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Facilely Fabricated Hair-Based Photothermal Materials with Microstructure for Deicing

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ABSTRACT: Icing poses significant challenges to infrastructure and energy systems, necessitating efficient and sustainable deicing solutions. This study presents a photothermal material that is facilely fabricated from waste human hair, offering a low cost and environmentally friendly deicing approach. A microstructure is introduced to enhance light absorption through internal trapping. Under 1 sun irradiation, the optimized material reaches 65°C within 10 min and maintains stable performance during prolonged and cyclic heating. It exhibits excellent anti-icing, deicing, and defrosting capabilities, successfully melting ice layers up to 5 mm thick on a blade model within 90 s. With high flexibility and durability, the waste-derived photothermal material provides a scalable, economical, and sustainable strategy for practical deicing applications.

KEYWORDS: Photothermal materials; hair; heat; deicing

1 Introduction

Icing is a widespread and unavoidable natural phenomenon that causes inconvenience in daily life and leads to substantial energy losses. As for wind energy, ice accretion on turbine blades changes their profile and increases the load and drag, resulting in low efficiency [1]. Thus, deicing is essential to maintain operational efficiency and ensure structural safety. Currently, deicing strategies can be broadly classified into active and passive methods. Active approaches, such as hot air [2], electrothermal methods [3–7], and ultrasonic techniques [6–10], often require high energy input and structural modifications [11]. In contrast, passive methods, such as chemical treatments [12–14], biochemical processes [15,16], and surface coatings [17–19], reduce energy consumption while maintaining the equipment structure [20]. Recently, photothermal materials have emerged as a promising passive solution [21], using the photothermal effect to transform sunlight into heat. Compared to other passive strategies, it is affordable for large-scale applications and tends to maintain efficiency over time. The sustainable approach offers a promising future for advanced anti-icing and deicing technologies.

In deicing applications, the manufacturing process determines the photothermal performance and cost of photothermal materials, a key to their practical applications. Currently, the most widely used photothermal materials are primarily composed of carbon-based substances and metal nanomaterials. The methods are limited by environmental hazards, inefficiency, high cost, or procedural complexity. Carbon-based materials [22], such as carbon nanotubes and graphene, exhibit excellent light absorption and efficient

photothermal conversion. However, their widespread use is hindered by high production costs and complex synthesis. In particular, Carbon nanotubes and graphene demand multiple steps and high-purity processing, and substantial density, markedly increasing production times and energy consumption. Meanwhile, metal nanomaterials also present certain disadvantage. For example, ferrocene and its derivatives [23] as photothermal materials also need high manufacturing costs and complicated synthesis. Besides the fact that higher density can affect device operation, the inherently high thermal conductivity of metals promotes rapid heat dissipation, thereby diminishing localized heat utilization efficiency. The irresponsible handling of the materials, such as random discarding or high-temperature incineration, creates substantial environmental hazards due to metal pollution. Therefore, developing a scalable and economical manufacturing process for photothermal materials is crucial for industrial deicing.

Human hair is a natural photothermal material due to its intrinsic composition. It is abundant, particularly in Asia and Africa, where black hair predominates. Chemically, it consists primarily of keratin, melanin, lipids, and moisture [24]. Melanin, which accounts for approximately 3–5% of hair, is the key component for its light absorption capacity. The photothermal conversion mechanism of melanin involves strong absorption across the visible (600–700 nm) and near-infrared (700–1100 nm) spectra. When irradiated within these wavelengths, melanin absorbs photon energy and converts it into heat through electron transition processes. However, across many regions, discarded hair is categorized as municipal solid waste and is commonly incinerated or landfilled with other wastes, leading to significant environmental problems. Global waste management data reveal that approximately 83% of waste hair is incinerated or landfilled, while only 17% is used in secondary applications such as wigs. During incineration, the high nitrogen content (16–18%) in hair promotes the emission of greenhouse gases, including nitrous oxide and carbon dioxide, under high temperature conditions, thereby contributing to the greenhouse effect. The process also releases organic pollutants persistently, such as dioxins and sulfur compounds, resulting in a large number of emissions that damage air quality and pose risks to human health [25]. When landfilled, hair decomposes under anaerobic conditions and releases methane. Furthermore, with a natural degradation period ranging from 2 to 5 years, hair can destroy soil structure, reduce soil aeration, and generate volatile organic compounds that produce malodorous emissions and other environmental problems. Using waste hair for photothermal applications presents a sustainable and economical strategy. The approach effectively relieves the environmental burdens associated with conventional hair disposal. Meanwhile, it enables an economical production of photothermal materials.

Herein, we develop photothermal materials from human hair through a facile process. Its performance is evaluated through a series of tests. To enhance light absorption efficiency, a microstructure is introduced to establish geometric light trapping pathways. The durability, stability, and practical applicability are tested through cyclic icing and deicing tests, fatigue tests, defrosting experiments, and deicing tests on the blade model. The results demonstrate exceptional performance of the material and low cost, underscoring its promising potential for broad practical applications.

2 Experimental Methods

2.1 Materials and Chemicals

PDMS and its curing agent were purchased from Dow Corning. The mold was fabricated by ablating an aviation aluminum surface using a femtosecond laser. Waste hair was obtained from local barbershops. Deionized water was prepared in the laboratory and used for all experiments. All chemicals were used without any further purification.

