This paper is dedicated to Professor Dr. Siegfried Schmauder, on the occasion of his 65th birthday

УДК 539.3

Материаловедение и актуальные проблемы развития ветроэнергетики

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В статье обсуждаются современные аспекты материаловедения, связанные с развитием и внедрением ветроэнергетики. Ввиду высоких требований к долговечности и надежности лопастей ветрогенераторов, а также высокие затраты на техническое обслуживание, материалы для их изготовления должны обладать высокой прочностью и сопротивлением усталости в сочетании с малым весом. Обсуждаются возможные методы защиты лопастей ветрогенераторов от наиболее распространенных механизмов разрушения, в частности, эрозии передней кромки, а также требования к защитным покрытиям. В качестве материала для снижения гравитационной нагрузки на лопасти рассмотрены гибридные композиты с упрочняющими легкими углеродными волокнами. Другим аспектом использования прочных и долговечных материалов для изготовления лопастей ветрогенераторов является их вторичная переработка. Данная проблема особенно актуальна в связи со старением ветрогенераторов первого поколения, установленных в начале 2000-х годов. Рассмотрены вопросы создания конструкционных композитов на основе биосырья, вторсырья из полимеров и термопластов, обладающих прочностью на уровне армированной стекловолокном эпоксидной смолы.

Ключевые слова: ветроэнергетика, лопасти ветрогенератора, техническое обслуживание, мониторинг состояния конструкций

DOI 10.24412/1683-805X-2021-5-36-44

Current challenges of wind energy development: Materials science aspects

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Contemporary materials science aspects related to the development and expansion of wind energy are discussed in this paper. With view on the extraordinary durability and reliability requirements toward wind turbine blades, and high maintenance costs, the wind turbine materials should demonstrate extraordinary strength and fatigue resistance, combined with low weight. Possibilities of wind turbine blade protection against the most common blade degradation mechanisms, in particular, leading edge erosion, and requirements toward protective coatings are reviewed. Hybrid composites reinforced with lightweight carbon fibers are discussed as a way to reduce gravitational load on the blades. Another side of using strong durable materials for wind turbine blades is related with the recycling challenges. In connection with ageing the first generation of wind turbines, installed in early 2000s, the problems of waste management and recycling becomes especially relevant. Possibilities of development of structural composites from bio-based elements, recyclable polymers and thermoplastics, which have the same strength as the usual fiber glass epoxy, are discussed in this paper.

Keywords: wind energy, wind turbine blades, maintenance, structural health monitoring

1. Introduction

The year 2020 was in no way a good year for the humankind. However, it was surprisingly positive year for the development of wind energy around the

world. Large strategic perspectives were opened for wind energy in 2020. In January 2020, European Parliament voted to approve the European Green Deal, a set of policy initiatives by the EC with the goal to

make Europe climate neutral in 2050. The European Green Deal Investment Plan were presented in January 2020. One year later, in January 2021, US President Joe Biden signed an executive order, aiming to double U.S. offshore wind capacity by 2030. USA also rejoined the Paris agreement.

New initiatives in wind energy are clearly visible in Denmark as well. In Danish Finance Act 2021, large budget was set aside for green economic recovery. Denmark also achieved that 50% of Denmark's electricity consumption is generated by renewable resources in 2020.

The intensive development of renewable energy in general, and wind energy, in particular, can be expected in next years and decades. In this paper, we discuss the materials science challenges, related with the development of wind energy around the world.

2. Requirements toward wind turbine blades

Wind turbines became larger and larger over last decades, with blades reaching hundred meters as of today. At the same time, due to social pressure, wind turbines tend to be installed in locations, which are less and less maintenance-friendly.

The majority of customers are very positive about the development of renewable energy, however, many prefer the NIMBY, “not in my back yard”, rule. The reasons are various, including noise from rotating wind turbines and landscape changes. In this way, the offshore wind energy is expanded. 2.9 GW of offshore capacity were added in Europe during 2020 (356 new offshore wind turbines) [1]. There are also efforts to install wind turbines in cold regions, e.g. Canada, Alaska or even Arctic [2].

