Development and Characterization of Polyamide Fiber Composite Filled with Fly Ash for Wind Turbine Blade

J. Joy Mathavan and Amar Patnaik

Abstract Proposing a suitable material for wind turbine blade is discussed in this paper. Low weight, high stiffness, high strength, and long durability are some of the salient features a material should possess to act as the wind turbine blade. Carbon fiber, glass fiber, and aramid fiber are used as blade materials in these days because they meet most of these features. In addition to, fly ash as filler material with polyamide fiber is discussed in this paper. The specimens were prepared by hand layup process. Erosion test is performed in air-jet erosion tester. The graphs are drawn according to smaller the better criteria of Taguchi L25 orthogonal array of two factors and five variables. Graphs obtained from dynamic mechanical analyzer for tensile test and three-point bending test are compared for different specimens. Hardness values are calculated by Rockwell hardness tester, and densities are calculated to analyze the void content.

Keywords Aramid fiber · Fly ash · Tensile strength · Wind turbine blade

1 Introduction

Getting rid of dependency on fossil fuel is an important objective for all the nations of the world today. The concentration is pointed on renewable sources of energy to achieve this target. Wind energy is an important source of renewable energy, and it is an environment-friendly way of obtaining energy [1]. So, it is important to utilize it and obtain a maximum use of it. Wind turbine is a method of converting wind power into energy. Proposing a suitable material for wind turbine blade is discussed in this paper. One of the main objectives of wind turbine blade research is to keep the weight of the blade under control [2]. Because the weight of the blade

J. Joy Mathavan (✉)
Faculty of Technology, University of Jaffna, Jaffna, Sri Lanka
e-mail: joymathavan1991@gmail.com

A. Patnaik
Malaviya National Institute of Technology, Jaipur, India
e-mail: patnaik.amar@gmail.com

L. Vijayaraghavan et al. (eds.), *Emerging Trends in Mechanical Engineering*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-32-9931-3_14

theoretically increases with the cube of its length, the power output only increases with the square of the length [1]. This is the reason why more attention is paid to the weight of the blade. To achieve this target, in the field of wind energy, a new material composite has been fabricated and tested for erosion in air-jet erosion tester. The erosion of turbine blade material is unavoidable, which in turn decreases the efficiency, reliability, and operating life of turbine blades. However, excessive erosion may lead to lack of performance. In order to minimize the erosion, extensive developments have been carried out for past few years by material researchers. The major areas of consideration when talking about windmill are the material used to make blade and rotor, shape of the blade, the coatings used on blades, and the optimum length of blade [3]. With the development in technology, different materials including carbon fiber, glass fiber, and aramid fiber are tested for wind turbine blade material considering its expected qualities like low weight, high stiffness, long fatigue life, high strength, long durability, and electrical and thermal resistance [4].

2 Research Background

Wind turbine blades were made up of aluminum and its alloys at the initial stage. But, thermal damage due to lightning strike [5], poor resistance due to corrosion and vibration of blade by wind load when it rotates were some problems accompanied and, in turn, resulted in the failure of the above-mentioned material [1]. Wind turbine blades made up of coated timber were used in developing countries, (mostly in remote areas of those countries) because of their economic conditions. It could be made by local carpenters is an additional advantage of this material. But, the blade material was limited for certain kinds of timbers, and the length of the blade was small [6]. It was used for small-level necessities. Currently, carbon-fiber-reinforced polymer, glass-fiber-reinforced polymer, and aramid-fiber-reinforced polymer are being used for manufacturing wind turbine blades [2]. Compared to aluminum alloys and coated timbers, the weight of these fibers is very low [7]. These fibers have high stiffness-to-density ratio, high strength-to-density ratio, and good fracture toughness [8]. According to the past studies, glass fiber has good electrical and mechanical properties and also has high heat resistance [9]. But, they are dielectric in nature [5]. Carbon fiber has an outstanding combination of high stiffness, light weight, high strength, and low density [9]. But, they are electrically conductive in nature [5]. Carbon fibers are three times stiffer, two times stronger, and also five times costlier than glass fibers [10]. Aramid fiber (aromatic polyamide) has admirable environmental and thermal stability, static and dynamic fatigue resistance, wear resistance and impact resistance [9].

