A STUDY ON MECHANICAL BEHAVIOR AND DAMAGE ASSESSMENT OF SHORT BAMBOO FIBER BASED POLYMER COMPOSITES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
in
Mechanical Engineering
(Specialization: Production Engineering)

BY

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CERTIFICATE

This is to certify that the thesis entitled ***"A Study on Mechanical Behaviour and Damage Assessment of Short Bamboo Fiber Based Polymer Composites"*** submitted by ***Kishore Debnath (Roll Number: 209ME2197)*** in partial fulfillment of the requirements for the award of ***Master of Technology*** in the department of Mechanical Engineering, National Institute of Technology, Rourkela is an authentic work carried out under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to elsewhere for the award of any degree.

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A C K N O W L E D G E M E N T

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ABSTRACT

Now-a-days, natural fiber reinforced polymer composites are increasingly being used for varieties of engineering applications due to their many advantages. Among natural fibers, bamboo has been widely used for many such applications due to its availability. Since these composites are finding wide applications in highly dusty environment which are subjected to solid particle erosion, a study of their erosion characteristics are of vital importance. Generally solid particle erosion, a typical wear mode leads to material loss due to repeated impact of solid particles. For a composite material, its mechanical behavior and surface damage by solid particle erosion depends on many factors. Attempts have been made in this paper to explore the potential utilization of bamboo fiber in polymer matrix composites. Therefore, the present research is focused on the mechanical and erosion wear behavior of short bamboo fiber reinforced composites filled with Alumina (Al_2O_3) particulate. It further outlines a methodology based on Taguchi's experimental design approach to make a parametric analysis of erosion characteristics. Finally, the morphology of eroded surfaces is examined using scanning electron microscopy (SEM) and possible erosion mechanisms are identified.

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CHAPTER 1

INTRODUCTION

1.2 Background and Motivation

When two or more materials with different properties are combined together, they form a composite material [1]. In general, the properties of composite materials are superior in many respects, to those of the individual constituents. This has provided the main motivation for the research and development of composite materials. There are two categories of constituent materials one is matrix and another is reinforcement. The primary functions of the matrix are to transfer stresses between the reinforcing fibers/particles and to protect them from mechanical and/or environmental damage whereas the presence of fibers/particles in a composite improves its mechanical properties such as strength, stiffness etc. The objective is to take advantage of the superior properties of both materials without compromising on the weakness of either. The matrix material can be metallic, polymeric or can even be ceramic. When the matrix is a polymer, the composite is called polymer matrix composite. The properties of polymeric composite materials are mainly determined by three constitutive elements such as the resin, the reinforcement, such as particles and fibers, and the interface between them.

Fiber reinforced polymer (FRP) composites can be simply described as multi-constituent materials that consist of reinforcing fibres embedded in a rigid polymer matrix. Many FRPs offer a combination of both strength and modulus that are either comparable to or better than many traditional metallic materials. A diverse range of polymers can be used as the matrix to FRP composites, and these are generally classified as thermoplastic (e.g. polyether-ether-ketone, polyamide) resins or thermoset (e.g. epoxy, polyester). Thermoplastics start as fully reacted high-viscosity materials that do not cross-link on heating. On heating to a high enough temperature, they either soften or melt, so they can be reprocessed a number of times. On the other hand, thermoset resins the most widely used matrices for advanced composites usually consist of a resin and a comparable curing agent. When they two are initially mixed they form a low viscosity liquid that cures as a result of either internally generated or externally applied heat. The curing reaction forms a series of cross links between molecular chains so that one large molecular network is formed, resulting in an intractable solid that cannot be reprocessed on reheating.

As far as the reinforcement is concerned, extensive use has been made of inorganic man-made fibers such as glass and organic fibers such as carbon and aramid. Recently, the rapidly increasing environmental awareness, geometrically increasing crude oil prices, growing global waste problem and high processing cost trigger the development concepts of sustainability and reconsideration of renewable resources. The use of natural fibres, derived from annually renewable resources, as reinforcing fibres in both thermoplastic and thermoset matrix composites provides positive environmental benefits with respect to ultimate disposability and raw material utilization [2]. The advantages associated with the use of natural fibers as reinforcement in polymers are their availability, non-abrasive nature, low energy consumption, biodegradability and low cost. In addition, natural fibers have low density and high specific properties. The specific mechanical properties of these fibers are comparable to those of traditional reinforcements. A number of investigations have been carried out to assess the potential of natural fibres as reinforcement in polymers.

Among the various natural fibers, bamboo finds widespread use in housing construction around the world, and is considered as a promising housing material in underdeveloped and developed countries. Being a conventional construction material since ancient times, bamboo fiber is a good candidate for use as natural fibers in composite materials. Many studies focus on bamboo is due to the fact that it is an abundant natural resource in Asia and its overall mechanical properties are comparable to those of wood. Furthermore, bamboo can be renewed much more rapidly compared with wood. Bamboo is an extremely light weight, functionally graded and high strength natural composite. The structure of bamboo is a composite material, consisting of long and aligned cellulose fibers immersed in a ligneous matrix. Besides, bamboo is one of the fastest renewable plants with a maturity cycle of 3 to 4 years. Although the utilization potential of this material for a number of applications has been explored, such superior mechanical properties have not been adequately well drawn for polymer-based composites.

The term 'filler' is very broad and encompasses a very wide range of materials plays an important role for the improvement in performance of polymers and their composites. Filler materials are used to reduce the material costs, to improve mechanical properties to some extent and in some cases to improve processability. Besides, it also increases properties like abrasion resistance, hardness and reduces shrinkage. So, although in FRP, a judicious selection of matrix and the reinforcing phase can lead to a composite with a combination of strength and modulus comparable to or even better than those of conventional metallic materials, their physical and mechanical properties can further be modified by addition of a solid filler phase to the matrix body during the composite preparation.

Polymer composites containing different fillers and/or reinforcements are frequently used for many applications in which friction and wear are critical issues. Also these composites are finding further applications that subjected to solid particle erosion, which is the loss of material that results from repeated impact of small, solid particles. Examples of such applications are in petroleum refining pipe line carrying sand slurries, pump impeller blades, high speed vehicles and aircraft operating in desert environments, helicopter rotor blades, aircraft engine blades, water turbines etc. [3-5]. Hence, erosion resistance of polymer composites has become an important material property, particularly in selection of alternative materials and therefore the study of solid particle erosion characteristics of the polymeric composites has become highly relevant. Also a full understanding of the effects of all system variables on the wear rate is necessary in order to undertake appropriate steps in the design of machine or structural component and in the choice of materials to reduce/control wear.

The present research work is undertaken to develop a new class of natural fiber reinforced polymer composite filled with ceramic filler and to study their mechanical and erosion wear behaviour. Attempts have been made to explore the potential use of bamboo fiber as reinforcement in polymer composites. The specific objectives of this work are clearly outlined in the next chapter.

1.2 Thesis Outline

The remainder of this thesis is organized as follows:

Chapter 2: Previous work relevant to the present research is described in this chapter.

Chapter 3: This chapter describes the details of materials required, fabrication techniques and characterization of the composites under investigation and also an explanation of the Taguchi experimental design.

Chapter 4: This chapter presents the physical and mechanical properties of the composites under study.

Chapter 5: Experimental results and parametric studies are presented and discussed in this chapter.

Chapter 6: Conclusions and recommendations for future work are presented in this chapter.

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CHAPTER 2

LITERATURE SURVEY

This chapter provides the background information on the issues to be considered in the present research work and to focus the relevance of the present study. The purpose is also to present a thorough understanding of various aspects of short bamboo fiber reinforced polymer composites with a special attention to their erosion wear behavior.

In fiber reinforced polymer composites, the fibers can be either synthetic fibers or natural fibers. Advantages of natural fibers over synthetic fibers include low density, availability, low cost, recyclability and biodegradablility [6-8]. Due to their many advantages they are comparable to those of synthetic fibers used as reinforcements. It is also known that natural fibers are non-uniform with irregular cross sections, which making their structures quite unique and much different from synthetic fibers. Generally, the natural fibers are consisting of cellulose, hemi-cellulose, lignin, pectin, waxes and water soluble substances. The chemical composition of natural fibers may differ with the growing condition and test methods even for the same kind of fiber. The physical mechanical properties of natural fibers are greatly influenced by their chemical compositions. The properties of some of these fibers are presented in Table 2.1 [9]. It is evident from Table 2.1 that, the tensile strength of glass fiber is substantially higher than that of natural fibers even though the modulus is of the same order. However, when the specific modulus of natural fibers is considered, the natural fibers are better as compared to glass fibers. Therefore, these higher specific properties are the major advantages of natural fiber as reinforcement in polymer composites for weight sensitive applications.

Table 2.1 Properties of natural fibers [9]

Fiber	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)	Density (g/cm^3)
Abaca	400	12	3-10	1.5
Alfa	350	22	5.8	0.89
Bagasse	290	17	-	1.25
Bamboo	140-230	11-17	-	0.6-1.1
Banana	500	12	5.9	1.35
Coir	175	4-6	30	1.2
Cotton	287-597	5.5-12.6	7-8	1.5-1.6
Curaua	500-1,150	11.8	3.7-4.3	1.4
Date palm	97-196	2.5-5.4	2-4.5	1-1.2
Flax	345-1,035	27.6	2.7-3.2	1.5
Hemp	690	70	1.6	1.48
Henequen	500 ± 70	13.2 ± 3.1	4.8 ± 1.1	1.2
Isora	500-600	-	5-6	1.2-1.3
Jute	393-773	26.5	1.5-1.8	1.3
Kenaf	930	53	1.6	-
Nettle	650	38	1.7	-
Oil palm	248	3.2	25	0.7-1.55
Piassava	134-143	1.07-4.59	21.9-7.8	1.4
Pineapple	400-627	1.44	14.5	0.8-1.6
Ramie	560	24.5	2.5	1.5
Sisal	511-635	9.4-22	2.0-2.5	1.5
E-Glass	3400	72	-	2.5

Mechanical properties of natural fiber based polymer composites are influenced by many factors such as fibers volume fraction, fiber length, fiber aspect ratio, fiber-matrix adhesion, fiber orientation, etc. [10]. A great deal of work has already been done on the effect of various factors on mechanical behavior of natural fiber reinforced polymer composites. The post-impact behaviour of jute fiber reinforced polyester composites subjected to low velocity impact has studied by Santulli [11]. Effect of fiber content on tensile and flexural properties of pineapple fiber reinforced poly (hydroxybutyrate-co-valerate) resin composites has studied by Luo and Netravali [12]. The fracture energies for fibers such as sisal, banana, pineapple and coconut fiber reinforced polyester composites using Charpy impact tests has studied by Pavithran et al. [13]. They reported that, except for the coconut fiber, the fiber toughness is increases due to increase in fracture energy of the composites. The mechanical behviour of jute and kenaf fiber reinforced polypropylene composites has been studied by Schneider and Karmaker [14]. It is concluded from their study that jute fiber based composites provides better mechanical properties than kenaf fiber based composites. A systematic study on the properties of henequen fiber has made by Cazaurang et al. [15] and reported that fibers have mechanical properties suitable for reinforcement in thermoplastic resins. Various aspects of banana fiber reinforced polymer composites has studied by various investigators [16-20]. The effect of various loading rate on mechanical properties of jute/glass reinforced epoxy based hybrid composites has studied by Srivastav et al. [21]. The mechanical properties of jute faber reinforced polyester composites were evaluated by Gowda et al. [22]. It is reported from their study that they have better strengths as comparison to wood based composites.

Bamboo fiber reinforced composites with different polymers have been reported, including epoxy resin [23,24], polypropylene (PP) [25,26], poly(butylenes succinate) (PBS) [27], and polylactic acid (PLA) [28]. The mechanical properties and fracture mechanisms of bamboo fiber reinforced polymer composites under different loading conditions is studied by Shin et al. [29-31]. Thwe and Liao [32] studied the effects of fiber content, fiber length, bamboo to glass fiber ratio, and MAPP content on mechanical properties of bamboo fiber reinforced plastics and bamboo-glass fiber reinforced plastics. Jiang et al [33] studied the mechanical behaviour of poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/bamboo pulp fiber composites. Okubo et al. [34] studied the tensile strength and modulus of bamboo fiber reinforced polypropylene based composites. The mechanical properties of bamboo fiber reinforced polypropylene composites was studied and compared with those of commercial wood pulp by

Chen et al. [35]. The effect of bonding agent on mechanical properties of bamboo fiber reinforced natural rubber composites was studied by Ismail et al. [36]. The effect of fiber length on tensile properties of short bamboo fiber reinforced epoxy composites was studied by Rajulu et al. [37]. In another investigation, Chen [38] studied the structure, morphology and properties of bamboo fiber reinforced polypropylene composites in details. The effect of environmental aging on mechanical properties of bamboo-glass fiber reinforced polymer hybrid composites was studied by Thwe et al. [39].

