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TOXIC FREE METALLIZATION PROCESS FOR PLASTIC SURFACES

3RD ISSUE

CONTENTS

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AN OVERVIEW OF FREEME PROJECT

SUMMARY

Plating on Plastics (PoP) is widely used in several manufacturing sectors including automotive, home appliances and aerospace to protect plastic items, parts, or components from wear, corrosion, impact, electromagnetic radiation etc., while also providing shiny, aesthetically attractive exterior. However, the current PoP process encounters significant challenges related to environmental hazards and occupational safety risks. The FreeMe project, funded by the European Union (Grant Agreement ID: 101058699), is revolutionizing PoP by incorporating Safe and Sustainable by Design (SSbD) methods and protocols to eliminate toxic or expensive materials from the PoP process, like hexavalent chromium (Cr^{6+}) compunds and palladium (Pd). FreeMe is addressing these challenges by implementing innovative surface metallisation technologies that involve less hazardous etching systems or spraying of bio-based epoxy resins (instead of Cr^{6+}) and use nickel (Ni) instead of Pd as activation sites.

OBJECTIVES

- Implement an SSbD strategy during the development of the two new FreeMe technologies for PoP that will cover the whole lifecycle.
- Technology-1: Pre-treatment of plastic surfaces with Piranha instead of Cr^{6+}-containing solutions and with nickel salts instead of Pd.
- Technology-2: Replace etching & activation of plastic surface pre-treatment stages with a spraying technology using sprayable and UV-curable composite biobased resins.
- Develop in-silico techniques (simulation and modelling) facilitating the development, synthesis and application of the sprayable composite resins as well as the optimisation of plastic surface etching using multi-scale models, ranging from atomic to mesoscopic scales.
- Develop fast and accurate inspection methods based on spectroscopic imaging ellipsometry and optical coherence tomography for micro-scale monitoring (up to 3μm) and quality control of the process.
- Demonstrate the FreeMe technologies in automotive, aerospace and home appliances demonstrators by applying and validating SSbD metallic coatings on plastic components.
- Assess the recyclability of coated polymers based on the current state-of-the-art technologies for recycling.
- Develop a data-driven Decision Support Tool combining data from SSbD assessment, in-silico approaches, experimental/manufacturing results, LCA/LCC assessment and specification/requirement of test cases, to support industrial end users on the selection, development and application of the most suitable PoP technology.
- Facilitate the acceptance of the new technologies by the market, defining the standardisation landscape and contributing to future standards development.
- Prepare business plans and define exploitation routes for the project partners and enhance the impact of results by undertaking targeted dissemination and exploitation activities, including training courses for the PoP industry.

FreeMe targets to achieve its objectives with collaborative work, divided into nine (9) work packages:

- **WP1:** Project's Requirements & Specifications — Leader: Gruppo Gaser
- **WP2:** Safe & Sustainable by Design Strategy — Leader: University of Burgos
- **WP3:** Sprayable Resins process — Leader: Politecnico di Milano
- **WP4:** Cr^{6+} and Pd free metallization process — Leader: Creative Nano
- **WP5:** Development of supporting technologies — Leader: IDENER
- **WP6:** Validation of technologies in end user's test cases — Leader: CRF
- **WP7:** Roadmap to market deployment — Leader: Politecnico di Milano
- **WP8:** Extroversion and Exploitation activities — Leader: EXELISIS PC
- **WP9:** Project Management — Leader: Gruppo Gaser

FreeMe

SSbD approaches for metallisation of polymeric surfaces		Supporting technologies	
Sprayable Composites resins process	Cr6+ & Pd free metallisation processes	In silico modeling	In line optical inspection system

INTERVIEW

IDENER TEAM

ISRAEL BELLANATO

ALBERT SABADELL RENDÓN

ANDREA MARTOS

FRANCISCO DANIEL GARCIA ROMERO

Please introduce yourself and describe your entity's role in the FreeMe project. Also, please introduce your team.

I am Andrea Martos, Team Manager at IDENER. My main research and scientific works have been carried out in the environmental engineering field of knowledge, and, in FreeMe, I am co-managing the scientific work with my colleague Francisco Daniel, and the technical team, Albert and Israel. All of them have a great experience in the computational methods, simulation and multiscale modelling.

