Chapter 2

Natural Fibre-Reinforced Polymer Composites for Wind Turbine Blades: Challenges and Opportunities

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I. INTRODUCTION

A wide variety of sources including wood, coal, coke, oil, natural gas and nuclear materials have been used to generate energy. Over the years, the consumption of energy has increased due to the increasing population and civilization. At the same time, the ecological awareness has become the major environmental issue in the global marketplace. In today’s scenario the major threat for the environment is the imbalance in the ecological system which is increasing due to the disposal of toxic waste. This issue has led to the increased interest on renewable and sustainable energy sources. The only concern for the sustainable development is minimum pollution and reduction in energy consumption. The increasing interest in the direction of using renewable energy has led to the development of the concept of wind energy. The wind energy is a prominent renewable energy source and is a solution of global energy problem. To convert the kinetic energy of the wind into mechanical or electrical energy, wind turbines or mills have been established. Most of the wind turbines basically consist of three rotor blades that rotate around a horizontal hub and convert the wind energy into the mechanical energy. The development of wind turbines for the generation of power is an emerging area. The rotor blades of wind turbines are considered as one of the key component of the wind turbine. The efficiency of the wind turbine majorly depends on the aerodynamic shape and length/angle of the blades as well as the materials used to manufacture the blades. Further, the wind turbines generate power according to the speed of the wind, not according to the demand. The basic criterion for the selection of materials for the wind turbine blades is that the material should possess high strength and stiffness, low density and adequate fatigue strength. The strength of the blade should be satisfactory so that the blade can withstand the load acting upon it without fracturing and stiff enough that it will not strike the tower during extreme loading conditions. The high fatigue strength of the blade means that it can withstand time-varying loads throughout its intended period of life. The wind turbine industries are constantly focussing on the development of light weight, cost-effective and environmental friendly materials for the production of wind turbine blades. The selection of suitable blade materials plays a significant role which determines the ultimate efficiency of the wind turbine.

Glass, carbon or aramid fibre-reinforced polymer (FRP) composites have replaced many metallic components in the various manufacturing sectors. But, the use of these materials is not considered as suitable for the environment, because these materials are highly dependent on petroleum based resources which are depleting rapidly. Due to the several environmental issues, the attention of the researchers and technologist has shifted on the utilization of natural biodegradable materials. Owing to this fact, the use of natural fibre-reinforced polymer (NFRP) composites is multiplying at a very fast pace. Recently, NFRP composites have been used as automotive parts because of their excellent combination of mechanical properties and lightweight characteristics. In addition, NFRP composites exhibit certain advantages those cannot be obtained with synthetic fibre-reinforced composites which include low density, low cost, non-abrasive properties, biodegradability and renewable nature. Natural fibres such as sisal, flax, hemp, kenaf, bagasse, banana, jute, abaca and bamboo are easily available and require low processing cost.

Mostly glass and carbon fibre-reinforced plastics (i.e., GFRP and CFRP, respectively) have been used for the production of large scale wind turbine rotor blades. The use of glass and carbon fibre is no more attractive to the rotor blade manufacturers, because the cost of these materials is high and the use of these materials causes environmental hazards. These attributes of synthetic fibres stimulate researchers to develop alternative materials for wind turbine rotor blades. Natural fibre-reinforced composites can be an alternative material for the manufacturing of wind turbine rotor blades. These materials can be used as a potential core material for the production of wind turbine rotor blades. Natural fibre-reinforced composites can be used as a viable alternative material in order to meet the demands of renewability and recyclability. Further, the uses of such materials minimize the total cost of the wind turbine. The increasing number of publication in terms of research articles in the area of development, processing and characterization of natural fibre-reinforced composites also emphasize the importance of these materials in the future wind turbine technology.

II. CONCEPT OF DEVELOPMENT OF NATURAL FIBRE REINFORCED COMPOSITES

Petroleum-based fibres (e.g., glass, carbon and aramid) are extensively used as reinforcement in polymer matrix composites. On the other hand, petroleum-based matrices such as epoxy, polyester and polypropylene are the major resin system reinforced with fibres to form fibre reinforced polymer composites. The composite materials consisting of petroleum-based fibres and matrix are mostly used in high-end structural applications where high strength and stiffness are required. However, the emerging global environmental awareness in the direction of recycling or reuse of the product at the end of their service poses a significant problem when petroleum-based fibre and matrix are used for the development of new products. This is due to the fact that both the fibre and matrix are non-biodegradable in nature which is a threat for the environment when ecological balance is the prime concerned. Due to the growing environmental awareness in the public, the utilization of petroleum-based composites is diminishing in the recent period. To avoid the depletion of limited fossil resources, increasing release of toxic fumes and volume of non-biodegradable composite waste, the development of natural biodegradable materials become significant to the users of composites. This fact leads to the development of natural fibre-reinforced composites or bio-composites. The use of natural fibre was found in ancient age of Egypt where mud and chopped straw have been used to made bricks. The mud and straw have been mixed together and then placed in the sun to bake into hard bricks. Mud bricks are excellent building materials because it can resist both squeezing and tearing. Another example of natural fibre composite is the Mongols bows which have been made by combining cattle tendons, horn, bamboo and silk where natural pine resin has been used for binding [1]. The development of bio-composites has intensified in late 1980s [2]. In 1990s, wood plastic composites were first introduced in the market for manufacturing of decks [3]. Over the time, variety of bio-composites has been developed with fairly good mechanical properties using different natural fibres and biodegradable/non-biodegradable polymers. The ultimate load carrying capacity of the developed natural fibre-reinforced composites is highly influenced by the properties of the natural fibres and the interfacial bonding strength between the fibre and matrix. In spite of having some disadvantages such a low modulus of elasticity, high moisture absorption and poor interfacial bonding between the fibre and matrix, the most important attribute of the natural fibre-reinforced composites is their biodegradable nature. Due to the biodegradability characteristic of the natural fibre-reinforced composites, they decompose in the environment and subsequently get transformed into water and carbon dioxide [4-6]. From this discussion, it is clear that the natural fibre-reinforced composites have the potential to replace the traditional petroleum-based non-biodegradable polymer composites. Recently, seeking for technologies for developing fire-proof natural fibre reinforced composites is also one of key issues to apply them for aircraft interior components [7].

