Materials, Innovations and Future Research Opportunities on Wind Turbine Blades—Insight Review

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Nowadays, wind turbine blades are manufactured using several materials and methodologies to save cost and to increase their performance. This article gives a brief overview of blade materials and prevailing manufacturing traits to make them more reliable and cost-efficient. The surface roughness, manufacturing defects, and fluctuating loads in flow fields significantly affect wind turbine power generation. However, these problems can be reduced by using appropriate materials. Therefore, selection of wind turbine materials is extremely important to maintain its performance even in harsh environmental conditions. This article describes an overview of current material solutions for overcoming material defects like delamination, structural distortion, and icing problems in the Polar Regions. It involves composites, smart alloys, protective coatings, etc. © 2018 American Institute of Chemical Engineers Environ Prog, 2018

Highlights

- *Types of loading, failure mechanisms and current manufacturing methods of wind turbine blades.*
- *Innovative blade material approach: Morphing concepts, Glass or Carbon fiber/Nano-/Bio-Composites.*
- *Active and passive strategies for anti-icing or de-icing of wind turbine blades.*

Keywords: wind turbine materials, anti-icing coating, material processes, and surface coating, Carbon Nanotubes, and blade structures

INTRODUCTION

Fast depletion of fossil fuels and climatic changes accelerates the paradigm shift on the conventional power generation. The wind is one of the widely available renewable energy sources; the large scale of power can be generated from the device which utilizing the speed of wind is known as Wind Turbine. The WT blade design was focused mainly on structural, aerodynamic and acoustic requirements, whereas the degradation in predetermined performances caused due to rugged environmental characteristics [1–4]. Nowadays, to satisfy the energy demand and reduces the cost per kW more power has to be produced, so that wind turbine is forced to installing at wherever the wind potentials presences rather than quantity of potential and operational difficulties. Therefore the designers move on with increasing the length of the blades to capture the more power and installing the turbines at snowfall, desert, and offshore regions which are now indispensable [5]. However, the diameter of turbine blade reaches up to 160 m, the longer length of the rotor needs suitable load controlling techniques to avoid the higher stress acting at the blade sections [6–8]. The blade designers and manufacturers to entitle the complex flow behavior and the varying requirements along the span that usually addressed as an optimization problem. The selection of design variables would be an important step to attain the objectives such as annual energy production, maximum tip deflection, overall sound power level, and blade mass. The airfoil geometrical variables such as leading and trailing edge geometry, a spanwise variation of airfoils and chord variables have much impact on wind turbine AEP as well as noise issues whereas chord variables highly impact on mass and maximum blade deflection [9]. The effective design of outboard airfoils endorses the high efficiency, extreme low load, stability, and a wide operating region along with structural requirement and noise issues through a multi-objective optimization [10]. The structural requirement of the rotor is to avoid the geometrical alteration at aerodynamically sensitive locations due to longer length and weight. Therefore, deployment of active morphing, passive morphing, and smart controls are widely accepted methods on the blade profile that used to ensure the low the extreme loads [11–14], and properties of morphing structures should have the load-carrying capability, deformability, and low weight.

Secondly, the wind turbines install from Polar to Sahara regions where geographical behaviors are deeply varied that influences on performances and cost of returns due to the ice accumulation, deboning, erosion, and buckling behaviour of materials [5,15]. The accumulation of ice and rain erosion on the blade surfaces makes a huge impact on the AEP, that also makes more load blades and tower which resulting into a higher vibration, dynamic unbalances, and structural damages of wind turbines [16]. The self-removal of the ice and dust can be achieved through different types of coating with respect to the regional climate conditions, i.e., ice repellent coatings used to lubricating blade-ice interfaces that will weaken cohesion forces of ice [17–23].

This article reviews the systematic approaches to solve the issues associated with the Wind turbines with longer blades and operating in rugged environmental that dealt through the material approach, manufacturing processes, types of the loads acting on the turbine, and different types of dust and ice removal machines in the following sections [24–26]. In addition, the desired properties required for the recyclability of blade materials for a different range of wind turbines are discussed [27–31].