2.2 Sample Preparation

The simple procedure for preparing the photothermal material is shown in Fig. 1. Initially, do a washing of the waste hair to clean impurities and contaminants. Subsequently, the cleaned hair is mechanically crushed into fragments. A precision grinding further turns the fragments into a homogeneous powder. After crushing, PDMS and the curing agent are mixed at a 10:1 mass ratio in a glass beaker. The requisite mass fraction of black hair for each photothermal material is introduced into the mixture. Then, stir the mixture for 20 min to ensure uniform dispersion of the hair powder. The solution is poured into smooth molds and microstructured molds slowly, achieving consistent thickness and complete substrate coverage. The filled molds are placed on a hot plate at 60°C for 60 min. Demolding obtains smooth samples and microstructured samples with structures for harvesting light. Upon examining the material, we observed no agglomeration in the composite and found that the hair was uniformly distributed. Fig. 2 shows the SEM images of the hair, its cross section, and the smooth and microstructured surfaces that incorporate hair.

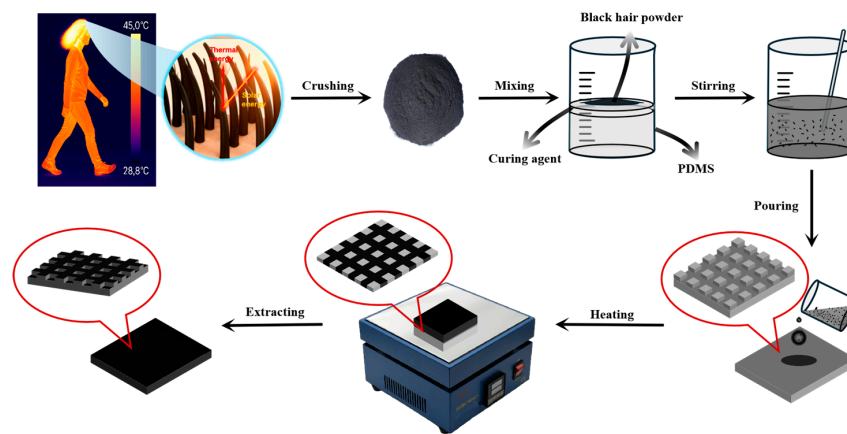


Figure 1: Schematic illustration of the preparation process for the photothermal materials.

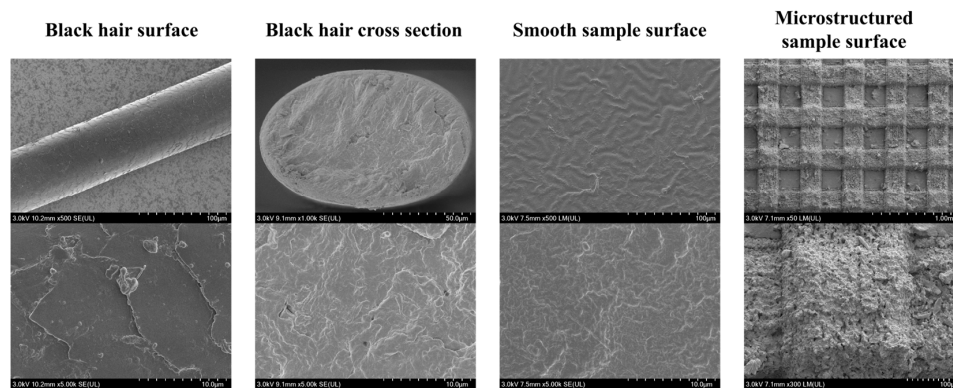


Figure 2: Hair surface, cross section, smooth material surface, microstructure material surface diagram, and their magnified diagrams.

Fig. 3 shows a cross-section of the photothermal material observed by SEM. The microstructures on the upper surface can reflect and refract light, while the light that enters the material is absorbed by melanin in the hair and subsequently converted into heat. The distribution of hair fibers in the sample was examined using a high-magnification optical microscope. As shown in Fig. 3, the fibers are uniformly distributed throughout the matrix without agglomeration, indicating a homogeneous distribution of the hair.



Figure 3: Cross sections of the photothermal material obtained by scanning electron microscopy.

2.3 Experimental Equipment

The photothermal conversion, anti-icing, deicing, and defrosting performances of the materials were evaluated on a homemade testing platform. As shown in Fig. 4, the platform was equipped with a semiconductor refrigeration counter, a thermocouple thermometer, a CMOS camera, and a xenon lamp that served as a solar simulator. The photothermal conversion capability was also verified by the UV-vis-NIR absorption spectrum and the infrared thermal imaging. The experiments were conducted at room temperature ($25 \pm 0.5^\circ\text{C}$) under adjustable irradiation, which was achieved by varying the distance between the lamp and the samples. Employing an approach with controlled variables, the optimal filler loading was identified as 20% for microstructured samples, based on the photothermal conversion. Durability validation comprised a 200 min continuous irradiation stability test and five consecutive thermal cycles, both tests were conducted on the platform. Subsequent anti-icing, deicing, and defrosting tests verified its performance, corroborating the superior efficiency of the 20% composition. Additionally, the applicability of the material was further demonstrated in a trial on a blade model and cyclic folding tests.

