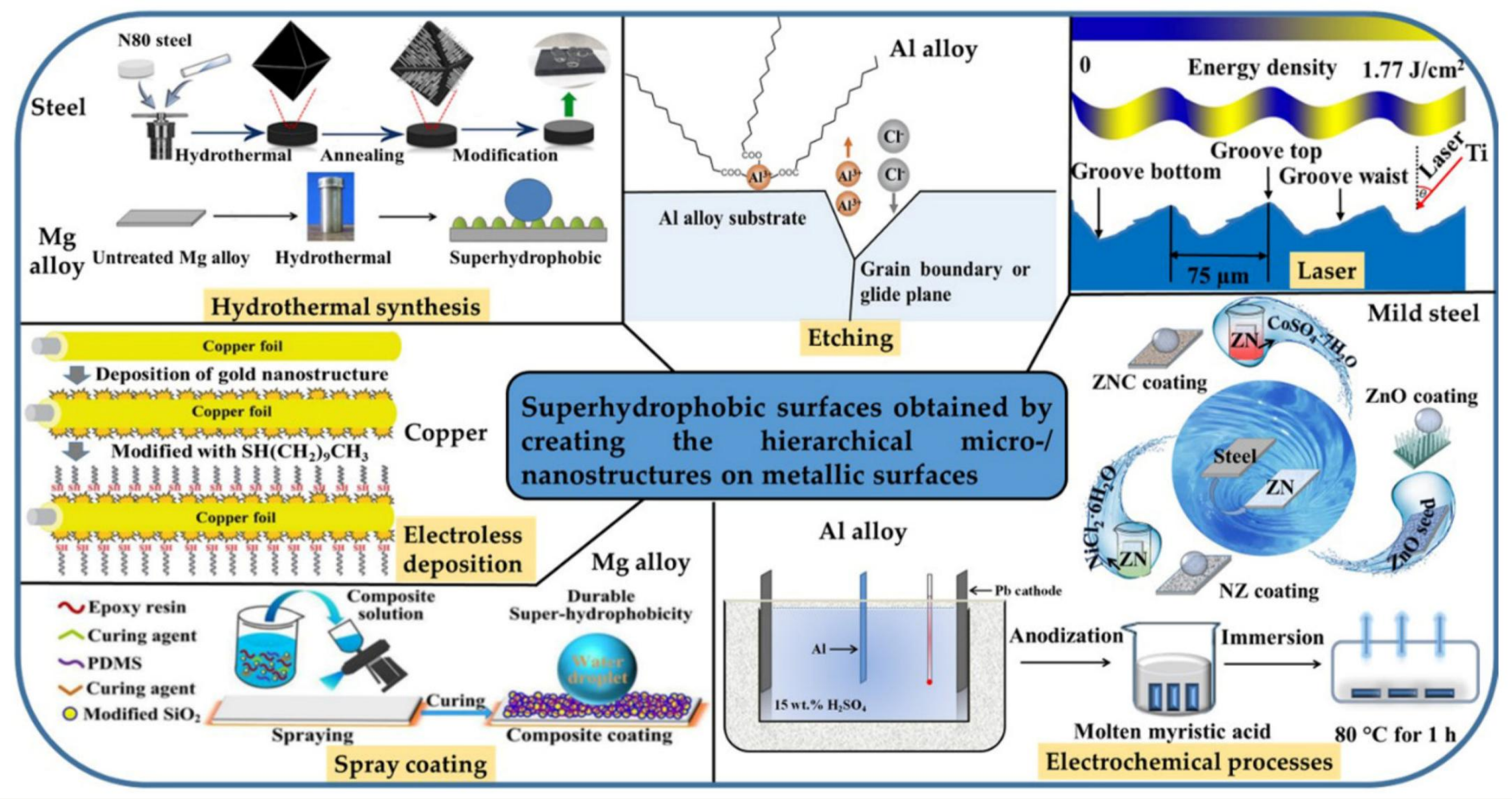
The **water contact angle (WCA)** is defined as the angle where a liquid-vapor interface meets a solid surface.

Besides static contact angle considerations, **contact angle hysteresis (CAH) and water sliding angle (SA)** are other important criteria for studying the surface behavior of various materials. The water SA is defined as the critical angle at which a water droplet of a certain weight begins a downward slide. CAH represents the difference between advancing and receding contact angles. Both are criteria of dynamic hydrophobicity. Generally, superhydrophobic surfaces are defined as any surface for which the static contact angle is> 150° and the SA or CAH is< 10°

