MECHANICAL CHARACTERIZATION AND SOILD PARTICLE EROSION RESPONSE OF PARTICULATE FILLED JUTE-EPOXY COMPOSITES

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

MASTER OF TECHNOLOGY

IN

MECHANICAL ENGINEERING

[Specialization: Machine Design and Analysis]

By

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207-ME-116

Department of Mechanical Engineering

**NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA**

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C E R T I F I C A T E

This is to certify that the work in this project report entitled **Mechanical Characterization and Soild Particle Erosion Response of Particulate Filled Jute-Epoxy Composites** by **Alok Kumar Jha** has been carried out under our supervision in partial fulfillment of the requirements for the degree of **Master of Technology** in *Mechanical Engineering* with *Machine Design and Analysis* specialization during session 2008 - 2009 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of our knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.

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ALOK KUMAR JHA

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ABSTRACT

Fiber reinforced polymer composites are now considered as an important class of engineering materials. This thesis depicts the processing and mechanical characterization of a new class of multi-phase composites consisting of epoxy resin reinforced with jute fiber and filled with silicon carbide (SiC) particulates. The SiC used as filler material in this work has been prepared from rice husk through plasma processing technique. The effect of filler in modifying the physical and mechanical properties of jute-epoxy composites has been studied. Rice husk is considered as an agricultural waste and it is thus interesting to explore the utilization potential of SiC derived from rice husk in composite making. Moreover, being cheap, inexhaustible and easily available, it would hopefully provide a cost effective solution to composite manufacturers.

With the increased use of these materials in erosive work environments, it has become extremely important to investigate their erosion characteristics intensively. In view of this, erosion trials are carried out at various test conditions. For this, an air jet type erosion test rig and Taguchi's orthogonal arrays are used. Significant control factors influencing the erosion wear rate are identified. This thesis also presents the development of a theoretical model for estimating erosion damage caused by solid particle impact on the composites. The model is based upon conservation of particle kinetic energy and relates the erosion rate with some of the material properties and test conditions. The theoretical results are compared and are found to be in good agreement with the experimental values.

The research reported in this thesis reveals that successful fabrication of multi-component hybrid jute-epoxy composites with reinforcement of SiC derived from rice husk by plasma processing route is possible. Incorporation of these SiC fillers modifies the micro-hardness, density, tensile, flexural and inter-laminar shear strengths of the composites. Hence, while fabricating a composite of specific requirements, there is a need for the choice of appropriate filler material and for optimizing its content in the composite system. It is demonstrated that if supported by an appropriate magnitude of erosion efficiency, the proposed theoretical model can perform well for epoxy based hybrid composites for normal as well as oblique impacts. The presence of particulate fillers in these composites improves their erosion wear resistance and this improvement depends on the weight content of the filler. Erosion characteristics of these composites have been successfully analyzed using Taguchi experimental design. Significant control factors affecting the erosion rate have been identified through successful implementation of this technique. Impact velocity, fiber/filler content and impingement angle in declining sequence are found to be significant for minimizing the erosion rate of all the composites. Erodent size is identified as the least influencing control factor for erosion rate.

Chapter 1

Introduction

Chapter 1

INTRODUCTION

Background and Motivation

Composites are materials consisting of two or more chemically distinct constituents, on a macro-scale, having a distinct interface separating them. One or more discontinuous phases therefore, are embedded in a continuous phase to form a composite. The discontinuous phase is usually harder and stronger than the continuous phase and is called the *reinforcement*, whereas, the continuous phase is termed the *matrix.* 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 (PMC). The reinforcing phase can either be fibrous or non-fibrous (particulates) in nature and if the fibers are derived from plants or some other living species, they are called natural-fibers. The fiber reinforced polymers (FRP) consist of fibers of high strength and modulus embedded in or bonded to a matrix with distinct interface between them. In this form, both fibers and matrix retain their physical and chemical identities. In general, fibers are the principal load carrying members, while the matrix keeps them at the desired location and orientation, acts as a load transfer medium between them, and protects them from environmental damages [1].

Natural Fibers

Natural fibers have recently attracted the attention of scientists and technologists because of the advantages that these fibers provide over conventional reinforcement materials, and the development of natural fiber composites has been a subject of interest for the past few years. These natural fibers are low-cost fibers with low density and high specific properties. These are bio-degradable and nonabrasive, unlike other reinforcing fibers. Also, they are readily available and their specific properties are comparable to those of other fibers used for reinforcements. However, certain drawbacks such as incompatibility with the hydrophobic polymer matrix, the tendency to form aggregates during processing, and poor resistance to moisture greatly reduce the potential of natural fibers to be used as reinforcement in polymers.

Types of Natural Fibers

Natural fibers are grouped into three types: seed hair, bast fibers, and leaf fibers, depending upon the source. Some examples are cotton (seed hairs), ramie, jute, and aflax (bast fibers), and sisal and abaca (leaf fibers). Of these fibers, jute, ramie, flax, and sisal are the most commonly used fibers for polymer composites. Natural fibers in the form of wood flour have also been often used for preparation of natural fiber composites.

On the basis of the source which they are derived from natural fibers can be grouped as:

- Fibers obtained from plant/vegetable
  (cellulose: sisal, jute, abaca, bagasse)
- Fibers derived from animal species
  (sheep wool, goat -horse hair, rabbit hair, angora fiber)
- Fibers from bird / aqueous species
  (bird feathers, fish scale)

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 [2]. The physical and mechanical characteristics can further be modified by adding a solid filler phase to the matrix body during the composite preparation. The improved performance of polymers and their composites in industrial and structural applications by the addition of particulate filler materials has shown a great promise and so has lately been a subject of considerable interest. A possibility that the incorporation of both particles and fibers in polymer could provide a synergism in terms of improved properties and performance has not been adequately explored so far. However, some recent reports suggest that by incorporating filler particles into the matrix of fiber reinforced composites, synergistic effects may be achieved in the form of higher modulus and reduced material costs, yet accompanied with decreased strength [3-8]. Such multi-component composites consisting of a matrix reinforced with fiber as well as particulate matters are termed as *hybrid* composites.

Polymer composites are often used in places where they are subjected to different kind of wear situations. A progressive loss of material from the surface of any component is called wear. It is a material response to the external stimulus and can be mechanical or chemical in nature. Wear is unwanted and the effect of wear on the reliability of

industrial components is recognized widely; also, the cost of wear has also been recognized to be high. Systematic efforts in wear research were started in the 1960's in industrial countries. The direct costs of wear failures, i.e., wear part replacements, increased work and time, loss of productivity, as well as indirect losses of energy and the increased environmental burden, are real problems in everyday work and business. In catastrophic failures, there is also the possibility of human losses. Although wear has been extensively studied scientifically, in the 21st century there are still wear problems present in industrial applications. This actually reveals the complexity of the wear phenomenon [9].

Solid particle erosion (SPE), a typical wear mode, is the loss of material that results from repeated impact of small, solid particles. In some cases SPE is a useful phenomenon, as in sandblasting and high-speed abrasive water jet cutting, but it is a serious problem in many engineering systems, including steam and jet turbines, pipelines and valves carrying particulate matter, and fluidized bed combustion (FBC) systems. Solid particle erosion is to be expected whenever hard particles are entrained in a gas or liquid medium impinging on a solid at any significant velocity. In both cases, particles can be accelerated or decelerated, and their directions of motion can be changed by the fluid.