Current Problems and Material Selection

In the current situation, delamination of the blade due to long-term use, damage caused by corrosive rain and reduction in performance due to adhesion of ice on the surface of the blade in the snowy regions are some of the major concerns in wind power production. In the rainy season, rain erosion is the major issue causing wearing off leading edge that results in the poor aerodynamic performance of turbine blade [32,33], It has been found that erosion of leading-edge results into power loss near to 9% which is quite significant. Therefore, before installation wind turbine in rainy reason, a series of computational analysis studies have to be done to understand its impact on power generation in that region [15,34,35]. The structural change affects the aerodynamics of the blade, which reduces the output of wind turbines. The materials for wind turbine blade are selected based on major load bearing direction such that fiber orientation in that direction withstands maximum possible load. To avoid the formulation of ice on the surface of the blade ice-phobic coatings can be used. Such coatings slow down the formation of ice on the surface which results in negligible ice adhesion to the surface [36–38]. Similarly, different ranges of roughness are formed due to the accumulation of contamination agents like insects and dirt. These contamination agents disturb the flow field and reduce machine power depending on their location, size, and density. According to a numerical analysis conducted on NACA 63-430 Airfoil, it has been observed that increase in surface roughness height will increase drag coefficient and reduces the lift coefficient, thereby causing a decrease in performance as shown in Figure 1 [5]. In polar region, atmospheric ice accretion will drive natural frequencies of the wind turbine down to the near resonance limit, i.e., reduces 4–5% of the natural frequency of nonrotating part, which could lead to significant issues on the structural integrity of the wind turbine. Furthermore, ice accretion leads to a dislocation of the separation point and hence promotes earlier flow separation, leading to an increase in drag and a decrease in lift and consequently a reduction in the generated power. The passive de-icing or active strategies will be used to get rid of ice the Polar Regions. However, in the case of the Sahara region, the blade surfaces are significantly affected by the dust particles, that erode the blade surfaces. In continuation, the wind flow characteristics are affected by the erosion of the blade surfaces, and the more research has yet to be conducted in dust accumulation and cost analysis. Hence, the wind turbine blades that designed for the polar region may not be suitable for the Sahara region.

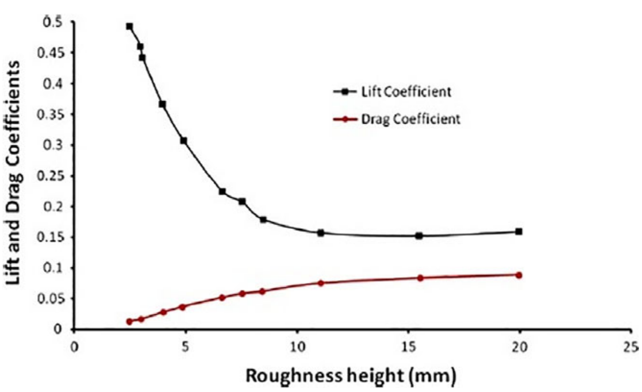

Figure 1. Effect of Roughness height on the aerodynamic characteristics of the blade region [5]. [Color figure can be viewed at **wileyonlinelibrary.com**]

The life of a rotor blade is another factor that has to be considered. Fatigue limit consideration is crucial for understanding structural distortion. In the case of plant fiber composites (PFCs), static properties like fiber strength, volume fraction has a huge impact on fatigue limit, which indicates very high fatigue loading capabilities for the entire lifetime of PFCs [24,39]. Considering bending moment distribution, blade lifespan also depends on turbine operating environment and production cost. High bending moment requires the high specific strength of materials to withstand the loads. Therefore, reinforced polymer composites like GFRP and CFRP have used as an ideal construction material for a turbine blades [39]. However, the production cost of such material is quite high as compared to natural fiber composites such as bamboo. Therefore a quest for selection of materials strongly depends on upon consumer's requirement and local environmental conditions [40]. In the case of large wind turbine composite blades, it has found that major fatigue failure is because of bumping motion created between maximum chord and root. The dominant reason for delamination and buckling failure are due to debonding between the pressure side and the suction side aerodynamic shells was the initial failure mechanism followed by its unstable propagation which leads to collapse [41]. Nowadays, researchers are trying to modify the laminated pattern to increase residual fatigue strength of a turbine blade [42–44]. In addition, there are three main requirements for the wind turbine blade material which has been satisfied to get the best turbine performance [45]:

1. Aerodynamic performances can be maximized by increasing material stiffness.
2. Gravity forces can be reduced using low-density materials.
3. Material degradation can be avoided through a selection of materials based on their fatigue life.

It is also essential to study, analyze and predict failures for new blade design concept. For example, for large turbine blades, quasi-static simulations can predict the evolution of failure crack and its propagation over the surface. Such parametric simulation studies are used for geometrical optimization of wind turbine [46]. Experimental investigation of structural collapse and failures needs video recording of failure. Strain measurement analysis is used to investigate the cause behind failure [47]. Another way to find out composite failures is through self-reporting color bleeding composites. It has a network of small fibers constantly running with colored fluid, and once there any composite failure, fiber punctures fluid come out and the color reports failure location [48].