III. NATURAL FIBRE REINFORCED COMPOSITES: TYPES AND CONSTITUENTS

Natural fibres can be classified based on their origin, derivations of plant, animal and mineral types [7]. Depending upon the source, natural fibres can be broadly divided into three categories: (i) plant fibres, (ii) animal fibres and (iii) mineral fibres. Fig. 1 shows the various types of natural fibres that are commonly used to develop natural fibre reinforced composites. The fact is that the natural fibre itself is a composite material where hollow cellulose fibrils are held together by lignin and pectin in hemicellulose matrix. The properties of natural fibres are mostly dependent on the cellulose content in the fibres, the degree of polymerisation of the cellulose and the angle of the microfibrils. Cellulose is an important constituent of the natural fibres. The type of cellulose present within the fibre defines the mechanical properties of the fibre, because each type of cellulose has its own cell geometry. Based upon the type of matrix, natural fibre reinforced polymer composites may be broadly classified into two categories: partially biodegradable and fully biodegradable composites. Reinforcing of biodegradable polymer with natural fibre results in fully biodegradable composites, whereas, reinforcing of traditional petroleum based non-biodegradable polymer with natural fibre results in partially biodegradable composites. According to Fig. 1, it should be noted that asbestos fibres are harmful to human health. Fig. 2 shows the various biodegradable and non-biodegradable polymers and the types of composites derived from these two types of polymers.

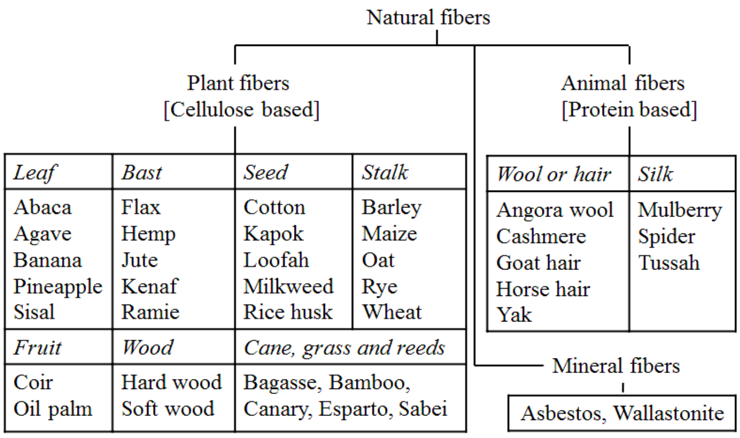

Fig. 1 Classification of natural fibres

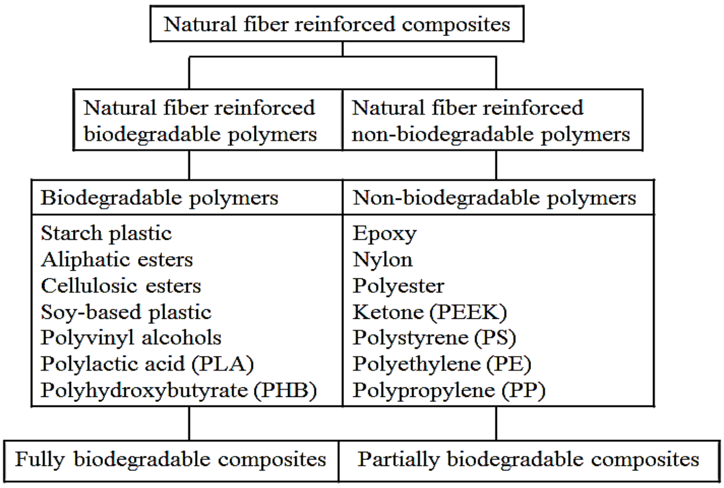

Fig. 2 Types of polymers and their composites

The two main constituents or phases of the natural fibre reinforced composites are reinforcement/fibres and matrix/polymer. Both the constituents are physically and chemically different from each other. There are a variety of natural fibres that can be used as reinforcement for the synthesis of polymer composites. The main function of the reinforcement is to carry the load and to provide the adequate strength and stiffness in the resulting composites. The natural reinforcements are the main load carrying member in natural fibre reinforced composites. The reinforcements are added in the matrix in order to enhance the mechanical properties of the neat resin system. The matrix also plays a significant role in determining the overall properties of the resulting composites. The matrix acts as a bridge to binds the fibres together, transfer the loads to the reinforcement, provide good surface finish and prevent the reinforcements from the environmental attack. The matrix materials should have the ability to deform easily under applied load, transfer the load onto the fibres and evenly distribute stress concentration. The presence of different constituents in composites results in a contiguous region between the reinforcement and matrix that is interphase. Interface has the characteristics that are not depicted by any of the constituent in isolation [4]. The interface of reinforcement and matrix plays a significant role during the service of the resulting composites in response to its load bearing capacity. The wettability characteristic of the reinforcement and matrix defines the adhesion efficiency of the constituents. The adequate adhesion means that the resulting composite has superior mechanical properties. The adhesion between reinforcement and matrix can be improved by treating the natural fibres. The treatment of natural fibres results in enhanced interfacial bonding strength between the fibre and matrix which means an enhanced mechanical strength and dimensional stability in the resultant composites. Chemical treatments of natural reinforcements based on the chemical source include: alkali, silane, acetylation, benzoylation, acrylation and acrylonitrile grafting, maleated coupling agents, permanganate, peroxide, isocyanate, stearic acid, sodium chlorite, triazine, fatty acid derivate (oleoyl chloride) and fungal [8].

IV. MAJOR PROBLEMS ASSOCIATED WITH THE USE OF NATURAL FIBRES

Despite several advantages, the use of NFRP composites has been restricted due to certain characteristics of the natural fibres such as moisture absorption tendency, poor wettability, poor adhesion with the synthetic counterparts and low thermal stability during processing. However, the major problem associated with the thermoplastic composite systems is the poor interfacial adhesion of the non-polar hydrophobic matrix material with polar hydrophilic fibre which results in poor mechanical properties in the final composites [9, 10]. When a material is intended for a prolonged period of usage, its durability becomes a critical issue. The physical and mechanical properties of polymer matrix composites are significantly influenced by hygro-thermo-mechanical loads. The mechanical properties of natural fibre reinforced composites deteriorate over a period of time as fibres, fibre-matrix interface region and matrix is typically affected by the moisture. The degree of deterioration and reversibility of the properties of the natural fibre composites is largely dependent on the extent of moisture absorption [11, 12]. Natural fibre encompasses abundant polar hydroxide groups which readily absorb moisture. The high moisture absorption level of natural fibre composites is a major obstacle in preventing their extensive engineering applications. Another disadvantage of natural fibres, to be used as reinforcement for the polymer matrix, is that they are thermally unstable at elevated temperature. Generally, most natural fibres are thermally weakened at about 160 ℃. Pre-treatment of natural fibres using chemical methods (for instance, use of coupling agent such as silane compound) enhances the adhesion at the fibre-matrix interface and reduces moisture sorption of natural fibres. The chemical treatment of fibres also helps in improving mechanical properties under both controlled and environmental aging conditions. In addition, the amount of moisture sorption can be reduced significantly by replacing natural fibres with a small amount of synthetic fibre such as glass or carbon [13-21]. Thermoplastic polymer composites are becoming popular and showing potential in many structural applications due to the advancement and improvements in the polymer industry. Recently, natural fibre reinforced bio-composites have been used as automotive parts because of their good mechanical properties and light weight. At present, many components of automobiles are fabricated by using natural fibre reinforced composite materials [22-24].