Can you share some background on your experience and expertise in this field?

I think, the background of my colleagues is key for the IDENER activities. Francisco Daniel holds a Double Bachelor's Degree in Chemistry and Materials Engineering. Israel holds a Bachelor's Degree in Physics, a Bachelor's Degree in Mathematics, and a Master's Degree in Mathematics. Albert holds a Double Bachelor's Degree in Physics and Chemistry, a Master's Degree focused on advanced scientific research, and a PhD in Computational and Theoretical Chemistry. During his doctoral studies and a subsequent two-year postdoctoral position, he worked extensively on the simulation of reactors. Together, the multidisciplinary background of our team allows IDENER to develop robust multiscale models that integrate chemical, physical, and engineering principles.

Is there a particular moment or achievement related to this project that you would like to share with us?

We are almost reaching the end of the third year of FreeMe. During this time, we have developed Molecular Dynamics models, atomistic models, and kinetic Monte Carlo simulations for the main case studies.

Among the key milestones, we completed a Molecular Dynamics model to study the adhesion of a sprayable epoxy resin on PLA surfaces, analyzing factors like distribution, diffusion, and interfacial bonding. Additionally, we modelled the piranha solution etching process on ABS substrates using a combination of DFT calculations, Molecular Dynamics, and kinetic Monte Carlo simulations, providing a full multiscale understanding of surface oxidation mechanisms.

How can subscribers stay informed about your entity's achievements?

Subscribers can stay informed about our latest achievements by following the IDENER.AI LinkedIn account, where we regularly share project updates, success stories, and developments across our initiatives. Additionally, our official website (www.idener.ai) offers a comprehensive overview of our activities, including news articles, publications, and project milestones.

4SEE CLUSTER

FOR SUSTAINABLE EUROPEAN ECONOMY: TOWARDS SAFER AND MORE SUSTAINABLE BY DESIGN METALLIC COATINGS

The 4SEE cluster is dedicated to advancing the development of metallic coatings that prioritize safety and sustainability through deliberate design choices. This collaborative effort, consisting of the FreeMe, MOZART, NICKEFFECT, and NOUVEAU projects, is driven by the shared goal of fostering innovation and progress within their respective fields. By focusing on enhancing the safety and sustainability of metallic coatings, the cluster aims to contribute to a future where industries can rely on materials and methods that are not only effective but also environmentally friendly and socially responsible. Through research, experimentation, and collaboration, the 4SEE cluster endeavours to pave the way towards a safer, more sustainable approach to metallic coatings, ultimately benefiting both industries and society as a whole.

THE NICKEFFECT PROJECT

NI-BASED FERROMAGNETIC COATINGS WITH ENHANCED EFFICIENCY TO REPLACE PT IN ENERGY & DIGITAL STORAGE APPLICATIONS

Platinum group metals (PGMs), such as platinum, palladium and iridium, etc., are indispensable in modern technologies due to their exceptional durability, catalytic activity and resistance to corrosion. These properties make them vital for several strategic sectors such as **renewable energy, electric mobility** and **digital technologies**. However, PGMs are scarce, expensive and primarily concentrated in Africa and Russia (https://rmis.jrc.ec.europa.eu/), thus creating high supply chain risks. Therefore, the European Commission has classified PGMs as Critical Raw Materials (CRMs). To address this challenge, the NICKEFFECT project is developing innovative, Ni-based solutions that can replace PGMs in key applications while maintaining the appropriate performance level.

Indeed, Ni is an earth-abundant metal with ferromagnetic character that can offer promising alternative to PGMs in many applications. By incorporating advanced deposition techniques, such as electrodeposition, electroless plating and sputtering, combined with advanced materials and process modelling technologies, NICKEFFECT is engineering Ni-based materials with targeted properties for three high-impact applications:

1. **Catalytic materials for water electrolysis (PEM WE)**
2. **Catalytic materials for fuel cells (PEM FCs)**
3. **Coating materials for low-power digital storage devices (MRAMs)**

To enhance performance of Ni-based materials, different levels of porosity (nano-, macro- and hierarchical) are introduced onto the materials, thus increasing surface area and catalytic activity without compromising durability. Additionally, the project integrates life cycle and cost analysis (LCA/LCC), environmental impact assessments (EIA), as well as chemical risk assessments (CRA) and recyclability approaches to ensure sustainability and scalability of the Ni-based electrodes' fabrication process from the early stages of materials design.