Innovative Materials Approach

In general, blade material should possess low density and high stiffness simultaneously in order to have better performance and handling. For example, fiber-reinforced polymer composites which include carbon, glass or natural fibers are used as a blade material [24,25,27,49]. According to the research study conducted at Roskilde University, Denmark, materials like wood (bamboo) integrated composites perform better than glass fiber composite. Thick composite laminates are applied in most of the high-performance laminates, and their material properties are controlled using at the time of manufacturing by the cooling rate which decides its crystallinity gradient [26,40,50].

Figure 2a shows the various parts of the wind turbine blade. The rotor blade may have several I, C and even box sections for internal support enables manufacturing of lightweight blades with a significant amount of weight reduction. Another improvement is sandwich composites with an

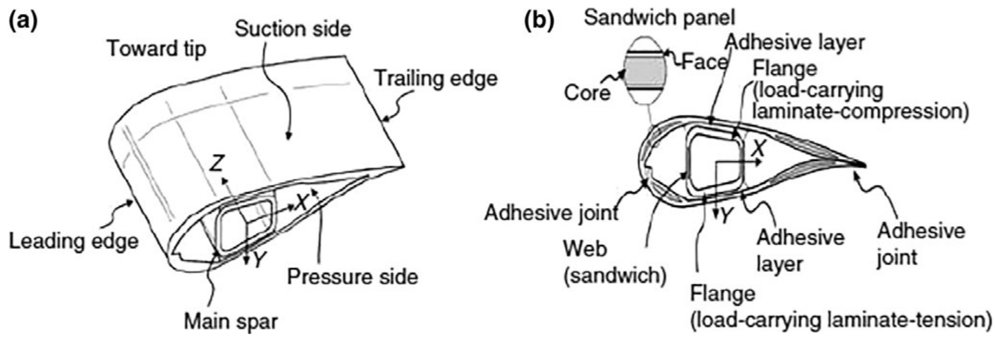

Figure 2. (a) Schematic diagram of a Wind Turbine Blade airfoil with shell and spar structures and (b) detailed material and structural layout [26].

optimized number of layers along with customized sequencing of fiber reinforcements. To impart bending stiffness and absorb gravitational loads, fibers are arranged along the axial direction of the blade in spar caps. Skins and webs are orientated at ±45° to resist shear loading and twisting [8,26]. People are more concern about wind turbine cost in a small wind turbine. It resulted in increasing demand for a cheap wind turbine with very less compromise in strength with the inclusion of natural fiber reinforcement. Using active smart materials in the various parts of the blade allow to change its surface profile. This can be used to increases aerodynamic performance in real time [11,14]. Previously, it was done by mechanical actuators using the principle of Smart-Materials Induced-Strain Actuation (ISA) for aeroelastic and vibrational control. For instance, piezoelectric ceramic materials are used in blade structural actuation to increase blade performance [13].

Manufacturing Processes and Methods

In reality, processes are developed based on the requirement of the manufacturer. For instance, vacuum-assisted resin transfer molding help in increasing fiber content, reducing volatile emissions, and improving the laminate quality of baseline wet lay-up process [51]. RTM (Resin Transfer Molding) is one of the successfully closed mold technology for small wind turbine blade. In addition, vacuum infusion process was useful for making large composite structures. In this process, bubbles from viscous resin are difficult to eliminate but, using the capillary effect of the porous medium acting as a micro-suction, removal of the resin from the bubbly medium is successful [52,53]. Different manufacturing techniques are explained in Table 1.

Wind Turbine Blade Loads

There is two type of loading observed in wind turbine blade: dynamic loading and structural loading. Structural effects consist of a dynamic rotation of blade especially in the case of Brazier's effect; it includes bucking of the blade results into a sudden decrease in efficiency. In addition, external factors like wind, rain, and snowing will cause additional stress on the turbine blade frame [3,6,54]. Also, it has been observed that the effect of wind turbine load has been dependent on wind profile models. Besides, the effect is limited up to 7%; wind load due to atmosphere stability is up to 17% of the total load depending upon which component of forces are analyzed [1]. The main sources of blade loading in wind turbine blades are operational, aerodynamic, centrifugal, gravitational, gyroscopic, etc. are given in Table 2.

In wind turbine, drive train with the main shaft supported by two spherical bearings that transmit the side loads directly onto the frame using the bearing housing. This prevents the gearbox from receiving additional loads. Also, the driver behind this research is to limit ultimate (extreme) loads and fatigue loads or to increase dynamic energy capture. In theoretical calculations, aerodynamic, flap wise and edgewise loads can be evaluated by using Blade Element Momentum (BEM) theory. In BEM theory, wind turbine blade is divided into three regions as per their importance into structural and aerodynamic characteristics as shown in Figure 3 [4,7,28,55].

