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Recent advancements in electro-thermal anti-/de-icing materials

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Icing is a common phenomenon in daily life, but the formation and accumulation of ice on critical surfaces can lead to catastrophic failures, economic losses, and safety issues. It is essential to implement effective anti-/de-icing strategies to solve these problems. Electro-thermal anti-/de-icing is a typical method and widely utilized in different engineering areas but still faces challenges like inefficiency, high energy cost, and poor temperature uniformity. Increasing studies have focused on design and fabrication of new electro-thermal materials with better performance for anti-/de-icing. This review summarizes recent advancements and applications of electro-thermal anti-/de-icing materials. First of all, the mechanism of electro-thermal anti-/de-icing is briefly presented. Subsequently, various electro-thermal anti-/de-icing materials are introduced according to the material types, *i.e.*, carbonaceous materials, metallic materials, and other materials. Furthermore, advances in the application of electro-thermal anti-/de-icing materials in aircraft, electric transmission-lines, wind power generation equipment and others are provided. To end, we summarize potential challenges and future perspectives in the design and fabrication of electro-thermal anti-/de-icing materials.

1. Introduction

Icing is an ordinary life phenomenon that usually occurs when there is sufficient moisture in the environment and the temperature drops to 0 °C or lower.[1,2] However, ice accumulation on critical surfaces such as aircraft wings, wind turbine blades, electric transmission-lines, *etc.* can lead to catastrophic failures, safety issues and economic losses,[3–6] so it is necessary to adopt effective anti-/de-icing strategies in these areas.

Anti-/de-icing methods including mechanical de-icing, liquid de-icing, hot air de-icing and electro-thermal de-icing have been widely investigated in the past few decades.[7,8] Among them, electro-thermal anti-/de-icing is believed to be a reliable and promising method by increasing the temperature of the surface through electro-thermal conversion and heat transfer.[9–11] Electro-thermal anti-/de-icing technology can realize high efficiency (compared to hot air anti-/de-icing), environmental protection (compared to liquid anti-/de-icing), and easy maintenance (compared to mechanical anti-/de-icing).[12] Hence, this technology has always been a hot topic for the research and development. Electro-thermal materials are the key components for energy conversion and transfer in the electro-thermal anti-/de-icing process, and highly conductive/thermal materials are generally the primary choice.[13]

The timeline of research and development of electro-thermal anti-/de-icing materials demonstrates the evolution of electro-thermal materials for anti-/de-icing applications from the mid-20th century to the present and future (Fig. 1A).[6,14] Indeed, anti-/de-icing electro-thermal materials are attracting more and more attention in recent years. It is crucial to note that the conventional electro-thermal elements equipped on current aircraft based on metal materials are characterized by low efficiency, heavy weight, low reliability, non-uniform heating and high thermal stress.[6,15] Novel metal-based electro-thermal materials such as metal matrix composite, liquid metal and so on are proposed and investigated.[16,17] In addition, to meet the needs of future aircraft development using more composite materials for instance, it is necessary to develop non-metallic electric heating materials.[6] Carbon-based materials and other materials like MXene could be a promising alternative for the anti-/de-icing for non-metallic substrates including but not limited to composite aircraft.[18,19] To date, electro-thermal materials for anti-/de-icing in different areas can be basically classified into three types: carbonaceous materials, metallic materials and others.[20] In particular, electro-thermal anti-/de-icing materials prepared from any type of the above materials with high electrical/thermal conductivity and excellent high-temperature properties are ideal for the latest anti-/de-icing developments.[14] For example, Dehaghani *et al.*[16] introduced a novel metal matrix composite (MMC) coatings-based heating

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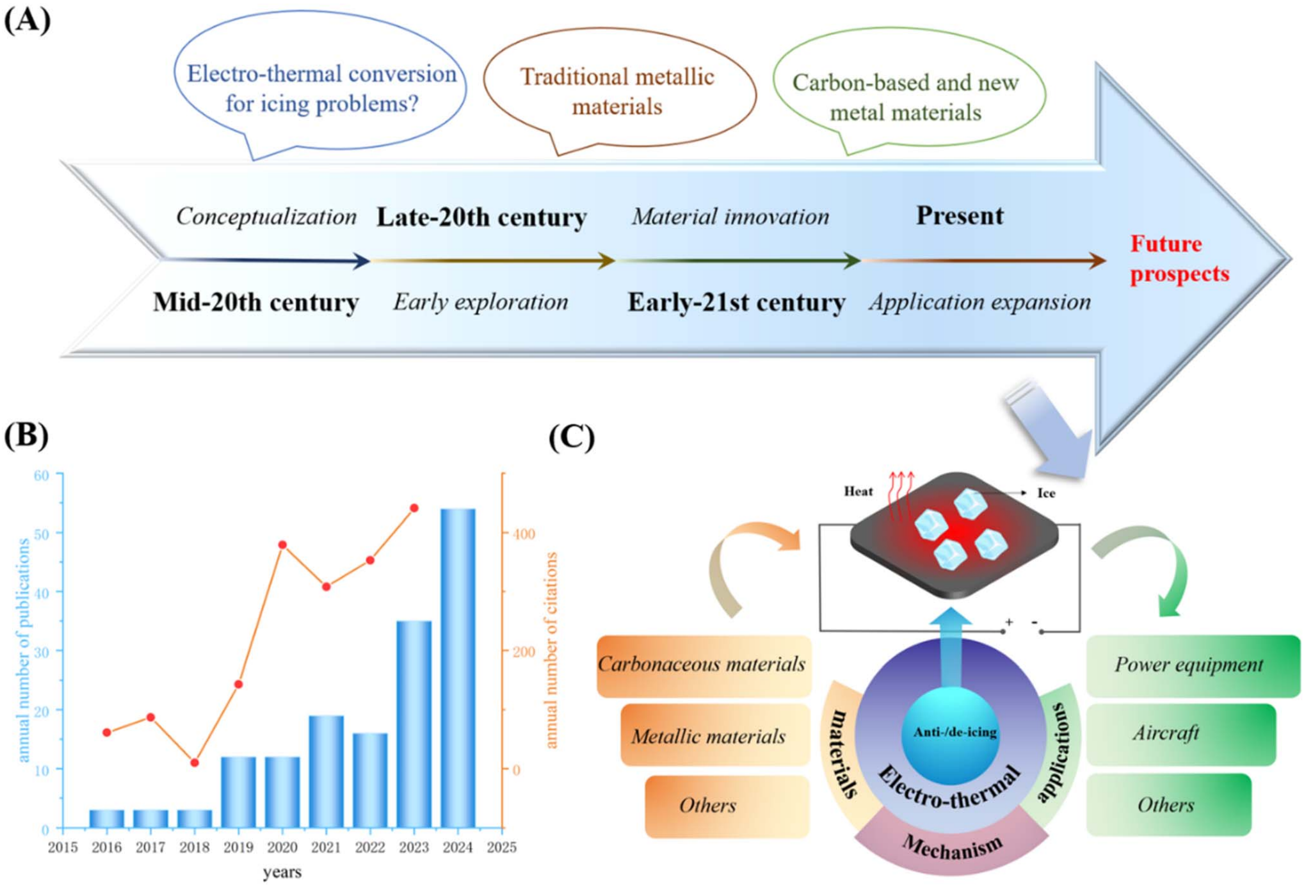

Fig. 1 (A) Research and development of electro-thermal anti-/de-icing materials; (B) number of the published articles per year indexed in the ISI web of science by the title of "electro-thermal and anti-icing"; (C) a schematic diagram illustrating the electro-thermal anti-/de-icing materials and its mechanism and applications.

system, which can directly heat the surface without an intermediate layer, improving the heating efficiency. Shao *et al.* [18] proposed the use of thermally stable and flame retardant poly(*m*-phenylene isophthalamide) and conductive carbon black (PMIA/CB) composite as electro-thermal films that can successfully realize stable and safe operation at high temperatures of > 200 °C under a safe voltage as low as 20 V, which shows excellent electro-thermal stability and reliability in long-term heating–cooling cycle tests. These high-performance electro-thermal anti-/de-icing materials exhibit tremendous potential in engineering application such as aerospace, communication and power transmission lines, and wind power generation equipment, and thereby bring significant convenience and huge economic benefits to the human society.[21,22]

Nowadays, increasing studies have focused on the design and fabrication of electro-thermal anti-/de-icing materials, and gradual advancements of the research have been witnessed (Fig. 1B). Many high-quality review articles have summarized anti/deicing materials and mechanisms but rare of them have focused on electro-thermal materials systematically, though some of them mention the design of active/passive anti-icing materials in combination with electro-thermal materials such as carbon fibers, carbon nanotubes, *etc.*[1,2,20,23–25] A comprehensive and systematic review of the recent advancements in electro-thermal materials has not yet been published.