Polymer composites are often used as engineering as well as structural components where erosive wear occurs. Due to the operational requirements in dusty environments, the study of solid particle erosion characteristics of the polymeric composites becomes highly relevant. Differences in the erosion behaviour of various types of composite materials are caused by the amount, type, orientation and properties of the reinforcement on the one hand and by the type and properties of the matrix and its adhesion to the fibers/fillers on the other. 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 wear [10].

The subject of erosion wear of polymer composites has not received substantial attention in past two decades. Interest in this area is commensurate with the increasing utilization of composites in aerospace, transportation and process industries, in which they can be subjected to multiple solid or liquid particle impact. Examples of these applications are pipe lines carrying sand slurries in petroleum refining, helicopter rotor blades [11], pump impeller blades, high speed vehicles and aircrafts operating in desert environments, water

turbines, aircraft engines [12], missile components, canopies, radomes, wind screens [13] and outer space applications [14]. Resistance to rain and sand erosion is called among the major issues in the defence application of non-metallic materials [14]. Although a great amount of work has already been devoted to this topic many questions are still open. A comprehensive and systematic investigation of erosion in polymer composites has not been performed yet. Studies made on the erosive wear of composites refer more on fiber-reinforced polymer (FRP) and less on filler-reinforced-systems. The effect of fillers is considered more as modification of the matrix and less as reinforcement, possibly because of the low percentage of fillers. As a result, the effect of particulate fillers on erosion characteristics of hybrid composites has hardly received any research attention.

Against this background the present work has been undertaken to investigate the erosion characteristics of epoxy based hybrid composites. The focus has been on fabrication of a series of hybrid composites (Jute-fiber-reinforced epoxy composites filled with SiC derived from rice husk), evaluation of their mechanical properties, and development of a theoretical erosion model, assessment of their relative wear performance and on statistical interpretation of the various test results.

Thesis Outline

The remainder of this thesis is organized as follows:

Chapter 2: Includes a literature review designed to provide a summary of the base of knowledge already available involving the issues of interest.

Chapter 3: Includes a detailed description of the raw materials, test procedures, and design of experiments methodology.

Chapter 4: Presents the physical and mechanical properties of the composites under study.

Chapter 5: Proposes a theoretical model for estimation of erosion wear rate.

Chapter 6: Includes the test results related to erosion of these composites

Chapter 7: Provides summary, specific conclusions drawn from both the experimental and analytical efforts and recommendations for future research.

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Chapter 2

Literature Review

Chapter 2

LITERATURE REVIEW

The purpose of this literature review is to provide background information on the issues to be considered in this thesis and to emphasize the relevance of the present study. This treatise embraces various aspects of polymer composites with a special reference to erosion wear characteristics. The topics include brief review:

- On Fiber/ Particulate Reinforced Polymer Composites
- On Multiphase Hybrid Composites
- On Mechanical Properties of Composites
- On Erosion Wear Characteristics of Composites
- On Erosion Wear Modeling
- On Implementation of DOE

At the end of the chapter a summary of the literature survey and the knowledge gap in the earlier investigations are presented.

On Fiber Reinforced Polymer Composites

Fiber reinforced polymer composites are now considered as an important class of engineering materials. They offer outstanding mechanical properties, unique flexibility in design capability and ease of fabrication. Additional advantages include light weight, corrosion and impact resistance and excellent fatigue strength. Today, fiber composites are routinely used in such diverse applications as automobiles, aircraft, space vehicles, off-shore structures, containers and piping, sporting goods, electronics and appliances. A fiber reinforced composite is not simply a mass of fibers dispersed within a polymer. It consists of fibers embedded in or bonded to a polymer matrix with distinct interfaces between the two constituent phases. The fibers are usually of high strength and modulus and serve as the principal load carrying members. The matrix acts as the load transfer medium between fibers and in less ideal cases where loads are complex, the matrix may even have to partly bear loads. The matrix also serves to protect the fibers from environmental damage before, during and after composite processing. In a composite,

both fibers and matrix largely retain their identities and yet result in many properties that cannot be achieved with either of the constituents acting alone. A wide variety of fibers are available for use in composites. The most commonly used fibers are various types of carbon, glass and aramid fibers. Besides, natural fibers such as: jute, sisal and ceramic fibers like alumina, silicon carbide, mullite and silicon nitride are also used in composite making. The unique combinations of properties available in these fibers provide the outstanding functional and structural characteristics such as: high specific strength and specific stiffness to the fiber reinforced composites.

A key feature of fiber composites that makes them so promising as engineering materials is the opportunity to tailor the materials properties through the control of fiber and matrix combinations and the selection of processing techniques. In principle, an infinite range of composite types exists, from randomly oriented chopped fiber based materials at the low property end to continuous, unidirectional fiber composites at the high performance end. 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 . The physical and mechanical characteristics can further be modified by adding a solid filler phase to the matrix body during the composite preparation. The improved performance of polymers and their composites in industrial and structural applications by the addition of particulate filler materials has shown a great promise and so has lately been a subject of considerable interest.

On particulate filled polymer composites

Hard particulate fillers consisting of ceramic or metal particles and fiber fillers made of glass are being used these days to dramatically improve the wear resistance, even up to three orders of magnitude [15]. Various kinds of polymers and polymer matrix composites reinforced with metal particles have a wide range of industrial applications such as heaters, electrodes [16], composites with thermal durability at high temperature [17] etc. These engineering composites are desired due to their low density, high corrosion resistance, ease of fabrication, and low cost [18-20]. Similarly, ceramic filled polymer composites have been the subject of extensive research in last two decades. The inclusion of inorganic fillers into polymers for commercial applications is primarily aimed at the cost reduction and stiffness improvement [21, 22]. Along with fiber-reinforced composites, the composites made with particulate fillers have been found to

perform well in many real operational conditions. When silica particles are added into a polymer matrix to form a composite, they play an important role in improving electrical, mechanical, and thermal properties of the composites [23, 24]. Currently, particle size is being reduced rapidly, and many studies have focused on how single-particle size affects mechanical properties [25]. The shape, size, volume fraction, and specific surface area of such added particles have been found to affect mechanical properties of the composites greatly. Yamamoto et al. [26] reported that the structure and shape of silica particle have significant effects on the mechanical properties such as fatigue resistance, tensile and fracture properties. Nakamura et al. [27-29] discussed the effects of size and shape of silica particle on the strength and fracture toughness based on particle-matrix adhesion, and also found an increase of the flexural and tensile strength as specific surface area of particles increased.

It has also been reported that the fracture surface energies of epoxy and polyester resin and their resistance to crack propagation are relatively low. But if particulate filler is added to these brittle resins, the particles inhibit crack growth. As the volume fraction of filler is varied, the fracture energy increases up to a critical volume fraction and then decreases again. Srivastava and Shembekar [30] showed that the fracture toughness of epoxy resin could be improved by addition of fly ash particles as filler. The fillers also affect the tensile properties according to their packing characteristics, size and interfacial bonding. The maximum volumetric packing fraction of filler reflects the size distribution and shapes of the particles [31].