Mounia Ticherfatine

O4.4-010

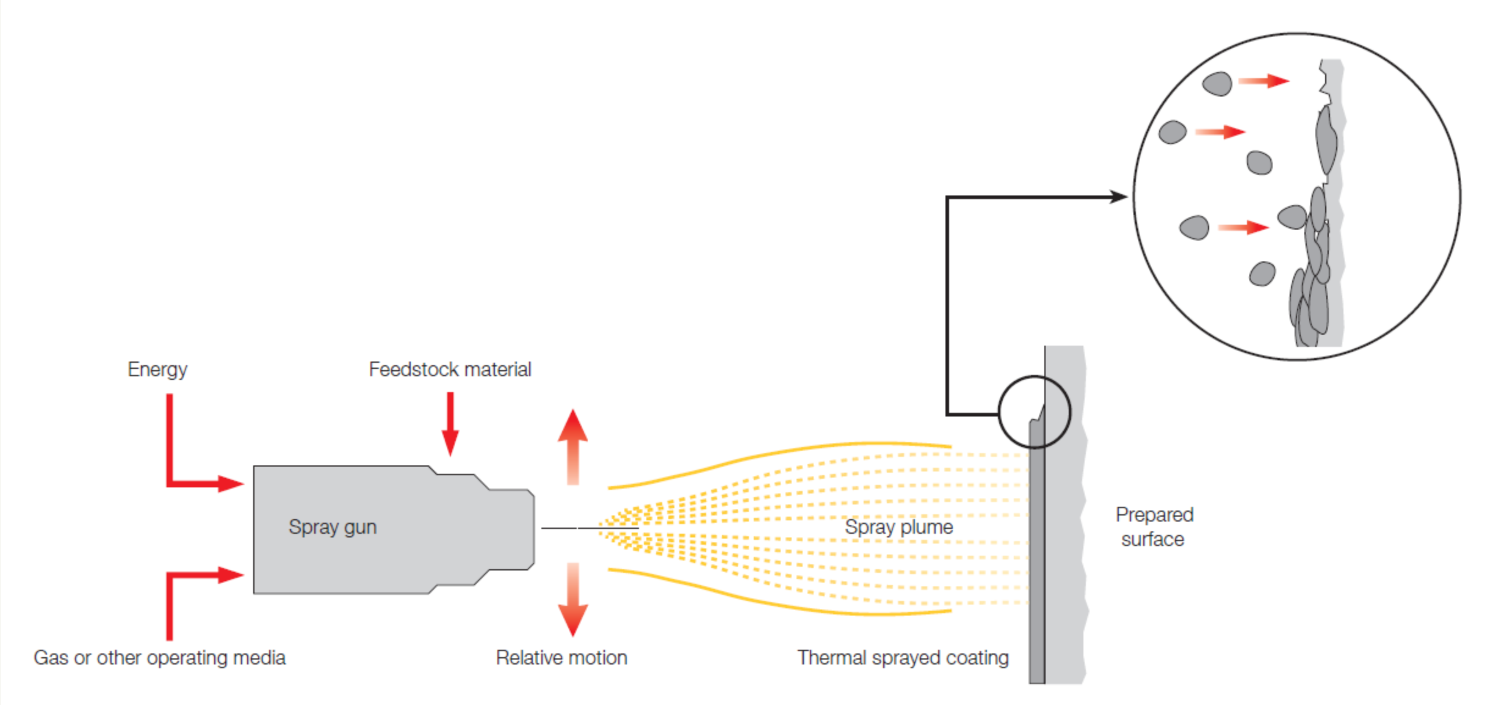
Fabrication of superhydrophobic surfaces



Mounia Ticherfatine

Thermal spray coating technology

Thermal spray coatings using ***high-performance thermosets*** deliver **robust anti-corrosion performance**, even under constant seawater exposure. These coatings form a durable, adherent barrier with excellent thickness control and minimal part distortion, preserving design flexibility. They significantly **extend service life**—often 10–20 years—reduce maintenance demands, and protect critical components like pumps, pipelines, and structural steel in offshore platforms.



Mounia Ticherfatine

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

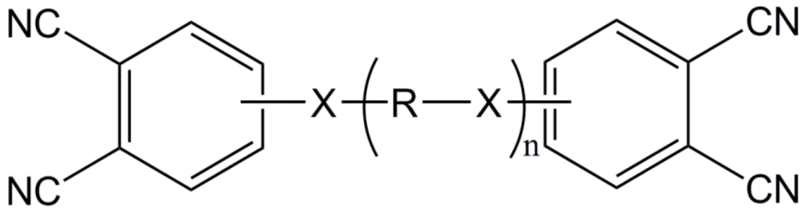
The ***phthalonitrile resins*** are considered as one of the most advanced thermosets featuring:

1- ***Exceptional thermal stability*** over a wide range of temperature;

2- ***Very low water uptake***;

3- High crosslinking degree ;

4- ***Very low-melt viscosity and a larger processing window*** allow the preparation of nanocomposite through the spray coating technique.



X = O, S, N, etc.

