Commentary
Volume 10:01, 2025

Journal of Nanosciences: Current Research

ISSN: 2572-0813

Open Access

Fabrication of Nano-micro Structured Photothermal and Hydrophobic Surfaces for Anti-icing Applications

Brevik Nagarsh*

Department of Industrial Engineering, Urmia University of Technology, Urmia, Iran

Introduction

The development of advanced surface engineering techniques has led to significant progress in controlling interfacial properties, particularly in environments where ice formation presents a critical challenge. Ice accumulation on surfaces poses serious risks in various fields, including aerospace, transportation, energy infrastructure, and outdoor equipment. Traditional de-icing and anti-icing strategies, such as mechanical removal, chemical de-icers, and heating systems, are often inefficient, environmentally hazardous, or energy-intensive. As a result, there is a growing interest in passive and energy-efficient anti-icing solutions that leverage surface modifications at the nano and micro scales. Among these, photothermal and hydrophobic surfaces with hierarchical nano-micro structures have emerged as promising candidates for preventing ice formation and enhancing surface functionality. Photothermal surfaces utilize the ability of engineered materials to absorb solar radiation and convert it into heat, which can be used to prevent ice nucleation or accelerate ice melting. By integrating nanoscale materials with high light absorption capabilities, such as carbon-based nanostructures, plasmonic metals, or black silicon, photothermal surfaces can efficiently increase localized temperatures with minimal external energy input. In parallel, hydrophobic and superhydrophobic surfaces exploit the principle of reducing surface wettability to delay water droplet adhesion, reducing the likelihood of ice formation. Inspired by natural surfaces like lotus leaves and desert beetles, engineered nano-micro structured surfaces can achieve extreme water repellency by introducing hierarchical roughness combined with low-surface-energy coatings.

Description

This study explores the fabrication of nano-micro structured photothermal and hydrophobic surfaces and evaluates their effectiveness in anti-icing applications. By combining photothermal energy conversion with surface wettability control, these engineered surfaces provide a dual-function approach to mitigate ice accumulation. The research highlights various fabrication techniques, material choices, and performance assessments to understand how these surfaces can be optimized for real-world applications. The integration of nanotechnology with surface physics offers a novel strategy for passive, energy-efficient, and durable anti-icing solutions. The fabrication of nano-micro structured surfaces with photothermal and hydrophobic properties involves a combination of advanced material processing techniques. Achieving the desired functional characteristics requires precise control over surface roughness, chemistry, and optical properties to enhance both photothermal heating and water repellency. Several fabrication methods are commonly used to engineer such surfaces, including laser processing, chemical etching, electrospinning, and nanoparticle deposition. Each method offers unique advantages in tailoring surface morphology and functionality for anti-icing applications.

***Address for Correspondence:** Brevik Nagarsh, Department of Industrial Engineering, Urmia University of Technology, Urmia, Iran, E-mail: nagarshbrevik22@gmail.com*

Received: 01 January, 2025, Manuscript No. jncr-25-163986; **Editor assigned:** 03 January, 2025, Pre QC No. P-163986; **Reviewed:** 17 January, 2025, QC No. Q-163986; **Revised:** 22 January, 2025, Manuscript No. R-163986; **Published:** 29 January, 2025, DOI: 10.37421/2572-0813.2025.10.275

Laser processing is a widely used technique for creating nano-micro structures on various substrates. Femtosecond laser ablation, for example, allows for the precise modification of surface topography by introducing controlled roughness patterns that enhance light absorption and hydrophobicity. The formation of microgrooves, nanostructured ripples, and hierarchical roughness through laser structuring provides an effective means of reducing water droplet adhesion while simultaneously enhancing the photothermal effect. The advantage of laser-based fabrication lies in its scalability and adaptability to different materials, including metals, polymers, and ceramics. Chemical etching is another common method for fabricating nano-micro structured surfaces. This technique involves selective etching of materials to create rough topographies that mimic natural water-repellent surfaces. For instance, black silicon, a material widely used in photothermal applications, can be fabricated through reactive ion etching or metal-assisted chemical etching. The resulting nanostructures significantly enhance light absorption across a broad spectrum, making black silicon an ideal candidate for photothermal anti-icing surfaces. In addition, the introduction of low-surface-energy coatings, such as fluorinated silanes or polytetrafluoroethylene, further enhances the hydrophobic nature of the surface.