On Multiphase Hybrid Composites

Garcia et al. [32, 33] are the first to suggest this kind of composite technique for improving the matrix-dominated properties of continuous fiber reinforced composites. In this technique, a supplementary reinforcement such as particulates, whiskers, or micro fibers is added to the matrix prior to resin impregnation. Jang et al. [34, 35] found a significant improvement in impact energy of hybrid composites incorporating either particulates or ceramic whiskers. Attempts to understand the modifications in the tribological behaviour of the polymers with the addition of fillers or fiber reinforcements have been made by a few researchers [36, 37]. The enhancement in tribological properties of Poly-phenylene-sulfide (PPS) has been reported with the addition of inorganic fillers [38] and fibers [39]. Bahadur et al. [40, 41] reported that the fillers such

as CuS, CuF_2, CaS, and CaO reduced the wear rate of polyamide but many other types of filler such as CaF2 increased the wear rate. But most of the above studies are confined to dry sliding and abrasive wear behaviour of composites. The erosive wear behaviour of epoxy based composites reinforced with a natural fiber along with particulate has not yet been reported in the literature.

On Rice husk and formation of SiC from it

India is one of the largest rice producing countries in the world. Therefore, a large quantity of rice husk is generated as a by-product of rice milling. It has been estimated that 18×3 million tons of rice husk is produced every year (Panigrahi and Overand 1997).[42] At present the rice husk is considered as an agricultural waste. Burning has been the primary means of disposal. Not only does burning create pollution problems but the extremely fine silica ash is also toxic and thus constitutes a health hazard. Even careful incineration procedures cannot completely eliminate this airborne silica. Thus, burning with its attendant problems of air pollution and ash disposal has proven to be an unsatisfactory solution. Fortunately, rice husk contains the necessary carbon and silica, intimately dispersed, to provide a nearly ideal source material for production of SiC, an industrially important ceramic material. Rice husk was first used by Cutler [43] (1973) as a starting material for the production of silicon carbide. Since the rice husk route appears to be promising, much attention has been paid to it (Mansour and Hanna [44] 1979; Nutt [45] 1988; Patel [46] 1991; Ray *et al* [47] 1991; Singh *et al* [48] 1993, [49] 1995; Romera and Reinso [50] 1996; Moustafa *et al* [51] 1997; Krishnarao *et al* 1998; Padmaja and Mukunda [52] 1999; Janghorban and Tazesh [53] 1999; Panigrahi *et al* [54] 2001). Almost all the processes investigated so far involve two process steps i.e. (i) cooking at lower temperature (400–800°C) in a controlled manner to remove volatiles and (ii) reacting the cooked rice husk at high temperature (> 1300°C) to form SiC. In a novel approach, Singh et al. attempted to prepare SiC from rice husk in a single step [55].

On Erosion Wear Characteristics of Composites

To ensure the durability of FRPs for industrial applications, it is necessary to discuss the degradation behaviour and mechanism under various conditions such as stress, corrosion and erosion, etc. Several parts and equipments are exposed to erosive conditions, for example pipes for hydraulic or pneumatic transportation [56–58], nozzle and impeller for sand-blasting facility [59], internal surface of vessels used for fluidized bed or with

catalysis [60], nose of high-velocity vehicle [61], blades/propellers of planes and helicopters [62], etc. Some of them are made from fibrous composites. Due to the operational requirements in dusty environments, the study of solid particle erosion characteristics of the polymeric composites is of high relevance.

Polymers are finding an ever increasing application as structural materials in various components and engineering systems. The high specific strength and stiffness of polymers are primarily responsible for their popularity. However, the resistance of polymers to solid particle erosion has been found to be very poor [63], and in fact it is two or three orders of magnitude lower than metallic materials [64]. One possible way to overcome such a shortcoming is to introduce a hard second phase in the polymer to form polymer matrix composites (PMCs). A number of investigators [65-70] have evaluated the resistance of various types of PMCs to solid particle erosion. Tilly [63] and Tilly and Sage [66] tested Nylon and epoxy reinforced with various fibers such as graphite, glass and steel and concluded that the reinforcement can either increase or decrease the erosion resistance depending on the type of fibers. Zahavi and Schmitt [64] tested a number of PMCs for erosion resistance and concluded that glass-reinforced epoxy composite had a particularly good erosion resistance. Pool et *al.* [11], conducted erosion tests on four PMCs and inferred that wee-handled, ductile fibers in a thermoplastic matrix should exhibit the lowest erosion rates. The above study was extended further by Tsiang [67]. He carried out sand erosion tests on a wide range of thermoset and thermoplastic PMCs having glass, graphite and Kevlar fibers in the forms of tape, fabric and chopped mat as reinforcements. Kevlar fibers in an epoxy resin provided the best erosion resistance. In a recent study, Mathias et al. [68] and also Karasek et al [70] have evaluated the erosion behaviour of a graphite-fiber-reinforced bismaleimide polymer composite. These investigators observed the erosion rates of the PMC to be higher than the unreinforced polymer. Many of the investigators [63-67] also consistently noted that the erosion rates of the PMCs were considerably larger than those obtained in metallic materials. In addition, composites with a thermosetting matrix invariably exhibited a maximum erosion rate at normal impact angles (i.e. a brittle erosion response) while for the thermoplastic polymer composites the erosion rate reached a maximum at an intermediate impact angle in the range 40^0-50^0, signifying a semi-ductile erosion response.

The wear behaviour of composite materials has received much less attention than that of conventional materials. However, as composites are utilized to an increasing extent in the aerospace, transportation and process industries, their durability may become a prime consideration. In erosion, material is removed by an impinging stream of solid particles. Studies to develop an understanding of the mechanisms of erosive wear have been motivated by reduced lifetimes and failures of mechanical components used in erosive environments, e.g. in pipelines carrying sand slurries, in petroleum refining [71, 72] and in aircraft gas turbine/compressor blades [73]. In addition to these studies, which were conducted to understand erosion behaviour in isotropic materials, there is increasing interest in understanding the erosion behaviour of anisotropic materials. Because of their very high specific stiffness and strength, composites are now used extensively in aircraft structures. The understanding of erosive wear behaviour is obviously important for such structures, e.g. helicopter rotor blades. While polymeric coatings have been developed to protect composite aircraft structures from rain erosion [74, 75], there is little understanding of the mechanisms of erosive wear in these materials. For polymers and composite materials, Tilly and Sage [66] investigated the influence of velocity, impact angle, particle size and weight of impacted abrasive for nylon, carbon-fiber-reinforced nylon, epoxy resin, polypropylene and glass-fiber-reinforced plastic. Their results showed that, for the particular materials and conditions of their tests, composite materials generally behaved in an ideally brittle fashion *(i.e.* maximum erosion rate occurred at normal impact). Fiber reinforcement may improve or worsen the resistance to erosion, depending on the type of fibers used. Zahavi and Schmitt [76] performed erosion tests on a quartz-polyimide composite and a quartz-Polybutadiene composite and again determined their behaviour to be like that of nearly ideally brittle materials. One interesting result was the behaviour of an E-glass-reinforced epoxy composite which exhibited erosion rates that were less than those of the other composites by a factor of 5. This was attributed to better adhesion between the matrix and the fibers and the lower porosity of this composite in comparison with the others studied.

The response of materials to solid particle erosion can be categorized as ductile or brittle depending on the variation in the erosion rate (E_r) with impact angle [77-78]. The impact angle is usually defined as the angle between the trajectory of the eroding particles and the sample surface. If E_r goes through a maximum at intermediate impact angles, typically in the range 15^0-30^0, the response of the eroding material is considered ductile.