Here in this review, a brief introduction to the mechanism of electro-thermal anti-/de-icing is first presented, which includes the process of thermal energy conversion, heat transfer and ice melting and crushing. Subsequently, recent advances in various electro-thermal anti-/de-icing materials, such as carbonaceous, metallic, and other materials, were introduced. Furthermore, the progress of electro-thermal anti-/de-icing materials in large-scale applications is presented. Finally, we concluded the review by outlining potential challenges and future investigation directions for electro-thermal anti-/de-icing materials (Fig. 1C). This review aims to facilitate the understanding and development of electro-thermal anti-/de-icing materials.

2. Mechanism of electro-thermal anti-/de-icing

Electro-thermal anti-/de-icing is a complex and continuous process primarily involving thermal energy conversion, heat transfer, and ice melting and crushing. Three types of heating methods have been employed in the current electro-thermal anti-/de-icing technology to realize the conversion of heat energy, including Joule heating (heat generated by the current through the resistive material), electromagnetic heating (generation of eddy currents in conductors by electromagnetic induction for heating), and arc heating (arc generates high temperatures for rapid heating).[26,27] Among them, joule heating, also known as resistive or electro-thermal heating, is the most prevalent, which generates heat by passing an electric current through a (semi-) conductor. The potential difference creates an electric field that accelerates charge carriers (usually electrons). Due to the resistance of the material, the current will be converted into heat *in situ*. This part of the heat can be calculated by Joule's law eqn (1):[28,29]

$$Q_1 = I^2Rt \tag{1}$$

with Q_1 the Joule heat (W), I the working current (A), R the working resistance (Ω), t the energizing time (s).

The generated heat transfers to the outer surface to prevent or remove ice *via* the heat conduction, and the conduction heat Q_2 can be calculated according to formula (2) and (3):

$$Q_2 = \Delta T/R' = \Delta T\,\lambda\,S\,L^{-1} \tag{2}$$

$$R' = L\,\lambda^{-1}\,S^{-1} \tag{3}$$

where Q_2 is the heat conducted (W), ΔT is the temperature difference before and after energizing the electric heating material (K), R' is the thermal resistance (K W^{-1}), L is the thickness (m), λ is the thermal conductivity (W m^{-1} K^{-1}), and S is the area (m^2).

The electro-thermal efficiency P is presented in eqn (4):

$$P = (Q_2/Q_1) \times 100\% \tag{4}$$

The above equation indicates that the electro-thermal efficiency of an electro-thermal material is related to its electrical conductivity/thermal coefficient and other factors.[14] Through electro-thermal conversion and conduction, the outer surface of the ice protection is maintained above the freezing temperature in the anti-icing mode, thus preventing water droplets from condensing into ice. In de-icing mode, the surface temperature rises to melt the bottom ice layer, decrease the adhesion between the ice layer and the outer surface, and detach the ice layer ultimately under aerodynamic/centrifugal force.[30]

3. Recent advances in electro-thermal anti-/de-icing materials

In the initial development and application of an electro-thermal anti-/de-icing system, the heating element is usually made of metal with superior electrical and thermal conductivity, such as copper, nickel alloy and so on.[6,15] However, in practice, the high energy consumption, low thermal efficiency, complex processing, poor durability and other problems of traditional electro-thermal anti-/de-icing materials limit its further development especially in the fields including aircraft, wind energy, *etc.*[5–7] Thereby different types of electro-thermal materials are proposed and investigated in past few decades, including carbonaceous materials (such as carbon nanotubes (CNT), graphene (GO), carbon fibers (CF), and others), novel metallic materials and others.

3.1 Carbonaceous materials

Carbonaceous materials have tremendous potential for fabricating electro-thermal materials for anti-icing applications due to their excellent electrical/thermal conductivity, processability, abundant material sources, and low cost.[31] The most widely applicable carbonaceous materials for electro-thermal anti-/de-icing mainly include graphene (GO), carbon nanotubes (CNT), carbon fibers (CF), carbon black (CB) and others. Table 1 presents the details of recent studies on carbonaceous electro-thermal anti-/de-icing materials. The specific research content will be elaborated in subsequent sections.

3.1.1 Graphene (GO). Graphene (GO) is a perfect two-dimensional material with ultra-high electrical and thermal conductivity and good flexibility properties, which makes it suitable for electro-thermal anti-/de-icing. It can be used as bulk material or filler for the electro-thermal composite films. Huang *et al.*[32] prepared an efficient anti-/de-icing material based on graphene foam (GF), which can melt and detach the ice layer within 400 s when applying 1 V at a low temperature of −20 °C. Chu *et al.*[33] proposed a graphene-based film with lightweight, high electric heat, and durability by exploiting the efficient electrical/thermal conductivity of the micro/nano-structured GO (Fig. 2A). The films start melting surface frost within 10 s and completely defrosting within 30 s at −20 °C and with 15 V applied, while 10 μL of super-cooled water droplets start to slide off within 20 s, demonstrating their efficient anti-/de-icing performance. Wei *et al.*[34] utilized GO as a conductive filler for a non-fluorinated, *in situ* self-healing electro-thermal/superhydrophobic coating. Magnesium alloy coated with such materials showed that it defrosts in only about 117 s at 18 V and 24 s at 32 V under −20 °C, respectively. Moreover, the ice melting time decreases with increasing voltage, with the ice completely melting in approximately 518 s and 72 s at 18 V and 32 V supply voltages, respectively (Fig. 2B).

In addition, the coupling of graphene's electro-thermal feature with superwetting property for anti-/de-icing has also attracted significant attention.[44,45] For example, Wang *et al.*[35] fabricated multiscale hybrid-structured femtosecond laser-induced graphene (FsLIG) on polyimide (PI) substrates using femtosecond laser direct writing technology in ambient air. By optimizing the laser scanning speed and structural design, the PI was transformed into a graphene structure with high electrical conductivity while endowed with excellent electro-thermal properties, and its surface temperature could be increased to about 193.1 °C in 30 seconds at 4 V. Wang *et al.*[36] systematically investigated the conversion of polyetherimide (PEI) to graphene by both experimental and molecular dynamics simulations and proposed a new method for obtaining Janus membranes by ethanol and plasma treatment of LIG. In particular, this membrane surface was able to reach 229 °C within the 60 s at

Table 1 Recent research on carbonaceous electro-thermal anti-/de-icing materials

Electro-thermal materials	Main fabrication method	Electro-thermal performance	Anti-/de-icing ability	Ref.
Graphene foam (GF), PDMS composite	Spray	Temperature rise to 83.1 and 155 °C in 200 s (with 1 V and 1.5 V)	De-icing: 1 V (400 s) at −20 °C	32
FDTS-modified SiO_2/rGO wrinkled films	Vacuum filtration	Temperature rise to 62.2 °C in 20 s (with 15 V)	De-icing: 15 V (30 s) De-frost: 15 V (10 s)	33
EP, PDMS, graphene, SiO_2 nanoparticles	Spray	Temperature rise to 169.6 °C (with 34 V)	De-icing: 32 V (72 s) De-frost: 32 V (24 s)	34
Femtosecond laser-induced graphene (FsLIG)	Femtosecond laser	Temperature rise to 193.1 °C in 30 s (with 4 V)	—	35
Laser-induced graphene (LIG)	CO_2 laser	Temperature rise to 229 °C in 60 s (with 7 V)	De-icing: 7 V (34 s) De-frost: 7 V (5 s)	36
SWCNT	Pressure-fusing method	Temperature rise to 160 °C (with 2 V)	—	37
MWCNT, high-temperature resistant rubber, glass cloth	Ultrasonic dispersion, heat-curing, hot-pressing	Temperature rise to 60 °C and 250 °C (with 0.1 W cm^{-2} and 1 W cm^{-2})	De-icing: 0.1 W cm^{-2} (68 s) 0.2 W cm^{-2} (20 s) 0.3 W cm^{-2} (6 s)	38
TPU, SWCNT, GNP	Spray, hot-pressing	Temperature rise to 96.5 °C in 30 s (with 9 V)	De-icing: 9 V (150 s)	39
Nickel-coated carbon fiber (NCCF)	Electroplate	Temperature rise to 166 °C (with 1.75 V)	De-icing: 2 V (6 min) at −30 °C	40
Nickel-coated carbon fiber reinforced polymer (Ni-CFRP)	Chemical plating	Max temperature in 205 °C (with 30 V)	De-icing: 30 V (110 s) (ice thickness: 30 mm)	41
Titanium nitride (TiN)/Acetylene black composite	Spray	Temperature rise to 91 °C in 4 min (with 0.25 W cm^{-2})	—	42
Polyimide (PI)/Carbon black (CB) composite	Spin-coating	Temperature rise to 170 °C (with 20 V)	De-icing: 20 V (280 s) (ice thickness: 10 mm)	43