V. COMPOSITE MATERIALS FOR WIND TURBINE BLADES

In the early stage of development of wind turbine blades, wood has been widely used. Plain wood and laminated wood have been used extensively for the construction of blades. The manufacturing of plain wood blade is typically based on the concept of wooden boat-building technique. The turbine blades made out of plain wood performed well but the high moisture absorption tendency of the wood poses a critical problem for long term service. Laminated wood-epoxy based blades have also been used in wind turbine industry because these are lightweight and acquire adequate strength for the whole blade structure. For the time being bamboo has been used in the aeroshells and for sandwich structure within the rotor blade. The mechanical properties and biodegradable nature of bamboo makes it an attractive material for wind turbine rotor blades. Bamboo-poplar epoxy laminate has also been developed for rotor blades. The mechanical properties such as tensile and compressive stress-strain behaviour, tension-tension fatigue life and fracture resistance of the bamboo-poplar laminate panes formed by hot pressing have been studied in order to ascertain their feasible use in wind turbine blades [25].

Fibre reinforced composites have been introduced in the wind industry decades ago for the production of wind turbine blades. Fibre reinforced composites are largely used for production of small to large size wind turbine blades. In 1959, the first fibre reinforced wind turbine blade has been built by Ulrich Hutter’s. The use of fibre reinforced composite for production of blades has intensified in the mid-1970s with the development of small scale Danish turbines. The concept of Danish turbines is similar to the Hutter’s one, but the only difference is that in Danish turbine polyurethane foam has been used in blades for better stability of the skins. In the later stage of development of blades, the single shear web concept has been exaggerated, where the unidirectional fibres have been placed below and above the shear web. The main reason of conceptualizing this technique lies in the fact that the stability of the skins has been improved and tip deflection has been reduced. After that, sandwich panel has been introduced at the leading and trailing edges of the blade. The final change in blade structure has been observed when second shear web has been introduced due to the increasing gravity load with the increase in length of blades [26]. The shells which define the aerodynamic profile of the blade are mostly manufactured using glass fibre reinforced polyester and sandwich panel comprising of polymer composite sheets and light weight polymer foam or balsa wood cores. For the production of large scale blades, E-glass laminates are extensively used. CFRP composites are now used by some wind turbine blade manufacturers. CFRP composites are well suited for turbine blades because of their high strength, high elastic modulus and increased fatigue life. CFRP composites can be potentially used as reinforcement for aeroshell of blades as these possess adequate properties but the only drawback is their high cost. Sometimes, both glass and carbon fibre laminates as hybrid composites are used in order to take the advantage of properties of both fibres. As a large section of the blades is made up of the synthetic fibre based composites, for a certain section such as aeroshell and internal sandwich structures, natural materials such as wood and natural fibre composites can be used. It has been established that the natural fibre with surface modification can have superior mechanical properties and can be used in high-end structural applications (e.g., wind turbine blades).

It is true that, the wind turbine becomes the central part of the energy generation, but the problem comes when all those wind turbines need to be replaced. The currently used materials like glass or carbon fibres in wind industry need to be replaced because these are not biodegradable in nature. It has been predicted that US alone will install 170,000 wind turbines by 2030 and each year 34,000 blades has to be trashed away. Each blade weighing 18 tons and can stretch the length of a standard football field need to be trashed which means a large amount of unplanned waste. The disposal of such large structure that is reflected as hidden pollution is going to be a big threat for the environment in future. For the prevention of this large waste, research effort has been made for developing the biodegradable blade materials. Today most of the used blades are ground up for incineration and burial in landfills. For the manufacturing of wind turbine components, the next generation best materials is the lingo-cellulose based natural fibre reinforced composites. National Science Foundation (NSF) has already granted 1.9 million dollars to investigate how the natural fibre based composites can be introduced in wind industry to replace the oil-based materials [27].

VI. NATURAL FIBRE REINFORCED COMPOSITES: ISSUES AND CHALLENGES

It is clear from the discussion that natural fibre reinforced composites have the potential to be introduced for the manufacturing of turbine rotor blades. These materials satisfy almost all the criteria to use as basic material for wind turbine rotor blades. But, there are some challenges with respect to their processing. The analysis of the challenges encountered during processing of natural fibre reinforced composites may expand their utilization in wind turbine industry or in other application fields. Therefore, in the following sections, the various pros and cons in light of the potential utilization of natural fibre reinforced composites for the manufacturing of wind turbine rotor blades have been discussed. The various issues and challenges encountered during adhesive bonding and machining of natural fibre reinforced composites has also been discussed. Adhesive bonding and machining of the composite parts are the two main secondary operations that have been performed in wind industry in order to get the complete structural integrity of the rotor blades. The various components of the blade are assembled together by means of adhesive bonding only. In addition, a large segment of the wind turbine blades necessitates machining operation to cut off excess material from the root end, milling of root face, drilling of axial and radial holes. Therefore, the machining behaviour of natural fibre reinforced composites has also been included in the present chapter.

A. Primary Manufacturing of Natural Fibre Reinforced Composites

The major design aspect that is considered during the manufacturing of wind turbine blade is the aerodynamic shape of the blade. The efficiency and durability of the blade mostly depend on its aerodynamic shape. The prerequisite shape of the blade can be achieved during its primary manufacturing. The most common techniques used for the manufacturing of wind turbine blades are wet hand-lay-up, filament winding, prepreg technology and resin infusion technology. These techniques have been developed mostly for the processing of glass, carbon or other synthetic fibre reinforced composites. The processing industry for natural fibre reinforced composites uses the same techniques without much modification. However, there are some challenges encountered during the primary manufacturing of natural fibre reinforced composites; those are discussed in the subsequent section.

Challenges with Primary Manufacturing:

The primary processing or manufacturing of natural fibre reinforced plastics is typically challenging because certain number of variables are involved during processing. In spite of having several good properties, it is important to understand the challenges associated with primary manufacturing of natural fibre reinforced composites in order to further expand their utilization. Fundamentally, the challenges encountered during the manufacturing of natural fibre reinforced plastics are different from those of synthetic fibre reinforced plastics. The following points give an inkling of some of the challenges arising during the manufacturing of natural fibre reinforced composite parts.

a) The variety of natural fibres and matrix and their combination and the number of manufacturing process and associated controlling parameters makes it very difficult to choose the best processing technique for the primary manufacturing of natural fibre reinforced composites. The selection of appropriate manufacturing process is a key consideration in order to ascertain good properties in the final composite product.

b) The physical and mechanical properties of the natural fibres vary according to the geographical location and environmental condition in which plants grow. The distinct physical, chemical and mechanical properties of the natural fibres and polymers make it difficult to blend them during primary processing. The proper blending of fibre and matrix substantially enhances the mechanical properties of the resulting composites.

c) It is well known that the natural fibres have poor adhesion property as compared to the traditional glass/carbon fibres. The poor adhesion between the fibre and matrix results in internal defects and low performance of the final composite parts. For that, several techniques have been developed in order to improve the interfacial adhesion between the natural fibre and matrix. Chemical treatment and coating of the natural fibres are the prominent methods used for the modification of fibre surface. Sometimes, additives, fillers and catalysts are added during the processing of natural fibre reinforced composites.

d) Various combinations of fibres and matrix make it difficult to control or optimise the processing parameters during primary manufacturing. This may be attributed to the fact that the different fibre and matrix present in composites demands different conditions for processing.