In contrast, if E_r continuously increases with increasing impact angle and attains a maximum at 90^0 (normal impact), the response of the eroding material is brittle. In addition, under ideally brittle erosion conditions the magnitude of E_r is determined only by the normal component of the impact velocity, and the size of the eroding particle strongly influences the erosion rate [79]. It is to be noted, however, that the above categorization of material behaviour as ductile or brittle is not absolute. For example, if spherical particles are used as the erodent instead of angular particles, the erosion rate exhibits a maximum at 90^0 even in the case of ductile materials such as copper and mild steel [80, 81]. Similarly, even a brittle material such as an inorganic glass exhibits ductile behaviour when impacted with very fine particles [82]. Erosion as well as abrasion experiments on metallic materials, ceramics and polymers have clearly indicated that the hardness of the eroding or abrading material by itself cannot adequately explain the observed behaviour [83]. As a result, combined parameters involving both hardness and fracture toughness have been utilized to correlate the erosion data of metals [84], ceramics [85] and polymers [86]. In addition, correlation between the fatigue and the erosion or wear resistance has also been observed in the case of polymers [87]. The hardness is unable to provide sufficient correlation with erosion resistance, largely because it determines only the volume displaced by each impacting erodent particle and not really the volume removed (eroded). Thus a parameter which will reflect the efficiency with which the volume that is displaced is removed should be combined with hardness to obtain a better correlation.

Erosion tests have been performed under various experimental conditions (erodent flux conditions, erosive particle characteristics) on different target composites. It has been concluded that composite materials present a rather poor erosion resistance [88]. A crucial parameter for the design with composites is the fiber content, as it controls the mechanical and thermo-mechanical responses. In order to obtain the favoured material properties for a particular application, it is important to know how the material performance changes with the fiber content under given loading conditions. The erosive wear behaviour of polymer composite systems as a function of fiber content has been studied in the past [89–90]. It was concluded that the inclusion of brittle fibers in both thermosetting and thermoplastic matrices leads to compositions with lower erosion resistance. Nevertheless, no definite rule is available to describe how the fiber content affects the ER of a composite. An analytical approach was presented by Hovis et al. [91]

which presumed that the ER of a multiphase material depends on the individual ER of its constituents. The linear (LROM) and inverse (IROM) rules of mixture were proposed and evaluated for a multiphase Al-Si alloy. The same rules of mixture were adopted by Ballout et al. [92] for a glass-fiber reinforced epoxy composite. These two rules of mixture were also proposed to model the abrasive wear of unidirectional (UD) fiber reinforced composite materials [93, 94].

Erosion of ductile materials by the impact of hard solid particles at low and moderate velocities (2-100 m/sec) can cause significant damage to structural components in many industrial applications. For example, erosion by non-combustible fly-ash particles causes premature material failures in the power generation industry [95]. During impact on the elastic–plastic target, particle energy transfers into rebound and plastic deformation of the target [96]. Rebound of the particle is caused by the elastic energy stored in the particle and target material, and the magnitude of this energy is determined by the ratio of the rebound to the initial particle velocity. This ratio, called the restitution coefficient (e), depends on the mechanical properties of the target material and erodent, and impact parameters (i.e. velocity, impact angle, and particle size). The extent of erosion damage is related to the ability of the material to elastically recover and therefore, it is important to understand the effect of target mechanical properties, such as hardness, on the restitution coefficient. Several studies have been conducted to measure the restitution coefficient of various target-erodent systems [96, 97]. However, these measurements are complicated and often inaccurate because of the difficulties involved in measuring rebound velocity of the particle.

In general, the erosive wear behaviour of material depends on various operating parameters, such as velocity and angle of impact, particle size, shape, flux rate, etc. [98]. Literature on the effect of velocity of erodent on wear performance is sparse as compared to that on other parameters [99-101]. Earlier studies have shown that the value of the velocity exponent depends on the nature of both the target and the erodent. Tilly and Sage [71] reported a value of velocity exponent of 2.3 for 125–150 μm quartz erodents impacting a range of materials from metals to plastics. They also reported that the velocity exponent decreased with decreasing size of the erodent. In contrast, Finnie [102] reported a high velocity exponent of 6.5 for 575 μm steel spheres impacting glass. While studying the erosive wear behaviour of glass eroded by 300 μm size iron spheres, Bitter [103] postulated that there was a threshold velocity value below which deformation was

elastic and hence no damage occurred. Tilly [104] proposed that the threshold velocity depended on the particle size of the erodent and obtained a value of 2.7 m/s for 225 μm quartz against 11% chromium steel. Wiederhorn et al. [105] documented the velocity exponents for seven types of target materials having a wide range of brittleness indices and microstructures. Scattergood and Routbort [106] found that the velocity exponent increased with decreasing particle size of the erodent. While studying the erosive wear behaviour of amorphous polystyrene, Thai et al. [107] found that the velocity exponent was 3.69. Karasek et al. [108] observed almost linear correlation between the erosion rate of graphite fiber reinforced bismaleimide composite and the impinging velocity. Arnold and Hutchings found that the erosion rate of natural rubber and epoxidized natural rubber had very strong dependence on the impinging velocity above 70 m/s. Rao et al. [109] reviewed the effect of impact velocity on the erosive wear of various polymers and composites.

Erosion due to the impact of solid particles can either be constructive (material removal desirable) or destructive (material removal undesirable), and therefore, it can be desirable to either minimize or maximize erosion, depending on the application. Constructive applications include sand blasting, high-speed water-jet cutting, blast stripping of paint from aircraft and automobiles, blasting to remove the adhesive flash from bonded parts, erosive drilling of hard materials, and most recently, in the abrasive jet micromachining of Si and glass substrates for optoelectronic applications, and the fabrication of components for MEMS and micro-fluidic applications. Solid particle erosion is destructive in industrial applications such as erosion of machine parts, surface degradation of steam turbine blades, erosion of pipelines carrying slurries, and particle erosion in fluidized bed combustion systems. In most erosion processes, target material removal typically occurs as the result of a large number of impacts of irregular angular particles, usually carried in pressurized fluid streams. The fundamental mechanisms of material removal, however, are more easily understood by analysis of the impact of single particles of a known geometry. Such fundamental studies can then be used to guide development of erosion theories involving particle streams, in which a surface is impacted repeatedly.

Available reports on the research work carried out on erosion can be classified under three categories; experimental investigations, erosion model developments and numerical simulations. Tilly [104] presented a thorough analysis of the various parameters affecting

erosion, including particle properties, impact parameters, particle concentration, material temperature and tensile stress. He also reviewed the different mechanisms of erosion, which were categorized into brittle and ductile behaviours. Wiederhorn [105] presented another review of the solid particle erosion phenomena considering single and multiple particle models on erosion of metals and ceramics. The significant parameters for eroding particles and material characteristics were also presented. Humphrey [110] reported a more comprehensive review of the fundamentals of fluid motion and erosion by solid particles. The review includes a discussion of the experimental techniques and the various fundamental considerations relating to the motion of solid particles. An assessment of the fluid mechanics phenomena that can significantly influence erosion of material surfaces by impinging particles was also presented. Because of its direct relevance to gas and oil industries, erosion of pipes and pipe fittings attracted many researchers. Several experimental studies were conducted with the main objective being to determine the rate of erosion in such flow passages and its relation with the other parameters involved in the process. Among these studies are the works by Rochester and Brunton [111], True and Weiner [112], Glaeser and Dow [113], Roco et al. [114], Venkatesh [115], and Shook et al. [116]. Soderberg et al. [117] and Hutchings [118] reported the advantages and disadvantages of such experiments. The recent experimental study by McLaury et al. [119] on the rate of erosion inside elbows and straight pipes provided correlations between the penetration rate and the flow velocity at different values of the elbow diameter, sand rate and size. Edwards et al. [120] reported the effect of the bend angle on the normalized penetration rate. The objective of most of these experimental studies was to provide data for establishing a relationship between the amount of erosion and the physical characteristics of the materials involved, as well as the particle velocity and angle of impact. Blanchard et al. [121] carried out an experimental study of erosion in an elbow by solid particles entrained in water. The elbow was examined in a closed test loop. Electroplating the elbow surface and photographing after an elapsed period of time were carried out to show the wear pattern.