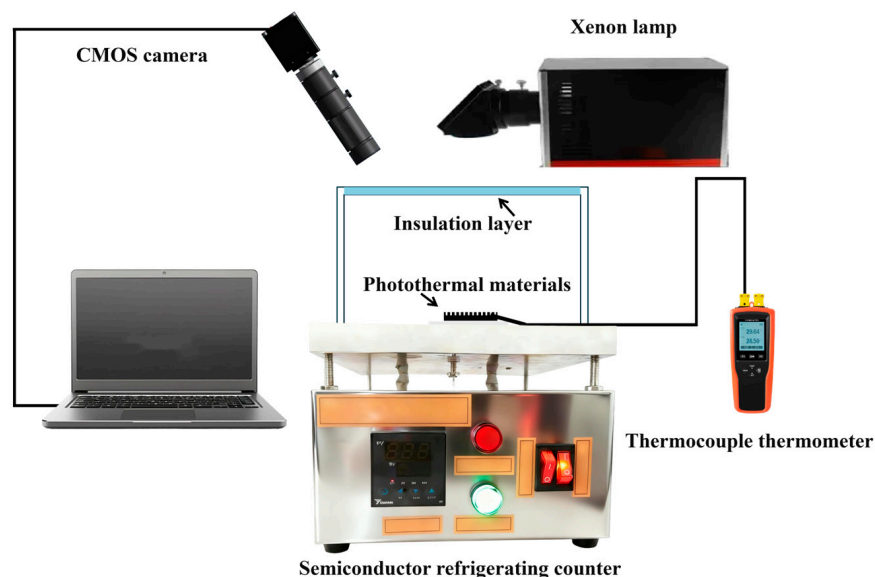


Figure 4: Schematic of the homemade device for evaluating photothermal performance as well as anti-icing, deicing, defrosting capabilities and so on.

3 Result and Discussion

3.1 Photothermal Response

3.1.1 Infrared Thermal Imaging

The working principle of this photothermal material is as follows: incident light undergoes multiple reflections and scatterings by the surface micropillar array, thereby enhancing light absorption by melanin in the hair. The photothermal effect occurs predominantly within the melanin. Melanin molecules possess an extensive conjugated π -electron system that enables efficient absorption of ultraviolet, visible, and near-infrared photons, exciting electrons from the ground state to a high-energy excited state. The excited-state energy then undergoes nonradiative relaxation via ultrafast internal conversion and excited-state proton transfer, rapidly converting the electronic excitation energy into vibrational thermal energy of the molecular bonds and the surrounding medium, thereby achieving efficient light-to-heat conversion. While several concepts are initially proposed to enhance light absorption, it is the opinion of microstructures that proves most effective. Through iterative adjustments to the microstructure dimensions, a microstructure with a square array of micro columns is selected. The corresponding mold is fabricated from an aviation aluminum plate, featuring columns measuring 250 μm in length and width, 50 μm in height, and a spacing of 250 μm between adjacent columns. The geometrical parameters of the microstructure are given after experimentally evaluating a range of structural parameters. The optical absorption spectra of different surfaces are measured by UV-Vis-NIR spectroscopy (Fig. 5a). The black hair is the same to microstructured photothermal materials; due to its fluffiness, enhance the absorption. The microstructured photothermal materials exhibit significantly stronger absorption than the smooth sample. It is attributed to the increased surface roughness introduced by the light trapping design, which promotes multiple internal reflections of incident photons within the microstructure array. Consequently, energy loss through specular reflection is reduced, effectively enhancing light absorption and overall photothermal conversion performance. The surface temperature change of the materials under one sun irradiance was recorded by an infrared thermal imager (Fig. 5b). The thermal image demonstrates a uniform temperature distribution across the material surface, with the microstructured samples exhibiting a higher temperature than the smooth samples. The temperature change is shown in Fig. 5c in detail. The surface temperature rises rapidly initially and enters a phase of decelerating increase latter. Under one sun condition, the microstructured samples reached a temperature of approximately 65°C within 10 min, about 5°C higher than the smooth samples, demonstrating their superior light harvesting efficiency. Under identical solar irradiation, the developed materials demonstrate superior surface temperature elevation compared to black hair, confirming their high photothermal conversion efficiency. The finding indicates the synergistic combination of blackbody properties and engineered microstructures endows the materials with superior photothermal conversion abilities.

3.1.2 Heating Performance of Materials with Different Concentrations

To identify the optimal concentrations for deicing applications, a series of photothermal samples were prepared with mass fractions of 0%, 1%, 3%, 5%, 10%, 15%, 20%, and 30%. The surface temperature of each sample was monitored using a thermocouple thermometer during exposure to one sun irradiation. The temperature change of the materials under one sun irradiation exhibits a gradually decelerating heating rate (Fig. 5d). Under one sun irradiation, the samples containing 0% black hair reach a temperature of approximately 35°C after 10 min, which is consistent with the environment temperature on one sun irradiation. At lower concentrations, an increase in mass fraction markedly enhances the photothermal

effect. Nevertheless, with further elevation of the mass fraction, the rate of improvement in the photothermal performance diminishes. Upon reaching a mass fraction of 15%, the temperature becomes nearly constant over a period of ten minutes. Samples with 15%, 20%, and 30% loading exhibit the same initial heating trajectories. Under prolonged irradiation, the performance differs significantly. The 20% and 30% samples maintain superior thermal accumulation, while the 15% sample exhibits a plateau. Considering the small increase in efficiency against the 50% increase in material consumption, the 20% samples are selected as the optimal balance between performance and sustainability.

