Eco-friendly plasma polymerized PFAS-free icephobic coatings

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Keywords: *icephobic coatings; plasma polymerization; PFAS-free; ice adhesion; sustainability*
Discipline: *ADVANCES IN SCIENCES OF PAINTS, ADHESIVES, INKS*

Introduction

The market for icephobic coatings is experiencing rapid growth, projected to increase from 423.4 million USD in 2018 to 1,268.1 million USD by 2023, at a CAGR of 24.5% over 5 years [1]. There is a demand not only for increased production of icephobic coatings but also for enhanced efficiency and eco-friendliness. Icing inhibition and ice removal methods can be divided into active and passive categories [2]. Active methods, such as electro-thermal heating, require an external source of energy, making continuous operation energy-intensive and technically challenging. This poses a particular challenge in energy-limited environments such as aerospace. Therefore, the combination of an efficient passive method, like an anti-icing solution, with an active solution is economically and technically crucial [3]. While there have been numerous efforts to develop passive icephobic coatings, most successful solutions, both in research and commercial products, are based on per- and poly-fluoroalkyl substances (PFAS). However, due to evolving regulations and environmental concerns, particularly regarding PFAS and volatile organic compounds (VOCs), there is a growing need for alternative, more sustainable solutions in the icephobic coatings market [4]. Our research, focusing on the development of eco-friendly plasma polymerized PFAS-free icephobic coatings, has the potential to impact the field of sustainability and inspire the creation of more environmentally friendly solutions.

Methodology

The study focuses on employing an atmospheric pressure plasma polymerization technique known as aerosol-assisted plasma polymerization to apply ice-repellent coatings. The utilized technology was PlasmaSpot® from MPG, which is based on a dielectric barrier discharge (DBD) plasma jet (as depicted in Fig. 1). This system allows for the generation of cold plasmas at atmospheric pressure close to room temperature. It comprises two concentric tubular electrodes: the outer electrode is covered with a dielectric layer and connected to the power source, while the inner electrode is grounded. The system is structured in a way that the plasma gas flows through the gap between the electrodes, and the chemical precursors are conveyed by the same type of gas inside the inner tube (Fig. 1). This setup facilitates the gentle activation of precursors, which are only activated by the plasma in the afterglow, and it prevents the unwanted coating deposition on the surfaces within the electrode gap [5].

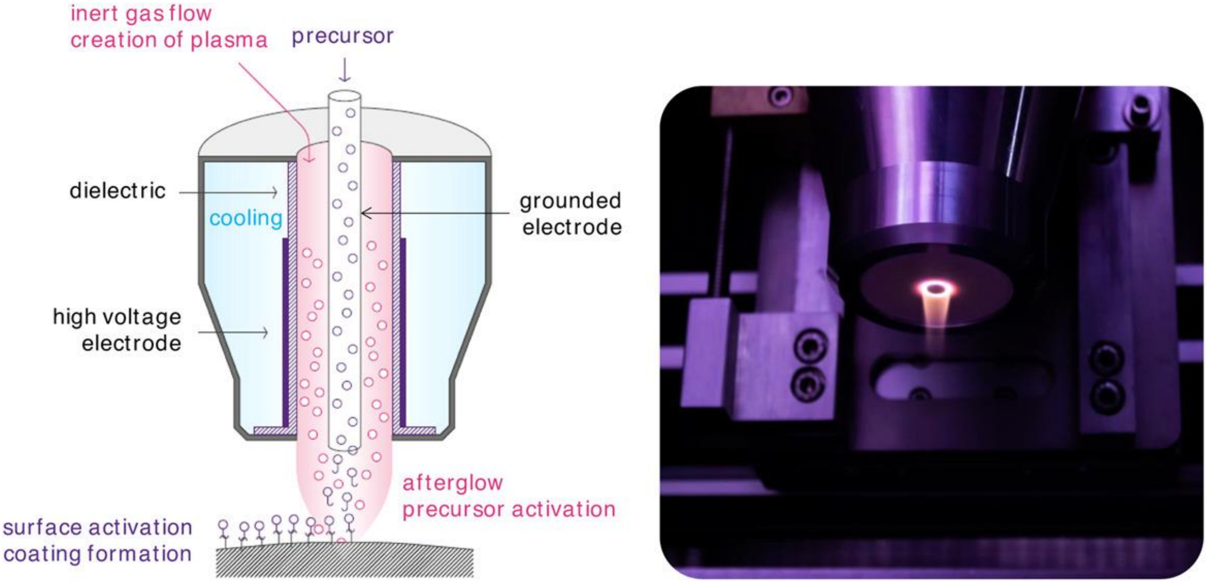

Figure 1. Schematic illustration of MPG PlasmaSpot® technology for aerosol-assisted atmospheric plasma polymerization (left) and actual plasma afterglow (right) [5]