Information on the solid particle erosion of materials has been available for many years now [122]. Two erosion modes are often distinguished in the literature: brittle and ductile erosion. Brittle erosion deals with material removal due to crack formation, while ductile erosion deals with material removal due to cutting and ploughing. The difference manifests itself in the impact angle dependent erosion rate. When a brittle material is

impacted by a hard sharp particle, the contact area is plastically deformed due to the high compressive and shear stresses and a radial crack is formed. After the impact, the plastic deformation leads to large tensile stresses that result in lateral cracks causing the material removal. As has been observed by some researchers, the composite materials present a rather poor erosion resistance. Thus, in order to obtain the desired material characteristics for a particular application, it is important to know how the composite performance changes with the fiber content under given loading conditions. The erosive wear behaviour of FRP composite systems as a function of fiber content has been studied in the past [88]. Miyazaki and Hamao [89] have examined the effect of fiber inclusion on the erosion behaviour by comparing the erosion rate of an FRP with that of a neat resin, which is the matrix material of the FRP. It was observed that the inclusion of brittle fibers in both thermosetting and thermoplastic matrices leads to compositions with lower erosion resistance. They have also studied the erosion behaviour of treated and untreated glass fiber reinforced epoxy resin composites. The results show the clear correlation between interfacial strength and erosion rate.

On Erosion Wear Modeling

Several erosion models/correlations were developed by many researchers to provide a quick answer to design engineers in the absence of a comprehensive practical approach for erosion prediction. The theoretical model developed by Rabinowicz [123] was used to calculate the volume of material removed from the target surface due to impact of solid particles entrained in a liquid jet. The results indicated that the sand particle trajectories appeared to be governed by the secondary flows and that there was no simple liquid velocity profile that can be used to calculate the particle trajectories in order to make an accurate prediction of the location of the point of maximum wear. One of the early erosion prediction correlations is that developed by Finnie [124] expressing the rate of erosion in terms of particle mass and impact velocity. In that correlation, the rate of erosion was proportional to the impact velocity squared. In a recent study, Nesic [125] found that Finnie's model over-predicts the erosion rate and presented another formula for the erosion rate in terms of a critical velocity rather than the impact velocity. The erosion model suggested by Bitter [126] assumed that the erosion occurred in two main mechanisms; the first was caused by repeated deformation during collisions that eventually results in the breaking loose of a piece of material while the second was caused by the cutting action of the free-moving particles. Comparisons between the

obtained correlations and the test results showed a good agreement. It was concluded that cutting wear prevails in places where the impact angles are small (such as in risers and straight pipes) and it is sufficient to use hard material in such places to reduce erosion. Tilly [104] suggested another two-stage mechanism for explaining different aspects of the erosion process for ductile materials. In the first stage, the particles indent the target surface, causing chips to be removed and some material to be extruded to form vulnerable hillocks around the scar. The second stage was the one in which the particles break up on impact causing fragments to be projected radially to produce a secondary damage. A correlation was presented relating erosion to the energy required to remove a unit mass and the particle velocity and size. The calculated values of erosion were compared with the experimental data for different particle sizes and a reasonable agreement was found, however, the validity of the work was limited to ductile materials and could not be generalized to include other materials. Other erosion models were suggested by Laitone [127], Salama and Venkatesh [128], Bourgoyne [129], Chase et al. [130], McLaury [131], Svedeman and Arnold [132], and Jordan [133].

In most erosion processes, target material removal typically occurs as the result of a large number of impacts of irregular angular particles, usually carried in pressurized fluid streams. The fundamental mechanisms of material removal, however, are more easily understood by analysis of the impact of single particles of a known geometry. Such fundamental studies can then be used to guide development of erosion theories involving particle streams, in which a surface is impacted repeatedly. Single particle impact studies can also reveal the rebound kinematics of particles, which are very important for models which take into account the change in erosive potential due to collisions between incident and rebounding particles [134].

In order to develop a mathematical model, it is important to understand the mechanism responsible for solid-particle erosion of composite materials. For a composite material, its surface damage by solid-particle erosion depends on many factors, including the impact velocity, particle size and shape of the erodent, mechanical properties of both the target material and the erodent, and the volume fraction, size and properties of the reinforcing phase as well as the bonding between the matrix and the reinforcing phase. The synergism of these factors makes it difficult to experimentally investigate the erosion mechanism for composite materials. Fortunately, computer simulation provides an effective and economic approach for such investigation. Computer models proposed

to simulate wear process may be classified into two groups: macro-scale models and atomic-scale models. The macro-scale models were proposed based on various assumptions or theories such as the cutting mechanism [124] and the platelet mechanism [135]. The cutting mechanism is based on the assumption that individual erodent particle impinges a target surface, cutting out a swath of the material. However, this mechanism is only suitable for ductile materials. Even for ductile materials, SEM observation of eroded surfaces has shown that erosion processes of metals involve extrusion, forging and fracture, and that micro-cutting does not often occur [136].

Another method, finite element analysis (FEM), is also used for erosion simulation [137]. The FEM can provide information on the stress/strain distribution in surface layer, which helps to predict the initiation of surface failure. However, continuous changes in surface geometry during erosion lead to the difficulty in simulation of an entire erosion process using FEM. Although many models have been proposed to simulate erosion processes, lack of generality, flexibility or feasibility make these models difficult to be used to simulate erosion under different conditions and to investigate microstructural effects on erosion. As a matter of fact, many wear models were proposed for mechanical design rather than for prediction of material performance. Therefore, they are not suitable for studying erosion processes in detail and for fundamentally investigating erosion mechanisms..

On Implementation of Design-of-Experiment (DOE)

Wear processes in composites are complex phenomena involving a number of operating variables and it is essential to understand how the wear characteristics of the composites are affected by different operating conditions. Although a large number of researchers have reported on properties, performance and on wear characteristics of composites, neither the optimization of wear processes nor the influence of process parameters on wear rate has adequately been studied yet. Selecting the correct operating conditions is always a major concern as traditional experiment design would require many experimental runs to achieve satisfactory result. In any process, the desired testing parameters are either determined based on experience or by use of a handbook. It, however, does not provide optimal testing parameters for a particular situation. Thus, several mathematical models based on statistical regression techniques have been constructed to select the proper testing conditions [138–140]. The number of runs

required for full factorial design increases geometrically whereas fractional factorial design is efficient and significantly reduced the time. This method is popular because of its simplicity, but this very simplicity has led to unreliable results and inadequate conclusions. The fractional design might not contain the best design point. Moreover, the traditional multi-factorial experimental design is the "change-one-factor-at-a-time" method. Under this method only one factor is varied, while all the other factors are kept fixed at a specific set of conditions. To overcome these problems, Taguchi and Konishi [141] advocated the use of orthogonal arrays and Taguchi [142] devised a new experiment design that applied signal-to-noise ratio with orthogonal arrays to the robust design of products and processes. In this procedure, the effect of a factor is measured by average results and therefore, the experimental results can be reproducible. Phadke [143], Wu and Moore [144] and others [145, 146] have subsequently applied the Taguchi method to design the products and process parameters. This inexpensive and easy-to-operate experimental strategy based on Taguchi's parameter design has been adopted to study effect of various parameters and their interactions in a number of engineering processes. It has been successfully applied for parametric appraisal in erosion wear process for glass polyester composites [147-156].