In polymers, fillers are used for a variety of reasons such as cost reduction, density control, improved processing, control of thermal expansion, optical effects, magnetic properties, thermal conductivity, electrical properties, improved hardness and wear resistance, flame retardancy etc. A great deal of work has been made on the effect of fillers on polymer composites. When silica particles are incorporated into polymer matrix, they play an important role in improving various properties of the composites [40,41]. Polymers and polymer matrix composites reinforced with metal particles have a wide range of industrial applications [42,43]. The effect of various filler parameters on mechanical properties of composites is studied by many investigators. The structure and shape of silica particle have significant influence on the mechanical properties of composites [44]. The effect of filler size and shape on the mechanical properties of composites was studied by Nakamura et al. [45,47]. The effect of filler type and content on the performance of polymer based hybrid composites were studied by few investigators [48, 49].

Many researchers have investigated the erosion behaviour of various polymers and their composites [50-62]. The effect of various parameters on the erosion behaviour of polymers and their composites was studied by Barkoula and Karger-Kocsis [63] and. Miyazaki and Hamao [64], Harsha et al. [65], Tewari et al. [66], Patnaik et al. [67-71]. Similarly, the effect of various parameters on the erosion behavior of bamboo fiber reinforced epoxy composites was studied by Biswas and Satapathy [72].

2.1 The Knowledge Gap

The literature survey presented above reveals the following knowledge gap in the research reported so far:

- Though much work has been done on a wide variety of natural fibers for polymer composites, very less has been reported on the reinforcing potential of short bamboo fiber in spite of its several advantages over others.
- A number of research efforts have been devoted to the mechanical and wear characteristics of either fiber reinforced composites or particulate filled composites. However, a possibility that the incorporation of both particulates and fibers in polymer could provide a synergism in terms of improved performance has not been adequately addressed so far
- Studies carried out worldwide on erosion wear behaviour of composites have largely been experimental and the use of statistical techniques in analyzing wear characteristics has been rare. Taguchi method, being a simple, efficient and systematic approach to optimize designs for performance, quality and cost, is used in many engineering applications. However, its implementation in parametric appraisal of wear processes has hardly been reported.

2.2 Objectives of the present research work

The knowledge gap in the existing literature review has helped to set the objectives of this research work which are outlined as follows:

1. Fabrication of unfilled and alumina filled short bamboo fiber reinforced epoxy composites.
2. Evaluation of mechanical properties of both unfilled and particulate filled composites such as tensile strength, impact strength flexural strength, and micro-hardness etc.

3. Study of solid particle erosion behaviour of unfilled and filled composites both in steady state condition and by Taguchi orthogonal array design.
4. To study the fracture surface morphology using SEM study for mechanical properties samples and eroded samples.

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CHAPTER 3

MATERIALS AND METHODS

This chapter describes the materials and methods used for the processing of the composites under this study. It presents the details of the characterization and tests which the composite samples are subjected to. The methodology based on Taguchi experimental design and the statistical interpretations by analysis of variance (ANOVA) are also presented.

3.1 Materials

3.1.1 Matrix Material

Among different types of matrix materials, polymer matrices are the most commonly used because of cost efficiency, ease of fabricating complex parts with less tooling cost and they also have excellent room temperature properties when compared. Polymer matrices can be either thermoplastic or thermoset. The most commonly used thermoset resins are epoxy, vinyl ester, polyester and phenolics. Among them, the epoxy resins are being widely used for many advanced composites due to their many advantages such as excellent adhesion to wide variety of fibers, good performance at elevated temperatures and superior mechanical and electrical properties. In addition to that they have low shrinkage upon curing and good chemical resistance. Due to several advantages over other thermoset polymers as mentioned above, epoxy (LY 556) is chosen as the matrix material for the present research work. It chemically belongs to the 'epoxide' family and its common name of epoxy is Bisphenol-A-Diglycidyl-Ether.

3.1.2 Fiber Material

Fiber is the reinforcing phase of a composite material. The present research work, bamboo fiber is taken as the reinforcement in the epoxy matrix to fabricate composites. In general, bamboo is available everywhere around the world and is an abundant natural resource. It has been a conventional construction material since ancient times. The scientific name of the type of bamboo used for this work is *Dendrocalamus strictus* [73]. This is one of the predominant species of bamboo in Orissa, Uttar Pradesh, Madhya Pradesh and Western Ghats in India. This species occupies approximately 53% of total bamboo area in India. Bamboo is an orthotropic material with high strength along and low strength transversal to its fibers. The structure of bamboo itself is a composite material, consisting of long and aligned cellulose fibers immersed in a ligneous matrix. In this work, short bamboo fiber is used as the reinforcement in the composites. The fiber mats are dried in an oven at a temperature of 105°C for 72 h to remove moisture prior to composite making. The average thickness of each bamboo fiber is about 1.5 mm. Figure 3.1 shows short bamboo fibers and bamboo fiber reinforced epoxy composite.

Figure 3.1 Short bamboo fiber and bamboo based composite

3.1.3 Particulate Filler Materials

Particulate fillers are plays an important role for the improvement of performance of polymers and their composites. Various types of fillers of natural or synthetic, both organic and inorganic is already being used as reinforcement in polymeric composites. Among them, alumina (Al_2O_3), silicon carbide (SiC), silica (SiO_2), titania (TiO_2) etc. are most widely used as conventional fillers. Due to the many advantages, different weight percentages of alumina (Al_2O_3) particulate is used as filler material for fabrication of bamboo fiber reinforced epoxy composites in the present work.

Generally, Al_2O_3 is an inorganic material that has the potential to be used as particulate filler material in various polymer matrices. Al_2O_3 commonly referred to as alumina, can exist in several crystalline phases which all revert to the most stable hexagonal alpha phase at elevated temperatures. This is the phase of particular interest for structural applications. It is the most cost effective and widely used material in the family of engineering ceramics. It is hard, wear resistant, has excellent dielectric properties, high strength and stiffness, resistance to strong acid and alkali attack at elevated temperatures. Due to its many advantages and with a reasonable price, the fine grain technical grade Al_2O_3 has a very wide range of engineering applications.

3.2 Composite Fabrication

In this study, short bamboo fiber is taken as reinforcement is collected from local sources. The epoxy resin and the hardener are supplied by Ciba Geigy India Ltd. Al_2O_3 powders are obtained from NICE Ltd India in a range of 80-100 μm. A stainless steel mould having dimensions of $210 \times 210 \times 40$ mm^3 is used for composite fabrication. The short bamboo fiber and Al_2O_3 particulates are mixed with epoxy resin by the simple mechanical stirring and the mixture is poured into various moulds conforming to the requirements of various testing conditions and characterization standards. The composite samples of four different compositions (EB-1 to EB-4), in which no particulate filler is used. The other composite samples EBA-1 to EBA-4 are prepared in four different percentages of alumina particulates (0wt%, 5wt%, 10wt% and 15wt% of alumina) is used keeping bamboo fiber at a fixed percentages (i.e. 45wt%). A releasing agent is used to facilitate easy removal of the composite from the mould after curing. The entrapped air bubbles (if any) are removed carefully with a sliding roller and the mould is closed for curing at a temperature of 30°C for 24 h at a constant pressure of 10 kg/cm2. After curing, the specimens of suitable dimension are cut for mechanical and erosion tests. The composition and designation of the composites prepared for this study are listed in Table 3.1.

Table 3.1 Designation of Composites

Composites	Compositions
EB-1	Epoxy + Bamboo Fiber (0 wt%)
EB-2	Epoxy + Bamboo Fiber (15 wt%)
EB-3	Epoxy+ Bamboo Fiber (30 wt%)
EB-4	Epoxy + Bamboo Fiber (45 wt%)
EBA-1	Epoxy + Bamboo Fiber (45 wt%) + Alumina (0 wt%)
EBA-2	Epoxy + Bamboo Fiber (45 wt%) + Alumina (5 wt%)
EBA-3	Epoxy + Bamboo Fiber (45 wt%) + Alumina (10 wt%)
EBA-4	Epoxy + Bamboo Fiber (45 wt%) + Alumina (15 wt%)

3.3 Mechanical testing of composites

The tension test was performed on all the three samples as per ASTM D3039-76 test standards. The tension test is generally performed on flat specimens. A uni-axial load is applied through the ends. The ASTM standard test recommends that the length of the test section should be 100 mm specimens with fibers parallel to the loading direction should be 11.5 mm wide and.

To find out the flexural strength of the composites, a three point bend test is performed using Instron 1195. The cross head speed was taken as 10 mm/min and a span of 30 mm was maintained. The strength of a material in bending is expressed as the stress on the outermost fibers of a bent test specimen, at the instant of failure. In a conventional test, flexural strength expressed in terms of MPa is equal to

$$\text{Flexural Strength} = 3PL / 2bd^2 \qquad (3.2)$$

Where, P= applied central load (N)

L= test span of the sample (m)

b= width of the specimen (m)

d= thickness of specimen under test (m)

Leitz micro-hardness tester is used for micro-hardness measurement on composite samples. A diamond indenter in the form of a right pyramid of a square base of an angle 136° between opposite faces is forced under a load F into the sample. After removal of the load, the two diagonals of the indentation (X and Y) left on the surface of the sample are measured and their arithmetic mean L is calculated. The load considered in the present study is 24.54N and Vickers hardness is calculated using the following equation:

$$H_V = 0.1889\frac{F}{L^2} \quad \text{and} \quad L = \frac{X+Y}{2} \tag{3.1}$$

Where F is the applied load (N), L is the diagonal of square impression (mm), X is the horizontal length (mm) and Y is the vertical length (mm).

Finally, impact tests are carried out on composite specimens as per ASTM D 256 using an impact tester. The pendulum impact testing machine ascertains the notch impact strength of the material by shattering the V-notched specimen with a pendulum hammer, measuring the spent energy, and relating it to the cross section of the specimen. The standard specimen for ASTM D 256 is 64 × 12.7 × 3.2 mm and the depth of the notch is 10.2 mm.

3.4 Scanning electron microscopy (SEM)

Scanning electron microscope of Model JEOL JSM-6480LV (Figure 3.2) was used for the morphological characterization of the composite surface. The samples are cleaned thoroughly, air-dried and are coated with 100 Å thick platinum in JEOL sputter ion coater and observed SEM at 20 kV. To enhance the conductivity of the composite samples a thin film of platinum is vacuum evaporated onto them before the micrographs are taken. The fracture morphology of the tensile fracture surface of the composites were also observed by means of SEM.

Figure 3.2 SEM Set up

3.5 Erosion testing of composites

The erosion testing of composite specimens is performed on a standard erosion test rig as per ASTM G76 standard. The pictorial and the schematic diagram of the erosion test rig are shown in Figure 3.3 and Figure 3.4 respectively. The test rig consisting of an air compressor, a conveyor belt-type particle feeder, an air drying unit, an air particle mixing and an accelerating chamber. The dried and compressed air is mixed with the silica sand which is then fed constantly into the mixing chamber by a conveyor belt feeder and accelerated by passing the mixture through a convergent brass nozzle of internal diameter of 3 mm. The set-up is capable of creating erosive situations for assessing solid particle erosion wear resistance of the composite samples. The erodent particles impact the composite specimen which can be held at different impingement angles with respect to the direction of erodent flow. The apparatus is equipped with a heater which can regulate and maintain the erodent temperature at any pre-determined fixed value during an erosion test. Dry silica sand of 450μm is used as erodent particle in the present study. After erosion testing, the weight loss is recorded for subsequent calculation of erosion rate. The ratio of the weight loss to the weight of the eroding particles causing the material loss is then computed as a dimensionless incremental erosion rate. The process is repeated till the erosion rate achieves a constant value called steady state erosion rate.