Aramid fiber has the highest specific tensile strength (strength/density ratio) among all commercially existing continuous-filament yarn. They have very low densities [9]. But all of them (glass and aramid fibers for small blade and carbon fiber for long blade) are used across the world today [11]. It is anticipated that the addition of inorganic filler material will help to improve the required qualities of the fiber composite to be used as wind turbine blade. In this study, fly ash is added in different percentages with polyamide fiber and polyester resin combination and tested for erosion behavior under air-jet erosion tester. It is noticeable that the tests performed for hydraulic turbine blade material having granite dust as a filler material gave good results while considering stability and durability [12].

3 Experimental Procedure

3.1 Preparation of the Specimens

The composition of wind turbine blade material contains a polymer matrix (organic part), inorganic filler particles (distributed part), and an adhering agent to bind filler with matrix (interface). Here, polyamide needle fiber considered as the base material, fly ash is the filler material, and polyester resin is taken as adhering agent. Incorporating inorganic fillers to the fiber composites results in increment in mechanical properties (such as hardness, density, and tensile strength) [12].

Addition of any filler which can work on the perception of resistance to erosion and good in mechanical properties will be beneficial for the researches in the field of wind turbine blade material. In the current work, it is fly-ash-filled with polyamide needle fiber. The major elemental constituents of fly ash are Si, Al, Fe, Ca, C, Mg, K, Na, S, Ti, P, and Mn, and it has a specific gravity of 1.22–1.225 g/cm^3 [13]. So, it can enhance the erosion resistance and hardness values which will satisfy the requirements along with better physical, mechanical, and tribological properties. We can study the preparation and testing procedures in three steps. First step is preparing composite material, i.e., the fabrication of polyamide fiber composite filled and unfilled with fly ash. Second step is testing the prepared composite material samples for erosion properties. This includes the determination of erosion rate with its impact factors such as impingement angle and percentage addition of fly ash. Third step is experimenting with mechanical properties. It includes the characterization of physical (density), mechanical, and thermo-mechanical properties (hardness, tensile strength, and three-point bending) of polyamide fiber composite samples filled and unfilled with fly ash.

The designation and composition of samples are shown in Table 1. Hand layup method is used to prepare the specimens. In this method, polyamide fiber gets added layer by layer and polyester resin mixed with fly ash used as the matrix to adjoin and strengthen the composite. Specimens of 20 * 10 cm were prepared, and they were cut into necessary dimensions according to the requirement of the tests performed.

Table 1 Sample designation and composition

Sample designation	Composition
Specimen 1	Polyamide fiber + polyester resin
Specimen 2	Polyamide fiber + polyester resin + 5% fly ash
Specimen 3	Polyamide fiber + polyester resin + 10% fly ash
Specimen 4	Polyamide fiber + polyester resin + 15% fly ash
Specimen 5	Polyamide fiber + polyester resin + 20% fly ash

3.2 Description about the Tests

The samples were tested for erosion in air-jet erosion tester (TR-871-400) as per the standards of ASTM G76 international test method. The experiments were conducted under air-jet velocity of 60 m/s because 56 m/s is the maximum normal wind velocity measured on earth. To test the variation of impingement angle, there are specimen holders of five different angles 30°, 45°, 60°, 75°, and 90°. The specimens were cut in a shape of 25 * 25 mm to fit into the specimen holder. The feed rate of erodent was fixed at 5 g/min. The erodent used for the experiment was 50-micron-sized normal sand (SiO_2) because most of the erodent particles that strike the wind turbine blades mixed with wind are of this category. The experiments were conducted at 40 °C average temperature. The erodent feed rate and velocity of the air jet in air-jet erosion tester kept constant throughout the experiments. Weights of the samples were weighed by Precisa 125 A balance. Its least count is 1 mg and the range is 0–450 g. The samples were cleaned before and after the experiments, and the weight loss was calculated. The tensile test is conducted in dynamic mechanical analyzer (DMA 8000). The maximum thickness of the sample is 3 mm and length can be varied in between 10 and 20 mm to suit the machine standards. The width is kept around 5 mm; because if we increase the width, it may result in an improper holding of the sample in the clamp. Hardness test is performed in Rockwell hardness tester according to ASTM E-18 standard. An average of ten independent tests were performed and the average of them taken into account.