B. Joining Behaviour of Natural Fibre Reinforced Composites

The construction of wind turbine blade may be a one-piece or two-piece construction. In one-piece construction, a spar is fixed to the inner shell and then to the outer shell through adhesive joining. Whereas, in two-piece construction, the shear webs are adhesively joined with the shells. In addition to adhesive bonding of spar or shear webs, the shells of the blade are also bonded together by means of adhesive joining. In wind industry, two component metering and mixing equipment have been used to apply the adhesive to the blade. Two-component adhesive containing resin and hardener are mechanically pumped through a delivery pipe from their respective containers to the mixer head. In the mixer head, the resin and hardener are mixed together and then discharged. The adhesive bonding of various components in turbine blade typically consists of five steps. In the very first step, the adhesive is applied to the first shell. In the second step, spar or shear webs are installed in the desired position. The third step involves the application of adhesive to the top of the spar or shear webs for the bonding of the second shell. In the fourth stage, the second shell is placed over the spar or shear webs which define the complete construction of the blade components. In the final stage (fifth stage), the mould is closed and left for a required period of time till the adhesive is cured [28]. In Fig. 3, the adhesive joining of various sections of the blade has been represented for both one-piece and two-piece construction of blades.

In adhesive bonding or joining, two substrate materials are joined together by means of applying an adhesive. It is usually known that, to join the thermosetting polymer based composite parts, thermosetting polymers as adhesive is usually used, whereas for the joining of thermoplastic polymer based composite parts, thermoplastic adhesives are mostly used. Thermoplastic adhesives have some advantages over thermosetting adhesives. The major advantage of using thermoplastic adhesive is the processing time of joining is very short as compared to the thermosetting adhesive. Further, the high thermal stability, high chemical resistance, low moisture absorption tendency, and retention of bond strength at elevated temperature can be achieved while using thermoplastic adhesives. The most common types of thermoplastic adhesives are polyvinyl acetate, polyvinyl acetals, polyvinyl alcohols, polyamides, acrylics and phenoxies. The selection of an appropriate adhesive is an important joining consideration which depends on the several factors such as type of substrate material to be adhesively joined, required joint strength, impact resistance, resistance to chemical attack, electric current and humidity, service temperature and cost requirements. The efficiency of the adhesive bonding depends upon various factors, such as surface preparation of the substrates, type and amount of adhesive to be used for bonding, fitting of substrates to be joined and the curing procedure. Depending upon the requirements of the bond strength, an adhesive is generally chosen on the basis of its ability to wet the substrate surface, resistance to heat, resistance to moisture and chemicals, shear, peel strength and toughness of the resulting joint. The adhesive joining of natural fibre reinforced composites usually follow the same steps as the joining of typical synthetic fibre reinforced plastics. The steps involved for adhesive joining of natural fibre reinforced composites are shown in Fig. 4.

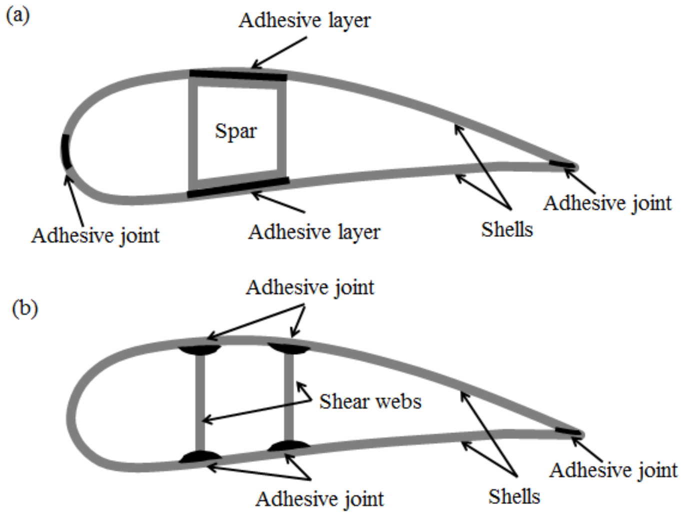

Fig. 3 Adhesive joints at the various sections of the blade: (a) one-piece construction, (b) two-piece construction

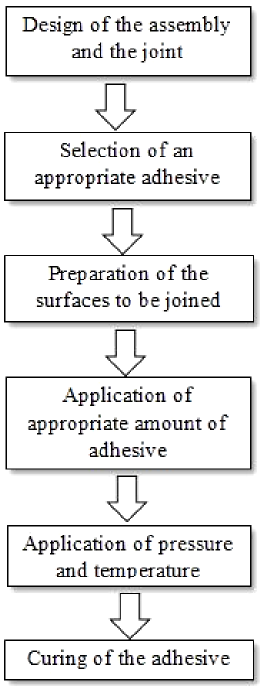

Fig. 4 Steps involved in adhesive joining of natural fibre reinforced composites

1) Challenges with Adhesive Joining:

In spite of having various positive characteristics, there are few drawbacks in adhesive joining. The major problem encountered during adhesive bonding is that the surface preparation of the substrates, that cannot be avoided. During the preparation of surfaces of the substrates, surfaces are pre-treated in order to enhance the wettability which in turn improves the joint strength by improving the contact between the adhesive and substrate. Surface preparation is important because the surface has to be free from contaminants (e.g., dust, dirt, foreign particles, greases, oil etc.) to avoid poor bonding. For example, thermosetting polymer based composite parts are often found to be contaminated with mould release agents, additives, waxes etc. These contaminants can be removed by abrading the surface with emery paper. But, in case of thermoplastic based parts, oxidation by flame treatment, plasma and corona treatment, ionised inert gas treatment, or application of primers or adhesion promoters are usually adopted to clean the surface [29]. Another disadvantage of the adhesive joining is the nature of adhesive bonding, which may be permanent or semi-permanent type; this means the components which have been joined together cannot be disassembled or may be disassembled by compromising with the surface damage. While considering the type of failure of adhesive joining, two different types of failure mode namely adhesive and cohesive failure have been observed. The adhesive failure basically occurs at the interface between the adhesive and the substrates. Adhesive failure may be due to inadequate surface preparation, selection of wrong adhesive and high peeling stress. But, in case of cohesive failure, the failure occurs only in the adhesive or in the substrate material. The main reason of cohesive failure is believed to be related to the stronger bonding strength between the adhesive and the substrate than the individual mechanical strength of the adhesive or the substrate material. If, the applied load exceeds the individual strength of the adhesive or the substrates, then the cohesive failure appears. The quality of the joint can be considered as poor if the failure occurs adhesively at the interface between the adhesive and substrate. It confirms that the bond strength is weaker than the individual strength of the adhesive or the substrate material.