Figure 3.3 Solid particle erosion test set up

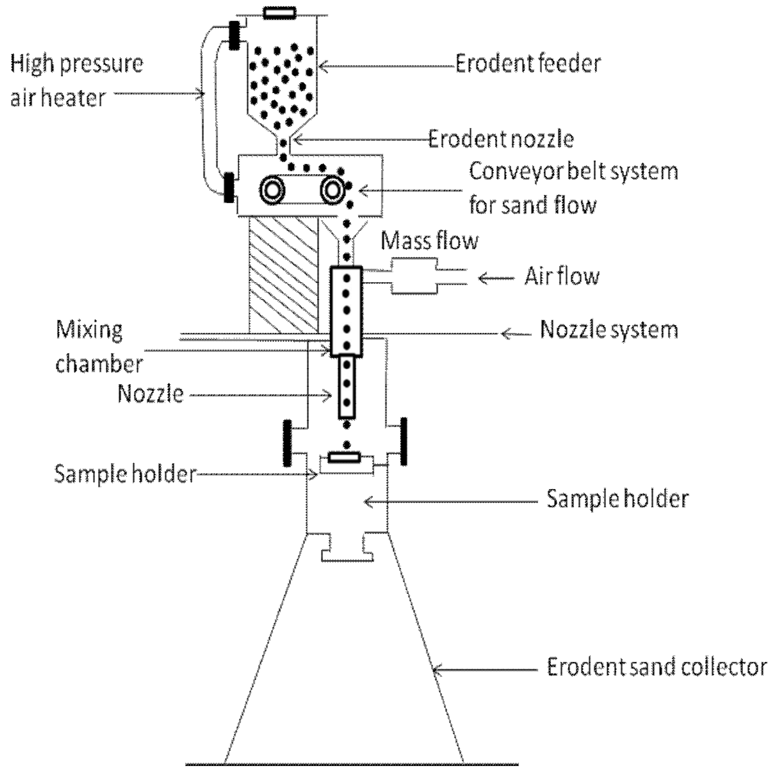

Figure 3.4 A schematic diagram of the erosion test rig

3.6 Taguchi Method

Taguchi's parameter design is an important tool for robust design. It offers a simple and systematic approach to optimize the design parameters because this systematic approach can significantly minimize the overall testing time and the experimental costs. Two major tools used in robust design are signal to noise ratio (S/N), which measures quality with emphasis on variation, and orthogonal array, which accommodates many design factors simultaneously. In design of experiment, the most important stage lies in the selection of the control factors. Through exhaustive literature review on erosion behavior of polymer composites, it has been observed that factors viz., impact velocity, impingement angle, filler content, erodent temperature and stand-off distance etc. mostly influence the erosion rate of polymer composites [74]. For elaboration of experiments plan the method of Taguchi for five factors at four levels is used, being understood by levels taken by the factors. The array chosen is the L_{16} (4^5) which has 16 rows corresponding to the number of tests with 5 columns at four levels. The selected parameters viz., impact velocity, filler content, erodent temperature, stand-off distance, impingement angle and erodent size, each at three levels, are considered in this study. The control factors and the parameter settings for erosion test are given in Table 3.2. Table 3.3 presents the selected levels for various control factors. The tests are conducted as per the experimental design given in Table 3.4 [75]. The experimental observations are transformed into signal-to-noise (S/N) ratios. There are several S/N ratios available depending on the type of characteristics such as:

'Smaller-the-better' characteristic: $$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \quad (3.3)$$

'Nominal-the-better' characteristics: $$\frac{S}{N} = 10 \log \left(\sum \frac{\overline{Y}}{S^2}\right) \quad (3.4)$$

'Larger-the-better' characteristics : $$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \quad (3.5)$$

where n the number of observations, y the observed data, $\overline{Y}$ the mean and S the variance. The S/N ratio for minimum erosion rate comes under 'smaller is better' characteristic, which can be calculated as logarithmic transformation of the loss function by using Eq. (3.3).

Table 3.2 Parameter settings for erosion test

Control Factors	Symbols	Fixed parameters	
Impact velocity	Factor A	Erodent	Silica sand
Fiber / Filler content	Factor B	Erodent feed rate (g/min)	10.0 ± 1.0
Impingement angle	Factor C	Nozzle diameter (mm)	3
Stand-off distance	Factor D	Length of nozzle (mm)	80
Erodent Temperature	Factor E	Erodent size	450 micro-m

Table 3.3 Levels for various control factors

Control factor	Level				Units
	I	II	III	IV	
A: Impact velocity	35	45	55	65	m/sec
B1: Fiber loading	0	15	30	45	wt %
B2: Filler content	0	5	10	15	wt %
C: Impingement angle	45	60	75	90	°C
D: Stand-off- distance	55	65	75	85	mm
F: Erodent Temperature	35	70	105	140	Degree

Table 3.4 Orthogonal array for L_{16} (4^5) Taguchi Design

Sl. No.	Impact velocity (m/sec)	Fiber/ filler content (wt %)	Impingement Angle (Degree)	Stand-off-distance (mm)	Erodent Temperature (°C)
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

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CHAPTER 4

MECHANICAL CHRACTERISTICS OF COMPOSITES: RESULTS & DISCUSSION

This chapter presents the results of mechanical properties of short bamboo fiber reinforced epoxy composites. This chapter consisting of two parts, in the first part the results of mechanical behaviour of short bamboo fiber reinforced epoxy composites without filler and in the second part mechanical behavior of alumina filled bamboo fiber reinforced epoxy composites is presented.

Part-1: Bamboo fiber reinforced epoxy composites without filler

4.1 Mechanical characteristics of composites without filler

The mechanical properties of the short bamboo fiber reinforced epoxy composites with different fiber loading under this investigation are presented in Table 4.1. It is evident from the Table 4.1 that at 45wt% of fiber loading the composites show better mechanical properties as compared to others.

Table 4.1 Mechanical properties of the composites without filler

Composites	Hardness (Hv)	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (J)
EB-1	32	4.62	16.41	0.2451
EB-2	38	7.59	25.70	0.3044
EB-3	45	9.86	31.27	1.0258
EB-4	46	10.48	19.93	1.3764

4.1.1 Effect of fiber loading on hardness of composites

Surface hardness of the composites is considered as one of the most important factors that govern the erosion resistance of the composites. Figure 4.1 shows the effect of fiber loading on hardness of composites. The test results show that with the increase in fiber loading, hardness value of the short bamboo fiber reinforced epoxy composites is significantly increasing.

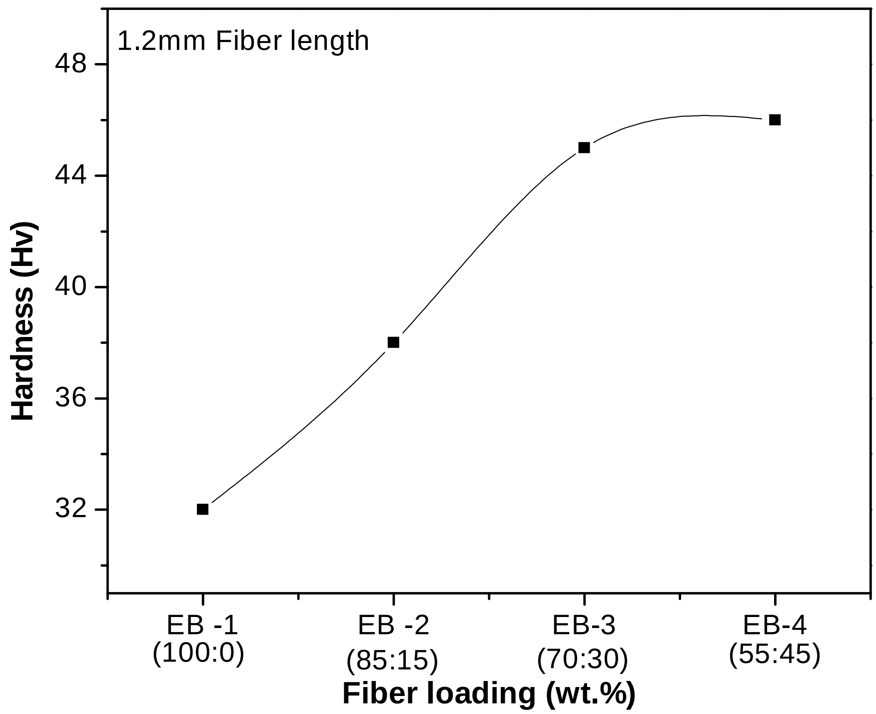


Figure 4.1 Effect of fiber loading on hardness of composites

4.1.2 Effect of fiber loading on tensile strength of composites

The effect of weight fraction of fibre on the tensile strength of the composite is shown in Figure 4.2. As the weight fraction of fibre increases in the composites up to 45 wt%, the tensile strength of composite is increases up to 10.48MPa. The tensile properties measured in the present work are well compared with various earlier investigators [76-81], though the method of extraction of bamboo fiber is different.

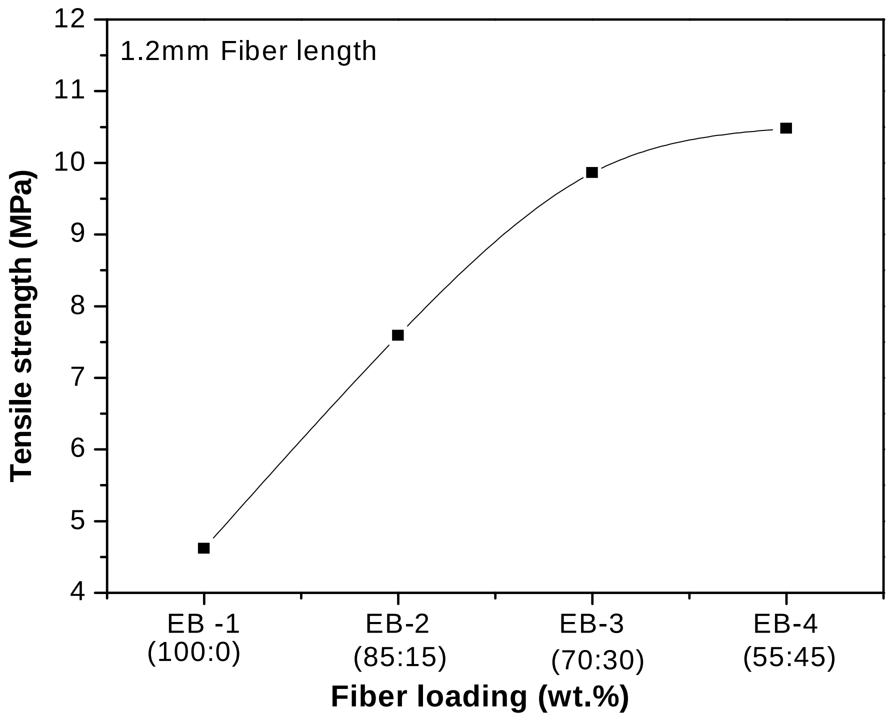


Figure 4.2 Effect of fiber loading on tensile strength of composites

4.1.3 Effect of fiber loading on flexural strength of composites

Figure shows the effect of fiber loading on flexural strength of composites. Adversely, as shown in Figure 4.3, the flexural strength increased by the increase of fiber loading up to 30wt%. For instance, flexural strength of bamboo-epoxy composite is increased from 16.41MPa to 31.27MPa i.e up to 30wt% and then decreased from 31.27MPa to 19.93MPa i.e. upto 50wt% respectively (Figure 4.3). It is also observed from Figure 4.3 that a linearly increasing trend up to a certain value of fiber loading (30wt%) and suddenly drops due to failure of specimens and the arrest points correspond to breakage and pull out of individual fibres from the resin matrix. This is due to higher flexural stiffness of bamboo composite and the improved adhesion between the matrix and the fibre. The effect of weight fraction of fibre on mean flexural strength for other fibre reinforced composites in comparison to bamboo composites are more. According to Ismail et al. [82] and Yao and Li [83], this decrease is attributed to the inability of the fiber, irregularly shaped, to support stresses transferred from the polymer matrix and poor interfacial bonding generates partially spaces between fiber and matrix material and as a result generates weak structure. As flexural strength is one of the important mechanical properties of the composites. For a composite to be used as the structural application it must possess higher flexural strength.