Use Case 1: PEM Water Electrolyzer electrodes for hydrogen production

Platinum is currently the benchmark electrocatalyst for the hydrogen evolution reaction (HER) in proton exchange membrane (PEM) water electrolyzers. While catalyst costs represent approximately 5% of kW-scale systems today, this contribution is expected to grow in MW-scale electrolyzers, which is expected to dominate future green hydrogen production. NICKEFFECT has developed 100% Pt-free Ni-based catalysts with optimized activity and durability through machine learning-driven

THE NICKEFFECT PROJECT

design (R. de Paz-Castany et al., ChemSusChem 2025, 18, e202400444).
Furthermore, by engineering hierarchical porosity into the deposits the team has achieved a high surface-to-volume ratio in the catalysts while maintaining the optimized properties. After successful lab-scale validation, the process has been scaled up to produce large-format 450 cm² electrodes (Figure 1) which are currently being validated in the real environments.

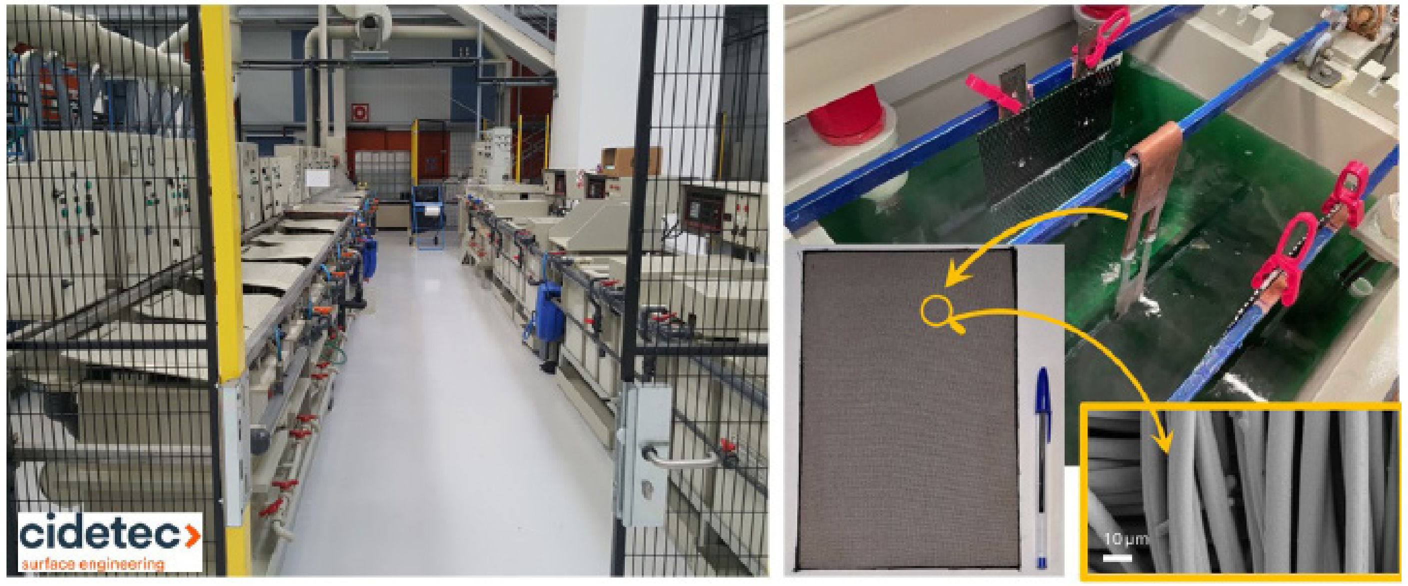


Fig. 1 CIDETEC's pilot line (left) and the produced 450 cm2 PEM WE Ni-based porous electrodes (right).