The main criteria for selection of materials for wind turbine blades are that the materials should possess high-strength to weight ratio, high-stiffness to weight ratio, adequate fatigue strength, damage tolerance and corrosion resistance. Nowadays, wind industry is continuously trying to replace the current thermosetting based composites materials with the thermoplastic based composite materials in order to take the advantages of sustainability like recyclability and benefits of joining methods such as resistance welding and repair methods. In the subsequent section, an alternative method for joining natural fibre reinforced thermoplastic composite parts has been proposed. This method has shown superior joint strength as compared to the joint made by means of applying adhesive for the same natural fibre reinforced composites.

2) An Alternative Technique for Joining Natural Fibre Reinforced Composite Parts:

The issues and challenges associated with adhesive bonding of natural or synthetic fibre reinforced composite have been discussed. It can be inferred from the discussion that the adhesive bonding is not a perfect joining method. The adhesive joining can be replaced by established microwave joining technique. This promising joining technique is suitable for joining natural fibre reinforced composite structural parts. Microwave joining has been established to minimize all the defects detected in adhesive joining. The main benefit of using microwave energy for joining is that it does not change the microstructure and property of the substrates to be joined together. Microwave joining basically involves the use of high frequency electromagnetic radiation to heat a susceptor material located at the joint interface. The generated heat melts the thermoplastic materials and joins the materials upon cooling. Basically, a susceptor has a high dielectric constant material which can absorb electromagnetic energy and then convert it to heat energy. This dielectric property of a material determines its ability to absorb microwave radiation. A susceptor may be of ceramic or metallic materials. The important process parameters that can affect the joint strength are exposure time, power level, applied pressure and percentage of susceptor to be used. Microwave joining comprises several advantages over traditional joining methods, such as:

a) Rapid processing,
b) Saving of energy and no generation of polluting gases,
c) Joining of complex geometries,
d) Volumetric heating and uniform temperature distribution,
e) High strength and homogenous microstructure of the joint.

3) Microwave Heating Mechanism:

The wavelength and frequency of microwaves can vary from 1 mm to 1 m and 300 GHz to 300 MHz, respectively. For general heating purpose, frequencies of 0.915 GHz and 2.45 GHz have been commonly used. The household microwave oven works at a frequency of 2.45 GHz corresponding to a wavelength of 12.2 cm; whereas, industrial microwave oven works at 0.915 GHz. The microwave heating process is fundamentally different from the conventional heating process. In conventional heating, the external surface of the material is heated first and then heat is transferred to the inside of the material by thermal conduction; whereas, in microwave heating material is heated all the way through at the same time. Because of this volumetric nature of the heating, microwave heating consumes 10 to 100 times less energy. It is well understood that in microwave heating, electromagnetic energy is converted into thermal energy. The energy is transfered to the material through molecular interaction with the electromagnetic field. Since microwaves can penetrate the material and supply energy, heat can be generated throughout the volume of the material resulting in volumetric heating. In the case of conventional heating, a slow heating rate is always preferred to reduce thermally induced stress.

A typical microwave furnace consists of three major components, such as source, transmission line and applicators. Fig. 5 represents a typical microwave processing setup. The main purpose of source is to generate electromagnetic radiation, where transmission lines carry away the electromagnetic energy from the source to the applicator. In the applicator the energy is either absorbed or reflected by the material. The design of these three basic elements and their combination into an efficient system require an understanding of the electromagnetic theory. The theoretical analysis of each component is governed by the appropriate boundary conditions and Maxwell's equations [30].

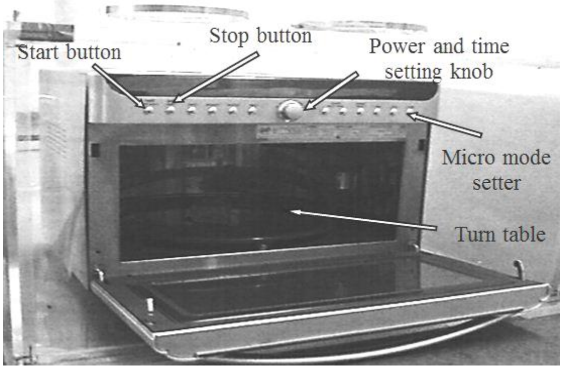

Fig. 5 Microwave processing setup

4) Microwave Joining of Plastic Materials: Research Initiatives:

Microwaves have been used for many years for kitchen and industrial heating applications as it significantly saves the processing time as well as energy. Now-a-days primary and secondary processing of various materials is readily done by using microwave energy. This is because the microwaves heat the materials volumetrically. In addition to material processing applications, microwave heating can also be used for joining advanced materials [31]. For joining metallic materials, it has been applied successfully [32]. Microwave welding of thermoplastic materials is an electromagnetic bonding technique which is relatively a new polymer welding technique [33]. Microwave processing of conventional materials is an emerging field, which is progressing very rapidly during the last several years. Sintering of various materials by means of microwave heating is a very innovative method and can be applied to traditional ceramics, advanced ceramics, specialty ceramics and ceramic composites. Development of functionally graded materials: joining, melting, fibre drawing, reaction synthesis of ceramics, synthesis of ceramic powder, phosphor materials, whiskers, microtubes and nanotubes, sintering of zinc oxide varistors, glazing of coating surface and coating development have been performed using microwave heating. In addition, microwave energy is being explored for the sintering of metal powders also [34]. The welding characteristics of engineering thermoplastics (ultra-high molecular weight polyethylene, polycarbonate and acrylonitrile-butadiene-styrene) using focused microwave energy have been studied [35].

The joining process is carried out in two different stages. In the first stage microwave energy is directly focused onto the specimen joint interface, whilst in the second stage, epoxy based primer is used to promote the joining by means of microwave energy. Finally, the bond strength is determined to see the quality of the bond at the interface by performing tensile test on the specimen. The work underlines the various aspects such as time required, bond strength, and quality of the joint. The study concluded that at a higher input power (1000 W), the time taken was three times less, where, bond strength was 2.5 to 3 fold greater for both the thermoplastic materials namely polycarbonate and acrylonitrile-butadiene-styrene.

A state-of-the-art review of microwave technologies, processing methods and industrial applications, using variable frequency microwave (VFM) facility has also been presented [36]. It has been reported that the welding of thermoplastic materials through microwave irradiation took place in 2–120 s with lap shear strength of 19.0 $\pm$ 2.0 N/mm^2 [37]. Inevitable limitations of mechanical and adhesive bonding can be minimized using microwave joining of composite materials as it provides several advantages through energy saving, rapid heating, reduction in manufacturing cost and unique micro structure [38]. The load carrying capacity of the natural fibre reinforced composite parts bonded through microwave radiation has been experimentally investigated [5].