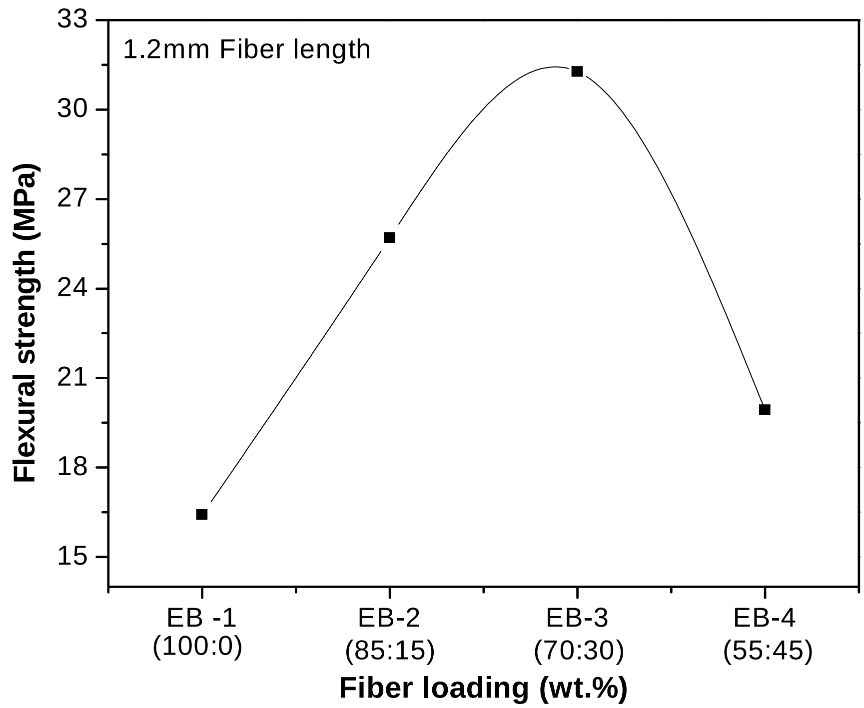


Figure 4.3 Effect of fiber loading on flexural strength of composites

4.1.4 Effect of fiber loading on impact strength of composites

Since fiber reinforced polymer composites are mainly used in structural applications, their impact resistance is also one of the important concerns. The improvement in impact strength of composites with respect to fiber loading is shown in Figure 4.4. The impact strength of the composites increases slightly with increase of fiber loading up to 15wt% and on further increase in fiber loading the strength increases drastically. The decrease in impact strength or smaller variation in strength may be due to induce micro-spaces between the fiber and matrix polymer, and as a result causes numerous micro-cracks when impact occurs, which induce crack propagation easily and decrease the impact strength of the composites [84, 85].

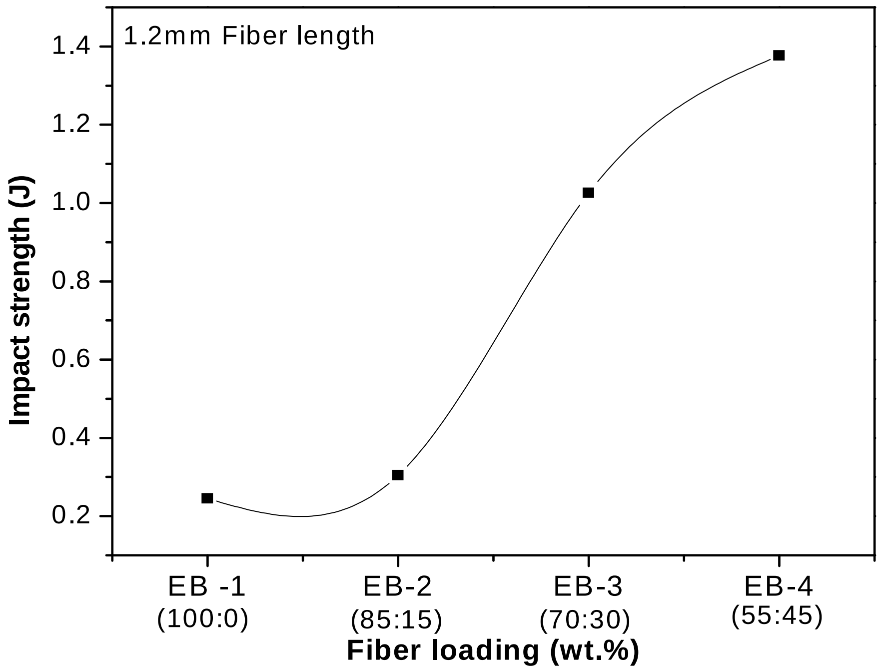


Figure 4.4 Effect of fiber loading on impact strength of composites

Part-2: Alumina filled bamboo fiber reinforced epoxy composites

4.2 Mechanical characteristics of composites with filler

The mechanical properties of alumina filled bamboo fiber-epoxy composites with different fiber loading under this investigation are presented in Table 4.2. It is evident from the Table 4.2 that at 45wt% of fiber loading the composites show better mechanical properties as compared to others.

Table 4.2 Mechanical properties of the composites with filler

Composites	Hardness (Hv)	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (J)
EBA-1	46	10.48	19.93	1.3764
EBA-2	49	15.14	26.1	0.2895
EBA-3	55	9.33	14.4	0.4860
EBA-4	59	5.67	12.15	0.4370

4.2.1 Effect of fiber loading on hardness of composites

Effect of fiber loading on the hardness of composites filled with alumina is shown in Figure 4.5. As is seen in Figure, the composite micro-hardness has significantly improved with the addition of alumina content i.e. from 0wt% to 15wt%. An increase in hardness is evident as the content of the ceramic alumina filler increases. It is clear from figure that the composite with alumina filler shows better tribological behaviour.

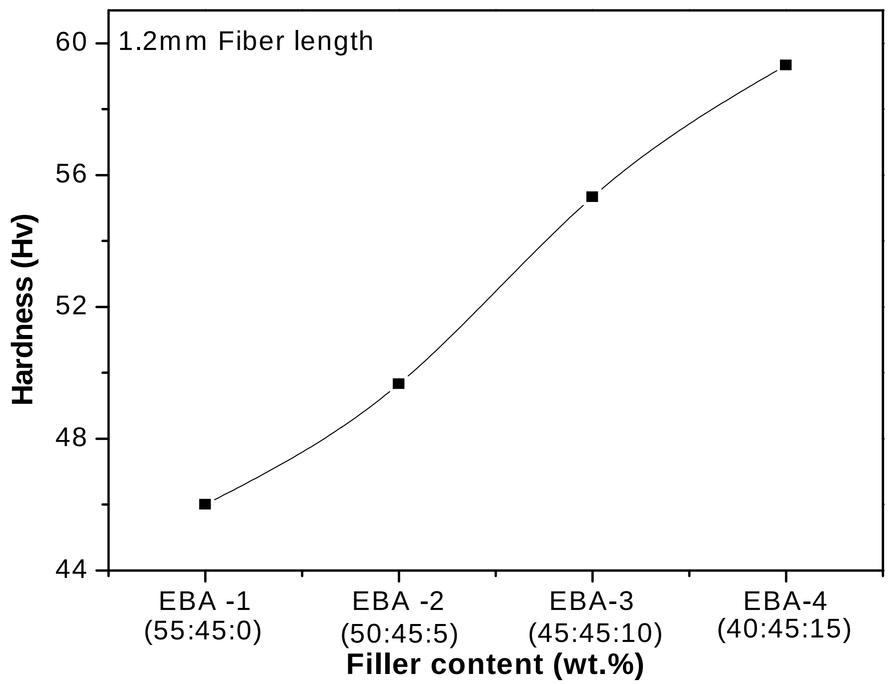


Figure 4.5 Effect of filler content on hardness of the composites

As far as hardness is concerned, this is an expected fact, since bamboo fiber display considerably higher hardness than that of the soft polymer matrix. This should be of importance when the wear properties of such systems are evaluated. As a matter of fact, the hardness values are a measure of the better erosive wear resistance, since hard materials better resist friction and wear.

4.2.2 Effect of filler content on tensile strength of the composites

The influence of filler content on tensile strength of composites is shown in Figure 4.6. It can be seen that the tensile properties have become distinctly improved with the incorporation of alumina particles (5wt %) in the matrix.

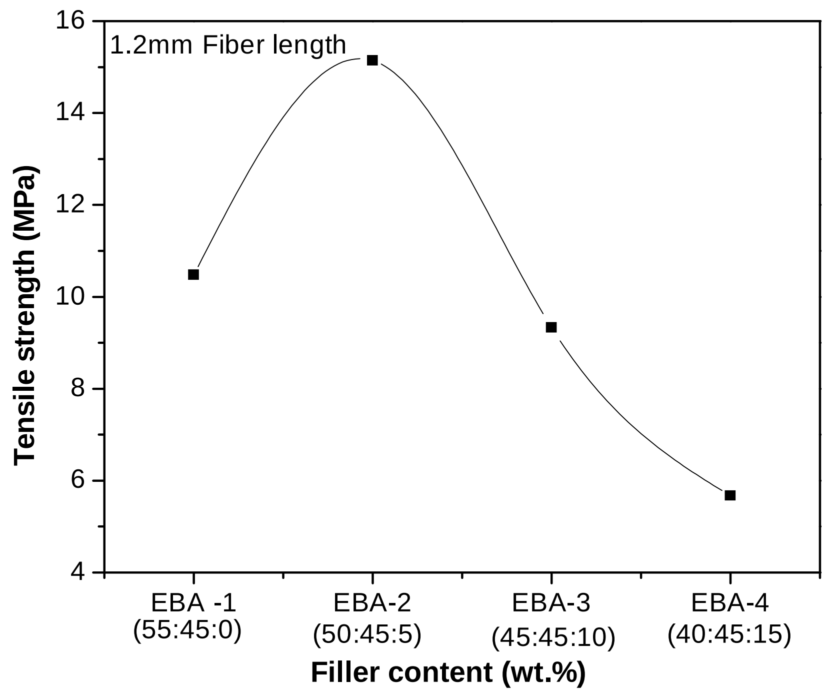


Figure 4.6 Effect of filler content on tensile strength of the composites

The significant variation of tensile strength for different systems indicates fiber alignment is not the only factor which affects mechanical performance; interfacial adhesion and the bamboo fibre influences epoxy matrix properties also have a significant effect. Generally, modulus reflects the performance of both fibre and matrix interface material to transfer the elastic deformation in the case of small strains without interface fracture. Therefore, it is not surprising that the tensile modulus is less sensitive to the variation of interfacial adhesion than the tensile strength which is strongly associated with interfacial failure behaviour. The increase in tensile strength is due to the cross-linking network formation between the fibers and the filler filled polymer matrix. However, with increase in filler content above 5wt% the tensile strength starts decreasing irrespective of filler content.

4.2.3 Effect of filler content on flexural strength of the composites

The variation of flexural strength of the composites with filler content is shown in Figure 4.7.

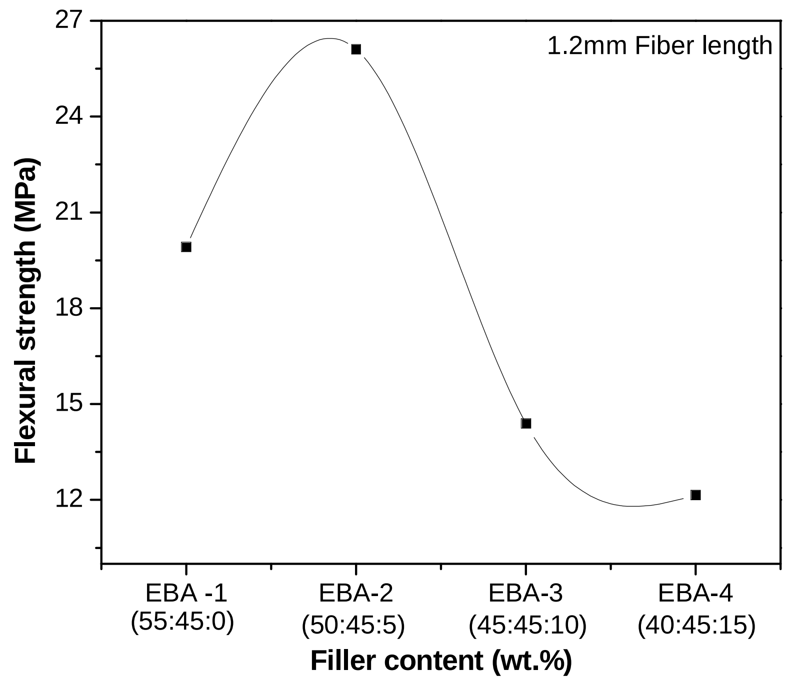


Figure 4.7 Effect of filler content on flexural strength of the composites

It is evident from Figure that this variation is in a similar fashion as it effects on tensile strength of composites. The decreases in mechanical strengths of the composites are probably caused by an incompatibility of the alumina particles and the epoxy matrix with bamboo fiber, leading to poor interfacial bonding. However, it also depends on other factors such as the size and shape of the filler taken in the composites.