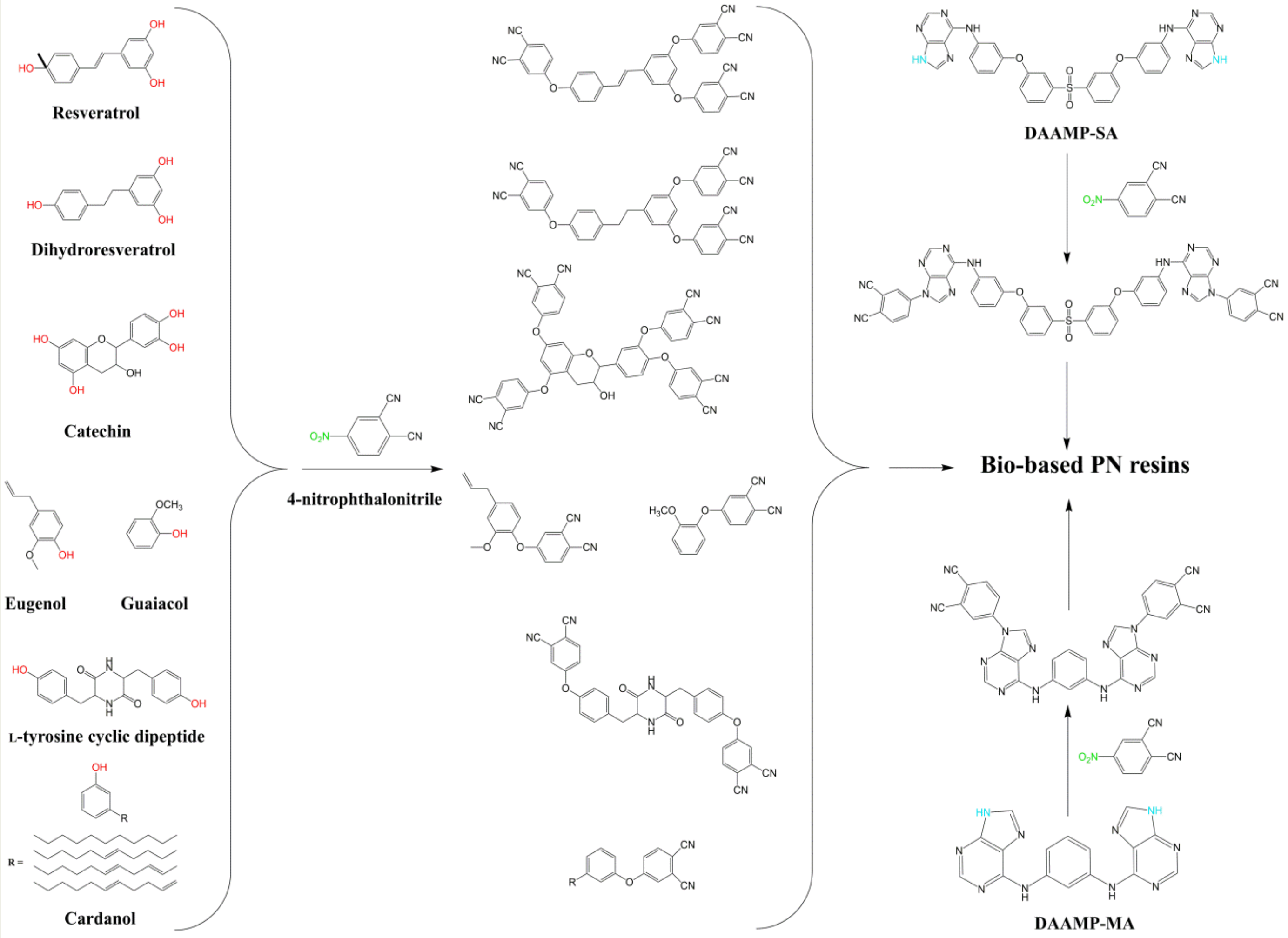
R= Aliphatic spacer: $-(CH_2)_n-$

Aromatic spacer: _Ar_Ar_ , _Ar_C(CH_3)$_2$_Ar_, etc.

N= Number of repeating units

Mounia Ticherfatine

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites



The phthalonitrile are synthetized via a simple nucleophilic displacement of a nitro substituent activated by the cyano functions. Multitudes of possibilities are available by changing the phenolic precursors in order to tailor the final properties of the polymer.

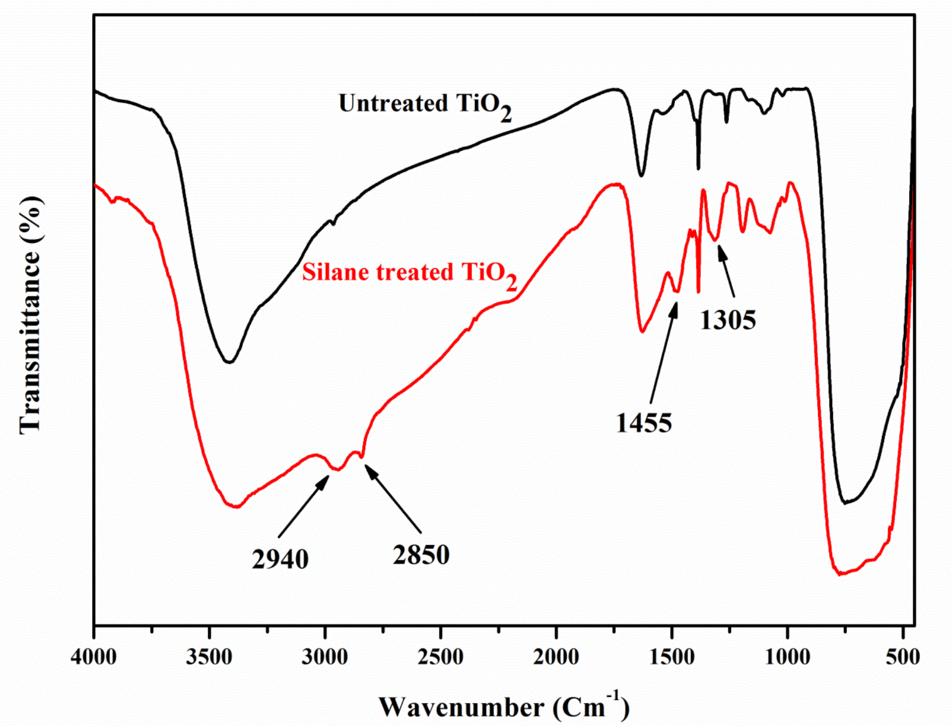
1. Composites et nancomposites
2. Copolymers
3. Hybrid materials

Mounia Ticherfatine

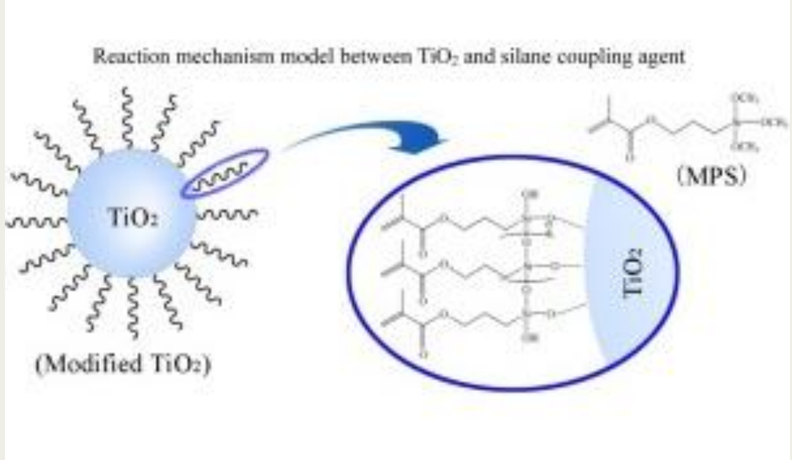
Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

Surface Modification

FTIR analysis was used to explore the effect of the silane coupling agent on the titania nanoparticles outer surface. The figure shows the spectra of both the native and treated titania nanoparticles.