Use Case 2: PEM Fuel Cell electrodes for energy conversion

Proton exchange membrane fuel cells (PEM FCs) are crucial for decarbonizing transportation (e.g., hydrogen vehicles). However, PGM-based catalysts account for 50-80% of the membrane electrode assembly (MEA) cost. The EU aims to reduce system costs to €1,000/kW, but eliminating PGMs is challenging due to the harsh acidic conditions and anodic potentials required for the oxygen reduction reaction (ORR) on the cathode. NICKEFFECT has produced stable Ni-based nanoparticle catalysts with minimal Pt content and deposited directly on gas diffusion layers. Prototype electrodes (up to 25 cm²) have been fabricated and are being tested under real operating conditions in collaboration with project's End Users. Advanced artificial intelligence (AI) algorithms were developed to enable high-throughput quantification of particle size, distribution, aspect ratio and other metrics needed for statistical analysis or process optimization (Figure 2).

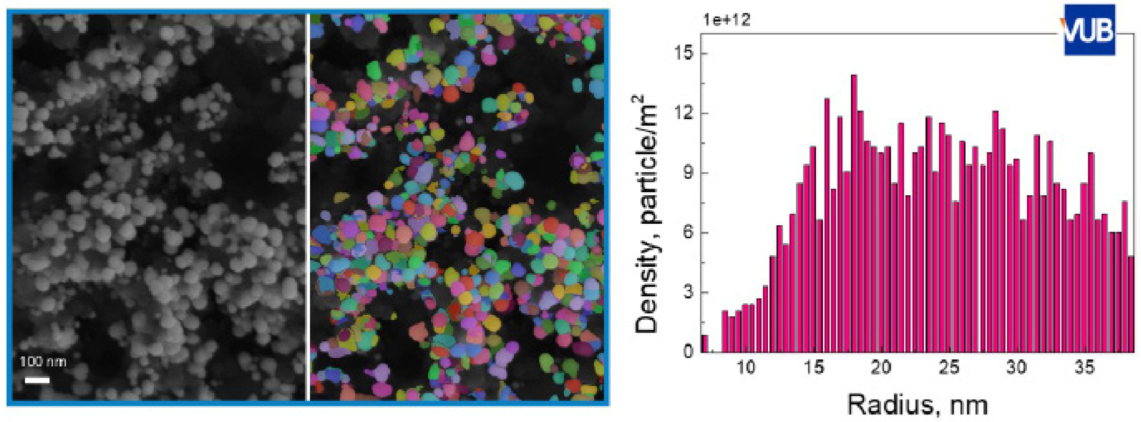


Fig. 2 AI-driven nanoparticles quantification: FE-SEM image of Ni-based nanoparticles electrodeposited on GDL and its AI analysis (left); the obtained histogram (right).

Use Case 3: MRAM coatings for low-power consumption electronics

Magnetic random-access memory (MRAM) is a rapidly growing technology due to its ultra-low power consumption, high speed and non-volatility, which makes it ideal for flexible electronics and advanced computing. Conventional MRAM relies on Pt-containing multilayers (e.g., Co/Pt) to achieve perpendicular magnetic anisotropy (PMA) - a key property for data storage. NICKEFFECT has demonstrated two breakthrough strategies to reduce Pt dependence:

1. **Sputtered Ni/Co multilayers that achieve PMA without Pt by precisely controlling layer thicknesses at sub-nanometer scale (Z. Ma et al., Adv. Mater. 2025, 2415393).**
2. **Magneto-ionic control in nanoporous Ni-Co alloys, enabling voltage-controlled magnetism for ultra-efficient memory devices (A. Arredondo-López et al., ACS Appl. Mater. Interfaces. 2025, 17, 9500-9513).**

By combining advanced materials engineering, AI-driven optimization and scalable manufacturing the NICKEFFECT project not only addresses supply chain risks but also reduces costs and environmental impacts in EU strategic sectors.

For the latest development and news on the NICKEFFECT project, please check our website and LinkedIn page.

In case you have any questions, or you would like to have more information about the project and its results, please contact the coordinator (CIDETEC Surface Engineering, Aliona Nicolenco: anicolenco@cidetec.es)

EVENTS

SICT 2025 COATINGS CONFERENCE

SICT is an international conference that took place from 23-25 April 2025 in Albufeira, Portugal. It brought together experts from academia and industry to explore the latest advances in surfaces, interfaces and coatings technologies. The event covered a broad range of topics, from surface engineering and functional coatings to applications in fields like catalysis, bio-interfaces and energy materials.