Table 1. Different manufacturing technique for wind turbine blades [45,53]

Manufacturing techniques	Description
Wet hand lay-up	In the early days, smaller glass fiber reinforced polyester blades were manufactured using the traditional wet hand lay-up technique in open molds. The reinforcements were all glass fibers and mainly Chopped Strand Mats (CSM) with random fiber orientation, and after processing individual shells, the upper and lower shells were adhesively bonded together to form the airfoil-shaped blade
Filament welding	Filament winding consists of placing a huge amount of roving in a controlled manner around a rotating mandrel. The shape of a wind turbine blade is not cylindrical, the majority of the fibers have to be placed along the blade length, and then welding has to be done
Prepreg technology	It is based on the use of a semi-raw product Fabrics are pre-impregnated with resin, which is not yet cured. At room temperature, the resin is like a tacky solid, and the tacky prepregs can be stacked on top of each other to build the desired laminate. By increasing the temperature, the resin becomes liquid/viscous, and the laminate can be consolidated under pressure and cured into the final component
Resin infusion technology	It works under the principle of placing dry fibers in a mold, encapsulating and sealing off the fiber package, injecting the liquid resin into the fiber package, and curing the composition

Table 2. Different types of load on wind turbine blade [7]

Loads	Description
Aerodynamic load	The aerodynamic load is generated by the lift and drag of the blades aerofoil section, which is dependent on wind velocity, blade velocity, surface finish, the angle of attack (α), and yaw
Gravitational and centrifugal loads	Gravitational, centrifugal forces are mass dependent which is thought to increase cubically with increasing turbine diameter
Structural-load analysis	3—D CAD models are generated and analyzed by FEM
Flap wise bending	It is a result of the aerodynamic loads, which can be calculated using BEM theory
Edgewise bending	It arises from mass and gravity, significant only when turbine diameter greater than 70 m in diameter
Fatigue loads	The major loading conditions applied to the blade are not static. Fatigue loading can occur when a material is subjected to a repeated noncontinuous load, which causes the fatigue limit of the material to be exceeded. It is possible to produce a wind turbine blade capable of operating within the fatigue limit of its materials. It is a result of cyclic gravitational loads

Materials for Morphing Structures

In morphing structures of the blade, the foam is inserted at the trailing edge of the blade whereas most of the torsion, the axial and bending load is balanced by the box beam. Here the skin of the blade has to withstand with tensile, compressive and shear forces and transfer it to the inner central hub [11,12]. The overall structures on the blade are shown in Figure 2b. This section considers the materials that allow large deformations for morphing wind turbine blades. As previously discussed, the ideal material properties for a morphing structure must meet three conflicting requirements: load-carrying capability, deformability, and low weight. Some of the types of materials used in such structure as follows in Table 3.

THE RECENT APPROACH TOWARD MATERIALS FOR SMALL WIND TURBINE BLADE

Glass and Carbon Fiber Composite

Modern wind turbine blades are made of hybrid material structures that are manufactured using polymer matrix composite (PMC) material. The combination of monolithic and sandwich glass fiber-reinforced composite is preferred due to reduced weight. In addition, carbon fiber reinforced composites are used in the large scale [24,26,27,56,57]. In 2014, it was analyzed that an orientation of carbon fibers has a great effect of buckling resistance of wind turbine [58]. Even though the hybrid material structures is expensive, it has the following advantages; Since the usage of carbon fiber can be reduced by using hybrid reinforcements (E-glass/carbon, E-glass/aramid, etc.). Subsequently, it gives more strength and improved life cycle for the blades and ecofriendly [44]. Researchers at Norwegian University analyzed carbon/glass fibers in hybrid wind turbine blade with varying fiber orientation to understand the effect and trend of variation in its mechanical properties as given in Table 4.

The study has been conducted to understand the buckling behavior under the load. The result from these EWM buckling study has given a table at [58]. A maximum increase of 8% in CBL was achieved by changing the orientation of the stability lies from ±45° as specified in the reference blade to ±70°. This had a negligible effect on bending stiffness and the first flap wise natural frequency. Reductions in torsional stiffness were observed for the optimal fiber orientations but were found to have negligible impacts on the flap-wise loads and CBLs [29,58].