Silane surface modification of titania nanoparticles enhances surface hydrophobicity by bonding hydrophobic organic chains to the nanoparticle surface. The silane molecules react with hydroxyl groups on the titania, forming a hydrophobic layer that repels water. This modification reduces the surface energy of the nanoparticles, leading to decreased wettability and improved resistance to moisture.

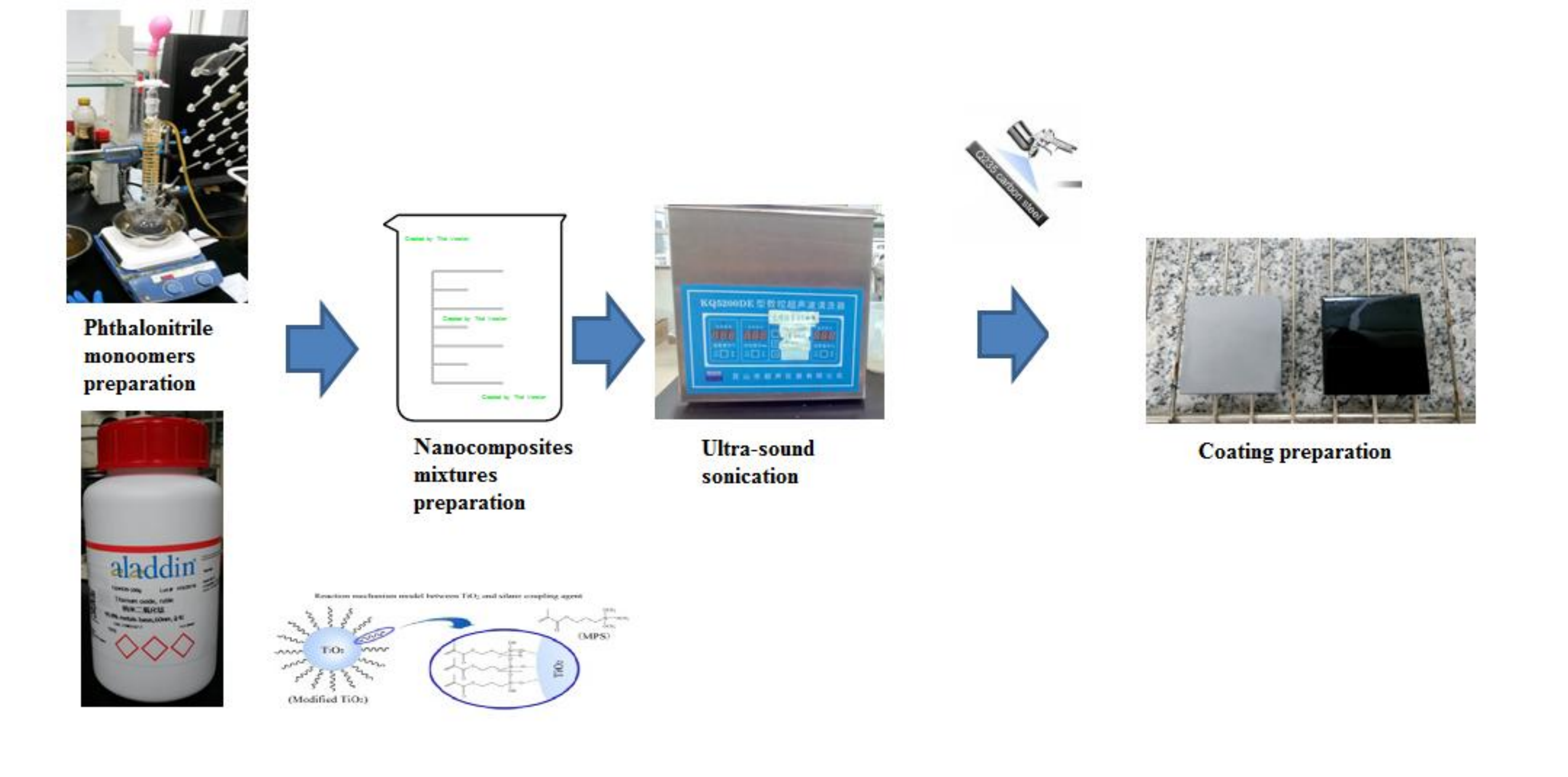