4 Results and Discussion

4.1 Erosion Analysis

Taguchi orthogonal array is used to analyze the erosion rate. In a Taguchi designed experiment, we manipulate noise factors to force variability to occur and from the results, identify optimal control factor settings that make the process robust to variation from the noise factors [14]. This is known as signal-to-noise (SN) ratio. Lower the erosion rate, better to be used in our applications. Based on this, smaller is better criteria in Taguchi table was chosen, and the equation for it is shown below. Here, n is the simulation repetition number under the same design parameter conditions and Y is the measured results.

$$\mathrm{S/N} = -10\log\left[\sum \left(Y^2\right) \Big/ n\right] \tag{1}$$

The results attained from Taguchi analysis table of L25 orthogonal array, 5 * 2 (5 factors and 2 variables) are shown in Figs. 1 and 2. The percentage addition of fly ash and the angle of impingement are the two variables here. The signal-to-noise ratio for angle of impingement shows 90° is the best applicable angle to minimize erosion and 75° stands the next. The Taguchi graph shows that the erosion rate is

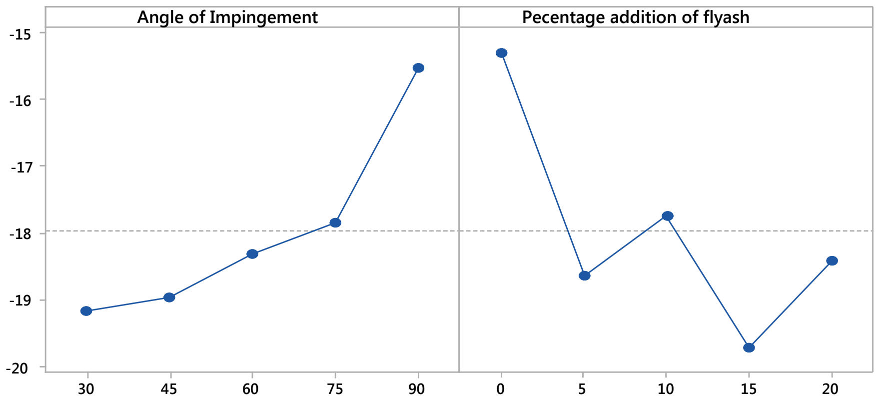

Fig. 1 Results of erosion analysis—mean of SN ratios

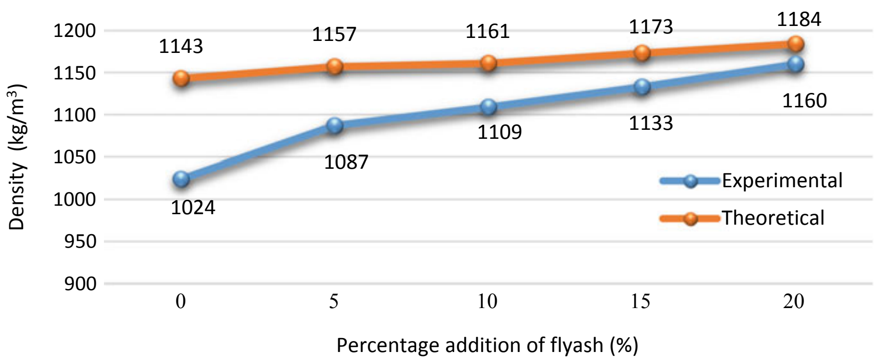

Fig. 2 Theoretical and experimental density comparison

decreasing generally when we increase the impingement angle. While we consider the percentage addition of fly ash, pure polyamide fiber sample and 10% fly ash added fiber are good for the application because both of them are above the mean line. It can be noticed that both 5 and 15% fly-ash-added specimens show low erosion resistance.

4.2 Density Analysis

The density analysis is a major component to be considered while discussing the material selection for wind turbine blade material. High stiffness-to-density ratio and high strength-to-density ratio are desirable characters of a material to be used in this field. Carbon fiber, glass fiber, and aramid fiber already possess these qualities [8]. Generally, the theoretical density can be found for any composite material in terms of weight fraction by the equation given below [15].

$$\rho_{\mathrm{cm}} = 1 \Big/ \left[\left(w_{\mathrm{p}} \big/ \rho_{\mathrm{p}} \right) + \left(w_{\mathrm{m}} \big/ \rho_{\mathrm{m}} \right) + \left(w_{\mathrm{f}} \big/ \rho_{\mathrm{f}} \right) \right] \tag{2}$$

Here, w denotes weight fraction and ρ denotes density.

The suffixes denote the individual constituents used here. (p–polyamide fiber, m—matrix, f—fly ash, and cm—composite material). There are three constituents in this composite, which are matrix-polyester resin, polyamide fiber, and particulate filler-fly ash. Traditional water immersion method is used to find the actual density (ρ) of the composite experimentally. From the graph, it can be observed that the density values are increasing with the increase in percentage addition of fly ash. The volume fraction of voids getting reduced with the increase in the percentage addition of fly ash. Void content is the difference between theoretical and practical density values.