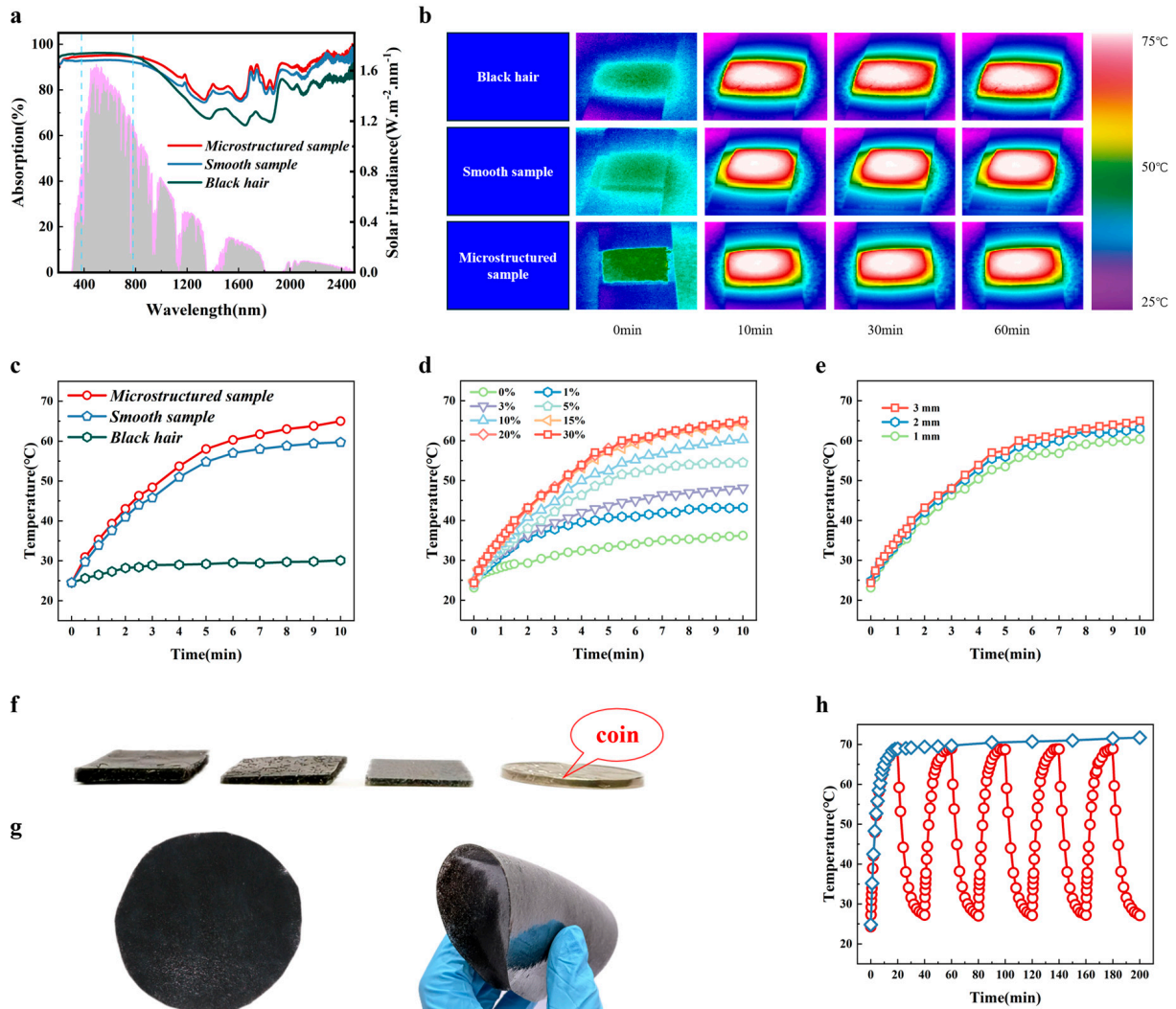


Figure 5: (a) Solar spectrum irradiance (AM 1.5 G) and the UV-vis-NIR absorption of the materials. (b) Infrared thermal camera image of the microstructured sample, smooth sample and black hair under 1 sun irradiation. (c) Record the temperature increasing process of the microstructured sample, smooth sample and black hair under one sun irradiation. (d) Recorded temperature variations of microstructured samples with different concentrations over a 10 min duration. (e) Recorded temperature variations of microstructured samples with different thickness in 10 min. (f) Width comparison between the photothermal material and a one-yuan coin. (g) Demonstration of the flexibility of the photothermal material. (h) Temperature profiles of the material under continuous 200 min irradiation and five cyclic irradiation tests.

3.1.3 Heating Performance of Materials with Different Thickness

To identify the optimal material thickness for deicing applications, we prepared photothermal samples with three different thicknesses: 1 mm, 2 mm, and 3 mm. As shown in Fig. 5f, the photothermal material is clearly thin, demonstrated by comparison with a one-yuan coin. Fig. 5g demonstrates outstanding flexibility. Regarding the effect of thickness on temperature, the photothermal effect occurring at the material surface needs to be considered. Under standard one sun illumination, the surface temperature of each sample was monitored in real time using a thermocouple, as shown in Fig. 5e. After 10 min of illumination, the temperature difference among the three samples was approximately 2°C. Due to the thickness leading to higher thermal resistance, which promotes heat accumulation at the surface and consequently results in a higher steady temperature. Considering the energy loss and efficiency, we selected the 2 mm material as the optimal choice for subsequent application.