The requirements toward wind turbine materials are extraordinary high, in particular, for wind turbine blades. A wind turbine is expected to serve for 25–30 years. For comparison, an airplane is inspected before each flight, and maintenance teams are available in each and every airport. To repair a car requires typically just a short phone call, and a nearest car station is typically not too far. Repairing a wind turbine, which is located in North Sea, many kilometers from the coast, means considerable efforts. Structural repair of a single wind blade can cost up to \$30 000 and a new blade costs, on average, about \$200 000 [3, 4]. An out-of-service turbine can cost \$800–\$1600 per day, with most repairs taking 1–3 days. If a crane is required to repair or replace a blade, the cost can run up to \$350 000 per week. An average blade repair (offshore) can cost up to \$30 000

(for onshore blades, it can be two times less) and a new blade costs, on average, about \$200 000 [3, 5].

Thus, the challenges of the wind turbine maintenance and high costs of repair require an extraordinary high manufacturing quality of wind turbine parts, their damage resistance and design.

3. Degradation and protection of wind turbine blades

Wind turbines are subject to complex environmental and mechanical loading during their service time, including cyclic deformation, high moisture and temperature variations, but also extraordinary events, like transportation damage, lightning strikes, bird impact [6, 7].

Typically observed wind turbine blade damage can be classified as surface defects (e.g., erosion), nonstructural damage, delaminations and structural damage, with fiber failure [7] (see Fig. 1). The surface erosion (most often observed at the leading edge of wind turbine blades) is caused by fatigue from repeated rain drop and hail impacts, causing surface microcracks, leading to pits, gouges, delaminations and surface roughness, which in turn reduce the energy production of the wind turbine [8, 9]. The structural damage can include surface cracks and delaminations (e.g., from impact). For instance, in thick composite parts wrinkles may lead to the formation of compression failure and delamination. Cracks and delamination can also start from processing details such as ply-drops that locally causes a stress concentration.

Fig. 1. Typical damage mechanisms of wind turbine blades (color online)

Leading edge erosion is the most common mechanism of blade degradation. It can be often detected even 1–2 years after the wind turbine installation, and can reduce the annual generation of wind energy by 5–7% and even higher. In the survey of wind farm owners and service companies, carried out by Indian NIWE (National Institute of Wind Energy) and DTU (Technical University of Denmark) in the framework of MAINTAINERGY project [10], dealing with the blade damage mechanisms, 81% of respondents observed surface erosions, against 63% observing lightning strike and 44% structural cracks (each respondent could mark several options).

The costs for repair of blade erosion, or, alternatively, caused by the fall of energy production due to erosion, are very high, with millions of euros per wind parks. The problem of preventing the leading edge erosion, by developing erosion resistant coatings, changing surface parameters or service regimes, attracted large interest of wind energy and materials specialists [4]. In many projects, new antierosion coatings, predictive models of erosion or special regimes have been investigated (see the review in [7]). For the optimization of coating and service regimes, better understanding of the erosion mechanisms, and predictive computational models are required.

A number of computational models of erosion of wind turbine blades has been developed. Such models typically include several steps, in particular, evaluation of loading (rain density, droplet size distribution, dust, flow velocity), rain droplet impact contact modelling, modelling of materials degradation over time. Therefore, the modelling of surface rain erosion is a complex problem, including the random factors (rain scenario, random loading), fluid mechanics, solid and damage mechanics. For instance, in parametric 3D model of raindrop hitting the coated laminate developed in [11], both smoothed particle hydrodynamics (SPH) and coupled Eulerian Lagrangian (CEL) were used and compared. It was observed that both methods tend to predict similar trends of time-dependent stress evolution. Fatigue degradation prediction model, based on Miner–Palmer fatigue rule, the critical plane approach of multiaxial fatigue (i.e., assuming that fatigue damage accumulates on a specific plane in the material, denoted the “critical plane”), and the rainflow counting to simulate random damage was developed. Figure 2 shows the eroded surface of wind turbine blades, and a simulated stress field in the coating. Among the interesting results of the analysis, the authors showed that multilayer protective coatings, with highly damping

Fig. 2. Eroded surface of wind turbine blades (a) and computational model of rain drop hitting the blade (b) [11] (color online)

layers, can reduce the erosion of blades. The multilayer coatings allow the reflection of impact waves (caused by high speed rain droplet or hail impact) on interfaces, thus, reducing the coating and blade damageability. The viscoelastic, damping coatings can transform the stress impact waves into internal or thermal energy, thus, reducing the local stresses.