Four different natural fibre based composites (nettle- PP, grewia optiva- PP, nettle- PLA and grewia optiva- PLA) have been developed in order to study their microwave joining behaviour. The joint strength has been determined for all the developed composites as per standard procedures. The results show that microwave joining offers higher joint strength as compared to adhesive bonding. Fixed frequency of 2.45 GHz and a maximum power output of 900W have been employed for microwave joining. Two different input parameters, power and exposure time have been considered for microwave joining. It has been found that the bonding strength of natural fibre reinforced PLA composites improved when specimen were exposed for 200 s. The microwave heating process has been accelerated by using a susceptor material. Charcoal has been used as susceptor material because it quickly couples with the microwave energy and produce rapid heating effect.

For proper joining of the specimens, an initial holding pressure has been applied to the joint by using a teflon tape. The top surfaces of the composite specimen to be joined get heated through conventional modes of heat transfer from the heated charcoal. As the process continues, there is eventually sufficient rise in temperature which causes fusion of the interfaces. From the experimentation of such technique, it has been observed that the grewia optiva fibre reinforced PLA adherends recorded maximum joint strength, whereas nettle fibre reinforced PP adherends showed minimum joint strength. Microwave joining of natural fibre reinforced composites has a potential of being a viable and sustainable alternative as it is a green processing technology. The steps involved for microwave joining of natural fibre reinforced composites are shown in Fig. 6.

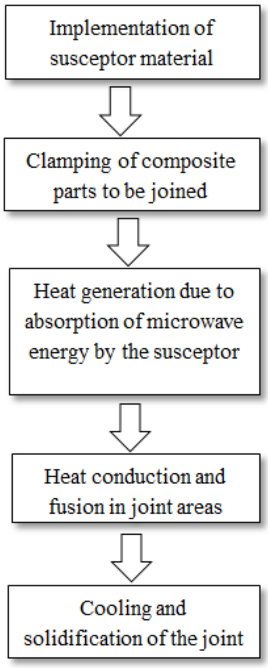

Fig. 6 Steps involved in microwave joining of natural fibre reinforced composites

C. Machining Behaviour of Natural Fibre Reinforced Composites

Most of the composite parts are made to a near-net shape through primary manufacturing. But, the complexity in the product makes the machining process necessary in order to ascertain the structural integrity. Machining operation such as drilling, milling, grinding, and boring are the most common machining operations frequently performed on composite parts. Among all the machining operations, drilling is the most frequently and widely used machining operation. Drilling is performed in polymer composites in order to fulfill the purpose of joining through bolting or riveting. Drilling is almost an unavoidable machining operation for any material, because several components need to be assembled together to make a complete assembly. While considering the machining of wind turbine blades, number of machining operations need to be performed in order to achieve the complete blade structure and to install the blade in the turbine hub. The specific machining operations, such as cutting off excess material from the root end, milling of root face, drilling of axial and radial holes are frequently performed by wind turbine industry. Facing of the root end and drilling of both the axial and radial holes within the required tolerances is important in order to precisely position the blade [39]. The turbine rotor blade contains both an axial hole drilled span wise and a radial hole drilled from the root that intersects the axial hole. Round metallic steel nut is inserted into the radial hole and the threaded root bolt is inserted into the axial hole and screwed into the barrel nut. This forms a very robust and strong mechanical joint rather than a bond joint [40].

The joining through adhesive bonding is not always possible for obtaining the ultimate structural integrity. Mechanical fastening such as riveting and bolting are the important methods of joining of natural fibre reinforced composite parts. The mechanical fastening demands the making of good quality holes of the desired size in composite parts. The making of holes is mostly done through conventional drilling. Various novel techniques have been developed for making of holes in polymer composites, but the conventional drilling is one of the most common methods of drilling. The fundamental concept of drilling of natural fibre reinforced composites is similar when compared with the drilling of traditional polymer matrix composites. But, the fact is that, the drilling behaviour of natural fibre reinforced composites is different from the drilling of traditional polymer matrix composites. Drilling of natural fibre reinforced composites is a tedious task, because several factors are involved that control the quality of the drilled hole. The optimization of the operating variables such as cutting speed and feed rate, selection of compatible tool material, designing of optimum tool point geometry and the evaluation and characterization of machining induced damage are some of the research areas that need substantial attention in order to enlarge the applications of the natural fibre reinforced composites.

1) Drilling Behaviour of Natural Fibre Reinforce Composites: Research Initiatives

The application spectrum of natural fibre reinforced composites has increased in past few years. Now, these materials are used for both structural and non-structural applications. The simple shaped of natural fibre composite parts has been created through primary manufacturing processes. But, the fabrication of complex parts necessitates joining of many components to ascertain final shape. Mostly, composite parts are joined together by means of mechanical fastening. The mechanical fastening of natural fibre composite parts necessitates desired size of hole in the components to be joined together. Conventional drilling is often used to generate holes in the composite components. Extensive work has been performed in light of drilling of polymer matrix composites, but the studies on drilling behaviour of natural fibre reinforced composite are scanty. It is interesting to note that, recently, the drilling behaviour of sisal fibre reinforced PP composite has been investigated [41].

The effect of cutting speed, feed rate and tool geometry on the thrust force and torque has been studied. It has been found from the investigation that drill point geometry has substantial influence on the drilling forces during drilling of sisal- PP laminated composites. It has also been observed that trepanning tool which is hollow in nature performed well in terms of quality of drilled hole as compared to twist drill (solid in nature) for the drilling of sisal fibre reinforced PP composites. This is because the fundamental mechanism of cutting of fibre and matrix is different for both drill point geometries.

In twist drilling, the drilling operation starts from the center of the drill i.e., the chisel edge of the twist drill first creates an indentation on the composite part and then the complete engagement of the drill starts with the composite laminate. But, in the case of trepanning tool, there are two cutting edges on the periphery of a hollow cylindrical shank, and cutting action takes place from the outer periphery of the trepanning tool. Further, the twist drill removed the material from the composite in the form of continuous chips but the trepanning tool removed material in the form of round circular plate. The drilling of coir fibre reinforced polyester composites has been studied in light of the effect of drill diameter, spindle speed and feed rate on the thrust force, torque and tool wear. From the experimental study, it has been observed that drill bit of 6 mm diameter is most suitable for minimum drilling forces and tool wear [42]. A comparative study on drilling behaviour of glass and natural fibre (hemp, jute and banana) reinforced polyester composites has been performed in order to compare the drilling induced delamination. The study reveals that the quality of the hole produced in the natural fibre reinforced composites is comparable with the corresponding quality of hole produced in GFRP. According to the results, it has been established that hemp fibre reinforced composites performed better in terms of minimum hole damage out of all the composites. Whereas, jute fibre reinforced composites experienced maximum damage in all drilling conditions [43].