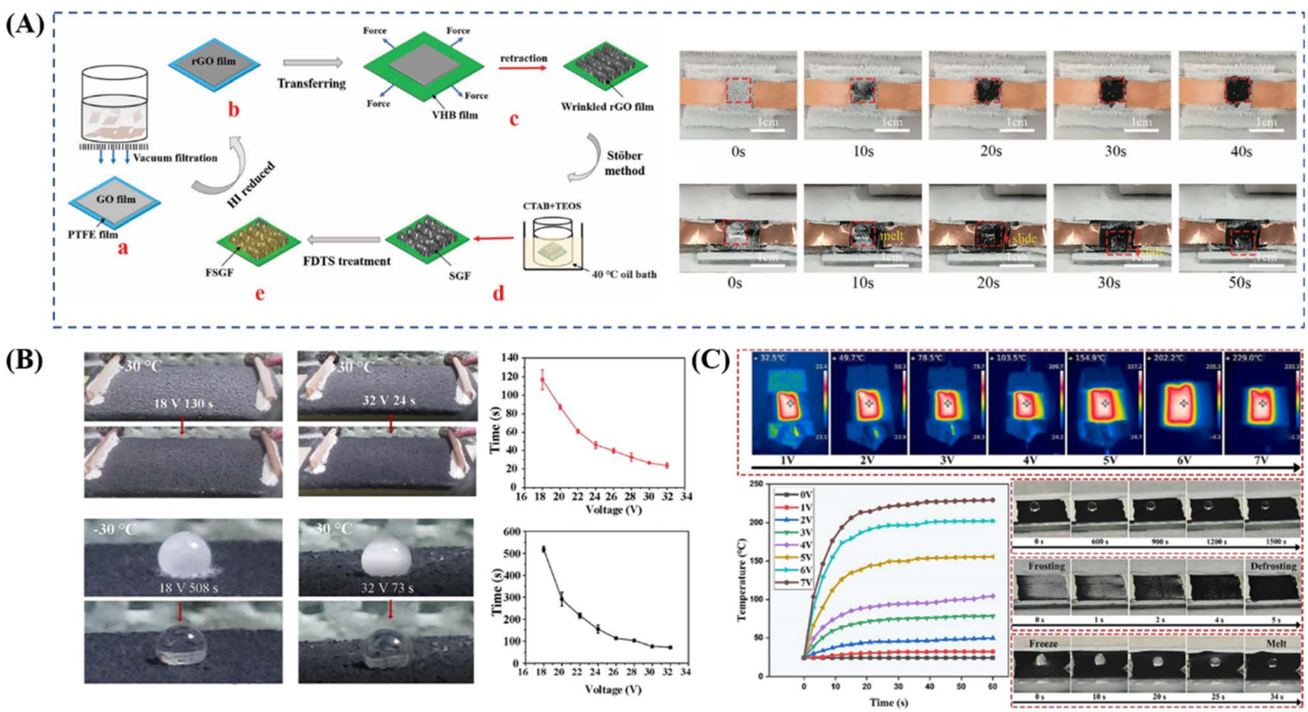

Fig. 2 (A) Schematic illustrations of the fabrication of the film, defrosting and deicing process of the optimal sample after applying a DC voltage of 15 V;[33] (B) De-frosting and de-icing performance of superhydrophobic coating under different applied voltages at −30 °C;[34] (C) Infrared images, Joule heating profile of EtOH-LIG with a pore size of 120 μm at different voltages, and electro-thermal anti-icing and de-icing performance of EtOH-LIG with a pore size of 80 μm.[36] Reproduced with permission from,[33,34,36] Copyright 2019 John Wiley and Sons, Copyright 2023 Elsevier, Copyright 2024 Elsevier, respectively.

7 V. Simultaneously, it showed excellent electro-thermal de-icing performance by realizing fast defrosting in 5 s and transforming ice droplets into water droplets in 34 s at −20 °C and with 7 V applied (Fig. 2C).

It shall be mentioned that the exceptional electro-thermal performance of graphene-based materials stems from their unique electronic structure and high thermal conductivity. Graphene's two-dimensional honeycomb lattice permits efficient charge carrier mobility, enabling rapid Joule heating upon electrical stimulation.[14,46] Moreover, the strong in-plane thermal conductivity ensures uniform heat distribution across the material surface, thereby enhancing ice melting efficiency. To further enhance the performance of graphene-based electro-thermal materials, future research could concentrate on optimizing the reduction process of graphene oxide to minimize residual oxygen groups, thus enhancing electrical conductivity.[34,36] Additionally, incorporating heat-resistant polymers or ceramic nanoparticles could improve thermal stability, and developing flexible and stretchable graphene composites would be beneficial for applications that demand mechanical flexibility.[32,33]

3.1.2 Carbon nanotubes (CNT). Carbon nanotubes (CNT), formed by rolling graphene layers at specific angles, show great potential for anti/deicing application due to their excellent electrical/thermal conductivity.[47] Single-walled carbon nanotubes (SWCNT), which are composed of a single layer of carbon atoms, have fewer structural defects, higher electrical conductivity, and faster electro-thermal response, which can more efficiently convert electrical energy into thermal energy, making them suitable for scenarios with high requirements for rapid anti-/de-icing. Jiao *et al.*[37] fabricated single-wall CNT (SWCNT) fiber nonwoven fabrics (NWFs) that are composed of interconnected SWCNT fibers with fused joints by a simple pressure-fusing method (Fig. 3A), which have a high electrical conductivity of 3.7×10^5 S m^{-1} and a high specific electrical conductivity of 803 (S m^{-2}) per kg, and reaches a temperature of 160 °C at a low voltage of 2 V.

However, the single-wall structure is fragile, and performance degradation occurs in complex mechanical environments. For this reason, multi-walled carbon nanotubes (MWCNT) consisting of multiple layers of concentric cylindrical carbon atoms are employed, which have higher mechanical strength and toughness, and are able to withstand higher current densities. Zhao *et al.*[48] produced a novel flexible, biaxial stretchable electric heating film (BSF) with the fast thermal response by adding MWCNT to the substrate to improve electrical/thermal conductivity. In particular, unstretched BSF completely melted frost ice into water in 314 s when 35 V was applied, while the melting time was 478 s when stretched 40% along the *X*-direction, and 461 s when stretched 40% along the *Y*-direction, which indicates that the material still has an efficient de-icing effect under bi-directional stretching (Fig. 3B). Chen *et al.*[38] prepared a novel electro-thermal sandwich composite (NESC) by hot pressing an electro-thermal film into a load-bearing composite, in which modified MWCNT were dispersed in a high-temperature heat-resistant rubber matrix to