A great potential in developing of antierosion coatings is related with nanoengineered, architected coatings. In [4, 8], the coatings with polymer with interpenetrating structures are identified, as quite promising antierosion coatings. In [12], Kevlar pulp reinforced engineered coatings were studied in computational experiments. Figure 3 shows the computational model of coatings with Kevlar pulp reinforcement.

These examples demonstrate also the challenges of computational mechanics modeling in the analysis of factors, influencing the blade degradation. The wind turbine blades are extralarge structures with complex internal architecture, subject to multiphysics loading, random mechanical loading, and expected to

Fig. 3. Computational model of coatings with Kevlar pulp reinforcement (color online)

work over very long time. The modelling of such processes pushes borders of computational mechanics of materials.

With view on the materials development, the requirements toward the antierosion coatings (and to a lesser degree to adhesive layers and laminates) are also extraordinary. The development of materials, which can sustain multiple fluid impacts (with 50–100 m/s velocity), moisture, weathering and mechanical loadings over several decades is a challenge for next years.

4. Lightweight structures, carbon and hybrid composites

One of the ways to increase the durability and reliability of wind turbine blades is to reduce load on them, thus, reducing internal stresses and increasing lifetime. Apart from various design based solutions, such load reduction can be realized by using lighter materials. Lighter wind turbine blades allow reducing gravitational load on the blades, thus, reducing internal stresses.

Lighter blades can be made by partial or full replacement of currently widely used glass fibers by carbon fibers in the laminates [13]. Carbon fibers have density 1.75–2.00 g/cm³, while glass fibers are 2.65 g/cm³, ~30–50% heavier. At the same time, they have much higher stiffness (200–500 GPa versus 70–90 GPa of glass fibers) and higher strength, and typically 2.5 times lower diameters. It allows making the blades lighter and thinner, thus, reducing the gravitational component of loads on the rotating blade. Full replacement of glass fibers by carbon can lead to 80% weight savings (however also to 150% cost increase), and a partial 30% replacement leads to only 90% cost increase and 50% weight reduction [14].

Such modifications of internal structure of the wind turbine blade materials requires additional in-

vestigations, on the influence of carbon or hybrid blade reinforcements on the damage and fatigue resistance of the blades. Carbon fiber composites, as different from widely used glass fibers, demonstrate buckling and kinking damage mode. This additional damage mechanism depends on the properties (strength and shear modulus) of polymer/fiber interfaces, and on fiber misalignment. This adds requirements toward the manufacturing quality of composites (fiber alignment) and strong interfaces.

The strength and fatigue resistance of carbon and hybrid composites have been studied in many projects, using experimental and theoretical approaches. In [15], it was demonstrated that carbon fiber reinforced composites perform better in fatigue loading, in comparison to glass fiber reinforced composites. In [16] hybrid, pure glass and pure carbon samples were tested. The authors concluded that the longest tensile fatigue lifetime is observed in pure carbon fibers for all load ratios. In [13, 17, 18], it was demonstrated that the hybrid carbon/glass composites (while demonstrating higher stiffness than pure glass composites), can show lower strength and elongation to failure as compared with usual glass fiber polymer composites. The critical elongation of the hybrid composites decreases with increasing the fraction of carbon fibers in the hybrid.

Figure 4 shows 3D finite element unit cell model of hybrid carbon/glass fiber composites with fiber misalignment [13]. The effect of the kinking failure mechanism of carbon fibers on the strength of composites was studied numerically as well [19]. Weaker and softer fiber/matrix interface in composites leads to the higher sensitivity of composites strength to fiber misalignment, and to more often carbon fiber kinking. This can be solved by using special fiber sizing.