In polymer composites, structural distortion occurs mainly due to fatigue failure. To make material composites, which have a high fracture, toughness has been crucial for fabrication of wind turbine blade. Recently unique structural and transport properties of carbon nanotubes (CNTs) has attracted the attention of manufacturers to develop a nanotube-reinforced composite blade. Due to its exceptional mechanical properties, it has been multifunctional and can be controlled to get desired properties. Also, dispersion and alignment of CNTs play a significant role in directional properties of the composite [30,31,35,47,59,60]. There are several methods to align CNTs using the template as shown in Figure 5. When it comes to strength and density factors, CNT reinforced composite optimizes the material system. CNT composites can further be developed with better properties like hybridization with natural fibers for an eco-friendly material with high strength, low weight characters which makes it a suitable advanced material for wind turbine blade [62].

Wood and Bamboo

The wooden blades are considered eco-friendly. It also has good strength to mass ratio. As there are no multiple parts, the long directional wooden piece has less affinity for structural distortion. It has been analyzed that bamboo has high fracture toughness, specific strength, and modulus of elasticity among most of the other trees like birch [40]. Nowadays, scientists are interested in mimicking the structure of bamboo, as its varying density in radial direction might be the way to get excellent properties from the modified commercial material. Most of this wood is used for epoxy laminates where delamination can be reduced by avoiding air gaps and cavities by using good quality of epoxy resin [29].

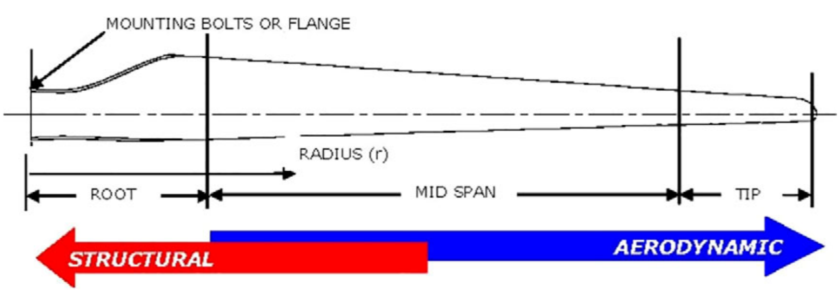

Figure 3. Design aspects of wind turbine blade [7]. [Color figure can be viewed at wileyonlinelibrary.com]

Table 3. Different materials for morphing structure

Materials	Physical properties	Main functions	Examples and applications
Elastomeric materials	Low density and low stiffness (0.5–50 MPa)	Withstand large strains which are useful for morphing skin	In Kikuta's report, the Tecoflex® 80A was found to be the best compromise regarding strain capability, recovery rate, and material type It can be combined with woven material like Spandura® to achieve high strain and recovery rate with high strength from fibers [11,71] is given in Figure 4a
Anisotropic materials	High directional strength	To absorb shocks and distribute it over the large area	Daynes and Weaver used an aramid hexagonal cell honeycomb core covered on one side by a 0.25 mm thick woven carbon fiber reinforced polymer (CFRP) skin and on the other side by a silicone skin which gives the excellent directional properties [11,72]
Multi-stable materials	High deformation with a low actuation force	Intrinsic structural properties and their ability to snap between positions with little delay make the multi-stable structure	Application of bistability was investigated by Schultz. His device was constructed by assembling two rectangular, carpenter-tape-shaped shells with their concave surfaces facing toward each other Each shell was made of a 0/90 graphite/epoxy FRP lay-up, developing bi-stability at room temperature. As the short edges of the shells were pressed together, twist developed along the structure as shown in Figure 4b[11,71,73]

Table 4. Material properties [58]

Material	E(11) (GPa)	E(22) (GPa)	v(12)	ρ (kg/m^3)	G(12) (GPa)	G(13) (GPa)	G23 (GPa)
0° Glass	41.0	9.0	0.30	1890	4.10	4.10	3.30
0° Carbon	139.0	9.0	0.32	1560	5.50	5.50	4.40
Core	0.25	0.25	0.35	200	0.073	0.073	0.073
Lining	9.65	9.65	0.30	1670	3.86	3.86	3.86
Gel coat	3.44	3.44	0.30	1230	1.38	1.38	1.38

Bio-composites

There is two main area of research where bio-composites are used in wind turbine blade. First, developing natural fibers with fully or partially replacing glass/carbon fibers, can reduce the cost in a significant amount [31]. Second, develop bio-resins with partially or fully replacing the petroleum-based resin in the composites [61]. For instance, Akesson *et al.* had tried two types of bio-resin: Acrylated Epoxidized Soybean Oil (AESO) resin and a Poly Lactic Acid resin; the results showed that AESO works better than PLA though both need to be studied more [31,61].