The evaluation of delamination during drilling of rice husk reinforced polyester composites has been studied. It has been experimentally found that the delamination value is lower in rice husk reinforced polyester composites as compared to the GFRP [44]. An investigation on influence of alkali treated fibres on the mechanical and machinability of Roselle and sisal fibre hybrid polyester composites has been performed. It has been concluded form the study, that after alkali treatment the mechanical properties and machinability of the Roselle and the sisal fibre hybrid polyester composites has improved [45].

From the above research initiatives, it can be emphasized that natural fibre reinforced composites have the potential to replace GFRP in many applications where machining is needed. There are only few studies reported on the drilling of NFRP composites, which means a significant research scope is available in the field of machining behaviour of natural fibre reinforced composites.

2) Challenges Encountered During Drilling of Natural Fibre Reinforced Composites:

The importance of the drilling operation has already been discussed in the previous section. The researchers and technologists are continuously focusing their research activities on the development of cost-effective high quality drilling methods. Machinability study of anisotropic materials like natural fibre reinforced composites is an emerging area. But, there are many challenges associated with drilling of natural fibre reinforced composites. The major challenges encountered during drilling of natural fibre reinforced composites are highlighted as follows:

a) The drilling response of natural fibre reinforced composites is completely different as compared to the drilling of metals. The fundamental difference between drilling behaviour of natural fibre reinforced composite and metals lies in the fact that in natural fibre reinforced composite, tool has to cut two distinct phases (natural fibre and matrix) simultaneously, whereas, in case of drilling of metals the tool experiences only the cutting of a single phase. Drilling of natural fibre reinforced composites is a very complex process. The drilling response fluctuates according to the interaction of the tool with the distinct phase of material being machined.

b) The drilling behaviour of natural fibre reinforced composites is influenced by several factors related to the specification of composites, such as properties of the natural fibre and the matrix, volume fraction of natural fibre, and the orientation of the natural fibre in the resulting composite. The optimum drilling conditions for a particular composite may not be applied to the composite of same material but having different fibre volume fraction and fibre orientation. Further, the optimum drilling condition for a particular combination of fibre and matrix may not be the same for other types of composites with different constituents.

c) Drilling of NFRP composites results in exposure of fibres to the environment. The exposed natural fibres have the tendency of absorbing moisture which may adversely affect the overall load bearing capacity of the natural fibre composite structure.

d) Drilling parameters such as cutting speed, feed rate, tool material, and tool geometry are some of the key variables which determine the amount of surface damage. The most common types of damage observed in drilling of natural fibre reinforced composites are matrix burning and deformation, delamination, fibre pull-out, splintering etc. These types of damage adversely affect the structural integrity of the natural fibre reinforced composite. The optimization of all the drilling parameters can minimize the drilling induced surface damage.

3) Damage Analysis During Drilling of Natural Fibre Reinforced Composites:

The difficulties encountered during the drilling of natural fibre reinforced composites have already been discussed. From the discussion, it is clear that the major problem encountered during the drilling is the damage phenomenon that appears in the form of surface delamination. The characterization of the drilling induced delamination is an important issue, because the delamination during drilling is responsible for the failure of the complete composite structure. It is well known that the main reason of delamination is the generation of thrust force during drilling. Further, the generation of thrust force has been affected by drill point geometry. Fig. 7 represents the two different types of drill point geometry commonly used for drilling of natural fibre reinforced composite laminates. The thrust force signal during the drilling of nettle fibre reinforced PP composites has been presented in Fig. 8. As the drilling progresses, thrust force start to increase and then the magnitude of the thrust force is almost constant in a specific domain. In this domain, the drill bit is fully engaged with the composite laminate. Finally, drill bit comes out of composite laminate and shows a continuous decrease in thrust force. The drilling behaviour of natural fibre-reinforced composites can be critically analysed in respect of the thrust force signal and correlated with the drilling induced delamination.

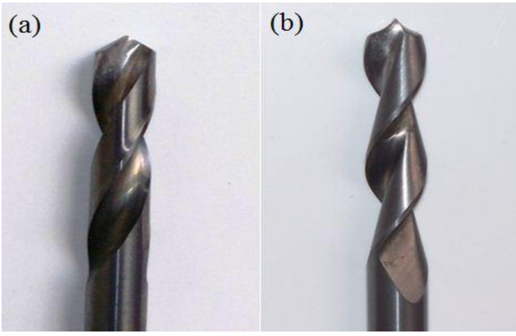

Fig. 7 Drill point geometry: (a) twist drill, (b) parabolic drill

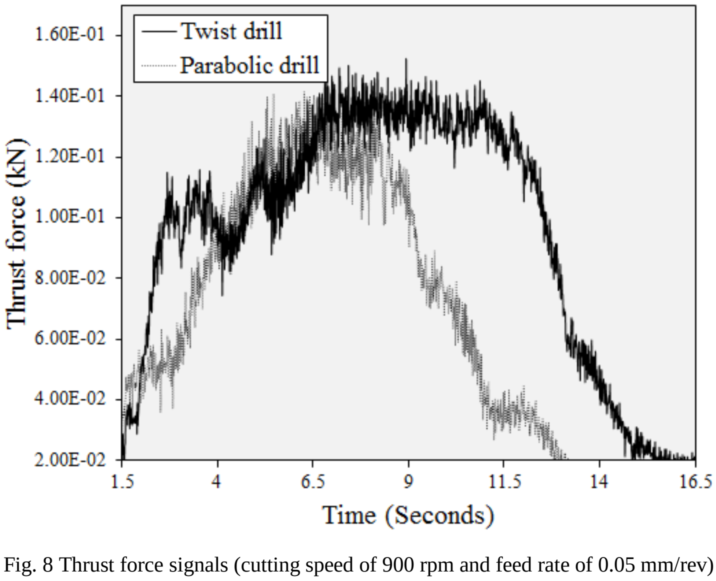

Fig. 8 Thrust force signals (cutting speed of 900 rpm and feed rate of 0.05 mm/rev)