The exhaustive literature survey presented above reveals that:

- Though much work has been reported on various wear characteristics of metals, alloys and homogeneous materials, comparatively less has been reported on the erosive wear performance of polymers and composites and in fact no study has been found particularly on epoxy based natural fiber / particulate reinforced composites.
- A possibility that the incorporation of both particles and fibers in polymer could provide a synergism in terms of improved wear resistance has not been adequately addressed so far and there is inadequate data available about phenomena behind the modified wear behaviour due to the addition of particulate fillers to the fiber reinforced polymer composites.
- As far as erosion study of polymer matrix composites is concerned, no specific theoretical model based on the assumption that the kinetic energy of the erodent is utilized to cause micro-indentation leading to material loss has been developed.

- Studies carried out worldwide on erosion behaviour of composites have largely been experimental and use of statistical techniques in analyzing wear characteristics is rare.
- Taguchi method, in spite of being a simple, efficient and systematic approach to optimize designs for performance, quality and cost, is used only in a limited number of applications worldwide. Its implementation in parametric appraisal of wear process has hardly been reported.

It is thus clear that the effect of fiber reinforcement and ceramic particulate filling on erosion characteristics of epoxy composites has still remained a less studied area. It is felt that, a further study in this respect is needed particularly with the inclusion of ceramic fillers both in view of the scientific understanding and commercial importance.

In view of the above, the present work is undertaken to investigate the solid particle erosion wear characteristics of epoxy based hybrid composites under multiple impact conditions. The objectives of this work are outlined as follows:

1. Fabrication of a series of jute fiber reinforced epoxy matrix composites filled with and without SiC derived from rice husk.
2. Mechanical characterization of these composites
3. Development of a theoretical model for estimation of erosion wear rate under multiple impact condition.
4. Parametric appraisal of erosion wears process of unfilled jute-epoxy composites using Taguchi experimental design.
5. Parametric appraisal of erosion wears process of particulate filled hybrid jute-epoxy composites using Taguchi experimental design.
6. Development of predictive equations for wear rate based on Taguchi approach

Chapter Summary:

This chapter has provided an exhaustive review of research works on fiber and particulate reinforced polymer composites reported by various investigators. It has also clearly outlined the objectives of the present work. The next chapter discusses experimental planning, characterization details and the Taguchi experimental design technique.

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Chapter 3

Materials and Methods

Chapter 3

MATERIALS AND METHODS

This chapter describes the materials and methods used for the processing of the composites under this investigation. It presents the details of the characterization and erosion tests which the composite samples are subjected to. The methodology related to the design of experiment technique based on Taguchi method is also presented in this part of the thesis.

MATERIALS

Matrix Material

Epoxy LY 556 is the resin which is used as the matrix material. Its common name is Bisphenol-A-Diglycidyl-Ether and it chemically belongs to the 'epoxide' family. The epoxy resin and the hardener are supplied by Ciba Geigy India Ltd.

Fiber Material

Jute is a long, soft, shiny vegetable fiber that can be spun into coarse, strong threads. It is produced from plants in the genus *Corchorus*, family Tiliaceae. Jute is one of the cheapest natural fibers and is second only to cotton in amount produced and variety of uses. Jute fibers are composed primarily of the plant materials cellulose (major component of plant fiber) and lignin (major components wood fiber). It is thus a ligno-cellulosic fiber that is partially a textile fiber and partially wood. It falls into the bast fiber category (fiber collected from bast or skin of the plant) along with kenaf, industrial hemp, flax (linen), ramie, etc. The industrial term for jute fiber is *raw jute*. The fibers are off-white to brown, and 1–4 meters (3–12 feet) long. Woven mats of this fiber have been used as the reinforcing phase in the composites used in this work.

Particulate Filler Material

Silicon carbide (SiC) is a ceramic material that has the potential to be used as filler in various polymer matrices. It is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products for over one hundred years. It is the only chemical compound of carbon and silicon. It was originally produced by a high temperature electro-chemical reaction of sand and carbon. Today the material has been

developed into a high quality technical grade ceramic with very good mechanical properties. It is used in abrasives, refractories, ceramics, and numerous high-performance applications. The material can also be made an electrical conductor and has applications in resistance heating, flame igniters and electronic components. Structural and wear applications are constantly developing. Silicon carbide is composed of tetrahedra of carbon and silicon atoms with strong bonds in the crystal lattice. This produces a very hard and strong material. It is not attacked by any acids or alkalis or molten salts up to 800°C. The high thermal conductivity coupled with low thermal expansion and high strength gives this material exceptional thermal shock resistant qualities. Silicon carbide has low density of about 3.1 gm/cc, low thermal expansion, high elastic modulus, high strength, high thermal conductivity, high hardness, excellent thermal shock resistance and superior chemical inertness.

SiC produced from rice husk by plasma processing route has been used as filler in the composites used in the present investigation.

Synthesis of SiC from rice husk in a plasma reactor

A single step is adopted to prepare SiC directly from raw rice husk in an indigenously developed pot type extended arc plasma reactor using graphite electrodes. A graphite crucible containing the charge acts as the bottom electrode. The extended arc is formed by the movement of the top graphite electrode with an axial hole through which the argon plasma forming gas is introduced. Experiments are carried out in batch operations and experimental conditions such as power and time are varied. A typical experimental condition is as follows: Argon gas flow, 2 lpm; current, 300 A; load voltage, 50 V. After the end of the experiment argon gas is allowed to pass for 1 h and then the crucible is allowed to cool to room temperature. The plasma treated sample is found to be green in colour and fragile in nature, thus could easily ground in a mortar and pestle. Rice husk contains silica in hydrated amorphous form and cellulose which yields carbon when thermally decomposed. When such a product is further heated at high temperature (> 1400°C) a reaction occurs between silica and carbon resulting in the formation of SiC. Thermal plasma can reduce the reaction time significantly as the formation of SiC is observed in a short time of 5 min.The details of SiC preparation from rice husk by this route is described elsewhere [157].

Composite fabrication

Cross plied jute fibers are reinforced in epoxy resin in three different weight proportions (20 wt%, 30 wt% and 40 wt%) to prepare the composites A_1, B_1 and C_1 respectively. Jute fibers and epoxy resin have modulus of about 55 GPa and 3.42 GPa respectively and possess density of 1300 kg/m^3 and 1100 kg/m^3 respectively. No particulate filler is used in these composites.

The other composite samples C_2 and C_3 with silicon carbide fillers of fixed weight percentage are fabricated by the same technique. The low temperature curing epoxy resin and corresponding hardener (HY951) are mixed in a ratio of 10:1 by weight as recommended. The mix is stirred manually to disperse the particulate fillers in the matrix. The mixing is done thoroughly before the jute-fiber mats (40 wt%) are reinforced in the matrix body. Composites C_2 and C_3 contain SiC particles in 10 wt% and 20 wt% proportions respectively. Each ply of jute-fiber is of dimension 200 mm× 200 mm. The composite slabs are made by conventional hand-lay-up technique followed by light compression moulding technique. A stainless steel mould having dimensions of 210 × 210 × 40 mm^3 is used. A releasing agent (Silicon spray) is used to facilitate easy removal of the composite from the mould after curing. Care is taken to ensure a uniform sample since particles have a tendency to clump and tangle together when mixed. The cast of each composite is cured under a load of about 25kg for 24 h before it removed from the mould. Then this cast is post cured in the air for another 24 h after removing out of the mould. Specimens of suitable dimension are cut using a diamond cutter for physical characterization and mechanical testing. Utmost care has been taken to maintain uniformity and homogeneity of the composite. The designation and detailed composition of the composites are given in Table 3.1.