4.3 Hardness Test (RHB)

Hardness is the measure of resistance of a material to localized plastic deformation. As defined in ASTM E-18, the Rockwell hardness test is used to find the hardness of the samples. Several scales may be used from possible combinations of indenters and loads, which permit the testing of all metal alloys and polymers. Indenters include spherical and hardened steel balls having diameters of 1/16, 1/8, 1/4, and 1/2 inch. Conical hard steel with indenter size of 1/16″ was used in this experiment. The applied load is 100 kgf. The graph shows the variation of RHB value with the percentage addition of fly ash to the composite. With the addition of fly ash, the hardness values are increasing subsequently (Fig. 3).

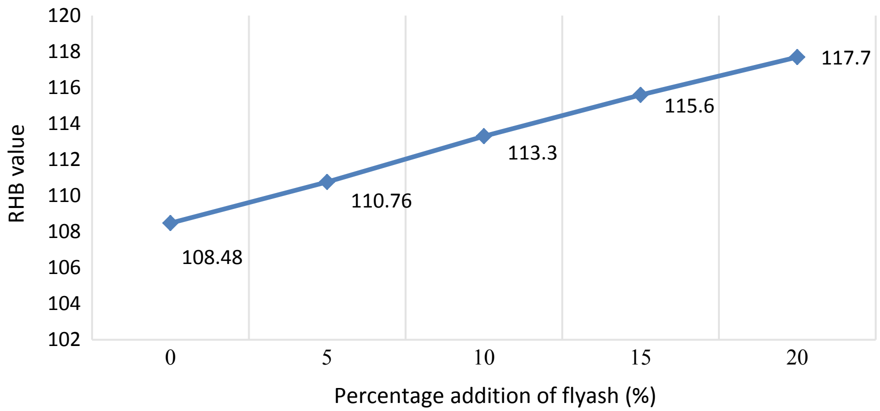

Fig. 3 Rockwell hardness test (B test)

4.4 *Tensile Test*

Tensile test is also done through dynamic mechanical analysis. The samples were cut in the size of 2 * 3 * 12 mm in order to keep them in the space provided in DMA. The graph of tensile analysis was drawn for modulus vs temperature. The graphs which are drawn for samples with a different percentage addition of fly ash are then compared. As like the three-point bending test, the peak temperature was fixed at 120 °C. The rate of change of temperature is kept at 3 °C per minute.

Loss modulus means being proportional to the energy dissipated during one loading cycle. For example, it can be said that energy lost as heat and is a degree of vibration energy that has been converted during vibration. It cannot be recovered. Figure 4 represents the variation of storage modulus with temperature. We can see

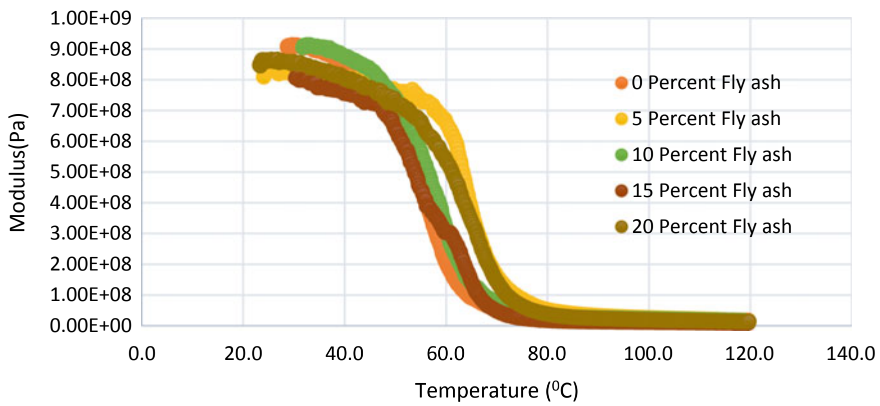

Fig. 4 Variation of modulus with temperature

that there are three significant regions in this graph. There is a zone from 20^0C to 50^0 C where the modulus values are high; from 50^0C to 80^0C there is transmission region where a significant reduction in the storage modulus occurs; and from 80^0C to 120^0C the graph shows elastic behavior where the deterioration is severe. It can also be noticed from the graph that 10% granite-dust-added sample has a high modulus of 900 Mpa and 15% granite-dust-added sample has minimum of 800 MPa. All the samples show above 800 MPa, and the range is between 800 and 900 MPa.