This plasma polymerization method is environmentally friendly as it directly transforms liquid monomer feed into solid polymer films rapidly within seconds, without the use of solvents, volatile organic compounds (VOCs), or other vehicles. In line with sustainability practices, the research utilizes PFAS-free monomers. The specific monomers used include silicone-based molecules such as Hexamethyldisiloxane (HMDSO), 1,1,3,3-Tetramethyldisiloxane (TMDSO), Hexamethyldisilazane (HMDSN), as well as long alkyl chain chlorosilane monomers (C12 and C18). By adjusting various plasma polymerization parameters, including monomer flow rate, plasma power, number of polymerization passes, and polymerization linear velocity, 34 distinct coatings were deposited on aluminum 1050 surfaces and subsequently compared in terms of ice-repellent performance through horizontal shear ice adhesion testing and freezing time/temperature analyses. Additionally, the coatings' characteristics, including morphology, wettability, chemistry, and stability, were thoroughly examined.

Results and conclusions

Ice adhesion tests conducted at -10℃ showed that coatings based on HMDSO, HMDSN, and chlorosilanes decreased ice adhesion by 51%, 30%, and 45%, respectively. Additionally, the HMDSO and HMDSN coatings demonstrated a significant increase in freezing time at -10℃, with freezing times extending by more than 45 times. Notably, water droplets did not freeze when in contact with the chlorosilane coating at -10℃ and -15℃ for up to 15 minutes. The durability of the coating ice-repelling properties was evaluated over 6 months, during which no decline in performance was observed despite multiple icing/ice-detachment cycles.

In conclusion, aerosol-assisted plasma polymerization has shown great promise in developing sustainable, environmentally friendly, and long-lasting icephobic coatings without the use of PFAS and high VOC wet chemistry methods. The work is ongoing, using plant-based and waterborne polymerization feed in combination with femtosecond laser-textured aluminum surfaces.

Acknowledgment

This work received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956703 (SURFICE-Smart surface design for efficient ice protection and control). Navid Mostofi Sarkari appreciates ATIPIC (Belgian Association of Technicians from the Paint and Allied Industries) and FATIPEC (Federation of Associations of Technicians for Industry of Paints in European Countries) for granting the ETCC2024 Young Scientist Award to present this work. The authors acknowledge Research Foundation Flanders-FWO (Medium-scale infrastructure project I009220N) and KU Leuven Internal funding (Medium-scale infrastructure project AKUL/17).

References

[1] GLOBAL ICE-PHOBIC COATING MARKET INSIGHTS, FORECAST TO 2029, 2023.

[2] M. Shamshiri, R. Jafari, G. Momen, Potential use of smart coatings for icephobic applications: A review, Surf Coat Technol 424 (2021) 127656. https://doi.org/10.1016/j.surfcoat.2021.127656.

[3] X. Huang, N. Tepylo, V. Pommier-Budinger, M. Budinger, E. Bonaccurso, P. Villedieu, L. Bennani, A survey of icephobic coatings and their potential use in a hybrid coating/active ice protection system for aerospace applications, Progress in Aerospace Sciences 105 (2019) 74–97. https://doi.org/10.1016/j.paerosci.2019.01.002.

[4] J. Glüge, M. Scheringer, I.T. Cousins, J.C. DeWitt, G. Goldenman, D. Herzke, R. Lohmann, C.A. Ng, X. Trier, Z. Wang, An overview of the uses of per- and polyfluoroalkyl substances (PFAS), Environ Sci Process Impacts 22 (2020) 2345–2373. https://doi.org/10.1039/D0EM00291G.

[5] J. Borek-Donten, B. Nisol, M. Filimon, M. Lopes, D. Collard, M. Chassaing, H.M. Cauchie, R. Heyberger, The industrial process for virucidal plasma coatings on textiles: From idea to upscaling, Plasma Processes and Polymers 19 (2022) 2100249. https://doi.org/10.1002/PPAP.202100249.