Designation	Composition
A_1	Epoxy + 20 wt% jute fiber
B_1	Epoxy + 30 wt% jute fiber
C_1	Epoxy + 40 wt% jute fiber
C_2	Epoxy + 40 wt% jute fiber + 10wt% SiC
C_3	Epoxy + 40 wt% jute fiber + 20wt% SiC

Table 3.1 Designation and detailed composition of the composites

MECHANICAL CHARACTERIZATION

Micro-hardness

Micro-hardness measurement is done using a Leitz micro-hardness tester. A diamond indenter, in the form of a right pyramid with a square base and an angle 136^0 between opposite faces, is forced into the material under a load F. The two diagonals X and Y of the indentation left on the surface of the material after removal of the load are measured and their arithmetic mean L is calculated. In the present study, the load considered F = 24.54N and Vickers hardness number is calculated using the following equation.

$$H_V = 0.1889\frac{F}{L^2} \tag{3.1}$$

and $L = \dfrac{X+Y}{2}$

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).

Density and Void Fraction

The theoretical density of composite materials in terms of weight fraction can easily be obtained as for the following equations given by Agarwal and Broutman [1].

$$\rho_{ct} = \frac{1}{(W_f/\rho_f)+(W_m/\rho_m)} \tag{3.2}$$

Where, W and ρ represent the weight fraction and density respectively. The suffix *f, m* and *ct* stand for the fiber, matrix and the composite materials respectively.

The composites under this investigation consists of three components namely matrix, fiber and particulate filler. Hence the modified form of the expression for the density of the composite can be written as

$$\rho_{ct} = \frac{1}{(W_f/\rho_f)+(W_m/\rho_m)+(W_p/\rho_p)} \tag{3.3}$$

Where, the suffix '*p*' indicates the particulate filler materials.

The actual density (ρ_{ce}) of the composite, however, can be determined experimentally by simple water immersion technique. The volume fraction of voids (V_v) in the composites is calculated using the following equation:

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \tag{3.4}$$

Tensile strength

The tensile test is generally performed on flat specimens. The commonly used specimens for tensile test are the dog-bone type and the straight side type with end tabs. During the test a uniaxial load is applied through both the ends of the specimen. The ASTM standard test method for tensile properties of fiber resin composites has the designation D 3039-76. The length of the test section should be 200 mm. The tensile test is performed in the universal testing machine (UTM) Instron 1195 and results are analyzed to calculate the tensile strength of composite samples is shown in Figure 3.1.

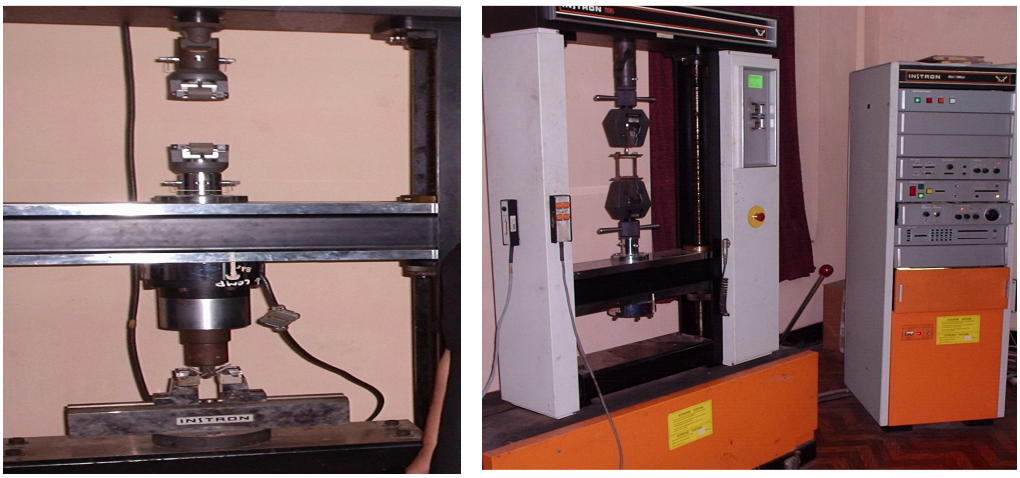

Figure 3.1 Photograph of the machine (Instron 1195) for tensile and 3-point bend Test

Flexural and Inter-laminar shear strength

The short beam shear (SBS) tests are performed on the composite samples at room temperature to evaluate the value of inter-laminar shear strength (ILSS). It is a 3-point bend test, which generally promotes failure by inter-laminar shear. The SBS test is conducted as per ASTM standard (D2344-84) using the same UTM. The loading arrangement is shown in Figure 3.2. Span length of 40 mm and the cross head speed of 10 mm/min are maintained. The ILSS values are calculated as follows,

$$ILSS = \frac{3P}{4b.t} \tag{3.5}$$

Where, P is maximum load,

b the width of specimen, and

t the thickness of specimen

The data recorded during the 3-point bend test is used to evaluate the flexural strength also. The flexural strength (F.S.) of any composite specimen is determined using the following equation.

$$F.S = \frac{3PL}{2bt^2} \tag{3.6}$$

Where, L is the span length of the sample.

Figure 3.2 Loading arrangement for the specimens

Scanning electron microscopy

The surfaces of the specimens are examined directly by scanning electron microscope JEOL JSM-6480LV. The composite samples are mounted on stubs with silver paste. To enhance the conductivity of the samples, a thin film of platinum is vacuum-evaporated onto them before the photomicrographs are taken.

Erosion Test Apparatus

The set up used in this study for the solid particle erosion wear test is capable of creating reproducible erosive situations for assessing erosion wear resistance of the prepared composite samples. It consists of an air compressor, an air particle mixing chamber and

accelerating chamber. The schematic diagram of the erosion test rig is given in Figure 3.4 and pictorial view is presented in Figure 3.5.

Figure 3.3 Scanning Electron Microscope JEOL JSM-6480LV

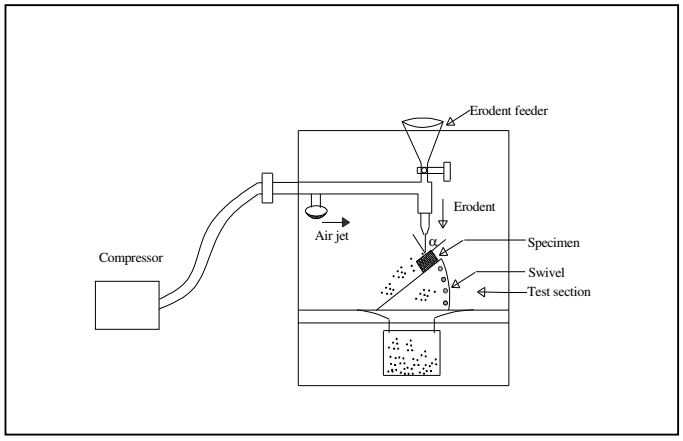

Figure 3.4 A schematic diagram of the erosion test rig

Figure 3.5 Solid Particle Erosion Test Set Up

Dry compressed air is mixed with the erodent particles which are fed at constant rate from a sand flow control knob through the nozzle tube and then accelerated by passing the mixture through a convergent brass nozzle of 3mm internal diameter. These particles impact the specimen which can be held at different angles with respect to the direction of erodent flow using a swivel and an adjustable sample clip. The velocity of the eroding particles is determined using standard double disc method [158]. The conditions (confirming to ASTM G 76 test standards) under which erosion tests are carried out are listed in Table 3.2. In the present study, dry silica sand of different particle sizes (200µm, 300 µm and 400µm) are used as erodent. The samples are cleaned in acetone, dried and weighed to an accuracy of ± 0.1 mg before and after the erosion trials using a precision electronic balance. The weight loss is recorded for subsequent calculation of erosion rate. The process is repeated till the erosion rate attains a constant value called *steady state erosion rate*. The ratio of this weight loss to the weight of the eroding particles causing the loss is then computed as a dimensionless incremental erosion rate. The erosion rate is defined as the weight loss of the specimen due to erosion divided by the weight of the erodent causing the loss.