5 Conclusion

(1) The impingement angle is a deciding factor in erosion rate. Highest erosion occurred in the angle of 30° and the lowest erosion occurred in the angle of 90°. Erosion rate generally decreasing with increase in angle from 30° to 90°.

(2) Percentage addition of fly ash is another factor which influences the erosion rate. Lowest erosion occurred in 0% fly-ash-added sample, and it is followed by 10% fly-ash-added sample. Highest erosion occurred when we add 15% fly ash and is followed by 5% fly ash. Since it is showing a zig-zag pattern in this region, further study may give an exact percentage addition of this filler material.

(3) Density values are increasing with the increase in percentage addition of fly ash. A small deviation observed between the experimental and theoretical densities. The deviation might be occurred because of the absorption of water molecules by the sample when we tested it for practical density. The volume fraction of voids getting reduced with the increase in the percentage addition of fly ash.

(4) With the increase in the percentage addition of fly ash, the hardness values are increasing.

(5) When we consider tensile analysis, all the specimens are showing a tensile value above 8×10^8 Pa while 10% fly-ash-added sample shows a highest value of 9×10^8 Pa. All of them are deteriorating in the region around 60 °C.

The established wind turbine blade composite material shows better tribological, mechanical, and physical characteristics. The erosion resistance of the above composite increases its durability. Its weight is also very less compared to alloys. Hence, in long term, the cost of the proposed material will be reasonable and worthwhile.

References

1. Kumar A, Dwivedi A, Paliwal V, Patil PP (2014) Free vibration analysis of Al 2024 wind turbine blade designed for Uttarakhand region based on FEA. Procedia Technol 14:336–347
2. Ashwill TD, Paquette JA (2008) Composite materials for innovative wind turbine blades. Wind Energy Technology Department Sandia National Laboratories Albuquerque, NM 87185

3. Mandell JF, Samborsky DD, Agastra P (2012) Composite materials fatigue issues in wind turbine blade construction. Department of Chemical and Biological Engineering, Monatana State University, Bozeman, MT 59717
4. Chen X, Zhao W, Zhao XL, Xu JZ (2014) Preliminary failure investigation of a 52.3 m glass/epoxy composite wind turbine blade. Eng Fail Anal 44:345–350
5. Wang Y, Zhupanska OI (2015) Lightning strike thermal damage model for glass fiber reinforced polymer matrix composites and its application to wind turbine blades. Compos Struct (in press)
6. Mishnaevsky L Jr, Freere P, Sinha R, Acharya P, Shrestha R, Manandhar P (2011) Small wind turbines with timber blades for developing countries: materials choice, development, installation and experiences. Renew Energy 36:2128–2138
7. Jang YJ, Choi CW, Lee JH, Kang KW (2015) Development of fatigue life prediction method and effect of 10-min mean wind speed distribution on fatigue life of small wind turbine composite blade. Renew Energy 79:187–198
8. Mustafa G, Suleman A, Crawford C (2015) Probabilistic micromechanical analysis of composite material stiffness properties for a wind turbine blade. Compos Struct 131:905–916
9. Suresh Babu K, Subba Raju NV, Srinivasa Reddy M, Nageswara Rao D (2006) The material selection for typical wind turbine blades using MADM approach & analysis of blades. MCDM 2006, Chania, Greece, June 19–23
10. Wind turbine blade structural engineering, WE Handbook-3-Structural Design
11. Ancona D, McVeigh J (2001) Wind turbine—materials and manufacturing fact sheet. Prepared for the Office of Industrial Technologies, US Department of Energy by Princeton Energy Resources International, LLC, August 29
12. Mathavan JJ, Shrestha S, Kaifi R, Patnaik A (2019) Analysis of erosion properties of polymer composite filled with granite dust for hydraulic turbine blade material. In: Ghosh S (ed) Waste management and resource efficiency. Springer, Singapore
13. Arivumangai A, Felixkala T (2014) Strength and durability properties of granite powder concrete. J Civil Eng Res 4(2A)
14. Pouretedal HR, Damiri S, Shahsavan A (2018) Modification of RDX and HMX crystals in procedure of solvent/anti-solvent by statistical methods of Taguchi analysis design and MLR technique. Defence Technol 14:59–63
15. Agarwal BD, Broutman LJ (1990) Analysis and performance of fiber composites. Wiley, New York