4.2.4 Effect of filler content on impact strength of the composites

As seen from the Figure 4.8, the effect of filler content has least effect on the impact strength of the composites by the addition of filler contents. However, the impact strength starts decreasing up to 5wt% alumina content and on further increase in alumina content the impact strength goes on increasing but comparatively lesser than unfilled composite. As impact strength is the ability of a material to resist the fracture under stress applied at high speed. The impact properties of composite materials are directly related to its overall toughness. Composite fracture toughness is affected by inter-facial strength parameters.

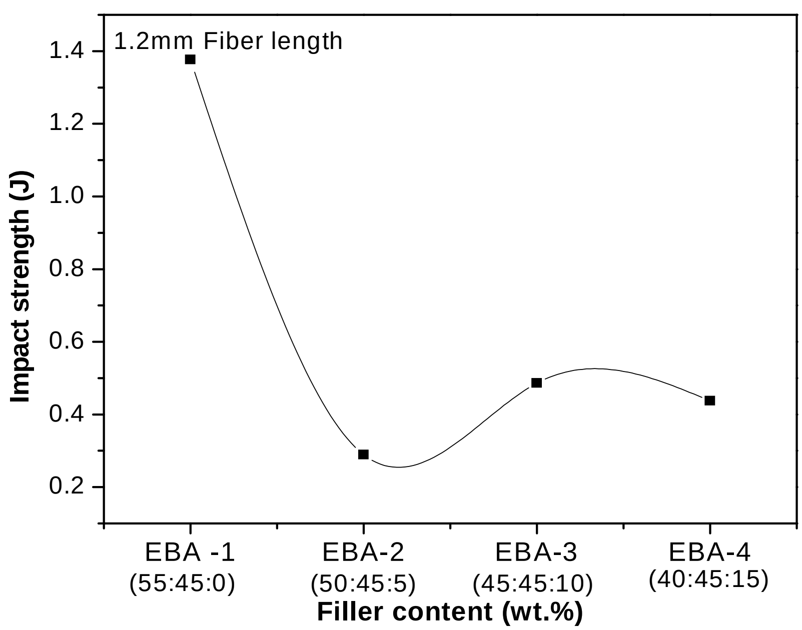
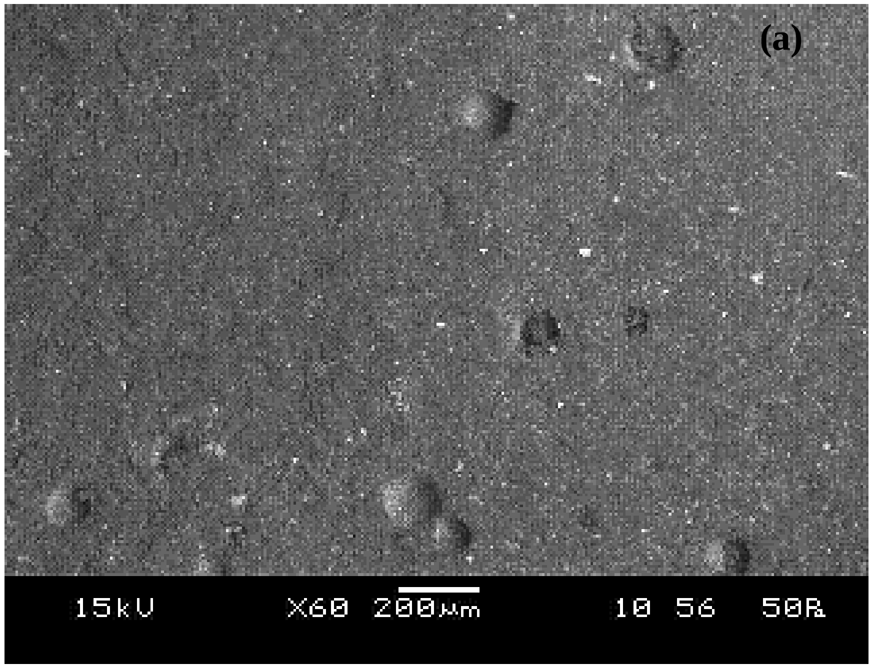
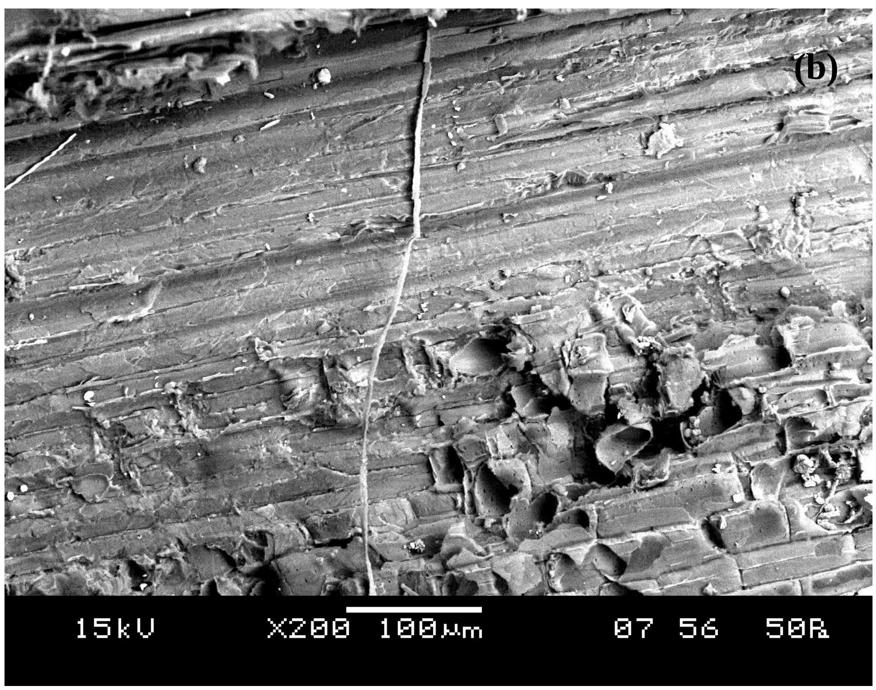


Figure 4.8 Effect of filler content on impact strength of the composites

4.3 Surface morphology of the composites

The fracture surfaces study of short bamboo fiber reinforced epoxy composite before and after the tensile test has been shown in Figure 4.9.


(a)
15kV X60 200µm 10 56 50R


(b)
15kV X200 100µm 07 56 50R

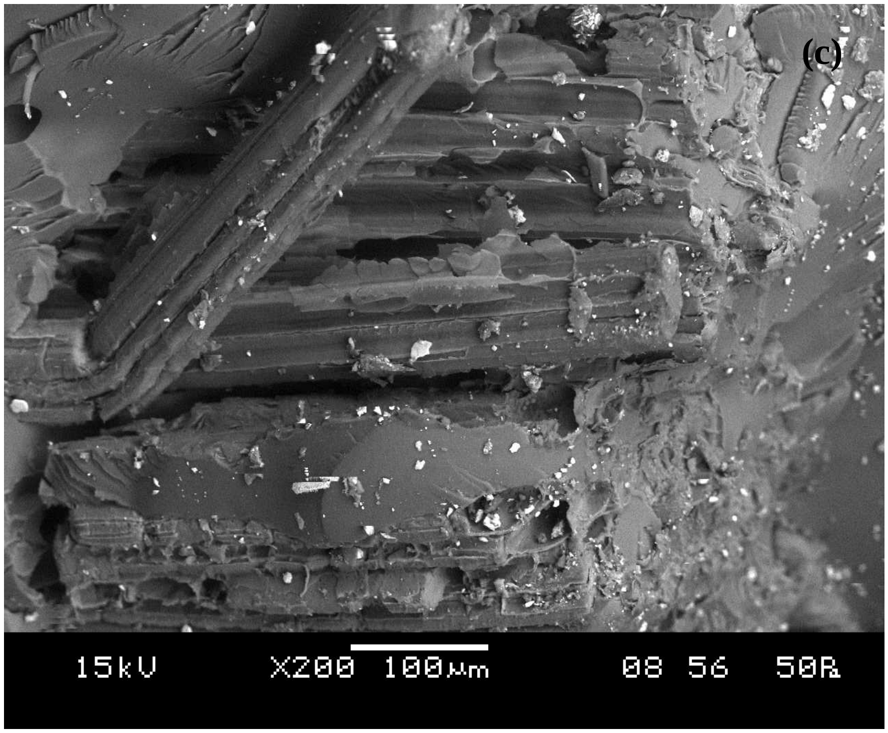


Figure 4.9 Scanning electron micrographs of bamboo fiber reinforced epoxy composite specimens before and after tensile testing

Figure 4.9(a) shows the fiber reinforced epoxy composite without tensile test sample. It is observed from the figure that the surface looks very smooth and lesser void content as shown on the upper surface of the composite sample. On applying tensile load on the 45wt% of bamboo fiber reinforced epoxy composite the fractured surface of composite shows breaking of matrix material under initial loading condition (Figure 4.9(b)). This is because without fibres to retard the crack growth upon external loading, the crack would propagate in an unstable manner. Besides, it is also observed that there is matrix plastic deformation near the crack tip, which contributes to plastic zone generation in the material. However, with the increase in tensile load up to yield point relatively long extruding fibres can be observed, which is depicted by fibre pullout as shown in Figure 4.9(c). It is an indication of crack deflection, where the crack path is changed by the fibre and directed along the fibre surface. This leads to fibre debonding, which is an indication of matrix separation around the fibres as crack front intersects the fibre/matrix interface. Subsequently, it causes fibre pull-out. In this case, energy is dissipated by shear. At higher fibre loading, there are more fibre surfaces in contributing to energy dissipation, thus further improving the fracture resistance.

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CHAPTER 5

SOLID PARTICLE EROSION CHARACTERISTICS OF BAMBOO FIBER REINFORCED EPOXY COMPOSITES

This chapter presents the effect of fiber loading and filler content on erosion behaviour of composites through steady state erosion test results and their experimental analysis through Taguchi experimental design. This chapter broadly classified into two parts. The first part deals with erosion wear behaviour of unfilled bamboo-epoxy composites and the second part covers erosion behaviour of alumina filled bamboo epoxy composites.

Part-1: Erosion wear behaviour of unfilled bamboo-epoxy composites

5.1 Steady state erosion test results

5.1.1 Effect of impingement angle on erosion rate of composites

The variation of erosion rate with cumulative weight of the impinging particle for the various impingement angles keeping all other parameters constant (impact velocity: 45m/sec, SOD: 75mm, erodent size: 450μm, erodent temperature: 105°C). It is observed from Figure 5.1 that the peaks of erosion rates are located at an angle of 60° for neat epoxy and all other bamboo fiber reinforced epoxy composites showed at 75° impingement angle. This shows semi-brittle erosion response for the bamboo fiber reinforced composites. It is further observed that with increased in fiber loading the erosion rate of the composites initially increases and then gradually decreased. This can be attributed to the fact that harder the material, larger is the fraction of the crater volume that is removed. Erosion rate of materials can be categorized into either ductile fracture or brittle fracture although this grouping is not definitive. However, there is a dispute about this failure classification as the erosive wear behavior depends strongly on the environment condition, experimental conditions and the also target material. From Figure 5.1 it is clear that 45wt% of bamboo fiber loading shows minimum erosion rate as compared with all other composites including neat epoxy. Therefore, it is also clear that with increase in fiber loading the erosion resistance increases. The increase in erosion resistance may be effect of increase in hardness of the composite. In this investigation higher hardness values have been recorded for composites with higher fiber loading and this is one reason why the composites exhibit declining erosion resistance with the increase in fiber loading.