Passive Solutions for Wind Turbine Application

Almost 2–3% drop in the performance of wind turbine in icy regions has significantly motivated scientists to come up with active as well as passive solutions to solve this problem. As active heating consumes a lot of energy, it is regarded as non-efficient technique as compared to passive solutions like hydro/ice-phobic coatings [63]. The interphase coatings on laminates are used for protection against rain corrosion. It can be of in-mold gel coating or post-mold leading edge protection coating [64]. These coatings are cheap and require almost no maintenance over a long period and most reliable solutions for ice accretion. However, constant coating ultrasonic monitoring might be essential to keep track of any physical damage [65]. In the case of large deposition of ice, active methods of surface heating or actuator arm for removing ice can be used. Here, we mainly focus on ice-phobic coatings that are the potential solution to prevent the formation of ice on the surface due to its low energy surface. There was conflict in deciding exact differences between the nature of hydrophobic surfaces, but

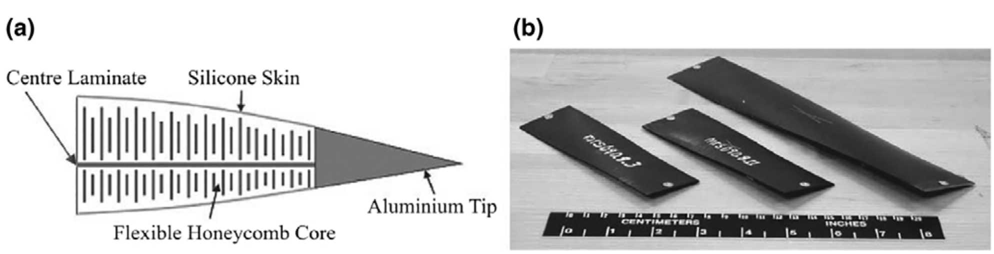

Figure 4. (a) Flexible trailing edge concept—silicone skin with honeycomb core on a center laminates. (b) Bi-stable twisting structures presented by [71].

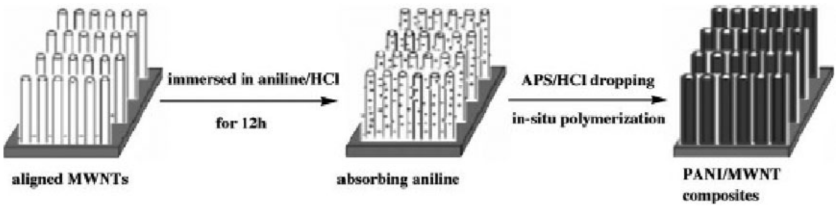

Figure 5. Process layout for making of well-aligned PANI/MWCNT composites [61].

the passive ice-phobic surfaces should possess hydrophobic characteristics [16,21,22,66,67]. Recent researches have provided new insights into the icing phenomenon and shed light on some promising bio-inspired anti-icing strategies. Commercially, PDMS, Teflon, etc. coatings are some of the most useful ice-phobic When ice already forms, ice adhesion can be significantly reduced if the liquid is trapped in surface textures as a lubricating layer. As such, ice could be shed off by the action of wind or its gravity surfaces used in various commercial applications [68]. Commercially, PDMS, Teflon, etc. coatings are some of the most useful ice-phobic surfaces used in various commercial applications.

Teflon (PTFE)

A simple treatment of PTFE coating helps to reduce ice adhesion on the wind turbine ensuring efficient energy production. This ice-phobic surface has satisfactory mechanical, optical, and electrical properties. A uniform coating is obtained by dipping the blade sample in a PTFE solution dispersion followed by annealing at 291°C for 2 min in an argon atmosphere. The resulting film is of contact angle 145°, a hysteresis of 30°, surface tension estimated to 11.7 mN/m. It has a slipping angle of 45° even at the temperature as low as −6°C. There was no observed effect of ice shedding events although this low energy surface coating is more promising in wind turbine applications [23].

Ice adhesion measurement and SEM images reveal that coating has excellent hydrophobic as well as ice-phobic character. The new coating in which oxidation is avoided in argon atmosphere has sufficient performance to allow natural ice-release through the effects of gravity and wind draft. It is also stable when exposed to UVC rays and pH = 1 acidic solution