FreeMe actively participated in SICT 2025 as exhibitor with a booth hosting FreeMe and two projects of the 4SEE cluster (NOUVEAU and NICKEFFECT) and showcased its innovations in sustainable and SSbD Plating on Plastics technologies. FreeMe also held a dedicated workshop alongside SICT 2025, engaging the scientific community in discussions around green alternatives to hazardous materials and promoting the uptake of its results in industrial applications. In his workshop, the audience had the opportunity to watch presentations from the FreeMe partners.

FREEME CONSORTIUM MEETINGS

5TH CONSORTIUM MEETING

FreeMe's 5th consortium meeting was held in Arcelik's premises in Instabul, Turkey between 24th and 25th of September 2024. Day 1 of the meeting featured engaging discussions on recent progress across work packages. The highlight of day 1 was an internal training on safe metallization processes conducted by FreeMe's partner, Creative Nano.

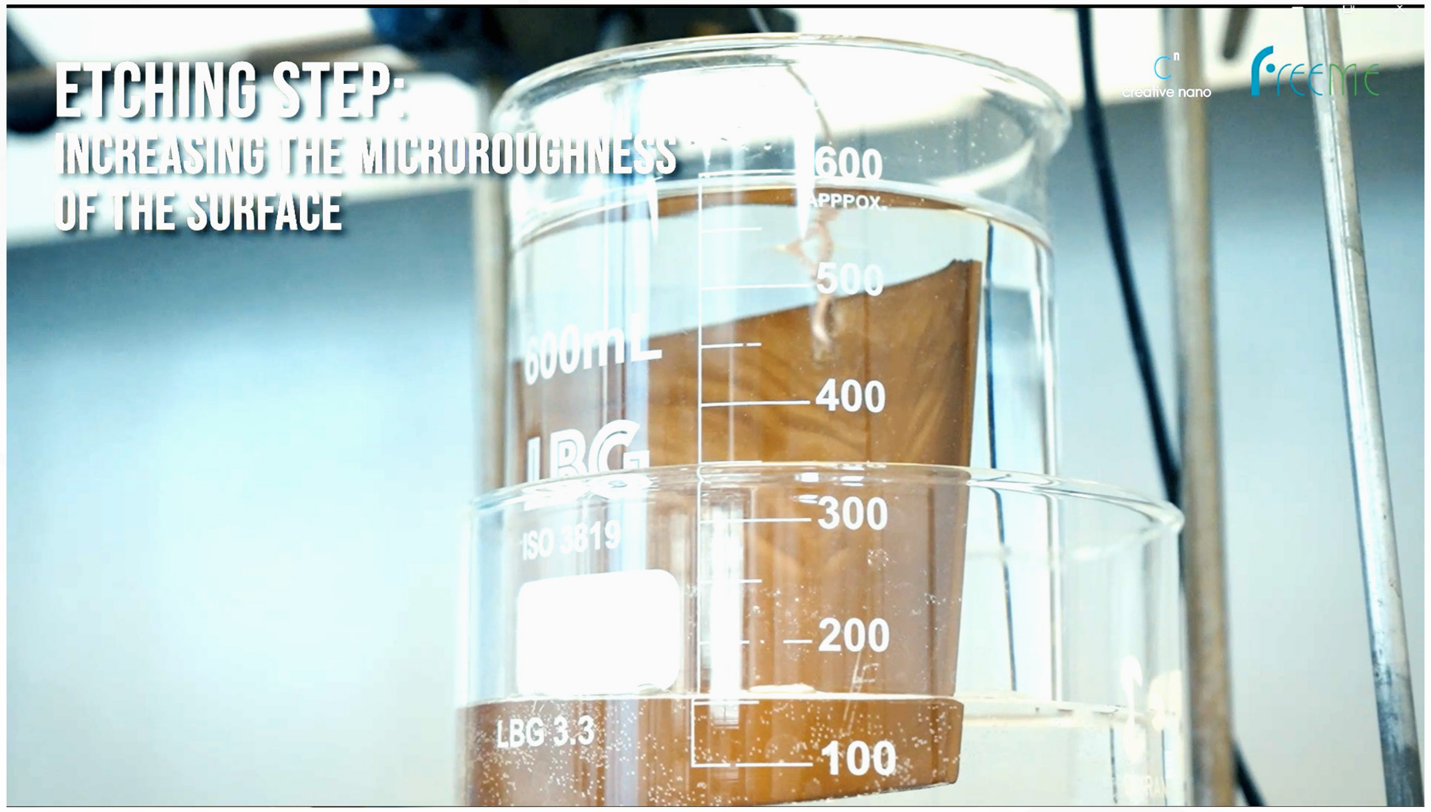
The 2nd day facilitated discussions on the remaining work packages as well as the second part of the internal training, on supporting technologies within the FreeMe project. This training was conducted by FreeMe's partner IRISS.