Mounia Ticherfatine

O4.4-010

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

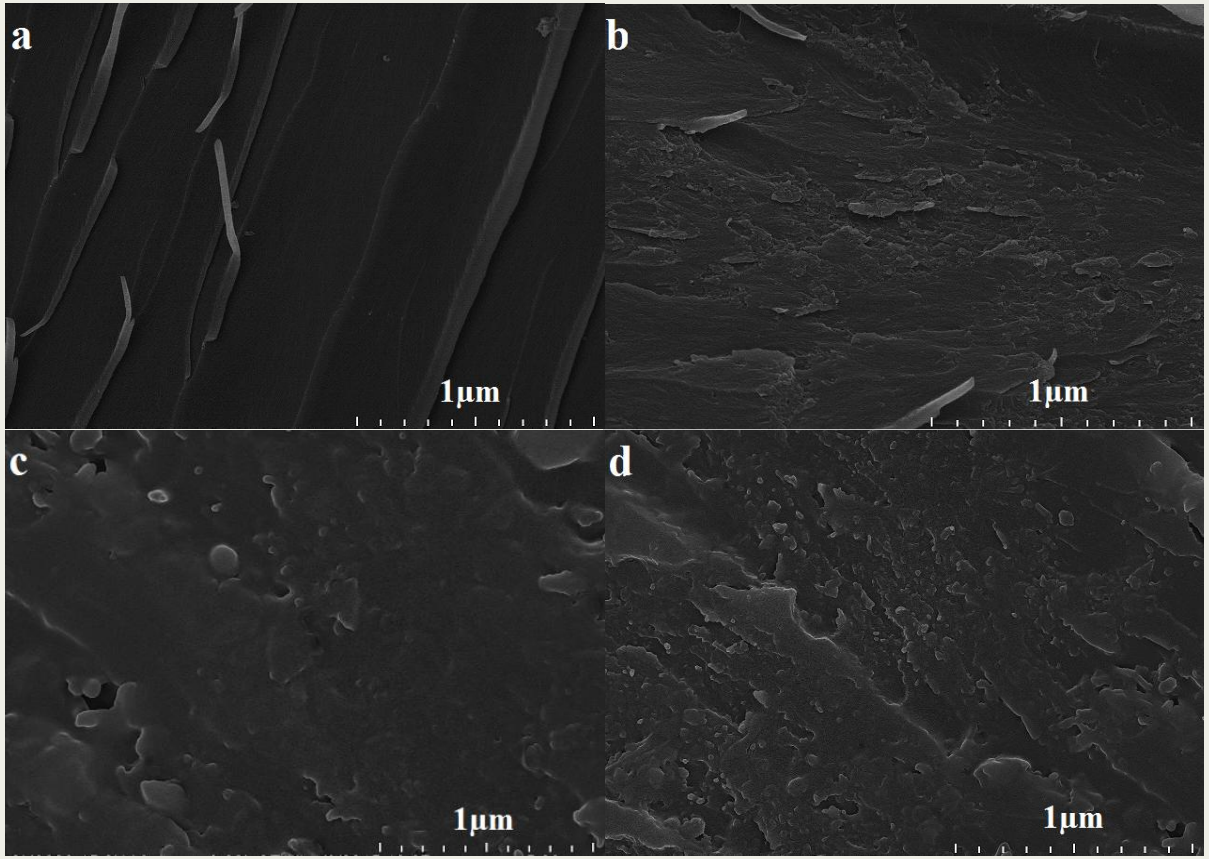
Fabrication process



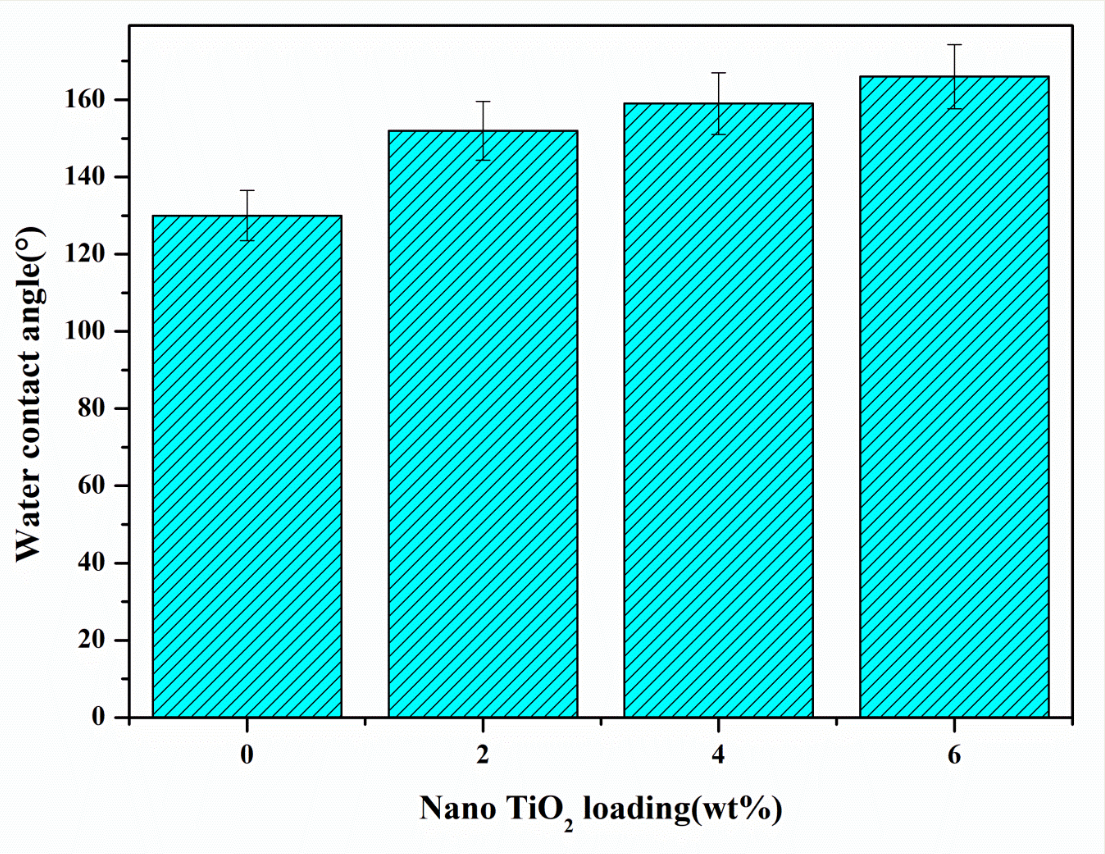
Mounia Ticherfatine

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

SEM and WCA



SEM micrographs of the P(Baph)/TiO_2 fractured surface at various nano-TiO_2 contents: neat resin (a), 2 wt% (b), 4 wt% (c), and 6 wt% (d).