Hybrid and carbon fiber based composites have large potential for developing lighter and stronger wind blades. Due to high sensitivity to the fiber mi-

Fig. 4. 3D finite element unit cell model of hybrid carbon/glass fiber composites with fiber misalignment [13]. Reprinted with kind permission from Elsevier

alignment and kinking/buckling damage mechanism, there can be additional requirements to the quality of manufacturing.

Recently, Danish company LM Wind Power (part of GE), in collaboration with the Technical University of Denmark (DTU), has developed a new hybrid composites used to build the world's largest wind turbine blades, 88 meters [20].

5. Maintenance and repair of wind turbine blades

Maintenance of wind turbines is an important and also expensive part of the wind farm owner function. Even best protected and strong wind turbine blades can be damaged during their decades long service time. Maintenance includes inspections or structural health monitoring, and following repair, and can be realized as corrective maintenance strategy (i.e., only after a failure or damage event), or preventive maintenance (i.e., regular scheduled inspections of wind turbines, or condition based maintenance, which requires permanent health monitoring).

Structural health monitoring of wind turbine blades can be done using vibration monitoring, strain measuring, acoustic emissions, impedance techniques, ultrasonic waves, smart paint, laser vibrometry and ultrasound, impedance tomography, thermography, nanosensors [21]. These technologies require however installation of special sensors into the blades, as well as signal transfer systems. An interesting option is to use conductive nanoparticles (for instance, carbon nanotubes/CNT, graphene) as nanosensors to be embedded in the composites and polymer layers. The electrical resistance of the materials with nanoparticles is changed under deformation and

failure, thus, changing the percolation path, and the tunneling resistance between two adjacent nanoparticles. However, such conductive path in the blades might require additional solutions with view on lightning protection of wind turbine blades, and also with view on manufacturing and recycling aspects. Thus, the quite common way to identify damage now is the regular inspections of wind turbines. After the damage in the blade is identified, repair procedure is started [7], including an assessment of the degree and type of damage, design of repair scheme, removal of damaged region by grinding, and attachment of scarf or shell to the damaged blade. The repair should be carried out in such a way, that it ensures long postrepair service time. The layup of patch, adhesive and the repair technology are very important for the postrepair time of wind turbine blades.

In several works [22–24], computational models of blade repair were developed for the optimization of repair design and technology. The models are based on beam theory, fracture mechanics, damage tolerance approach [10]. In [10], finite element model of repaired laminate structures, with composite patch, adhesive, coating and parent composite structure is developed. Figure 5 shows a photo on onsite repair of wind turbine blade and a computational model of repaired laminate (coatings/scarf/adhesive/laminate) with stress field in repaired blade.

The onsite repair of wind turbine blades can last several hours, and is rather expensive. One of the way to reduce the costs of the blade repair is to optimize the curing technology, for instance, by using ultraviolet (UV) curing or high temperature curing. Reducing the curing/bonding time of scarf and the

Fig. 5. Onsite repair of wind turbine blade (a), computational model of repaired laminate (coatings/scarf/adhesive/laminate) (b) and stress field in repaired blade (c) (reprinted from [25], reprinted with kind permission of Elsevier). Photo (a) reprinted with kind permission from Mira Rope Access, <http://www.mira-ra.com> (color online)

damaged blade can allow reducing the repair costs by several times. However, a formation of defects (void/trapped air, low cured regions) in cured adhesives is possible in this case, due to quick curing and inhomogeneous heat distribution in the adhesive layers. Thus, the challenge of repair of wind turbine blades lies in satisfying both the requirement of quick repair (to reduce the repair costs, by using quick bonding and curing technologies) and the requirement of high post repair reliability.

An interesting direction of ensuring efficient maintenance of wind turbine blades is to develop so-called smart composites, with self-sensing and self-healing/self-repairing functionalities [21]. Several technologies for the development of self-healing or easy-healing lightweight structural composites are investigated now: capsulation and microcapsulation, hollow fibers, vascular networks, also supramolecular polymers, vitrimers, Diels–Adler healable polymers [26–28].