Electrospinning provides another route to fabricate nano-micro structured surfaces by generating polymer or composite nanofibers with tailored surface properties. By carefully selecting polymer compositions and deposition conditions, electrospun fibers can achieve high surface roughness and porosity, contributing to superhydrophobic behavior. When combined with light-absorbing nanoparticles, such as graphene, carbon nanotubes, or plasmonic nanostructures, electrospun surfaces can exhibit excellent photothermal properties, making them highly effective for passive anti-icing applications. The ability to produce large-area coatings with electrospinning makes it a viable method for scaling up the fabrication of anti-icing surfaces. Nanoparticle deposition is another powerful technique for engineering photothermal and hydrophobic surfaces. By depositing plasmonic nanoparticles, carbon-based nanostructures, or metal oxides onto a substrate, it is possible to enhance light absorption and heat generation upon solar irradiation. Gold and silver nanoparticles, for example, exhibit strong localized surface plasmon resonance (LSPR), enabling efficient photothermal conversion when exposed to sunlight. Similarly, carbon-based materials like graphene and carbon black provide broadband light absorption and excellent thermal conductivity, which contribute to rapid heat dissipation across the surface. When combined with hydrophobic coatings, these nanoparticle-functionalized surfaces achieve both photothermal and anti-icing functionalities, offering a practical and energy-efficient approach to ice mitigation.

The performance of these nano-micro structured surfaces in anti-icing applications is typically evaluated through laboratory experiments that simulate real-world conditions. Ice adhesion tests, water droplet freezing delay measurements, and optical heating efficiency assessments provide insights into the effectiveness of the fabricated surfaces. One key metric for evaluating anti-icing performance is the ice adhesion strength, which quantifies the force required to remove ice from the surface. Surfaces with low ice adhesion strength exhibit better ice-repelling properties, reducing the risk of ice buildup and improving safety in cold environments. Hydrophobic surfaces with hierarchical roughness have been shown to significantly reduce ice adhesion by minimizing direct contact between water droplets and the surface. Water droplet freezing delay measurements provide another important indicator of anti-icing performance. In these experiments, droplets of supercooled water are placed on the surface, and the time taken for freezing to initiate is recorded. Photothermal surfaces with efficient light absorption can extend the freezing delay by continuously converting solar energy into heat, preventing ice formation even under sub-zero temperatures. The combination of photothermal heating and superhydrophobicity further enhances this effect, as water droplets tend to roll off rather than freeze in place. Experimental studies have demonstrated that surfaces integrating both photothermal and hydrophobic properties can extend freezing delay times by several orders of magnitude compared to untreated surfaces [1-5].

Conclusion

The fabrication of nano-micro structured photothermal and hydrophobic surfaces presents a promising strategy for developing energy-efficient and durable anti-icing solutions. By leveraging hierarchical surface structuring, advanced nanomaterials, and light absorption engineering, these surfaces effectively mitigate ice formation through a combination of photothermal heating and reduced water adhesion. The integration of laser processing, chemical etching, electrospinning, and nanoparticle deposition enables the precise design of surfaces with tailored optical and wetting properties. Experimental studies have demonstrated the effectiveness of these surfaces in delaying ice formation, reducing ice adhesion, and maintaining thermal stability under freezing conditions.

While significant progress has been made in the development of anti-icing surfaces, challenges remain in optimizing their long-term performance, scalability, and environmental stability. Future research should focus on improving the durability of hydrophobic coatings, enhancing the efficiency of photothermal materials, and developing self-healing surfaces that maintain functionality over extended use. Additionally, the integration of smart materials and responsive surfaces that dynamically adapt to environmental conditions could further enhance anti-icing capabilities. With continued advancements in nanotechnology and surface engineering, nano-micro structured photothermal and hydrophobic surfaces are poised to play a crucial role in addressing icing challenges across various industries, offering sustainable and high-performance solutions for extreme weather conditions.

Acknowledgment

None.

Conflict of Interest

None.

References

1. Li, Zhiguang, Xiaorui Wu, Xu Huang and Que Kong. "Composite Fiber Membrane with Janus Structure via Electrospinning Technique and its Separation and Antibacterial Properties." *Fibers Polym* (2025): 1-11.
2. Cao, Liangliang, Andrew K. Jones, Vinod K. Sikka and Jianzhong Wu, et al. "Anti-icing superhydrophobic coatings." *Langmuir* 25 (2009): 12444-12448.
3. Mishchenko, Lidiya, Benjamin Hatton, Vaibhav Bahadur and J. Ashley Taylor, et al. "Design of ice-free nanostructured surfaces based on repulsion of impacting water droplets." *ACS Nano* 4 (2010): 7699-7707.
4. Shen, Yizhou, Jie Tao, Haijun Tao and Shanlong Chen, et al. "Anti-icing potential of superhydrophobic Ti6Al4V surfaces: Ice nucleation and growth." *Langmuir* 31 (2015): 10799-10806.
5. Wu, Shuwang, Yingjie Du, Yousif Alsaid and Dong Wu, et al. "Superhydrophobic photothermal icephobic surfaces based on candle soot." *Proc Natl Acad* Sci 117 (2020): 11240-11246.

How to cite this article: Nagarsh, Brevik. “Fabrication of Nano-micro Structured Photothermal and Hydrophobic Surfaces for Anti-icing Applications.” *J Nanosci Curr Res* 10 (2025): 275.