The 2-day meeting concluded with a tour on Arcelik's cutting-edge facilities, where all the partners observed the company's advanced premises, laboratories, and technologies first-hand.

FREEME ACHIEVEMENTS

PLASTICS SURFACE PRETREATMENT PROCESS

FreeMe has achieved important advancements in the field of metallization of plastic surfaces by developing a safe and sustainable by design pretreatment process. This novel method eliminates the use of hazardous and rare chemicals such as hexavalent chromium (Cr^{6+}) for etching and palladium (Pd) for activation, which raise environmental and sustainability concerns. Instead, FreeMe introduces alternative ECHA compliant chemical agents (Piranha solutions and Nickel salts) that achieve high surface microroughness and catalytic activity significantly reducing toxicity (Cr^{6+}) and critical raw material dependency (Pd). The process has been successfully demonstrated across three key industrial sectors: the automotive sector by Centro Ricerche FIAT, the home appliances sector by Arcelik, and the aerospace industry by Israel Aerospace Industries. The technology has been initially validated at laboratory scale with promising results on geometrically complex and functional plastic components (ABS, PC-ABS, nylon), proving the versatility and scalability of the method.



Creative Nano: Etching Step

BIO-BASED SPRAYABLE RESINS

Within the FreeMe project, bio-based epoxy composite resins have been developed as a sustainable alternative to traditional resins revealing opportunities for innovative applications in plating on plastics (PoP). The resins have been synthesized at laboratory Dean-Stark apparatus and are tailored to exhibit mechanical strength, and thermal stability, all critical factors for industrial applications. Notably, the resins incorporate nickel precursors to be sprayed on plastic surfaces acting as both structural coatings and functional layers enabling metallization. Once applied to plastic surfaces via spraying, they can be UV cured to form a uniform coating layer that contains the Nickel nucleation sites that catalyse electroless plating on plastics, replacing the use for toxic and rare materials. This innovation offers a greener, more efficient path toward metallizing polymer substrates.