WCA at various nano-TiO_2 loadings

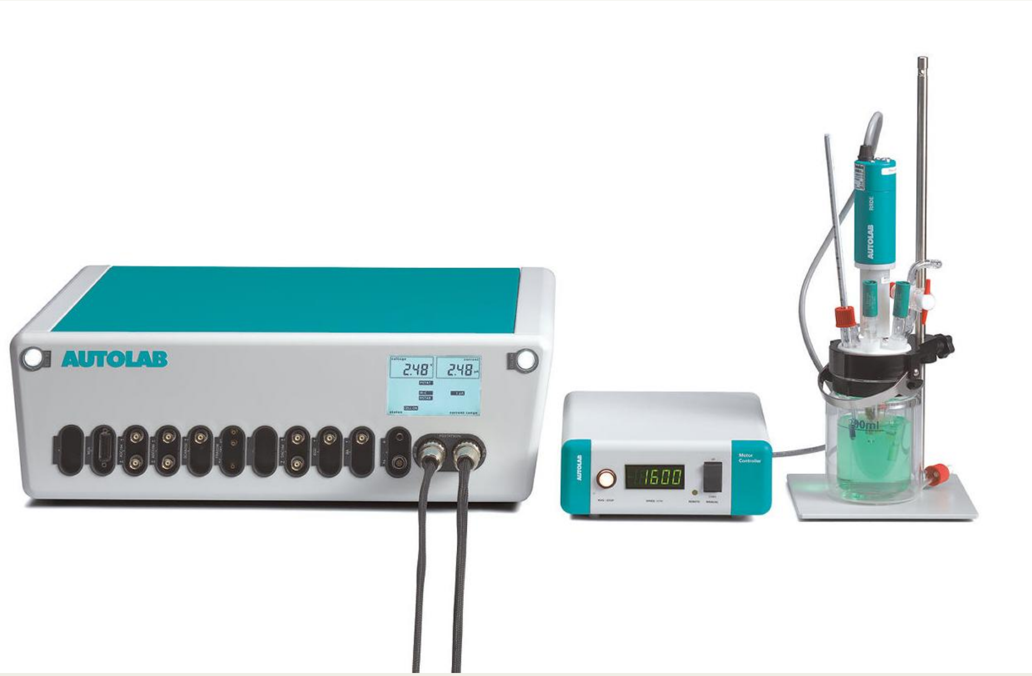
ENSTA

Mounia Ticherfatine

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

Corrosion resistance tests

The corrosion resistance of the nanocomposite coatings was evaluated using electrochemical impedance spectroscopy (EIS) with a three-electrode system (coated carbon steel as working electrode, platinum counter electrode, Ag/AgCl reference electrode) in 3.5% NaCl solution at room temperature. Measurements were performed over 100 kHz–10 mHz with a 10 mV sinusoidal signal at open circuit potential. Data were collected in four cycles at each frequency to ensure precision, at different immersion times.