3.1.4 Photothermal Stability of the Material

To assess the long-time photothermal stability under exposure to sunlight, the 20% sample was subjected to one sun irradiation for 200 min. The surface temperature exhibited an initial rapid heating to 65°C within 10 min, followed by a transition period reaching 70°C at 20 min. Thereafter, the sample entered a stable phase with minimal fluctuation, gradually approaching a final temperature of 71°C after 200 min of exposure. Fig. 5h demonstrates outstanding photothermal endurance with no performance decrease, an essential property in prolonged applications.

To evaluate photothermal stability under repetitive thermal cycling, the 20% sample was subjected to five consecutive cycles, each consisting of 20 min of solar irradiation followed by 20 min of passive cooling at environment temperature. Through recording the surface temperature of photothermal materials, we obtained the temperature change over time (Fig. 5h). During the initial heating phase, the temperature rise rate gradually decreased until stabilizing at 70°C. The subsequent cooling phase, driven by the large temperature difference with the environment, showed an initial rapid drop followed by gradual stability. However, the second heating cycle began from a higher baseline due to residual heat, yet it was closely common to the first cycle and reached the same peak temperature of 70°C. The trend persisted through cycles 3, 4 and 5, demonstrating stable performance under repeated thermal cycling and confirming the exceptional durability of the materials for practical applications.

3.1.5 Photothermal Efficiency

To quantitatively evaluate the photothermal conversion performance of the material, we calculated the photothermal conversion efficiency, defined as the ratio of the heat generated by photothermal conversion to the incident solar energy. The calculation formula is as follows:

$$\eta = \frac{Q}{q \cdot A} \quad (1)$$

where Q is the heat generated by photothermal conversion, q is the incident solar power density (1000 mW/m²), and A is the surface area of the photothermal material (taken as unit area here).

With light irradiation increased, the surface temperature gradually approaches a steady state. The heat generated by photothermal conversion reaches a dynamic equilibrium with the heat dissipated to the surroundings. Accordingly, the heat generated by the photothermal material can be expressed as:

$$Q = Q_s = h \cdot A \cdot (T_{sub} - T_{surr}) \quad (2)$$

where Q_s is the heat loss from the material to the surroundings, h is the average convective heat transfer coefficient at the material surface ($\text{W}/\text{m}^2\cdot\text{K}$), T_{sub} is the steady temperature of the sample, and T_{surr} is the ambient temperature. The convective heat transfer coefficient h can be calculated using the following equation:

$$Nu = \frac{h \cdot L}{\lambda} \quad (3)$$

where Nu is the Nusselt number, L is the characteristic length of the heat transfer region (taken as unit length here), and λ is the thermal conductivity of the fluid at the corresponding temperature. The Nusselt number in the experiment can be determined using the following empirical correlation:

$$Nu = 0.135 \times (Gr \cdot Pr)_m^{1/3} \quad (4)$$

where Gr is the Grashof number, Pr is the Prandtl number. The subscript m denotes that the reference temperature is taken as the arithmetic mean temperature of the boundary layer.

$$t_m = (t_w + t_\infty)/2 \quad (5)$$

The Grashof number Gr and Prandtl number Pr are calculated as follows:

$$Gr = g\alpha_v\Delta TL^3/\nu^2 \quad (6)$$

$$Pr = \nu/a \quad (7)$$

where g is the gravitational acceleration, α_v is the volumetric thermal expansion coefficient ($\alpha_v = 1/T_m$, where T_m is the mean temperature), ΔT is the mean temperature difference between the surface and the fluid, ν is the kinematic viscosity, and a is the thermal diffusivity. Assuming that the photothermal material reaches a steady temperature T_{sub} of 70°C , the ambient temperature T_{surr} is 25°C . The relevant physical properties were determined by thermophysical property tables, $\nu \approx 18 \times 10^{-6} \text{ m}^2/\text{s}$, $\alpha \approx 25 \times 10^{-6} \text{ m}^2/\text{s}$, $\lambda \approx 2.8 \times 10^{-2} \text{ W}/\text{m}\cdot\text{K}$, $\alpha_v \approx 3.14 \times 10^{-3} \text{ K}^{-1}$. Based on the above calculations, the results are as follows:

$$\eta = \frac{Q}{q \cdot A} = \frac{h \cdot A \cdot (T_{sub} - T_{surr})}{q \cdot A} = \frac{\lambda \cdot Nu \cdot (T_{sub} - T_{surr})}{q \cdot L} \approx 41\% \quad (8)$$

Since the material is a mixture, its physical properties are only approximate values; therefore, the calculated efficiency is approximately 41%.

3.2 Practical Application and Fatigue Analysis

3.2.1 The Wettability of the Material

The contact angle, measured at room temperature using an optical goniometer, was employed to characterize surface wettability [26]. A larger contact angle facilitates droplet rolling off by reducing the adhesion between solid and liquid. As shown in Fig. 6a, black hair exhibits a very small contact angle, causing liquid droplets to penetrate the hair structure rather than rolling off. In contrast, the contact angle increased significantly due to the combination with PDMS. The introduction of microstructure further increases the contact angle, promoting droplet shedding. The results demonstrate that only hair is unsuitable

for direct application, whereas the microstructure reduces the contact area between solid and liquid. The reduction minimizes water adhesion to the surface. It leads to a decrease in wettability, which consequently accelerates droplet shedding. As a result, the formation of surface ice is effectively mitigated.