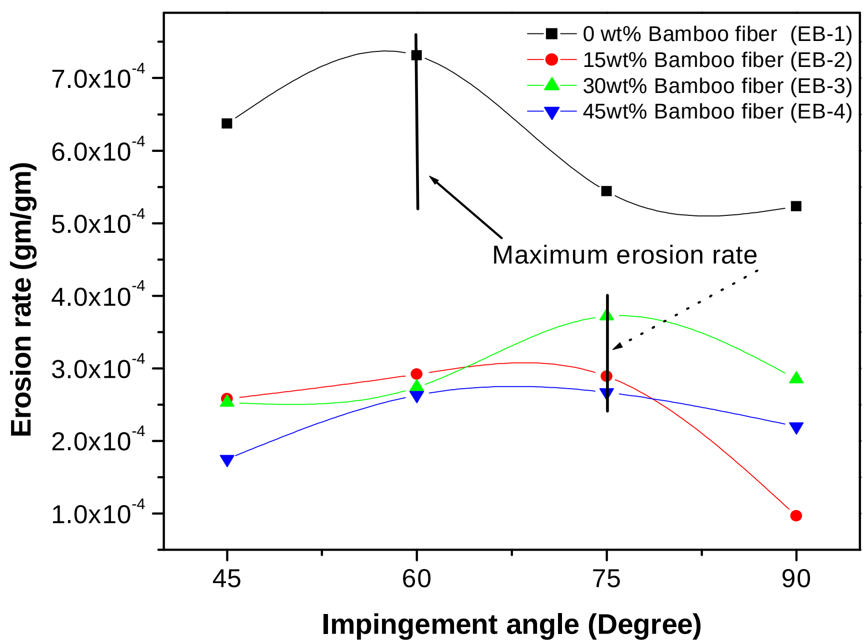

Figure 5.1 Effect of impingement angle on erosion rate of composites without filler

5.1.2 Effect of erodent temperature on erosion rate of composites

Figure 5.2 shows the effect of erodent temperature on erosion rate of the bamboo fiber reinforced epoxy composite. Erosion tests are conducted at four different erodent temperatures under constant impact velocity: 45m/sec, SOD: 75mm, Erodent size: 450micro-m, Impingement angle: 75° respectively. From Figure 5.2 it is clear that neat epoxy resin shows maximum erosion rate as compared with all fiber reinforced epoxy composites. But among fiber reinforced epoxy composites

45wt% of bamboo fiber reinforced epoxy composite shows maximum erosion resistance. However, erosion rate are initially increased with the increase in erodent temperature but on further increase in erodent temperature it showed reduction of erosion rate. Therefore, from this study it is clear that for bamboo fiber reinforced epoxy composites may be applicable for structural application for higher temperature i.e. in the range of 70-150°C.

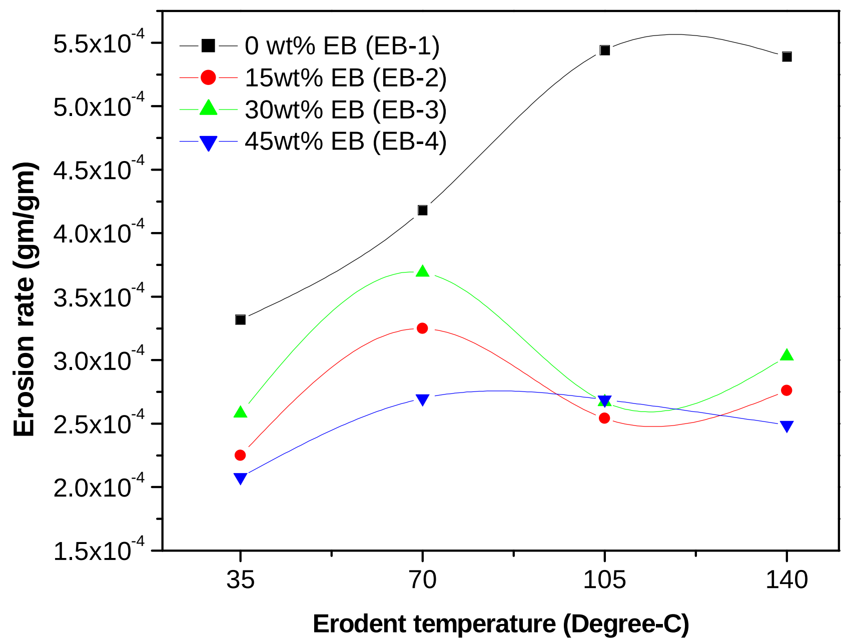

Figure 5.2 Effect of erodent temperature on erosion rate of the composites without filler

5.2 Taguchi experimental results (for unfilled bamboo-epoxy composites)

From Table 5.1, the overall mean erosion rate in terms of S/N ratio of the erosion rate is found to be 71.03 db. Figure 5.3 shows graphically the effect of the five factors on erosion rate. The analysis is done by using the design of experiment software known as MINITAB 15. Before any attempt is made to use this simple model as a predictor for the measures of performance, the possible interactions between the control factors must be considered. Thus factorial design incorporates a simple means of testing for the presence of the interaction effects. From this analysis it is concluded that factor levels A_1, B_1, C_1, D_1 and E_1 are significant levels to get minimum erosion rate.

Table 5.1 Experimental design using L_{16} orthogonal array (for unfilled bamboo epoxy composites)

Sl. No.	Impact Velocity (m/sec)	Fiber loading (wt %)	Impingement angle (°)	S.O.D mm)	Erodent Temp. (°C)	Erosion rate (gm/gm)	S/N Ratio
1	35	0	45	55	35	3.9382E-05	88.0940
2	35	15	60	65	70	1.8095E-04	74.8490
3	35	30	75	75	105	1.8308E-04	74.7474
4	35	45	90	85	140	8.1746E-04	61.7507
5	45	0	60	75	140	3.5484E-04	68.9994
6	45	15	45	85	105	1.8481E-04	74.6654
7	45	30	90	55	70	1.1761E-04	78.5913
8	45	45	75	65	35	5.3394E-04	65.4502
9	55	0	75	85	70	3.7884E-04	68.4309
10	55	15	90	75	35	2.1800E-04	73.2309
11	55	30	45	65	140	5.0046E-04	66.0127
12	55	45	60	55	105	4.7400E-04	66.4844
13	65	0	90	65	105	2.2040E-04	73.1358
14	65	15	75	55	140	3.4940E-04	69.1335
15	65	30	60	85	35	3.1060E-04	70.1560
16	65	45	45	75	70	7.2360E-04	62.8100

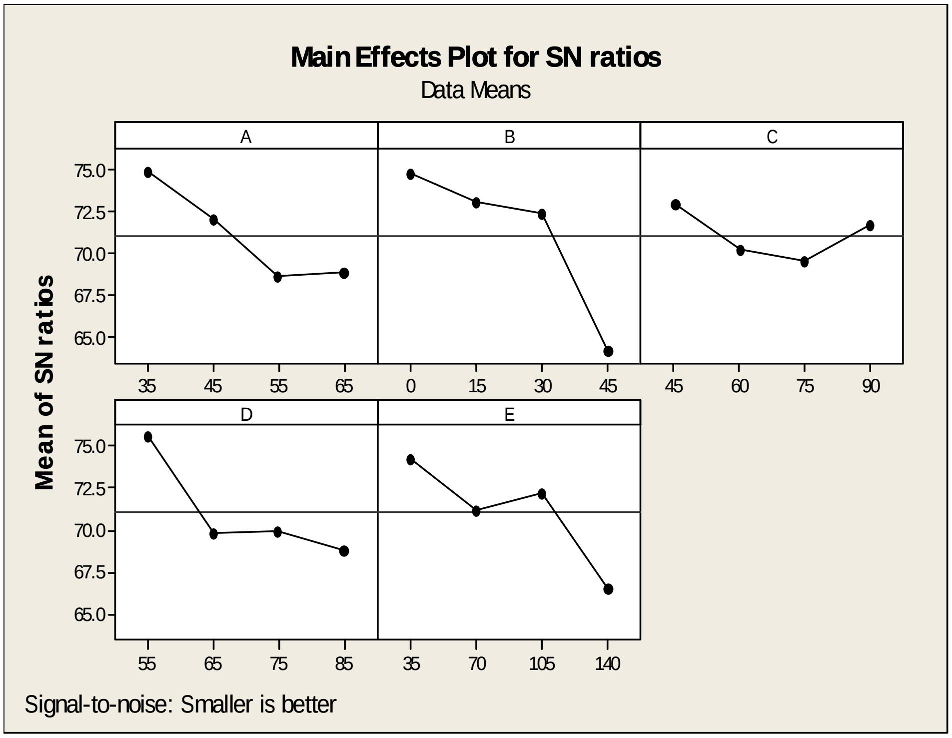

Figure 5.3 Effect of control factors on erosion rate (for unfilled bamboo epoxy composites)

5.3 ANOVA and the effects of factors

In order to understand a concrete visualization of impact of various factors, it is desirable to develop analysis of variance (ANOVA) table to find out the order of significant on output performance. Table 5.2 shows the results of the ANOVA with the erosion rate. This analysis was undertaken for a level of confidence of significance of 5 %. The last column of the table indicates that the main effects are highly significant (all have very small p-values). From Table 5.2, it is observed that the fiber loading (p=0.005), erodent temperature (p=0.032), impact velocity (p=0.036) and stand-off distance (p=0.045) have greater effect on erosion rate. However, impingement angle shows least effect on erosion rate, but as per literature and experimental analysis impingement angle is one of the major factor. Therefore, this cannot be neglected for further analysis.

Table 5.2 ANOVA table for erosion rate (without particulate fillers)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	3	92.80	92.80	92.80	5.82	0.036
B	3	207.58	207.58	207.58	13.02	0.005
C	3	3.76	3.76	3.76	0.24	0.638
D	3	83.15	83.15	83.15	5.22	0.045
E	3	98.46	98.46	98.46	6.18	0.032
Error	0	159.37	159.37	15.94		
Total	15	645.13				

5.4 Surface morphology

The surface morphology of eroded bamboo fiber reinforced epoxy composites are shown in Figure 5.4. To identify the method of material removal, the morphologies of eroded surfaces are studied under scanning electron microscope. Figures 5.4a, b show the un-eroded composites surfaces of neat epoxy resin and 10wt% of bamboo fiber reinforced epoxy composites respectively. Figure 5.4c presents the microstructure of the composite eroded at lower impact velocity (35m/sec), at lower stand-off-distance (65mm) and at an impingement angle of 60^0 for 15wt% bamboo fiber loading resulting in local removal of matrix material on the surface. However, with the increase in impact velocity from 35m/sec to 45m/sec, there is slight increase in erosion rate as shown in Figure 5.4d. This micrograph also reveals that due to sand particle impact on fibers there is formation of cracks that break these fibers. On further increase in fiber loading to 30wt%, with lower impact velocity and impingement angle from oblique to normal change the topography of the damaged surface very significantly and savior removal of matrix materials of the upper surface of the composites as shown in Figures 5.4e, f.