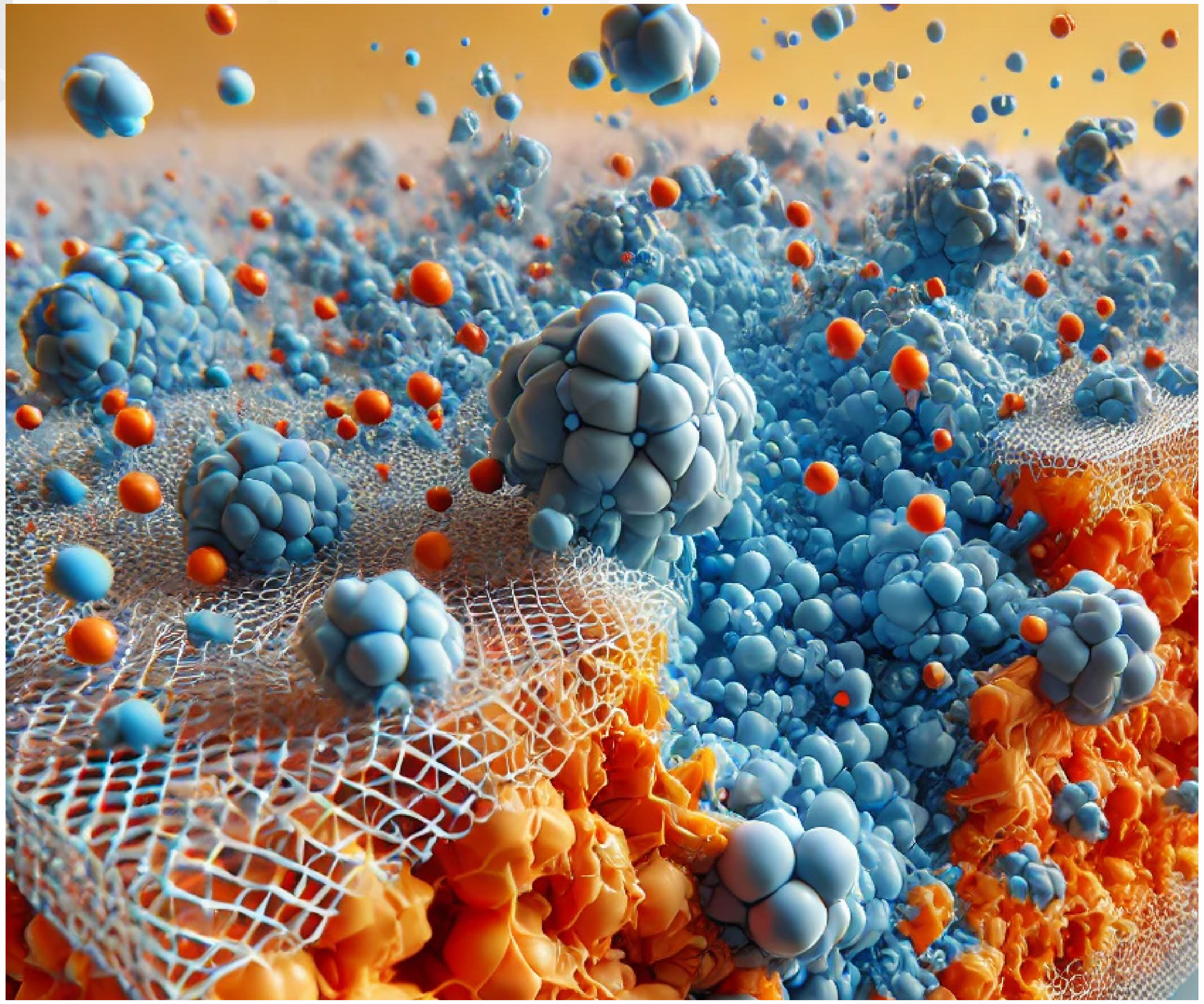
Polimi: Sprayed Resins

INNOVATIVE SIMULATION METHODS

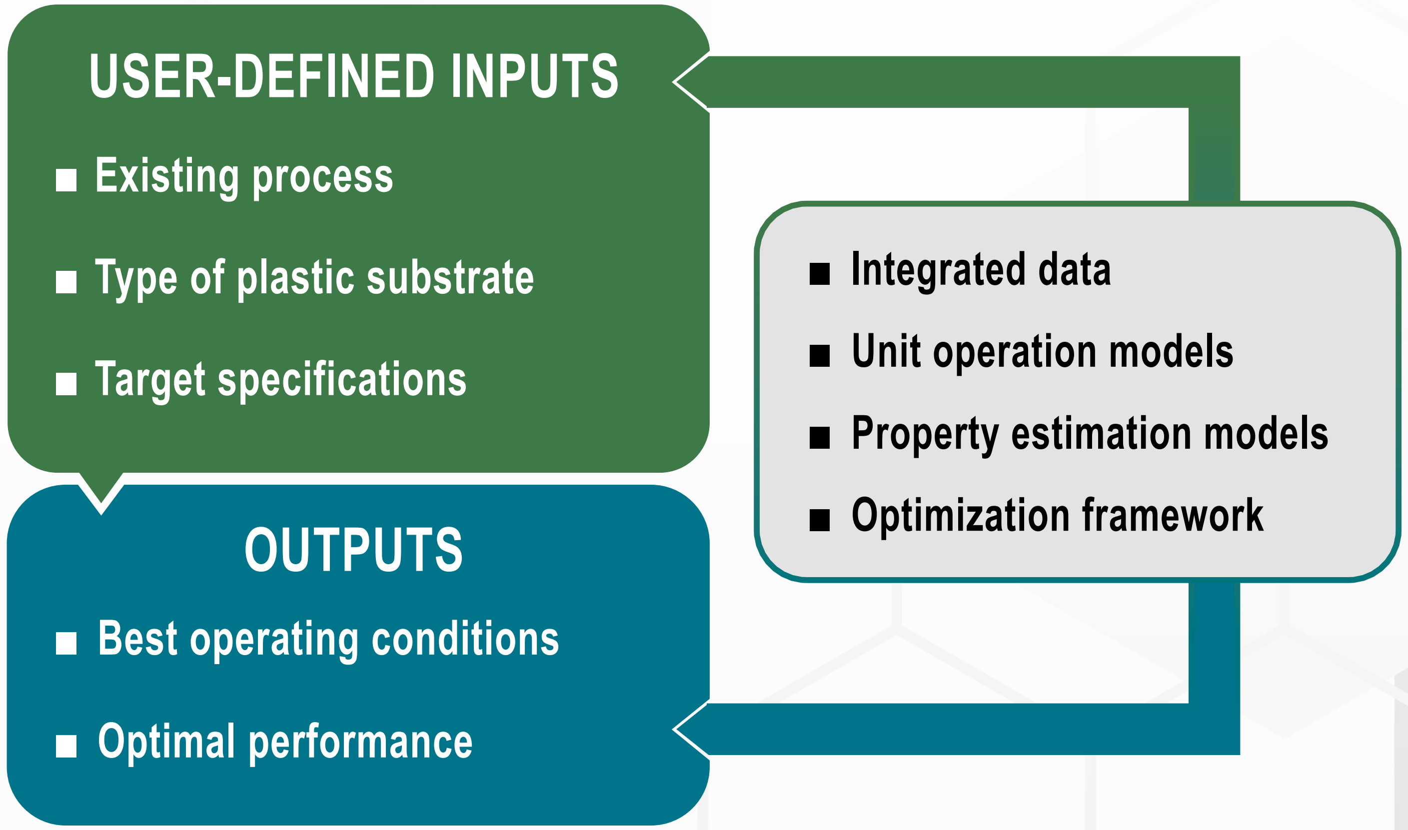
FreeMe is at the forefront of developing cutting edge computational tools to enhance the understanding and to optimize FreeMe PoP processes. One such technique is