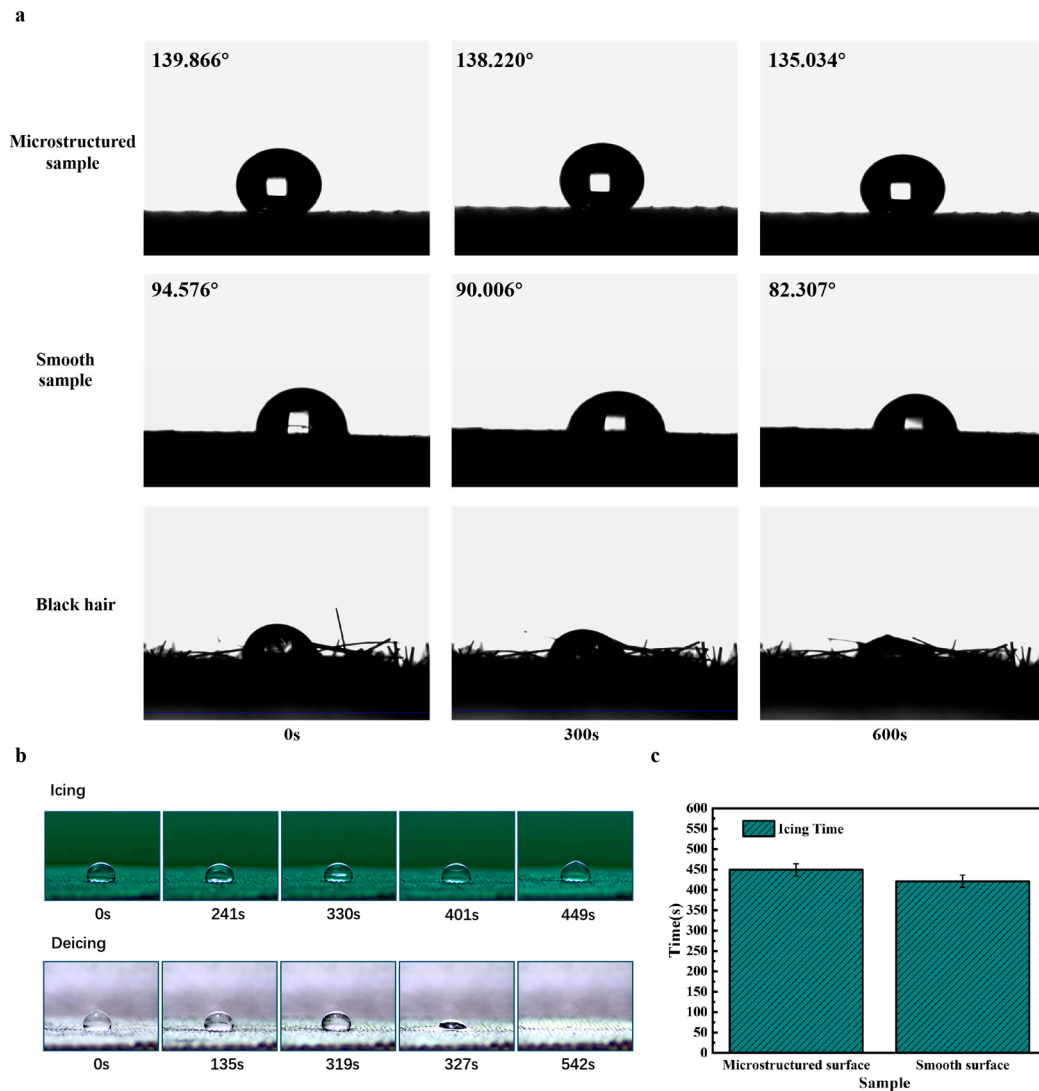


Figure 6: (a) Single water droplet adhesion test on the surface of the microstructured sample, smooth sample and black hair. (b) The icing process of a water droplet on the microstructured sample and deicing process of a water droplet on the microstructured sample. (c) The icing time of different surfaces.

3.2.2 The Anti-Icing and Deicing Behavior of Droplets

The anti-icing and deicing performance of the photothermal materials was quantified by direct observation of a 10 μ L deionized water droplet icing process. The samples were mounted on a refrigerated counter maintained at -20°C , while the dynamic processes were recorded using CMOS imaging (Fig. 6b). The freezing process was characterized by the transition of the droplet from a transparent liquid to an opaque solid. Due to direct contact with the cold stage, the droplet began freezing from the bottom, with the boundary between solid and liquid advancing upward. Freezing completed at 449 s when the droplet became fully opaque and formed a peach tip geometry. A slight contraction at the base of the droplet indicated a

certain degree of hydrophobicity of the materials. Compared to a smooth surface under identical conditions, the microstructured surface delayed ice nucleation and extended the total freezing time, demonstrating its significant anti-icing capability (Fig. 6c). The droplet deicing experiment was also monitored using a CMOS camera. While the refrigerating counter was maintained at -20°C , the frozen droplet was irradiated under one sun intensity using a xenon lamp. As shown in Fig. 6b, due to the photothermal conversion, deicing initiated from the bottom of the droplet in contact with the sample. Once the ice layer melted under sunlight, the middle ice layer subsequently continued to melt from the bottom upward. Owing to the freezing process having previously caused frost on the material surface, leading to the material preheating needing some time, the complete melting of the droplet took 542s. Although the low temperature of the refrigerating counter slowed the overall deicing process, the experiment clearly demonstrates the potential applicability of the materials in the field of deicing.