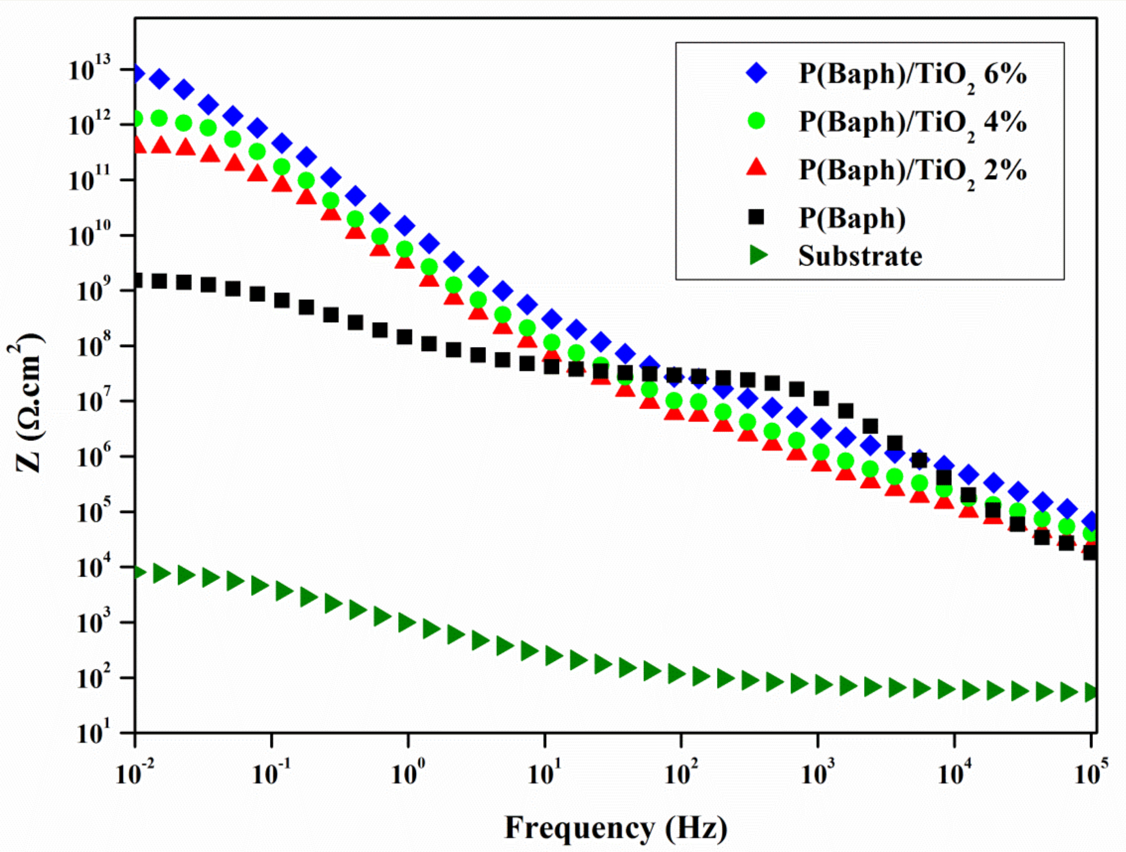


Mounia Ticherfatine

O4.4-010

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

Corrosion resistance tests



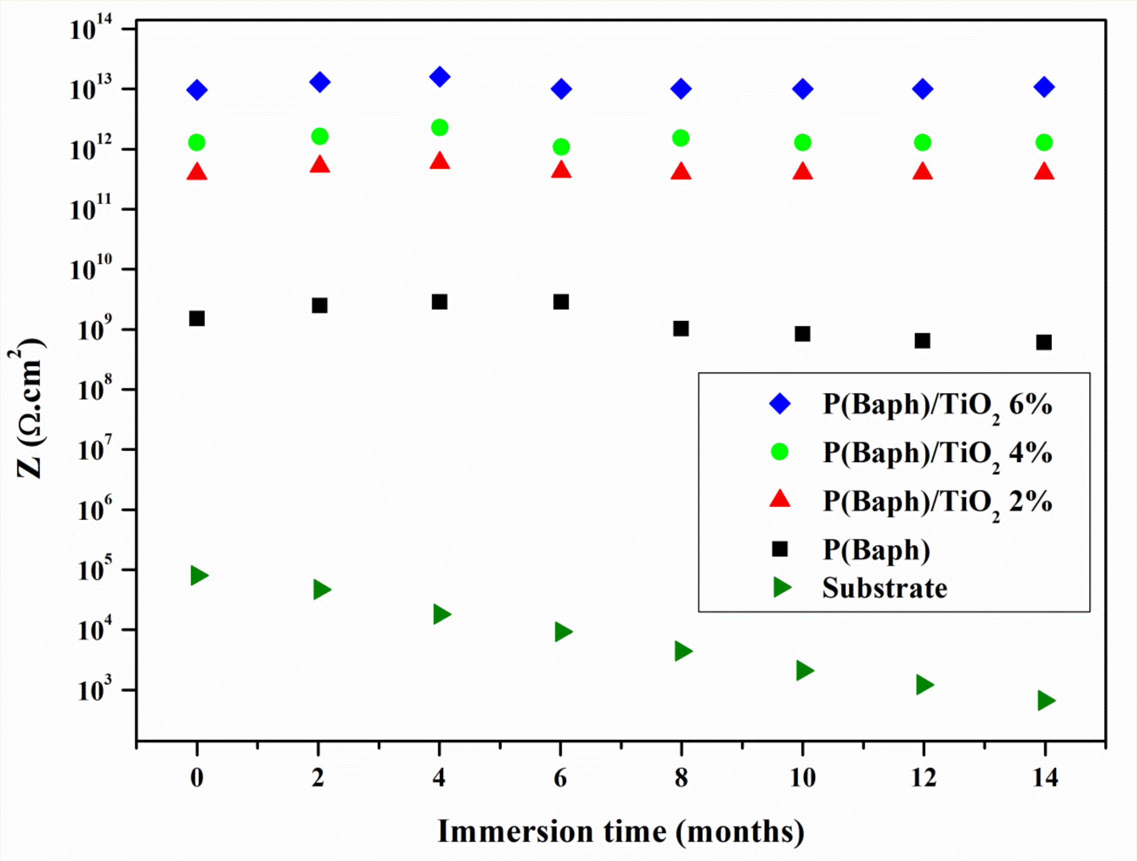
Evolution of the impedance modulus at the initial immersion stage for the substrate, the neat resin, and its related nanocomposites at 2, 4, and 6% nano-TiO_2 loading.

Adding the titania nanoparticles enhanced the corrosion protective properties of the coatings. A gradual increase in the modulus values has been recorded with the increasing of the amount of nanoparticles, reaching the highest value of 9.6 × 1012 Ω cm^2 at 6% nano-loading. These interesting results are mainly attributed to the superhydrophobicity and high crosslinking density which isolate the substrate from the solution leading to better anti-corrosion properties.

Mounia Ticherfatine

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

Corrosion resistance tests



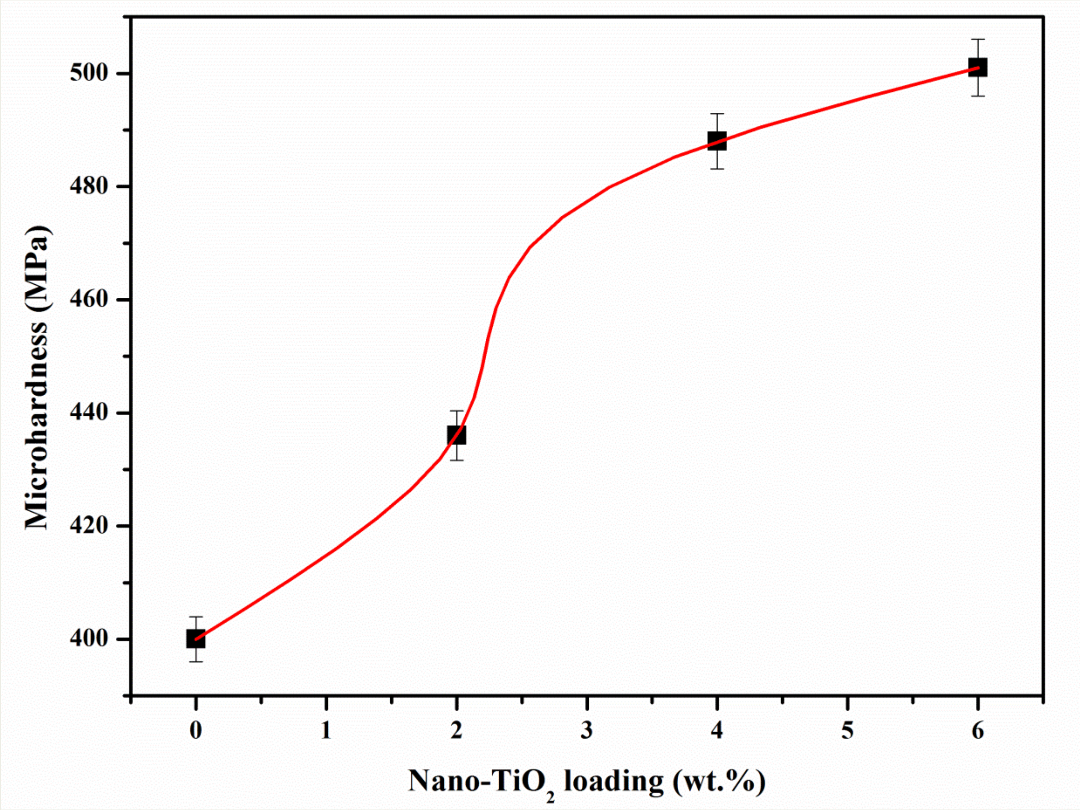
Evolution of the impedance modulus at low frequencies for all the samples at different immersion times.