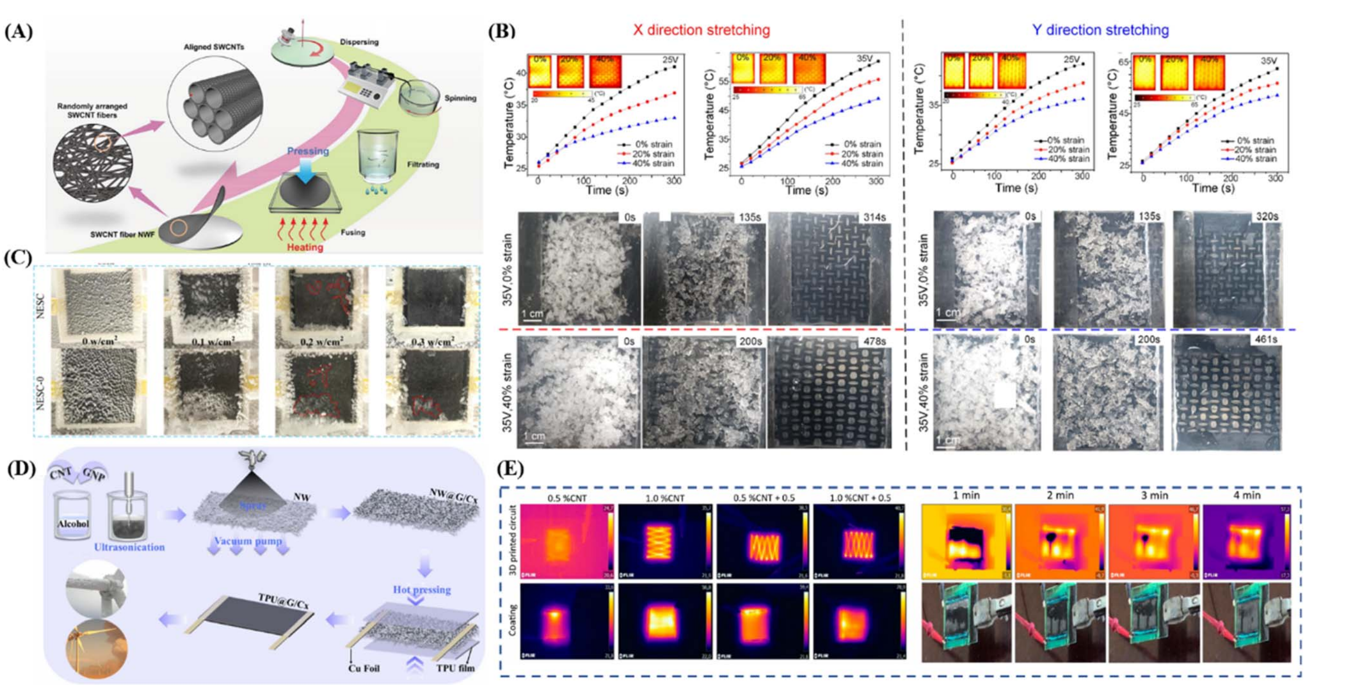

Fig. 3 (A) Schemic of the SWCNT fiber NWT fabrication process;[37] (B) the de-icing performance of BSF after encapsulated by silicone stretching along *X* and *Y* directions;[48] (C) anti-icing test of NESC and NESC-0 (0, 0.1, 0.2, 0.3 W cm^{-2});[38] (D) schematic diagram of the TPU@G/C_x film fabrication process;[39] (E) IR images taken during Joule's heating tests, IR thermographs and real pictures of the specimen at different times.[49] Reproduced with permission from,[37–39,48,49] Copyright 2024 Springer Nature, Copyright 2022 Elsevier, Copyright 2024 Elsevier, Copyright 2023 Royal Society of Chemistry, Copyright 2022 MDPI, respectively.

realize the electrically heated properties of the NESC. Specifically, the surface temperature of the material can reach 60–250 °C in a short time when a power density of 0.1–1 W cm^{-2} is applied. Meanwhile, when power densities of 0.1 W cm^{-2}, 0.2 W cm^{-2}, and 0.3 W cm^{-2} were applied, the surface ice layer was removed in 68, 20, and 6 s, respectively (Fig. 3C).

It shall be mentioned that, the electro-thermal performance of CNT is governed by their remarkable electrical conductivity and high aspect ratio, which facilitate efficient charge transport and heat generation. SWCNTs exhibit a superior electro-thermal response due to their minimal structural defects, whereas MWCNTs offer enhanced mechanical durability.[37,48] To advance the application of CNT-based electro-thermal materials, future research could focus on optimizing the dispersion and alignment of CNTs in composite matrices to maximize electrical and thermal percolation networks.[38,50] Improving the interfacial bonding between CNTs and polymer matrices could also enhance heat transfer efficiency.[39,49,51–54] Furthermore, developing hybrid systems that combine CNTs with other nanomaterials, such as graphene, could create synergistic effects for improved performance, which could unexpectedly impact the development of electro-thermal materials through the optimization of preparation and material ratios.[50,51] Cui *et al.*[39] prepared a flexible thermoplastic polyurethane nanotube/graphene nanoplatelet composite film with rapid electro-thermal de-icing performance and excellent solid particle erosion resistance *via* a simple "spray-hot pressing" method (Fig. 3D). In particular, the combination of carbon nanotubes and graphene forms a stable and well-developed three-dimensional conductive network, enabling the film to be heated up to 96.5 °C at 9 V, demonstrating rapid de-icing (150 s). Huang *et al.*[52] initially utilized CNT and GO to form an electrically conductive layer, and then prepared an electro-thermal coating by combining the layer with polymers such as polydimethylsiloxane (PDMS) to form a sandwich structure. The surface temperature of the coating is capable of rising exceptionally quickly, effectively preventing the formation of ice at −20 °C with a voltage of 2 V. Furthermore, Wang *et al.* [53] selected physically modified carbon nanotubes (CNT@X) and pristine graphene nanoplates (GNPs) as conductive-enhanced nanofillers, and thermosetting epoxy resin as a polymer matrix to prepare conductive material CNT@X-GNPs/EP nanocomposites to achieve an efficient anti-/de-icing effect. In order to explore the advantages of using a combination of carbon nanotubes (CNTs) and graphene nanoparticles (GNPs) for the preparation of electro-thermal materials, in particular the performance enhancement when compared to the use of either material alone, Cortés *et al.*[49] investigated the electrical and electro-thermal properties of CNT/GNP-doped nanocomposites to optimize their anti-/de-icing capabilities. The combination of CNT and GNP forms a more homogeneous conductive network and reduces the influence of localized defects (such as voids or nanoparticle aggregates) on the current path. This enhanced connectivity of the conductive network shows higher electrical/thermal efficiencies, for instance, in self-heating tests, the coatings with 1.0% CNT and 0.5% GNP reached higher average temperatures (ΔT_{av}) and higher maximum temperatures (ΔT_{max}) under the same conditions (Fig. 3E).

3.1.3 Carbon fiber (CF). Carbon fiber (CF) is also an excellent candidate for electro-thermal anti-/de-icing due to its extremely high strength and modulus, as well as its low density compared to traditional metal de-icing materials. Tian *et al.*[55] proposed a carbon fiber reinforced polymer (CFRP) surface ply-centric electrified spatiotemporal self-heating (STSH) approach by using carbon fiber (CF) in the surface ply as natural heating elements to achieve *in situ* adaptable electro-thermal anti-/de-icing (Fig. 4A). Adjusting the current waveform makes it possible to switch flexibly between a continuous stable temperature and a periodic peak temperature to meet the different heating needs of anti-/de-icing. Meanwhile, a spatial temperature gradient is formed through the staggered connection of carbon fibers to achieve concentration and optimal energy distribution. Cao *et al.*[40] developed a composite material with efficient electro-thermal properties by coating a nickel layer on carbon fiber (NCCF). At the same time, carbon fiber (CF) and nickel-plated carbon fiber (NCCF) bundles can reach up to 140 °C and 166 °C at an applied voltage of only 1.75 V (Fig. 4B). Pang *et al.*[41] plated a layer of nickel on the surface of carbon fiber reinforced composites (CFRP) by the chemical nickel-plating technique, and realized inductive heating and electro-thermal deicing by using the high magnetic and electric permeability of the prepared material. In particular, the rate of temperature rise of the sample increases significantly as the input voltage is increased and the equilibrium temperature increases accordingly, indicating that higher input voltages can drive the induction heating process efficiently (Fig. 4C).