On a smooth photothermal surface, a droplet lost heat to the surrounding air through thermal conduction and radiation. In contrast, due to the trapped air within the microstructure, the droplet on materials was considered a solid-liquid-gas triphasic system. During the freezing process, heat loss primarily across the gas-liquid and solid-liquid boundaries, as the trapped air within the microstructure significantly increases the thermal contact resistance between the droplet and the sample. Consequently, it reduces the heat loss, thereby endowing the surface with significant ice delaying capability. A greater volume of entrapped air beneath the droplet leads to less heat loss [27]. The findings suggest that microstructured surfaces hold broad potential for both anti-icing and deicing applications.

3.2.3 Performance of Defrosting, Deicing and Application

To simulate the impact of early morning frost events, a defrosting experiment was performed on the photothermal materials. The microstructured photothermal samples were placed on a refrigerating counter maintained at -20°C for one hour to induce frost formation, resulting in a uniform white frost layer approximately 2 mm in thickness. Then, the frost was irradiated under one sun irradiation from a xenon lamp. Complete defrosting was achieved in 355 s, with the lamp preheating time included. Fig. 7a illustrates the defrosting process, whereby melting initiated at the periphery due to edge effects. As the material temperature rose under irradiation, the defrosting rate accelerated markedly. However, the frost deposited around the photothermal materials remained intact, which directly corroborates the exceptional defrosting capability of the developed material.

Ice accretion on wind turbine blades increases their weight and alters mass distribution, which can lead to rotor imbalance and reduce aerodynamic efficiency. The icing phenomenon consequently leads to a decrease in power generation. Lightweight photothermal coatings therefore present a promising strategy for preventing ice formation on the blades. The deicing performance is tested in the following section. Droplets of deionized water were placed on the photothermal materials surface and frozen on a refrigerating counter, simulating the accumulation of ice at night. The resulting ice cube measured 5 cm in length and 3 mm in thickness. Subsequently, turn on the xenon lamp to irradiate the photothermal material under one sun irradiation and observe the ice melting process. The change in the ice layer was recorded over time. As shown in Fig. 7b, the ice melt rapidly from the bottom first, followed by upward melting. It led to separation and the falling of the ice. The entire process, initiated by photothermal conversion at the base, confirms the high photothermal deicing efficiency of the material.

To evaluate the deicing performance of the photothermal coating applied to wind turbine blades, an industrial application analysis of the material was carried out. The coating was applied and cured on a blade model, which was subsequently placed on a refrigerating counter for testing. Deionized water was

slowly dripped onto the photothermal surface and allowed to freeze, forming an ice layer approximately 5 mm thick. The process was repeated four times to create a series of uniformly spaced ice, distributed longitudinally from the blade tip to the root. Owing to the tapered geometry of the blade, the ice width decreased gradually from root to tip. The blade was then irradiated under a sun irradiation by a xenon lamp, while the process was continuously documented. As shown in Fig. 7c, the ice at the tip first melted from the bottom, with the molten region gradually expanding upward. Once the bottom boundary was completely melted, the ice slid downward. The ice then began to shed sequentially from the blade, one after the other. However, ice shedding results not from the complete melting of the entire ice mass, but from the synergistic effect of interfacial photothermal melting and gravity. Under light irradiation, a thin water film forms at the interface between the substrate and the ice. This film markedly reduces interfacial adhesion, allowing the ice block to slide off under the action of gravity. Without photothermal irradiation, the ice layer remains firmly attached to the blade surface, and gravity alone is insufficient to dislodge it. The entire process, from the first to the final ice at the root, was completed in 90 s, highlighting its strong potential for practical industrial deicing.