6. Sustainability and afterlife management

A significant proportion of the wind turbines, installed in 2000s, will come to the end of their lifetime

between 2020 and 2030 [29]. In 2021, about 6000 turbines can face decommissioning, due to the expiration of 20 years of support [30]. Many parts of wind turbines can be recycled, however, this is seldom the case for the composite wind blades [31].

Annual wastes are expected to grow ~12%/year until around 2026, and then 41% per year until 2034, reaching 28100 tonnes of blade material [32]. The problem of accumulating practically unbreakable nondegrading of polymer composites is in fact quite serious problem for environment, and also for the reputation of wind energy.

The way to deal with it is the development of recycling techniques for wind turbine blades. Since wind turbine blades (from thermoset composites) are designed to sustain long term extremal loads, their separation into reusable components and recycling is quite challenging (Fig. 6).

Different recycling technologies for the wind blades composites have been developed, among them, primary recycling for the same use, chemical recovering petrochemical components of plastics, and recovering energy in the form of heat [35]. The recycling technologies include mechanical modifi-

Fig. 6. Old wind turbines in the in the Sioux Falls, USA, two views (a) and (b). The photo from [33, 34] is reproduced with kind permission of Joe Sneve, Argus Leader

cation of materials (separated into smaller but still strong parts, which can be then used as reinforcements in various products; by shredding, crushing, milling), and thermal (pyrolysis), or chemical decomposition (solvolysis). The requirements to these technologies are the usability of output products, environmental friendliness of separation technology, acceptable costs. There are many projects underway, which seek to develop technologies for the wind turbine blade recycling [34].

In longer term, an alternative to the (quite challenging) recycling of durable and strong wind turbine blades is sought, namely, the development of easy recyclable, bio-based or environmentally friendly strong composites. While wooden wind turbine blades can be used for small wind turbines [36], glue laminated timber, laminated veneer lumber, wood strips and veneers can be used for medium wind turbines [34]. The applicability of wood products for wind turbine blades can be limited by moisture sensitivity (which still can be solved by choosing special coatings), variability of structures and properties, relatively low stiffness/weight of wood as compared to glass fiber/epoxy.

Another direction of the development of recyclable blades is based on application of thermoplastic composites and recyclable thermosets. The usability of thermoplastics for wind turbine blades is studied in several projects now [37, 38]. The main challenges of application of thermoplastic composites in blades are the high temperature processing, lower fiber adhesion, challenge to control the resin flow [34].

7. Conclusions

Current development of wind energy represents several challenges for the materials development.

The goal of extraordinary long service of wind turbines under high mechanical and environmental loads and high maintenance costs sets rather high requirements for the materials used in wind energy applications. Specifically, the higher lifetime and lower maintenance costs of wind turbines can be achieved, if expected and likely damage mechanisms are known, and the materials for the blade components are designed to resist these damage mechanisms.

With view on blade surface erosion, as the most common damage mechanism, development of multi-layer, damping, viscoelastic architected coatings is an important task for blade protection. Using lighter and stiffer carbon fiber based composites, instead of heavier glass fibers, allows reducing the load on blades, thus, also increasing their lifetime.

Still, even best protected structures need repair some day. Here, the challenge of bonding and repair of structures is in both the repair costs (which drastically increase the longer the repair goes, thus, requiring quick bonding and curing technologies) and long post repair warranty requirements (which can be compromised, if the quick curing leads to inhomogeneous, weakly cured regions or defects). Further, an important requirement is the recyclability and sustainability of wind energy materials. A number of activities on the development of recycling technologies for currently used composites, and on the development of recyclable new materials for next generation of wind turbine blades are underway now.

Funding

The author gratefully acknowledges the financial support of the Innovation Foundation of Denmark in the framework of the Grand Solutions project

DURALEGE, Durable leading edges for high tip speed wind turbine blades, file: 8055-00012A (www.duraledge.dk), and of the Ministry of Foreign Affairs of Denmark, in the framework of Danida grant MAINTAINERGY, Maintenance and repair strategy for wind energy development, file 19-M02-DTU (www.maintainergy.dk).

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Received 19.04.2021,
revised 19.04.2021,
accepted 27.04.2021