As for the electro-thermal mechanism of carbon fibers, it involves the conversion of electrical energy into heat through resistance heating, with heat dissipation facilitated by the fiber's high thermal conductivity. To further enhance the performance of carbon fiber-based electro-thermal materials, future research could focus on optimizing the fiber orientation and density in composites to enhance electrical connectivity.[14,40] Integrating heat-spreading materials could improve thermal management, and developing smart composite systems with embedded sensors would enable real-time temperature and ice detection.[41,55]

3.1.4 Other carbon-based materials. Aside from the aforementioned materials, other carbonaceous materials such as conductive blacks, acetylene carbon black, and carbon cloth also have the potential to be applied as electro-thermal anti-/de-icing materials. For example, Lei *et al.*[42] applied micron-sized titanium nitride and conductive nanosized acetylene black as functional fillers and combined them with a fluorine-modified epoxy resin (F-EP/ACET/TiN) to realize a multifunctional synergistic enhancement of the coating (Fig. 5A). Especially, at an electro-thermal power density of 0.25 W cm^{-2} (equivalent to a voltage of 27 V), the surface temperature of the coating could be increased to 91 °C within 4 minutes. Shao *et al.*[43] prepared a series of polyimide (PI)/carbon black (CB) composite electro-thermal films with excellent high-temperature stability and high-power density by a simple slurry coating method (Fig. 5B). Impressively, these PI/CB composite electro-thermal films with

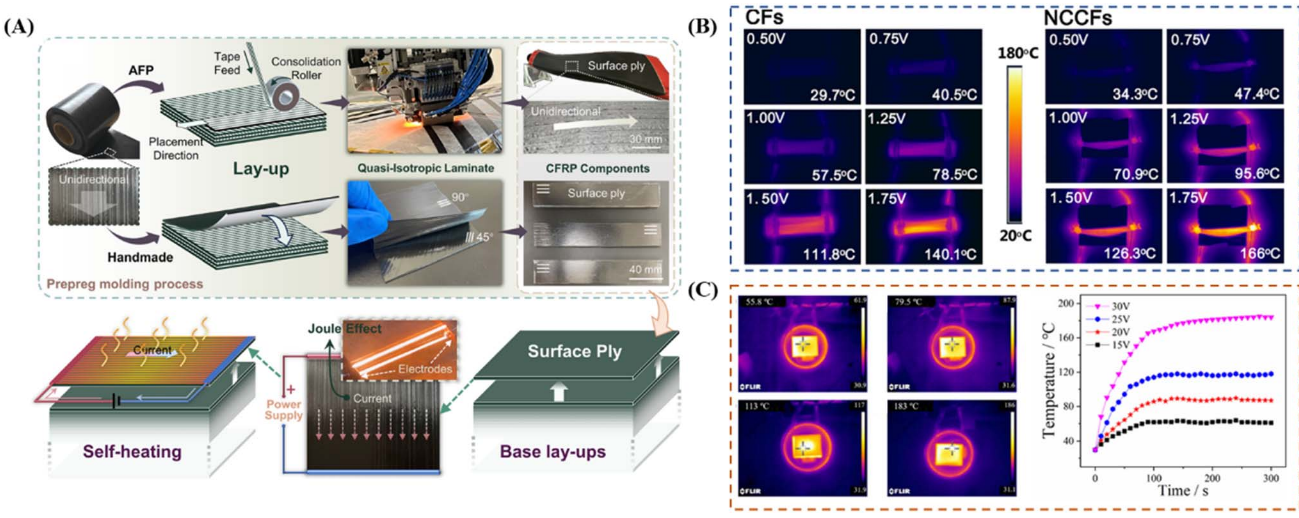

Fig. 4 (A) Manufacturing and molding processes of common CFRP components (the top) and schematic diagram of activating the electro-thermal properties of the CFs within CFRP surface (the bottom);[55] (B) thermal images of CFs and NCCFs;[40] (C) infrared images of Ni/CF-0.21 under induction heating with 15 V, 20 V, 25 V, and 30 V, and the diagram of temperature/time curve.[41] Reproduced with permission from,[40,41,55] Copyright 2024 Elsevier, Copyright 2019 Elsevier, Copyright 2023 MDPI, respectively.

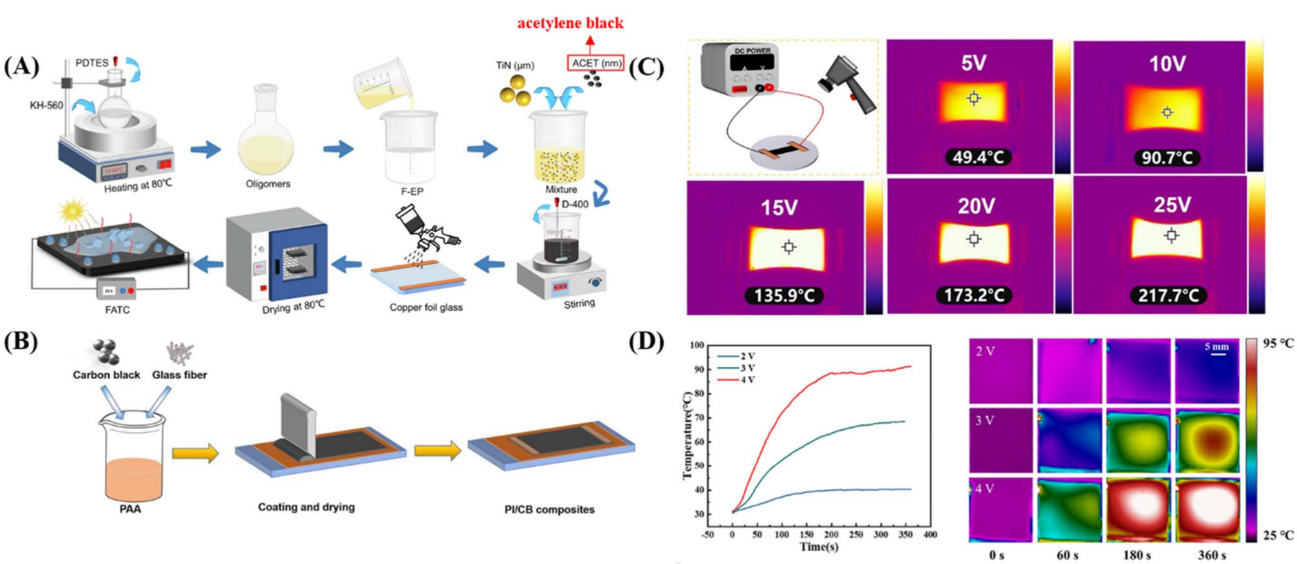

Fig. 5 (A) The preparation process of F-EP/ACET/TiN coating (FATC);[42]; (B) schematic of the fabrication process of PI/CB composite electro-thermal films; (C) schematic of surface temperature uniformity test by infrared camera and infrared thermal images of the PI/CB sample under different applied DC voltages;[43] (D) FLIR and temperature change of the P@TM/CC at different voltages.[56] Reproduced with permission from,[42,43,56] Copyright 2025 Elsevier, Copyright 2024 Springer Nature, Copyright 2024 Elsevier, respectively.

a uniform thin thickness of 45 μm exhibit high operating temperature (>200 °C), rapid heating response speed (<10 s), remarkable long-term working stability, and superior low-temperature operating reliability even at −30 °C (Fig. 5C). Moreover, Wei *et al.*[56] proposed an electro-photo-thermal material with adaptive temperature control performance based on carbon cloth (CC) as a conductive layer, and with a voltage of 4 V and a low temperature of −30 °C, the surface temperature of the material increases dramatically to 90 °C in a short period, exhibiting excellent electrical/thermal properties (Fig. 5D).

In brief, carbon-based electro-thermal anti-/de-icing materials can effectively convert electrical energy into thermal energy, realizing the effective utilization of energy, which has a great prospect in the field of anti-/de-icing.

3.2 Metallic materials

Metallic electro-thermal materials primarily rely on their inherent electrical conductivity for efficient heat generation. The mechanism involves Joule heating, where electrical energy is converted into heat due to the resistance of the metal.[14,57]