FREEME ACHIEVEMENTS

the "molecular gun," a simulation method that mimics the impact of Cr^{6+} free etching solutions on polymer surfaces at the molecular level. This approach allows researchers to visualize how chemical interactions alter the plastic surface, improving microroughness and reactivity. Density Functional Theory (DFT) simulations are employed to map out the energetic pathways of complex chain reactions during etching of plastic surfaces. These simulations enable accurate predictions of chemical behaviour, helping scientists fine tune process parameters for optimal performance. These methods provide a powerful toolkit to comprehend complex phenomena, guide experimental work, reduce the need for costly trial and error testing, and accelerate the development of safe and sustainable coating technologies.



DECISION SUPPORT TOOL (DST)



FreeMe has developed a DST to help plating shops adopt and adapt the FreeMe technologies into their existing plating on plastic plants. The DST receives as inputs the end-user needs including the type and size of plastic items (e.g. ABS items at 30 cm2), the production volume (e.g. 100 items), and target specifications (e.g. adhesion, thickness). The backend of the DST includes unit operation and property prediction models for simulating all PoP processing steps (etching, activation, reduction and plating). Finally, the tool returns best operating conditions to tune the whole line – including baths concentrations, operating times and plating conditions – ensuring the achievement of target specifications and optimizing certain objectives driven by Economic (EC), Environmental (EN) or Safety (S) indicators. Custom SSbD objectives can also be set by the user by custom weighting EC, EN and S indicators.

PROJECT PROGRESS

DELIVERABLES SUBMITTED

D1.1 - Report on specifications – GASER – M24

D2.1 - Recommendations for SSbD products and processes A – ICCRAM – M18

D3.1 - Intermediate report of progress of the activities of WP3 – PoliMi – M18

D4.1 - Intermediate report of progress of the activities of WP4 – Creative Nano – M18

D5.1 - First report of progress of the activities of WP5 – IDENER – M18

D8.1 - First PEDRC – EXELISIS – M6

D8.2 - Data Management Plan – PoliMi – M6

D8.3 - Second PEDRC – EXELISIS – M18

MILESTONES ACHIEVED

MS4 - First successful UV-curing of bio-based composite resin in lab – PoliMi – M14

MS5 - Utilization of spray apparatus for application of resin in substrates – PoliMi – M19

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