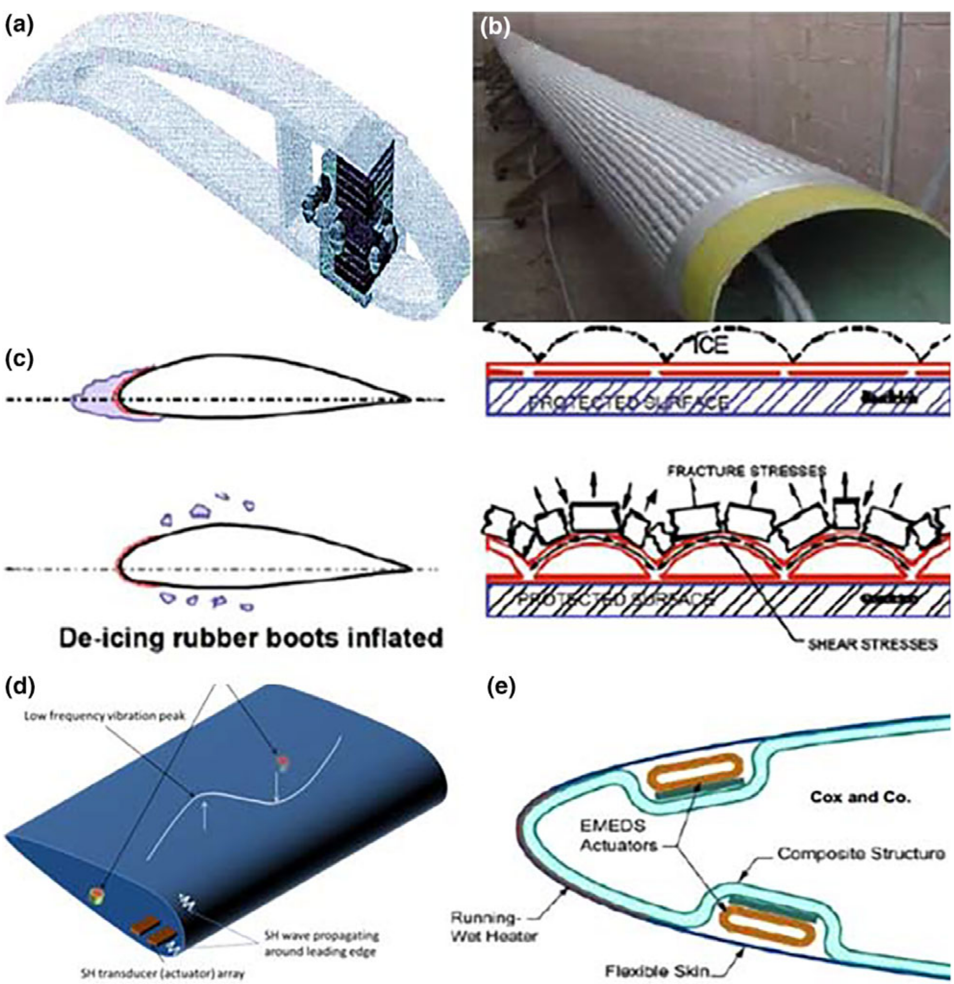

Figure 6. (a) 3D model of the ultrasonic transducer in wind turbine blade; (b) experimental pneumatic de-icing system; (c) working principal of rubber inflated boots; (d) ultrasonic de-icing technique currently being tested and (e) expulsive de-icing [70]. [Color figure can be viewed at **wileyonlinelibrary.com**]

which guarantees good resistance in the severe environment. Therefore, Teflon is efficient as well as inexpensive treatment for solving the ice accretion problems in wind turbine in most of the cold areas [20].

Poly Di-Methyl Siloxane

The preparation of silicon-oil-infused poly di-methyl siloxane (PDMS) is one of simple and cost-efficient technique that can be used for ice-phobic coatings. Its hydrophobic nature due to the absence of –OH, –C=O groups. In experiments conducted by Prof. Lin Zhu, the ice-phobic behavior is analyzed based on ice adhesion, contact angle, and dynamic icing photography. It has not yet implemented on wind turbine blade for solving icing problems on a large scale. This may be because of preparation cost for PDMS with an appropriate stiffness that can sustain aerodynamic loads [19,63,66].

ACTIVE SOLUTIONS FOR WIND TURBINE APPLICATION

Chemical Methods

In icy regions, freezing of droplets can be avoided by using anti-freeze chemicals. In such environment, materials go through repetitive thermal hysteresis between freezing and melting point as a result; local survivals produce anti-freeze protein by means of a biochemical reaction, and it helps them survive in extreme cold. In this method, anti-freeze fluid is pumped from a bottom tank to the blade surface to avoid ice adhesion and freezing. A non-water soluble liquid gel can also be used to reduce ice adhesion at the surface of blades. Liquid gels are commercially available, and they have the same constraints as ice-phobic viscous coatings. This approach can completely prevent the formation of ice on the structure, or simply help to maintain a thin film of gel between the structure and the ice to facilitate the elimination of natural ice by gravity or wind. It requires proper maintenance as well as timely accurate sensing of ice formation. The pumping system has to bring fluid back to the tank. It is a low-cost active method for anti-icing or de-icing modes [69].