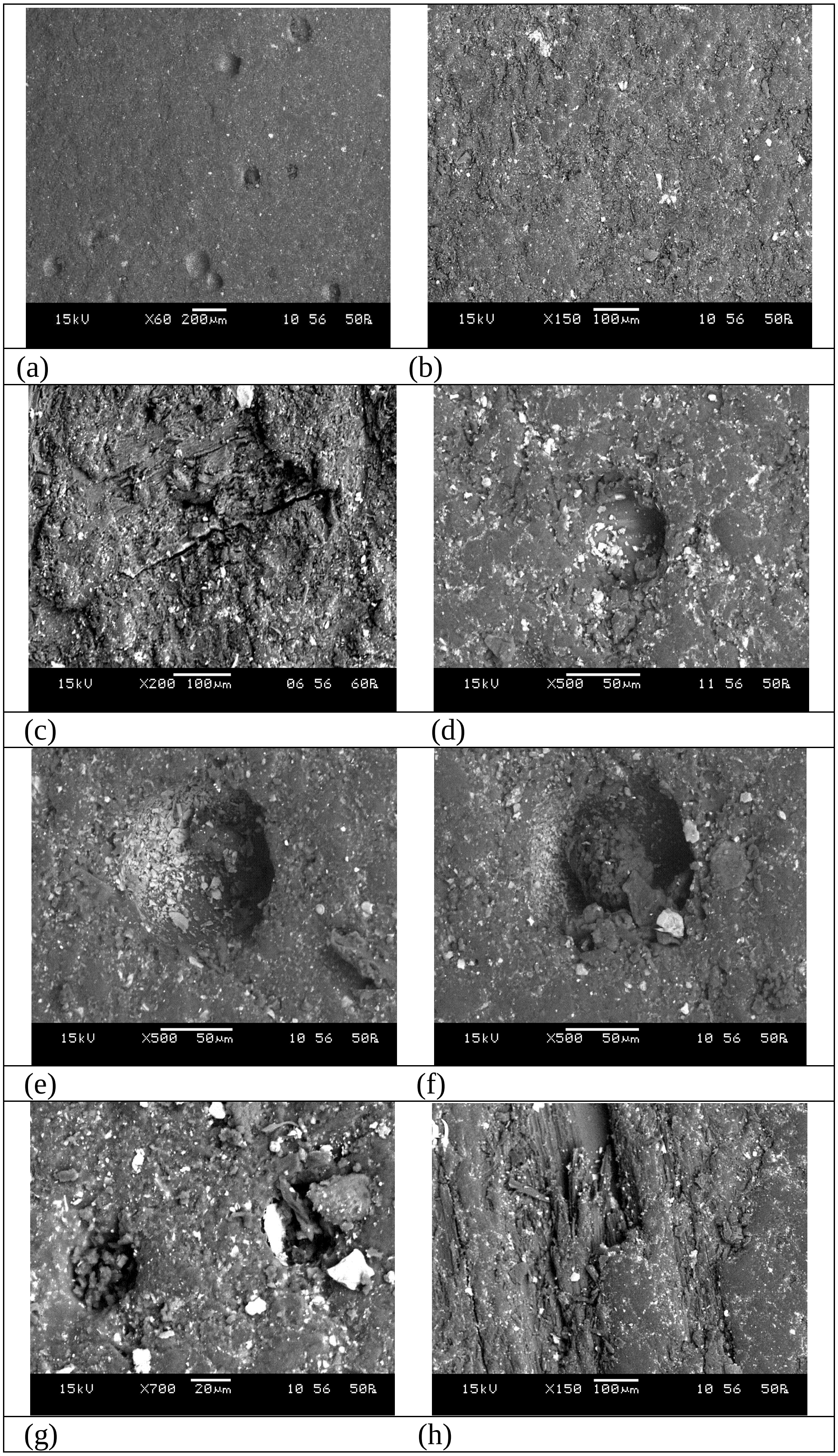

Figure 5.4 SEM micrograph of bamboo fiber-epoxy composite eroded surface

Figures 5.4g, h presents the microstructure of the composite eroded still higher impact velocity i.e. 65m/sec for 45wt% fiber loading. It appears that cracks have grown on the fibers giving rise to breaking of the fibers into small fragments. Further the cracks have been annihilated at the fiber matrix interface and seem not to have penetrated through the matrix. It can also be seen from Figures 5.4g, h that multiple cracks originate from the point of impact, intersect one another and form wear debris due to brittle fracture in the fiber body. After repetitive impacts, the debris in platelet form is removed and account for the measured wear loss. In this case, both abrasion and erosion processes play important roles. The sand particles after impacting, slide on the surface and abrade while dropping down. The wear and subsequently the damage are therefore more than that in the case of normal impact.

A possible reason for the above composites showed semi-brittle erosion behaviour in the present investigation and the fibers used as reinforcements for epoxy matrix are of typical brittle material. Their erosion is caused mostly by damage mechanism such as micro-cracking. Such damage is supposed to increase with the increase of kinetic energy loss of the impinging sand particles.

Part-2: Erosion wear behaviour of alumina filled bamboo-epoxy composites

5.5 Steady state erosion test results

5.5.1 Effect of impingement angle on erosion rate of alumina filled composites

The variation of erosion wear rate of the composites with angle of impingement is studied keeping all other parameters at fixed levels (Constant velocity: 45m/sec, SOD: 75mm, Erodent size: 450micro-m, Impingement angle: 75°) is shown in Figure 5.5. The behaviour of ductile materials like polymers is characterized by maximum erosion rate occurring at low impingement angles (15° to 30°). Brittle materials, on the other hand show maximum erosion rate at an impingement angle of 90°. However, reinforced composites have been found to exhibit semi-ductile behavior with maximum erosion rate occurring at intermediate impingement angles typically in the range of 45-60° [86].

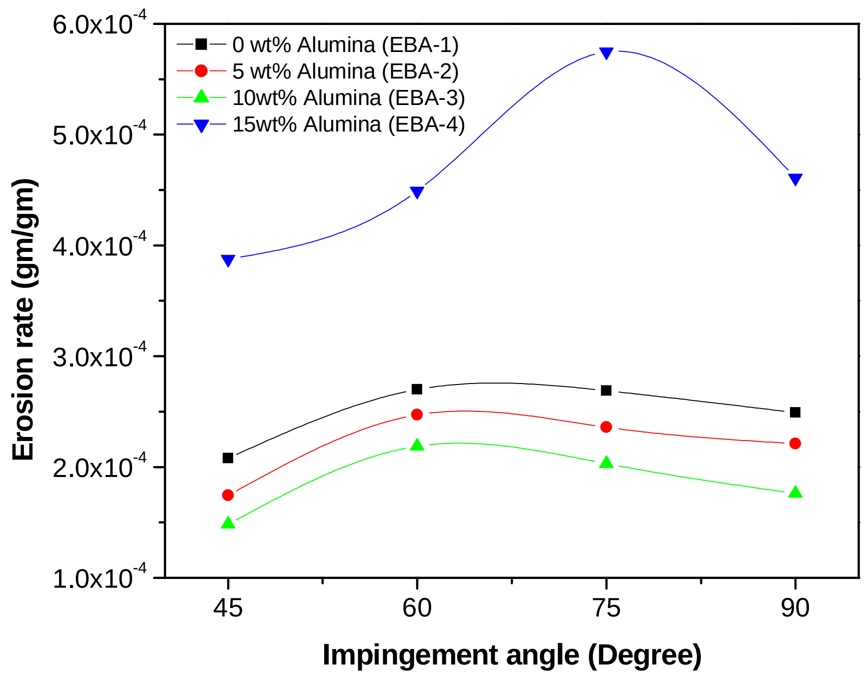

Figure 5.5 Effect of impingement angle on erosion rate of alumina filled composites

It is clear from Figure 5.5 that the rate of material loss of bamboo fiber reinforced epoxy composites reduces significantly with the addition of hard particulate fillers into the matrix. This improvement in the wear resistance depends on the type and content of filler. From this analysis it is clear that up to 10wt% alumina content in the bamboo epoxy composites show better erosion resistance than unfilled bamboo epoxy composite. However, on further increase in filler content up to 15wt% the erosion rate increase two to three times than unfilled composites. The reduction in material loss in these particle filled composites can be attributed to two reasons. One is the improvement in the bulk hardness of the composite with addition of these hard ceramic particles. Secondly, during the erosion process, the filler particles absorb a good part of the kinetic energy associated with the erodent. This results in less amount of energy being available to be absorbed by the matrix body and the reinforcing bamboo fiber phase. These two factors together lead to enhancement of erosion wear resistance of the composites. The loss of ductility may be attributed to the presence of ceramic filler and largely to the reinforcement of untreated bamboo fibers in all these composites. This can further be explained as follows: the erosion of fibers is mainly caused by damage mechanisms as micro-cracking or plastic deformation due to the impact of silica sand. Such damage is supposed to increase with the increase of kinetic energy loss. According to Hutchings et al. [87], kinetic energy loss is maximum at normal impact (90°), where erosion rates are maximum for brittle materials. Hence, although the polymer matrix itself is ductile, the composites show semi-ductile or often semi-brittle erosion behaviour. Similar observations for polyphenylenesulphide (PPS) composites have been reported by Tamer et al. [88].

5.5.2 Effect of erodent temperature on erosion rate of alumina filled composites

Figure 5.6 shows the effect of erodent temperature on erosion rate of alumina filled bamboo fiber reinforced epoxy composite. Erosion tests are conducted at four different erodent temperatures under constant impact velocity: 45m/sec, SOD: 75mm, Erodent size: 450micro-m, Impingement angle: 75° respectively. From Figure 5.5 it is clear that unfilled bamboo-epoxy resin composite shows maximum erosion resistance than filled composites. However, among particulate filled composites 10wt% alumina filled composite shows maximum erosion resistance.

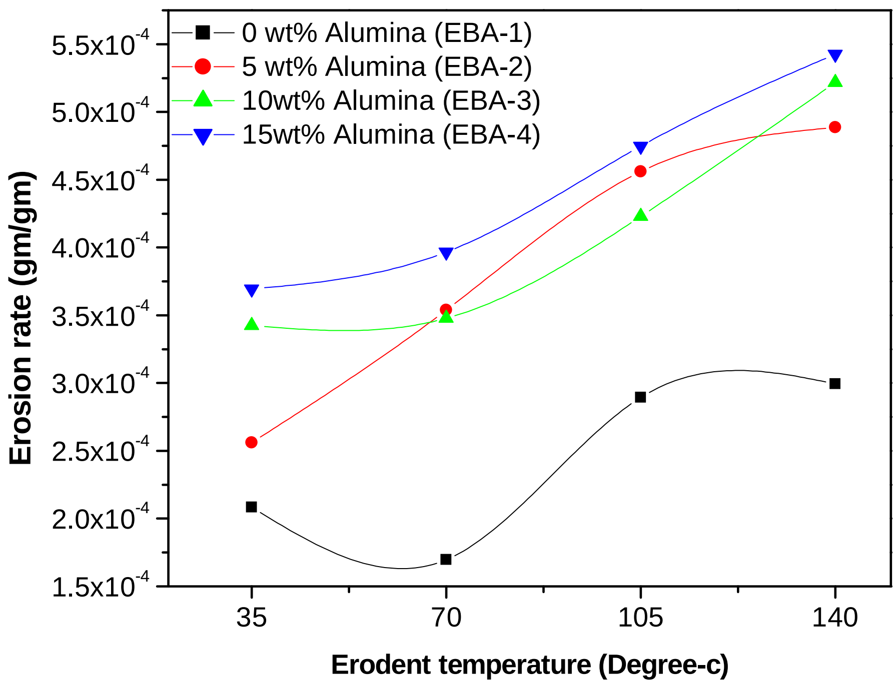

Figure 5.6 Effect of erodent temperature on erosion rate of alumina filled composites

5.6 Taguchi experimental results (for alumina filled bamboo-epoxy composites)

In Tables 5.3 the erosion rates of different composites for all 16 test runs and their corresponding S/N ratios are given. Each value is in fact the average of two replications. The overall mean for the S/N ratios of composites reinforced with alumina, is found to be 70.02db respectively. The analyses are made using the popular software specifically used for design of experiment applications known as MINITAB 15The effects of control factors on erosion rate of composites with the alumina fillers are shown in Figure 5.6. The analysis of the result gives the combination of factors producing minimum wear rate of the composites. These combinations are found to be different for different filler materials. For alumina filled bamboo epoxy composites the factor setting is A_2, B_2, C_3, D_4 and E_3 for minimization of erosion rate is concerned. Thus this analysis suggests that few of the factors have individual effect and similarly, some of the interactions have combined effect on erosion rate. Although, these plots are indicators of the relative significance of various control factors and their interactions, this can be confirmed only after performing the analysis of variance (ANOVA).