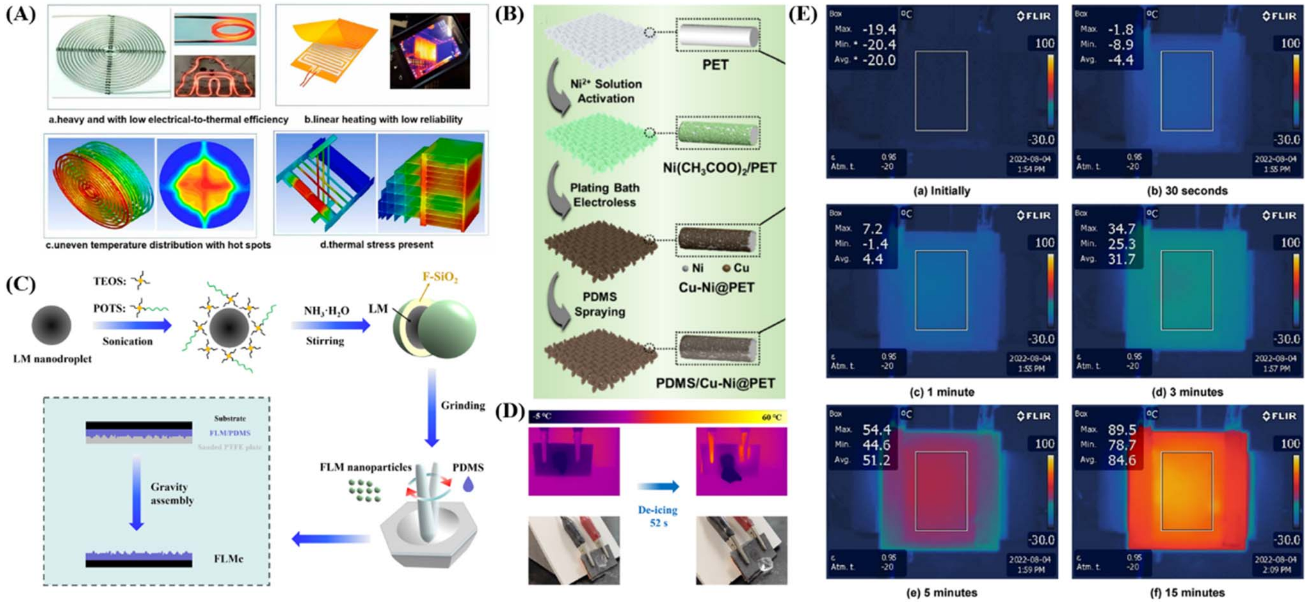

Fig. 6 (A) Low efficiency of traditional electro-thermal and anti-icing technology;[6] (B) schematic diagram of the preparation of photothermal and electro-thermal superhydrophobic materials;[58]; (C) schematic illustration of the formation process of the film; (D) electro-thermal de-icing property of the film;[17]; (E) thermal (infrared) images of the heating film when tested at an ambient temperature of 20 °C with a constant current of 8 A.[59] Reproduced with permission from,[6,17,58,59] Copyright 2024 MDPI, Copyright 2024 Elsevier, Copyright 2024 Elsevier, Copyright 2023 Elsevier, respectively.

However, as mentioned at the beginning, traditional metal element heating materials suffer from low efficiency, heaviness, low reliability, uneven heating and thermal stress (Fig. 6A).[6] Thus, the exploration of new metal electro-thermal materials is indispensable. Table 2 presents the details of recent studies on metallic electro-thermal anti-/de-icing materials. Yan *et al.*[60] developed an AlSi50 alloy coating as electro-thermal de-icing elements for FRPC structures using high-velocity oxy-fuel (HVOF) spray. Besides, the ice layer on the surface of the coating can be completely evaporated after a 120-minutes low-temperature test at −30 °C with a voltage of 5.9 V. Li *et al.*[58] developed a hydrophobic Cu–Ni fabric with dual energy conversion functions of photothermal and electro-thermal by spraying polydimethylsiloxane (PDMS) on a Cu–Ni coated polyester fabric (Cu–Ni@PET) (Fig. 6B). The Cu–Ni coating provides excellent electrical conductivity, resulting in surface equilibrium temperatures of 81 °C, 120 °C and 158 °C within 60 s for fabrics with voltages of 3 V, 5 V and 6 V, respectively. Inspired by the self-assembly of phospholipid molecules in cell membranes, Ji *et al.*[17] prepared a self-assembled corrosion-resistant liquid metal (LM) composite coating to protect the liquid metal from icing and corrosion hazards (Fig. 6C), in which the high electrical conductivity of the LM enabled the coating to achieve a surface temperature of 52.5 °C in 52 s when a power density of 4 W cm^{-2} was applied (Fig. 6D). Sullivan *et al.*[59] sequentially prepared an insulating layer, a silver-coated copper epoxy electro-thermal layer, and a superhydrophobic top layer on a stainless-steel substrate by a simple multilayer

Table 2 Recent research on metallic electro-thermal anti-/de-icing materials

Electro-thermal materials	Main fabrication method	Electro-thermal performance	Anti-/de-icing ability	Ref.
AlSi50 alloy coating	HVOF spraying on FRPC substrate	Temperature rise to 60 °C in 15 min (with < 8.5 W cm^{-2})	5.9 W cm^{-2} for anti-icing 8.3 W cm^{-2} for de-icing at −30 °C	60
NiCrAlY, ceramic/cermet reinforcements	Flame spraying	Heating rate: 0.044 °C s^{-1} (forced convection)	—	16
Liquid metal composite coating (LM, POTS, SiO_2)	Self-assembly encapsulation with fluorosilicon molecules	Max temperature in 52.5 °C (with 4 W cm^{-2})	De-icing: 5 V (52 s) at −30 °C	17
Hydrophobic Cu–Ni fabric with PDMS	Electroless plating and PDMS spraying	Max temperature in 158 °C (with 6 V)	De-icing: 3 V (182 s), 5 V (132 s), 6 V (97 s) at −10 °C	58
Ag–Cu epoxy, PDMS	Multi-layer spray coating on stainless steel	Temperature rise to 60 °C in 52 s max 120 °C in 4 min	Anti-icing: 0.34 W cm^{-2} at −20 °C	59

Table 3 Recent research on other electro-thermal anti-/de-icing materials

Electro-thermal materials	Main fabrication method	Electro-thermal performance	Anti-/de-icing ability	Ref.
Silver nanoparticles (Ag), MXene	Immersing PET textile in Ag/MXene solution multiple times	Stable temperature in 117 °C (with 3 V)	De-icing: 3 V (742 s)	61
Silver nanowires (AgNWs), MXene	Water mist deposition method	Temperature rise to 60.6 °C in 65 s (with 5 V at room temperature)	De-icing: 5 V (65 s)	62
Polypyrrole (PPy), MXene nanosheets	Coating PPy by *in situ* polymerization, decorating MXene by vacuum filtration	Temperature rise to 258 °C (with 4.2 V)	—	19
Polyurethane (PU), polypyrrole (PPy), polydopamine (PDA)	Scraping PU film, surface grafting of PDA, *in situ* polymerization of PPy	Max temperature in 118 °C in 20 s (with 5 V)	—	63
CuS nanosheets on polyimide (PI) film	*In situ* growth of CuS nanosheets on PI film	Surface temperature over 200 °C (with 8 V)	De-icing: 5 V (384 s)	64
ITO layer, PDMSME, CWO (cesium-doped Tungsten Trioxide), BTA (benzotriazole)	DC magnetron sputtering of ITO layer, spraying	Surface temperature over 60 °C (with 6 V)	—	65

spraying process to form an anti-icing coating with dual functions of superhydrophilicity and electro-thermal properties. At an ambient temperature of −20 °C and a constant current of 8 A, the average surface temperature of the heating film rises above freezing in less than 60 s and reaches a stable and uniform maximum average surface temperature of 85 °C within 15 minutes (Fig. 6E).

3.3 Other materials

Aside from the aforementioned carboned-based and metallic materials, a range of other materials with excellent electrical/thermal conductivity can realistically be utilized for electro-thermal conversion as well, as shown in Table 3. Two-dimensional MXene is a typical example material that can be utilized as electro-thermal material owing to its multi-functionality, high conductivity and structural stability. For example, Zhang *et al.*[61] developed an Ag/MXene composite material by utilizing MXene with excellent electrical/thermal conductivity and Ag nanoparticles to enhance the conductivity and photothermal effect. Cui *et al.*[62] combined MXene and silver nanowires (AgNWs) to develop an ultra-high-transparency safety film with surface-enhanced plasmonic resonance dynamics for photo-/electro-thermal conversion, which can achieve a temperature rise rate of 6.3 °C s^{-1} at 5 V while ultimately stabilizing at 60.6 °C (Fig. 7A). Furthermore, conductive polymer is another type of materials with potential for anti-/de-icing usage due to its high electrical conductivity, oxygen