Two different types of delamination has been observed during drilling of natural fibre reinforced composites, these are peel-up and push-down delamination. Peel-up delamination occurs during the entry of the drill bit. As the cutting edge of the drill bit comes in contact with the composite, a peeling force through the slope of the drill bit flutes separates the composite laminate and causes formation of delamination around the entry side of the drilled hole. Push-down delamination occurs during the exit of the drill bit. As the drill bit approaches to the hole exit side, thrust force plays a critical role, which defines the quality of the drilled hole. If the generated thrust force exceeds the inter-ply bonding strength, then there is formation of delamination around the drilled hole [46]. It has also been established that push-down delamination is much dangerous as compared to the peel-up delamination. Maximum products fail because of the push-down delamination. It is estimated that in the aircraft industry, 60% composite parts are rejected due to the drilling induced delamination around the drilled hole [47]. Many methodologies have been experimented upon in order to prevent the push-down delamination. These are the use of a backing plate during drilling, use of dedicated drill point geometry, use of non-conventional machining methods etc. Further, there are many techniques which have been developed in order to quantify the delamination; some of these are digital image analysis of the drilled hole, non-destructive dye penetrant test, X-ray non-destructive inspection test and ultrasonic C-scan. Fig. 9 typically represents the delamination area that can be obtained using digital image analysis technique. A digital image of the drilled hole has been magnified so that the damage around the hole can be clearly distinguished. The pixel aspect ratio has been maintained as unity so as to avoid any distortion of image that may result in invalid results. A factor known as delamination factor has been defined in order to measure the damage area. The delamination factor is the ratio of the maximum diameter of the delaminated area (D_{max}) to the diameter of the drilled hole (D). Fig. 10 represents the actual damage zone at the hole exit side during the drilling of natural fibre reinforced composites. The other types of damage observed during the drilling of natural fibre reinforced composites are matrix burning especially in case of drilling of thermoplastic composites, cracks in the resinous region, hole geometry error, fibre pull-out, uncut fibres etc.

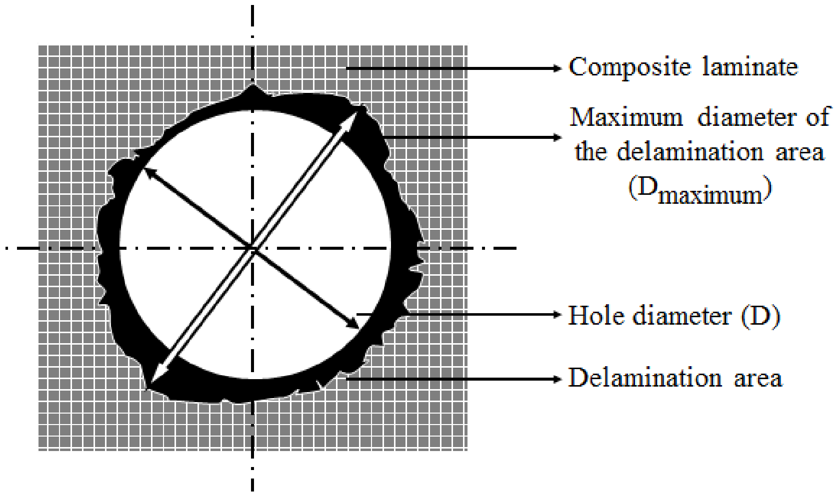

Fig. 9 Representation of delamination around the drilled hole

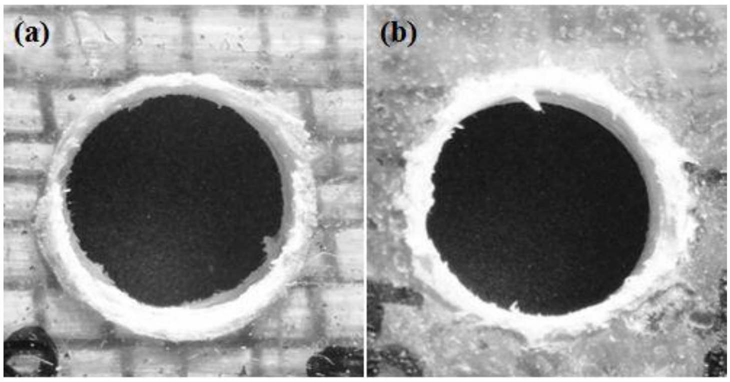

Fig. 10 Damage during drilling of (a) sisal-PLA composites and (b) grewia optiva-PLA composites

VII. CONCLUSIONS

The generation of energy is very essential for human survival and social development, but the generation of energy without polluting the environment is the biggest challenge of the twenty-first century. This problem can be solved by utilizing sustainable energy sources. Wind energy is the greatest example of sustainable energy source. Wind energy is clean, environmentally friendly and inexhaustible and can act as an alternative to fossil fuels. The fundamental concept of using sustainable energy lies in the fact that it can reduce greenhouse gases and pollution. It is true that wind power is the fastest-growing alternative energy system, but the materials used for wind turbine components are not environmentally attractive.

As the modern wind turbines are designed for estimated life span of 20 years, a large structure need to be disposed to the environment in future after the end of service life. The materials used for wind turbines are still non-biodegradable in nature. For this reason, scientists and engineers are constantly focussing on replacing the existing material system of wind turbines with bio-degradable materials. Natural fibre reinforced composites form one such class of materials which not only possess superior mechanical properties but are also bio-degradable in nature. Natural fibre reinforced composites can be a potential candidate where they can replace the conventional material systems of wind industry. These materials can be introduced for the manufacturing of various sections of a wind turbine. However, in order to expand the application spectrum of natural fibre reinforced composites, there is an imminent need to develop high-quality and cost-effective processing techniques.

In the present chapter, the viability of potential utilization of natural fibre reinforced composites for wind turbine blades has been discussed. The various issues and challenges in light of their primary manufacturing have also been addressed. Further, the chapter highlights the two important secondary processing techniques; adhesive joining and machining which are performed frequently in wind industry. As in wind industry, a large section of the blade requires joining in the form of adhesive bonding, it is necessary to find an alternative method of joining, as adhesive joining has its own limitations. For joining of plastic materials, an alternative joining technique namely microwave joining has been discussed in this chapter which can be implemented in the wind industry. It has been found that microwave joining of plastic materials produces superior joint strength as compared to the adhesive joint. Finally, the machining behaviour of natural fibre reinforced composites has been discussed. The machining in terms of drilling of fibre reinforced composites is a challenging task. Therefore, the various issues and challenges encountered during the drilling of natural fibre reinforced composites have been highlighted in order to get a comprehensive understanding in the area of processing of natural fibre reinforced composites.

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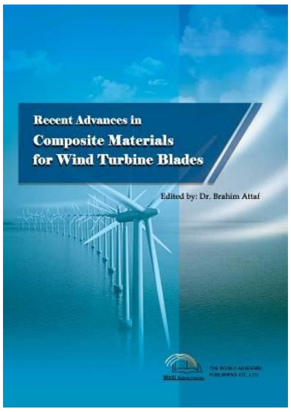

Recent Advances in Composite Materials for Wind Turbine Blades
Edited by Dr. Brahim Attaf

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This book of science and technology provides an overview of recent research activities on the application of fibre-reinforced composite materials used in wind turbine blades. Great emphasis was given to the work of scientists, researchers and industrialists who are active in the field and to the latest developments achieved in new materials, manufacturing processes, architectures, a
erodynamics, optimum design, testing techniques, etc.. These innovative topics will open up great perspectives for the development of large scale blades for on- and off-shore applications. In addition, the variety of the presented chapters will offer readers access to global studies of research & innovation, technology transfer and dissemination of results and will respond effectively to issues related to improving the energy efficiency strategy for 2020 and the longer term.

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