Table 5.3 Experimental design using L_{16} orthogonal array (for alumina filled composites)

Sl. No.	Impact Velocity (m/sec)	Filler Content (wt %)	Impingement angle (°)	S.O.D (mm)	Erodent Temp. (°C)	Erosion rate (gm/gm)	S/N ratio (db)
1	35	0	45	55	35	2.8845E-04	70.7986
2	35	5	60	65	70	2.8579E-04	70.8791
3	35	10	75	75	105	3.1453E-04	70.0468
4	35	15	90	85	140	4.8749E-04	66.2406
5	45	0	60	75	140	3.6122E-04	68.8445
6	45	5	45	85	105	1.7473E-05	95.1527
7	45	10	90	55	70	5.2386E-04	65.6157
8	45	15	75	65	35	3.4341E-04	69.2836
9	55	0	75	85	70	5.9288E-05	84.5407
10	55	5	90	75	35	6.0474E-04	64.3686
11	55	10	45	65	140	7.1085E-04	62.9644
12	55	15	60	55	105	3.5208E-04	69.0671
13	65	0	90	65	105	2.8920E-04	70.7760
14	65	5	75	55	140	3.0700E-04	70.2572
15	65	10	60	85	35	9.7740E-04	60.1986
16	65	15	45	75	70	8.4680E-04	61.4444

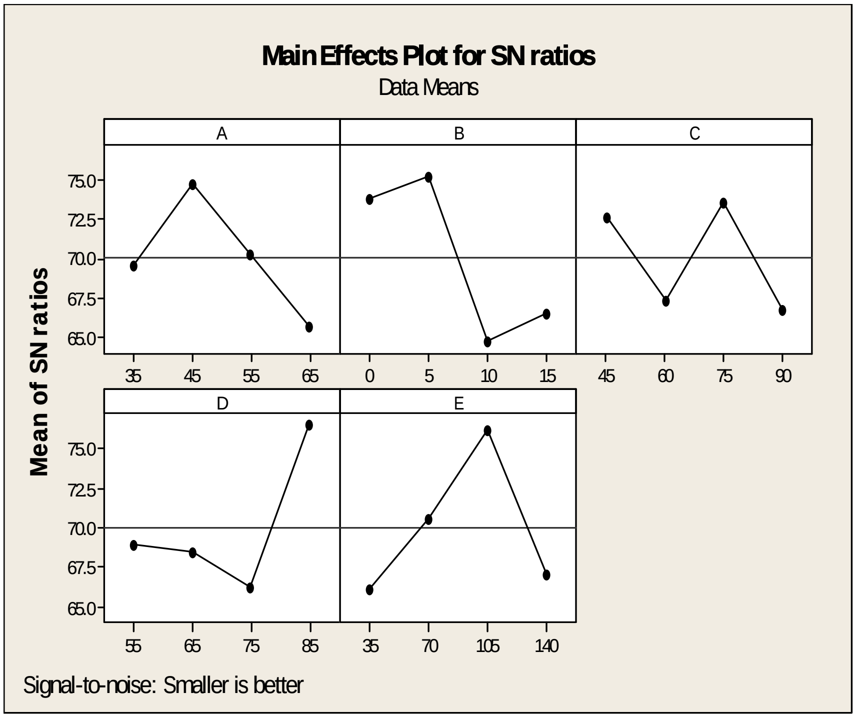

Figure 5.7 Effect of control factors on erosion rate (for alumina filled composites)

5.7 ANOVA and the effects of factors

In order to find out statistical significance of various factors like impact velocity (A), filler content (B), impingement angle (C), stand-off-distance (D) and erodent temperature (E) on erosion rate, analysis of variance (ANOVA) is performed on experimental data. Table 5.4 shows the results of the ANOVA with the erosion rate. This analysis is undertaken for a level of confidence of significance of 5%. The last column of each table indicates p-value for the individual control factors and their possible interactions. It is known that smaller is the p-value, greater is the significance of the factor/interaction corresponding to it.

In case of alumina filled bamboo-epoxy composites (Table 5.4), alumina content (p=0.128), stand-off-distance (p= 0.315) and impact velocity (p=0.430) have greater influence on erosion rate. Moreover, for all the composites, including even the alumina filled ones, erodent temperature and impingement angle show least significance as far as solid particle erosion of these hybrid composites are concerned.

Table 5.4 ANOVA table for erosion rate (for alumina filled composites)

Source	DF	Seq SS	Adj SS	Adj MS	F	p
A	3	50.92	50.92	50.92	0.68	0.430
B	3	206.74	206.74	206.74	2.75	0.128
C	3	25.24	25.24	25.24	0.34	0.575
D	3	84.01	84.01	84.01	1.12	0.315
E	3	14.06	14.06	14.06	0.19	0.675
Error	0	751.74	751.74	75.17		
Total	15	1132.71				

DF: degree of freedom; Seq.SS: sequential sum of squares; AdjSS: extra sum of squares; Adj MS: extra mean squares; p: level of significance

5.8 Surface morphology

Figure 5.8 shows the eroded surface of the alumina filled bamboo fiber reinforced epoxy composites under different operating condition. To characterize the morphology of as received and eroded surfaces and to identify the mode of material removal, the eroded samples are observed under scanning electron microscope. Figures 5.8a, b show the surface of the alumina filled composite eroded at an impact angle of 45°. The erodent particle size, stand-off distance and the impact velocity are set at 450μm, 55mm and 35m/sec respectively. At lower impact velocity the crack formation on the composite surfaces are minimum but removal of matrix material is uniform through the composite surface as shown in Figures 5.8a, b due to lower impingement angle. This may be due to either large erodent size which do not help in crack formation or lower impact velocity that has not favored the crack propagation.

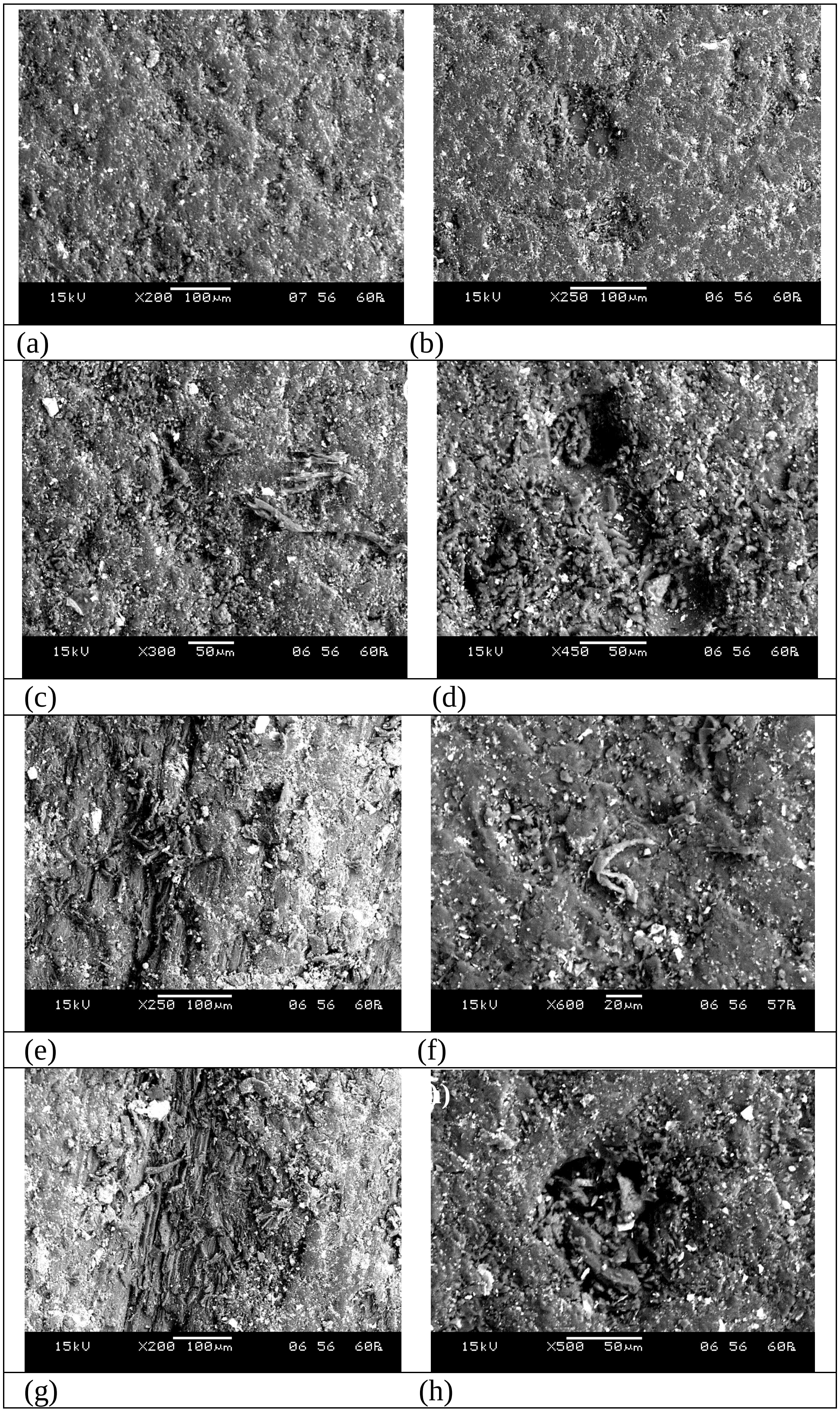

Figure 5.8 Scanning electron micrograph of alumina filled bamboo-epoxy eroded composite surface

On increase of filler content and impact velocity and erodent temperature from room temperature to 70^0C a relatively small fraction of the material is seen to be removed from the surface although formation of large amount of grooves is clearly visible as shown in Figures 5.8c, d. Figures 5.8e, f show the micrograph of surface eroded at an impingement angle of 60^0 and an impact velocity of 65 m/sec. A small portion of a fiber exposed during the sand erosion is noticed. The matrix covering the fiber seems to be chipped off and the crater thus formed shows the fiber body which is almost intact. Repeated impact of the erodent has caused roughening of the surface. Erosion along the fibers and clean removal of the matrix at the interface is observed in the magnified image given alongside. However, on further increase in filler content under similar impact velocity the matrix material removal is more as observed from Figures 5.8g, h and showed larger crater formation due to penetration of hard silica sand particles onto the surface and cause material removal mostly from the matrix regime. Small cracks and multiple fractures are also distinctly shown in this micrograph. On impact, the erodent particle kinetic energy is transferred to the composite body that leads to crater formation and subsequently material loss. The presence of hard fillers in the matrix helps in absorbing a good fraction of this kinetic energy and therefore energy available for the plastic deformation of polyester becomes less. This also delays the initiation of fiber exposure as compared to the composite without any filler. All these factors combined together result in exhibition of better erosion response by the particulate filled composites than that of unfilled composite except 15wt% alumina filled.

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CHAPTER 6

CONCLUSIONS

The experimental investigation on the effect of fiber loading and filler content on mechanical and erosion behavior of short bamboo fiber reinforced epoxy composites leads to the following conclusions obtained from this study are as follows:

1. The successful fabrications of a new class of epoxy based composites reinforced with short bamboo fibers have been done.
2. The present investigation revealed that 45wt% fiber loading shows superior hardness, tensile strength and impact strength. Whereas, for flexural strength show better in 30wt% of fiber loading. As far as inclusion of filler content in the bamboo-epoxy composites, the mechanical properties are inferior as compared to unfilled composites.
3. Study of influence of impingement angle on erosion rate of the composites filled with different weight percentage of particulates reveal their semi-ductile and semi-brittle nature with respect to erosion wear. The result shows the peak erosion taking place at an impingement angle of 60° for the neat epoxy resin and for unfilled bamboo-epoxy composites the peak erosion rate is around 75° impingement angle, whereas composite samples filled with alumina, the maximum erosion rate is recorded at an impingement angle of 60° under similar experimental conditions. This clearly indicates that these composites respond to solid particle impact neither in a purely ductile nor in a purely brittle manner. This behaviour can be termed as semi-ductile in nature. The erosion rate is also greatly affected by the erodent temperature.
4. The fracture surfaces study of short bamboo fiber reinforced epoxy composite after the tensile test has been done. From this study it has been concluded that the poor interfacial bonding is responsible for low mechanical properties.

5. Possible use of these composites such as pipes carrying coal dust, industrial fans, helicopter fan blades, desert structures, low cost housing etc. is recommended. However, this study can be further extended in future to new types of composites using other potential natural fibers/fillers and the resulting experimental findings can be similarly analyzed.

6. 1 Scope for future work

There is a very wide scope for future scholars to explore this area of research. This work can be further extended to study other aspects of such composites like use of other potential fillers for development of hybrid composites and evaluation of their mechanical and erosion behavior and the resulting experimental findings can be similarly analyzed.

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