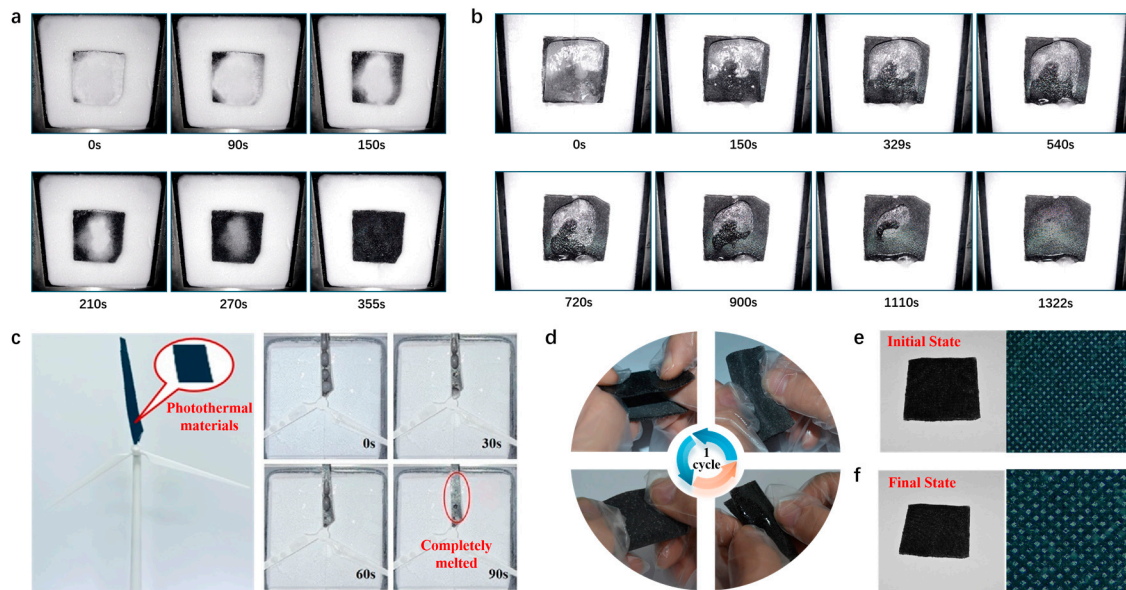


Figure 7: (a) Images of defrosting at the environment temperature of -20°C condition. (b) Image of ice deicing at the environment temperature of -20°C condition under one sun irradiation. (c) Images of deicing of homemade wind turbine blades at the environment temperature of -20°C condition under one sun irradiation. (d) Schematic diagram of bending flexibility test. (e) Macroscopic and microscopic images of the material before the fatigue test. (f) Macroscopic and microscopic images of the material after the fatigue test.

3.2.4 Fatigue Analysis of Materials

The photothermal materials demonstrate significant potential for deicing applications due to the low mass density and flexibility of PDMS. It is engineered with a smooth surface on one side and a surface topography for light harvesting on the other. Impact resistance and flexibility tests were conducted to evaluate their physical properties. The impact resistance of the photothermal materials was evaluated using a weight drop test. Weights of 1, 2, and 5 kg were released from a height of 1 m onto the samples. After ten repetitions per mass, no indentation or macroscopic damage was observed, demonstrating exceptional impact resistance. The materials exhibited exceptional flexibility durability, retained superior performance

after repeated 180° folding cycles. The testing process, illustrated in Fig. 7d, was quantified by performing ten complete bend and twist cycles. Each cycle consisted of forward and backward bending, followed by left and right torsion, and concluded with full unfolding. Following these cycles, no fracture, surface wrinkling, or degradation in photothermal surface was observed. The macroscopic and microscopic integrity of the material, both before and after fatigue testing, is shown in Fig. 7e,f, respectively. CMOS images further confirm that the surface microstructures remained intact, highlighting the exceptional durability of materials under complex mechanical loading. Owing to its outstanding physical and mechanical properties, the materials hold great potential for a wide range of applications.

While the aforementioned fatigue tests and photothermal stability experiments have confirmed the structural integrity and thermal response reliability of this material under mechanical deformation and intermittent light irradiation, we recognize that real outdoor service environments involve more complex aging factors. They include ultraviolet radiation, high humidity, freeze and pollutant deposition, all of which can affect the performance of the hair and polydimethylsiloxane (PDMS) composite over months to years. Specifically, although the PDMS matrix possesses excellent hydrophobicity and hydrolysis resistance, prolonged exposure may still induce surface chemical crosslinking or degradation, leading to a decline in flexibility and hydrophobicity. Meanwhile, under the synergistic effects of ultraviolet radiation and moisture, the melanin and keratin in the hair may undergo photochemical or biological degradation. Nevertheless, given the simple preparation process and the inexpensive, readily available raw materials, it is economically feasible in practical engineering maintenance to either replace the coating periodically or apply a peelable protective layer.

4 Comparative Analysis

As shown in Table 1, there are larger advantages in our materials. First, the acquisition of raw materials for carbon-based materials and metal nanomaterials is often challenging. This leads to high cost. Even when the raw materials are commercially available, the processing typically requires specific chemical solutions and involves complex procedures. For example, preparing graphene requires surfactants such as SDS to uniformly disperse the graphene powder and facilitate membrane formation. While graphene can be prepared from inexpensive graphite as an alternative, the process involves a complicated preparation procedure. In the case of metal nanomaterials, ferrocene and its derivatives require a combination of both oxidant and organic solvent to form a membrane material. While ferrocene itself can be prepared directly by iron, its subsequent processing remains significantly more challenging from a technical standpoint. Also, they take a lot of time to process. In contrast to the costly and complex methods discussed, the analysis underscores the advantages of hair as a raw material in terms of low cost and easy preparation. The three show little difference in photothermal performance. The selection of PDMS, despite its expense, is justified in our study owing to its exceptional durability.

Table 1: A comparison of the manufacturing costs and processing time and photothermal performance in 10 min associated with three different photothermal materials [28–31].

Types	Cost (\$/kg)	Processing Time (h)	Temperature under One Sun (°C)
PDMS+Hair	110.3	1.5	65
Carbon Nanotubes	754.1	3	68.4
Ferrocene and Its Derivatives	207.1	4	62.3

5 Conclusion

The photothermal materials, derived from waste hair, are engineered for the field of deicing applications. Owing to its simple synthesis, readily available raw materials, and scalable production, the materials show significant potential for deicing while mitigating the environmental impact of waste hair. During the preparation, a microtextured surface architecture was constructed to enhance internal light reflection based on the light trapping principle, thereby increasing the overall light absorption. Through repeated folding experiments, we found that the materials have exceptional flexibility and fatigue resistance. The optimal filler concentration was determined to be 20%. Under one sun irradiation, the formulation achieved a surface temperature of 70°C within 10 min and demonstrated a continued heat accumulation capability. The materials maintain excellent photothermal stability under both prolonged and intermittent light exposure. On a blade model, the materials successfully melted ice layers up to 5 mm thick within 0 s, demonstrating strong application potential. The photothermal material is expected to play an important role in the future field of deicing technologies.

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Availability of Data and Materials: All data needed to support the conclusions in the paper are presented in the manuscript. Additional data related to this paper may be requested from the corresponding author upon request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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