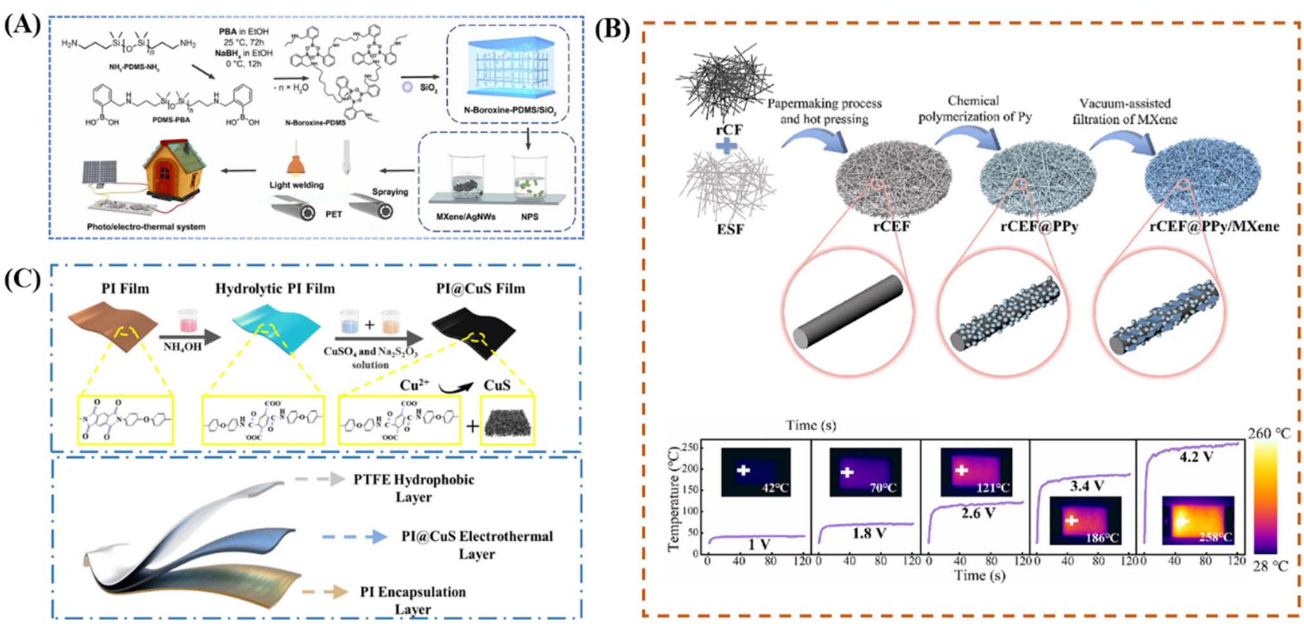

Fig. 7 (A) Schematic illustration of the synthesis process of the film and its application scenario;[62] (B) schematic illustration of the preparation and Joule heating performances of rCEF@PPy/MXene;[19]; (C) schematic illustration of the fabrication of electro-thermal film PI@CuS (the top) and diagram of the hierarchical structure of PTFE/PI@CuS/PI sandwich film (the bottom).[64] Reproduced with permission from,[19,62,64] Copyright 2024 American Chemical Society, Copyright 2023 Elsevier, Copyright 2024 Elsevier, respectively.

resistance, heterocyclic structure and non-toxicity. Polypyrrole (PPy) is one of the most widely researched one. Duan *et al.*[19] constructed a lightweight and flexible porous conductive network by anchoring the PPy and MXene on the surface of the substrate to achieve high electrical conductivity and electro-thermal conversion capability (Fig. 7B). Consequently, optimal samples can reach 258 °C at 4.2 V. Huang *et al.*[63] prepared polyurethane (PU)/dopamine (PDA)/polypyrrole (PPy) flexible composite electro-thermal films by a three-step process of scratch-coating, surface grafting and *in situ* polymerization, which demonstrated excellent uniform heating properties at 1–3 V. Li *et al.*[64] constructed a dense continuous network of electrically heated thin films by *in situ* growth of CuS nanosheets with stable interfacial bonding on the surface of polyimide (PI) films (Fig. 7C). Additionally, Wang *et al.*[65] proposed a bilayer transparent photo/electro-thermal coating with a liquid-like slippery property for all-day anti-/de-icing, in which the electro-thermal conversion is realized by introducing an ITO layer into the coating. Simultaneously, the transparency of ITO makes it possible to use anti-/de-icing in photovoltaic, windshield and other fields.

4. Application

Electro-thermal anti-/de-icing materials have a considerable application potential for various areas, especially for aircraft (aircraft wings, aircraft skins, *etc.*), electric transmission-lines, wind power equipment, and others. Nevertheless, many performance challenges remain to be overcome for the large-scale application of electro-thermal anti-/de-icing materials. A range of materials are not tested outdoors or can only be prepared on flat, rigid substrates, which limits their application.[66,67] The durability and large-scale realizability of the materials are also a significant issue. This section summarizes the applications of electro-thermal anti-/de-icing materials in some major areas, including aircraft, electric transmission-line and wind power equipment.

4.1 Application in aircraft

Icing and ice accretion at critical positions of aircraft including wings, tail, and intakes poses a significant threat to aircraft safety, as they may lead to a lift reduction, an increase in drag and a marked degradation of aerodynamic characteristics.[6] Hence, anti-/de-icing strategy must be employed to address the icing problems. Electro-thermal anti-/de-icing is a typical choice for the wings, tailplanes, and inlets of fixed-wing airplanes, UAVs, and helicopters (Fig. 8A and B).[6,68,73] Compared with the conventional metal-based electro-thermal anti-/de-icing materials (Fig. 6A), composite materials based on carbon nanotubes and graphene are more suitable for developing lightweight, efficient, flexible and low-energy-consuming electro-thermal anti-/de-icing systems for the future aircraft. Hence, they are wildly investigated recently. For example, Zeng *et al.*[74] prepared a coupled system combining a superhydrophobic coating with a graphene electric heater for anti-/de-icing of aircraft wings (Fig. 8C). The combination of passive and electro-thermal de-icing allowed the surface temperature to rise to 6 °C when the heating power density reached 0.98 W cm^{-2}, effectively preventing the formation of ice on the wing. Niu *et al.*[69] prepared high-performance hybrid electro-thermal films with enhanced reliability by combining reduced graphene oxide (rGO) and multi-walled carbon nanotubes (MWCNTs). In a dynamic icing environment, the hybrid films can achieve anti-icing (at 4 V) and de-icing (at 7 V). Though excellent anti-/de-icing performance of such materials are demonstrated in lab, they have not yet been installed on aircraft for actually usage as some challenges still remain, such as compatibility of the novel electro-thermal anti-/de-icing materials with existing aircraft structures and systems, flexibility and durability, and thermal responsiveness.

4.2 Application in electric transmission-lines

Icing will not only increase the mechanical load of communication and transmission lines, resulting in accidents such as tower collapse and conductor breakage, but also affect the electrical performance of the line, resulting in short circuits, flashover, and other problems.[4,75] For this reason, electro-thermal anti-icing systems in transmission lines obtain Joule heat to melt ice by energizing line conductors or grounds with higher than normal current densities of transmission current.[76] Therefore, it is necessary to use carbon-based composite materials with excellent electrical/thermal properties under high voltage conditions to meet the special environment of electric transmission-lines. For example, Wu *et al.*[70] prepared a high electro-thermal property and voltage-resistant graphene/crosslinked polyethylene (XLPE) composite as a anti-/de-icing material *via* an unconventional non-percolative structure (Fig. 8D). In particular, the composite is capable of achieving a temperature increase of 2–59.7 °C when applying a voltage of 1000–2500 V, and efficient de-icing at 1100 V for 18 minutes in a −20 °C environment, demonstrating their potential for practical anti-/de-icing applications in high-voltage environments. Yang *et al.*[77] designed a multifunctional superhydrophobic composite film with a combination of laser ablation and spraying, which has excellent integrated anti-/de-icing and icing monitoring properties. More importantly, it can monitor the whole anti-/de-icing process of droplets of different volumes and temperatures in real time by the change of film resistance owing to the temperature sensing performance of the composite conductive network of LIG/CNTs. The application of such films on electric lines is expected to provide early warning of icing conditions and help power authorities take timely action to reduce energy waste and de-icing costs.