Mechanical Methods

It involves the physical breaking of ice through scrapping or energy released through vibration or movement of the structure. When these systems are controlled properly, they can be used for anti-icing. Otherwise, manual methods like scrapping are considered for de-icing of turbine blades. There are the various techniques through which de-icing or anti-icing can be achieved as shown in Figure 6 [69,70].

Pneumatic Technique

It is commonly used for leading de-icing edges of wind turbine blades. When sufficient ice has accumulated over a time period, air chambers will successively inflate and deflate by means of compressed air [70].

Expulsive Technique

This method utilizes both electromagnetic and piezoelectric pulse to break off the ice from the blade. In both techniques, a surface profile is moved with a high frequency for expulsive ice removal [70].

Ultrasonic De-icing

The idea behind this technique is to break adhesion bonds between two surfaces. The equipment utilizes ultrasonic waves to create stress at the junction of two materials [70].

Thermal Methods

To prevent ice build-up on the blade surface, the temperature of the surface is maintained above freezing temperature to prevent ice formation. It requires an external source of energy and can be done through several means as follows [70]:

Hot Air Injection

In this technique, hot air is used to maintain a surface temperature above freezing point. It is suitable for applications where hot air is a by-product [70].

Resistive Heaters

These heaters are connected to sensing and controlling devices to heat surface in a controlled manner through electric current [70].

Microwave Heating

In 1982, Hansman proposed a microwave ice prevention system that can heat impinging supercooled water droplets by transmitting microwave electromagnetic energy to the droplets. The only concerns about this technique are safety issues [63].

Infrared Heating

It is used to deliver energy to a distant object from the power source. Its main advantages are that the energy is emitted through the air which does not require any installation but on the other hand, another component will also overheat due to this technique [63].

CONCLUSION

In the current scenario, wind turbine blades are manufactured by injection or infusion of the resin. However, advancement in material additives like CNTs and enhanced control over the manufacturing process has opened the windows for the next generation of wind turbine blades. Blade materials like bio-composites, woods etc. are also getting more attention due to their competitive mechanical properties and availability. Blades are the most important composite based part of a wind turbine, and the highest cost component of a turbine. As blade gets larger in size, it costs more percentage of the overall cost irrespective of its material, and that is why researchers are more interested in alternative materials and small wind turbine applications. Wind turbine blades were often produced using the wet hand lay-up technology, in open molds. However, disadvantages of the open mold technology are high labor costs, relatively low quality of products and environmental problems. Lately, the automated tape lay-up and fiber placement, segment wind blades, enhanced finishing technologies are used to improve quality and reduce costs of the composite blade manufacturing. In addition, hybrid reinforcements (E-glass/carbon, E-glass/aramid, etc.) are an attractive alternative to the pure glass or pure carbon reinforcements.

To avoid the operational failure and subsequent performance loss due to the rugged environment in the areas such as desert and Polar Regions, different types of coatings have developed and applied as active, passive and mechanically. In Polar Regions, it has been found that passive coating solutions like “Teflon” or “PDMS” coatings are the best cost-effective solutions to overcome ice accretion problem. In large span wind blades, active ice-removal solutions are preferred to avoid ice accumulation on blades. These active strategies need regular maintenance, and therefore passive solutions are a more feasible option for small wind turbines. We believe that such solutions and inspirations shall inculcate over the world to make wind turbine more efficient and eco-friendly.

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NOMENCLATURE

ρ	Density (kg/m^3)
PFCs	Plant fiber composites
GFRP	Glass fiber reinforced plastics
CFRP	Carbon fiber reinforced plastics
ISA	Induced Strain Actuation
RTM	Resin Transfer Molding
CSM	Chopped Sand Mats
BEM	Blade element momentum theory
PMC	Polymer matrix composite material
CBL	Maximum load
CNTs	Carbon Nano Tubes
PANI/	Xxx
MWCNT	Polyaniline/Multi-Walled Carbon Nano Tubes
EWM	Effective Width Method
LPF	Load Proportionality Factor
U_2	Flatwise bending deflection at the blade tip
UR_3	Maximum twist at blade tip
AESO	Acrylated Epoxidized Soybean Oil
PLA	Poly Lactic Acid resin
PDMS	Poly Di-Methyl Siloxane
PTFE	Poly Tetra Fluoro Ethylene
SEM	Scanning Electron Microscope
UVC rays	Ultraviolet C rays
T_2-	Temperature of an ice layer
T_1-	Initial leaf surface temperature
L	Latent heat of fusion for ice
a	Thickness of layer (water + ice)
h_W	Heat transfer coefficient for water
h_A	Heat transfer coefficient for air
f_{WA}	Fractional flat area of the water-air interface
r_f	Leaf-water interface roughness factor

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