A prolonged contact with a saline environment (more than 01 year) did not significantly alter the protective properties of the nanocomposites.

Mounia Ticherfatine

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

Mechanical properties



Microhardness of the P(Baph)/TiO_2 nanocomposites

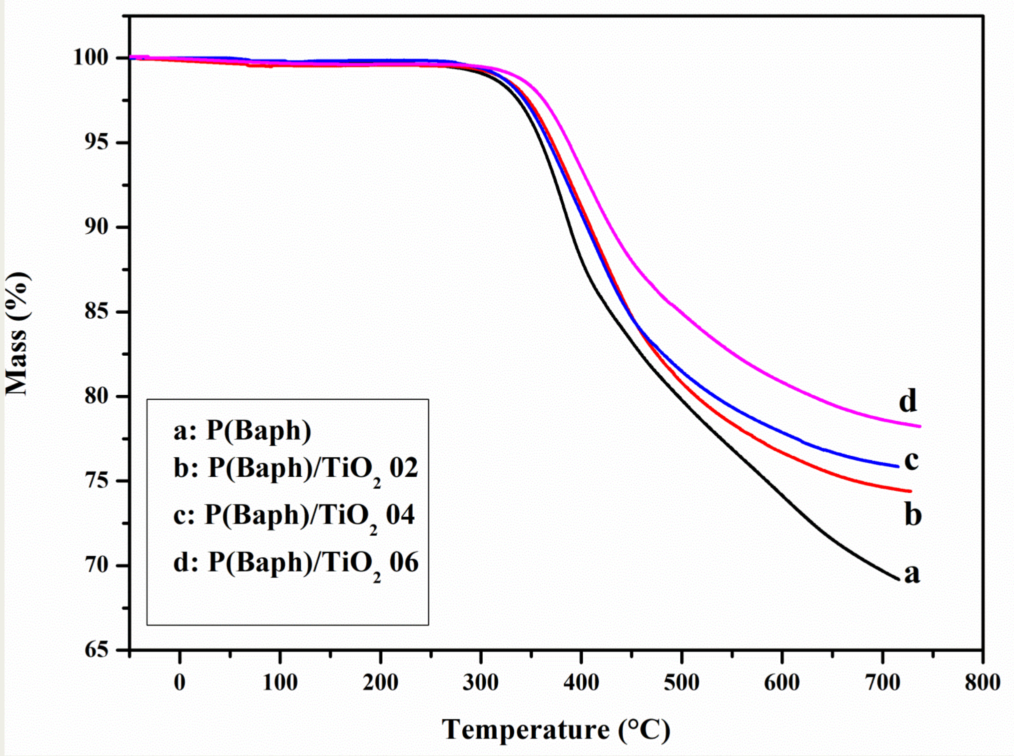
In deep-sea environments, materials are subjected to extreme conditions, including high pressures, corrosive seawater, and potential abrasive interactions with particles or marine life. A coating with high microhardness is generally more resistant to deformation under pressure, which can be advantageous for maintaining the structural integrity of the material it covers.

Evaluating the microhardness of the produced nanocomposites is therefore necessary to assess about their possible use as high performance coating materials. the different nanocomposites showed a much ameliorated microhardness values as the amount of titania nanoparticles increased. In fact, a maximum microhardness value of 501 MPa has been recorded at 6% nanofillers loading.

Mounia Ticherfatine

Case study: phthalonitrile/TiO_2 superhydrophobic nanocomposites

Thermal properties



Thermal stability of P(Baph)/TiO_2 nanocomposites at various nano-TiO_2 contents.

Coating materials for deep-sea applications must endure extremely low temperatures while maintaining their structural integrity.

Thermal stability performances assessed by Thermogravimetric analysis confirmed that the nanocomposites coatings retain their structural integrity over a wide range of temperature starting -50 up to 500 °C.

Mounia Ticherfatine

Conclusions

1- Superhydrophobic coatings create a barrier that significantly reduces water contact, effectively preventing corrosion in the harsh marine environments where hydroacoustic components operate.

2- Phthalonitrile/TiO_2 nanocomposites can be a cost effective candidate for use within a multi-layered defense strategy against corrosion.

3- The reduced corrosion and maintenance needs translate into long-term cost savings.

4- To confidently verify the long-term applicability of superhydrophobic coatings in hydroacoustic stations, further studies under real marine conditions are necessary, ensuring these solutions meet operational demands.

Future actions

Feasibility and collaboration

Future actions will focus on the feasibility and scalable manufacturing of the developed superhydrophobic coatings, in close cooperation with industry and other institutions operating in marine sectors, with the aim of tackling corrosion and ensuring long-term durability.

Sea tests

Another future action is to conduct real sea trials to assess the performance of these superhydrophobic coatings when applied to various components of the CTBTO hydroacoustic stations.

Mounia Ticherfatine

THANK YOU