4.3 Application in wind power equipment

About a quarter of the world's wind turbine capacity is installed in cold, ice-prone climates, or wind turbines are operated at low temperatures beyond their design operating limits, such as the offshore wind turbine blades during atmospheric icing (Fig. 8E).[5,71] For this reason, wind turbine manufacturers are investigating anti-icing systems, including electro-thermal anti-/de-icing.[4] In order to address the harsh outdoor environment of wind turbines, the selection of electro-

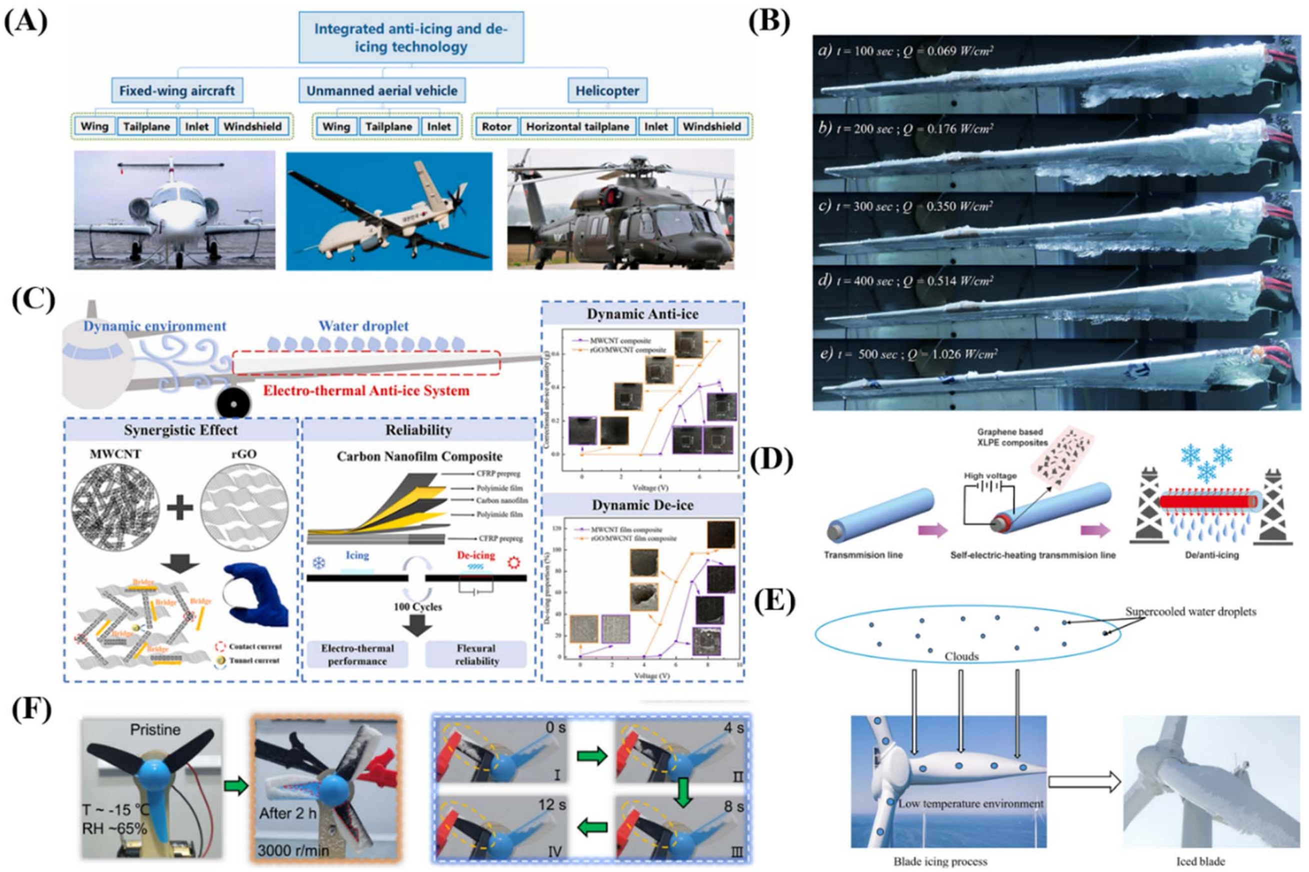

Fig. 8 (A) Analysis of application scenarios for integrated electro-thermal anti-/de-icing function structures in aircraft;[6] (B) photographs of the rotor blade taken during an anti-icing test where the heating power was increased at different instances;[68] (C) schematic diagram of electro-thermal anti-/de-icing system, synthesis effect, reliability, dynamic anti-/de-icing test;[69] (D) the schematic diagram of the self-heating transmission-line;[70] (E) schematic diagram of an offshore wind turbine blade during atmospheric icing;[71] (F) ice accumulation area of a wind turbine blade model after 2 h of operation at 3000 rpm and rapid de-icing process on the surface of a wind turbine blade model at 25 V.[72] Reproduced with permission from,[6,68–72] Copyright 2024 MDPI, Copyright 2023 Elsevier, Copyright 2025 Elsevier, Copyright 2022 Elsevier, Copyright 2022 Elsevier, Copyright 2024 Elsevier, respectively.

thermal anti-/de-icing materials requires a comprehensive consideration of electrical conductivity, thermal efficiency, mechanical properties, and weather resistance. Previous researches reveal that integrating electro-thermal feature with superhydrophobic property should be a good choice. For example, Fan *et al.*[78] prepared a two-layer epoxy-based nanocomposite coating consisting of an electro-thermal layer and a superhydrophobic layer for anti-/de-icing, combined the high electrical conductivity of epoxy resin/silver-plated copper (Ag–Cu) which can generate heat quickly under voltage, and the high thermal conductivity of epoxy resin/multi-walled carbon nanotubes (MWCNTs) which can conduct heat to the whole surface. The designed bilayer epoxy nanocomposite coating displayed electrical power consumption (0.2 W), low ice adhesion (0.01 MPa), long icing time (312 s), short deicing time (41 s), and good wear, acid, alkali, and salt resistance, making it promising for industrial application on wind turbine blades. Moreover, Guo *et al.*[72] developed the superhydrophobic multi-walled carbon nanotubes (MWCNTs)/epoxy coating for anti-icing application, which demonstrates a rapid de-icing process on the surface of a wind turbine blade model at 25 V (Fig. 8F). Despite the significant anti-/de-icing effects of electro-thermal technology on wind power equipment, it remains challenging in terms of energy consumption, material compatibility, thermal management, environmental adaptability, cost and maintenance. Future research needs to further optimize the efficiency and reliability of electro-thermal systems, as well as develop smarter ice monitoring and control systems.

5. Conclusions and prospects

In summary, we provide an overview of the mechanism of electro-thermal anti-/de-icing, as well as recent advances in electro-thermal anti-/de-icing materials, focusing on their large-scale engineering applications. Electro-thermal anti-/de-icing is advantageous compared to mechanical de-icing, liquid de-icing, and hot air de-icing due to its environmental friendliness and sustainability. However, there are still many limitations and challenges in the design, fabrication, and application of electro-

Table 4 Future research expectations for electro-thermal anti-/de-icing materials

Timeline	Short-term	Medium-term	Long-term
Focus	Enhancement of existing materials (*e.g.*, improving the fatigue resistance of carbon fiber composites) and optimization of manufacturing processes for cost reduction	Development of novel materials (*e.g.*, self-healing nanocomposites) and integration with smart systems	Realization of fully sustainable and autonomous electro-thermal systems
Actions	Conduct experimental studies on material fatigue and durability; pilot production lines for scalable manufacturing	Collaborative research on multifunctional materials; prototype development of integrated sensor-control systems	Research on bio-inspired materials and closed-loop recycling systems; large-scale field testing and deployment
Expected outcomes	Materials with improved performance and reduced production costs, ready for limited field trials	Functional prototypes demonstrating adaptive anti-/de-icing capabilities and enhanced reliability	Widespread adoption of eco-friendly, intelligent electro-thermal anti-/de-icing solutions across multiple industries

thermal anti-/de-icing materials. Firstly, most studies are limited to laboratory settings, with insufficient real-world testing in diverse environmental conditions. Secondly, long-term stability, particularly in harsh environments like corrosive or high-wear settings, has not been adequately demonstrated. Thirdly, economic factors are often neglected, with cost-benefit analyses being insufficient and little attention paid to lifecycle costs and large-scale economic viability. Lastly, interdisciplinary approaches are underutilized, requiring greater collaboration between materials science, engineering, data science, and environmental science to create comprehensive solutions. Bridging these gaps is essential for transitioning electro-thermal anti-/de-icing technologies from experimental to industrial applications.

Future studies are warranted to address the aforementioned challenges. Table 4 shows a proposed roadmap for the development of electro-thermal anti-/de-icing materials, illustrating short-term, medium-term, and long-term research focuses. It is expected that, with the help of collaborative efforts and sustained technological innovations within and outside the industry, electro-thermal anti-/de-icing materials will be further developed for a variety of fields and applications.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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