Control Factors	Symbols	Fixed parameters	
Velocity of impact	Factor A	Erodent	Silica sand
Impingement angle	Factor B	Erodent feed rate (g/min)	10.0 ± 1.0
Erodent size	Factor C	Test temperature	RT
Fiber/Filler loading	Factor D	Nozzle diameter (mm)	3
		Length of nozzle (mm)	80
		Stand-off distance (mm)	100

Table 3.2 Parameters considered during erosion test

Parametric Appraisal and Taguchi Method

Statistical methods are commonly used to improve the quality of a product or process. Such methods enable the user to define and study the effect of every single condition possible in an experiment where numerous factors are involved. Solid particle erosion is such a process in which a number of control factors collectively determine the performance output i.e. the erosion rate. Hence, in the present work a technique called Taguchi method is used to optimize the process parameters leading to minimum erosion

of the polymer composites under study. This part of the chapter presents the Taguchi experimental design methodology in detail.

Taguchi Experimental Design

Every single discipline has researchers carrying out experiments to observe and understand a certain process or to discover the interaction and effect of different variables. From a scientific viewpoint, these experiments are either one or a series of tests to either confirm a hypothesis or to understand a process in further detail. Experiments from a manufacturing point of view, however, are concerned with finding the optimum product and process, which is both cost effective and of a high quality. In order to achieve a meaningful end result, several experiments are usually carried out. The investigator needs to know the factors involved, the range these factors are varied between, the levels assigned to each factor as well as a method to calculate and quantify the response of each factor. This *one-factor-at-a-time* approach will provide the most favorable level for each factor but not the optimum combination of all the interacting factors involved. Thus, experimentation in this scenario can be considered as an iterative process. Although it will provide a result, such methods are not time or cost effective. But the design of experiments is a scientific approach to effectively plan and perform experiments, using statistics. In such designs, the combination of each factor at every level is studied to determine the combination that would yield the best result. The advantage of such design schemes is that it will always determine the effect of factors and possible interactions (between factors) on the performance output.

Taguchi design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors on performance output. The most important stage in the design of experiment lies in the selection of the control factors. Therefore, initially a large number of factors are included so that non-significant variables can be identified at earliest opportunity. Exhaustive literature review on erosion behaviour of polymer composites reveal that parameters viz., impact velocity, impingement angle, fiber loading, filler content, erodent size etc largely influence the erosion rate of polymer composites [147-156]. In the present work, the impact of four such parameters are studied using L_9 (3^4) orthogonal design. The operating parameters and the selected levels are given in Table 3.3. The tests are conducted at room temperature as per experimental designs given in Table 3.4 (for A_1,B_1,C_1) and Table 3.5 (for C_1,C_2 ,C_3) which gives the operating conditions under which each erosion test has been carried out.

Control factor	Level			
	I	II	III	Units
A: Velocity of impact	32	44	58	m/sec
B: Impingement angle	30	60	90	degree
C: Erodent size	200	300	400	µm
D: Fiber loading (for composites A_1,B_1,C_1)	20	30	40	wt%
Filler content (for composites C_1,C_2 ,C_3)	0	10	20	wt%

Table 3.3 Levels for various control factors

Four parameters viz., impact velocity, impingement angle, erodent size, and fiber/filler loading, each at three levels, are considered in this study. In Tables 3.5 and 3.6, each column represents a test parameter and a row gives a test condition which is nothing but combination of parameter levels. Four parameters each at three levels would require 3^4 = 81 runs in a full factorial experiment. Whereas, Taguchi's factorial experiment approach reduces it to 9 runs only offering a great advantage in terms of cost and time.

Test Run	Erodent Velocity (m/s) A	Impingement Angle (Degrees) B	Erodent Size (µm) C	Fiber Content (wt %) D
1	32	30	200	20
2	32	60	300	30
3	32	90	400	40
4	44	30	300	40
5	44	60	400	20
6	44	90	200	30
7	58	30	400	30
8	58	60	200	40
9	58	90	300	20

Table 3.4 Orthogonal array for L_9 Taguchi Design for composites A_1,B_1,C_1

Test Run	Erodent Velocity (m/s) A	Impingement Angle (Degrees) B	Erodent size (μm) C	Filler Content (wt %) D
1	32	30	200	0
2	32	60	300	10
3	32	90	400	20
4	44	30	300	20
5	44	60	400	0
6	44	90	200	10
7	58	30	400	10
8	58	60	200	20
9	58	90	300	0

Table 3.5 Orthogonal array for L_9 Taguchi Design composites C_1, C_2, C_3

The plan of the experiments is as follows: the first column is assigned to impact velocity (A), the second column to impingement angle (B), third column to erodent size (C), and the last column to fiber/filler loading (D).

The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum erosion rate coming under *smaller-is-better* characteristic, which can be calculated as logarithmic transformation of the loss function as shown below.

$$\text{Smaller is the better characteristic: } \frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right) \tag{3.7}$$

where n the number of observations, and y the observed data. “Lower is better” (LB) characteristic, with the above S/N ratio transformation, is suitable for minimizations of erosion rate.

Chapter Summary

This chapter has provided:

- The descriptions of materials used in the experiments
- The details of fabrication and characterization of the composites
- The description of erosion wear test
- An explanation of the Taguchi experimental design.

The next chapter presents the physical and mechanical properties of the polymer composites under study.

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Chapter 4

Mechanical Characterization of the Composites

Chapter 4

MECHANICAL CHARACTERIZATION OF THE COMPOSITES

This chapter presents the physical and mechanical properties of the jute fiber reinforced epoxy composites of different compositions prepared for this work. The interpretation of the results and the comparison among various composite samples are also presented in this part of the thesis, which deals with: the jute-epoxy composites without particulate filling (A_1, B_1 and C_1) and the silicon carbide filled ones (C_1-C_3).

MECHANICAL CHARACTERIZATION

Density and volume fraction of voids

The theoretical and measured densities of the composites along with the corresponding volume fraction of voids are presented in Table 4.1. It may be noted that the composite density values calculated theoretically from weight fractions using Eq.(3) are not equal to the experimentally measured values. This difference is a measure of voids and pores present in the composites. It is clearly seen that with the increase in fiber content from 20 wt% to 40 wt%, there is a increase in the void fraction. However, in all the three composites A_1, B_1 and C_1, the volume fractions of voids are reasonably small (< 1.5%) and this can be attributed to the absence of particulate fillers in these composites. With the addition of silicon carbide as the filler material, more voids are found in the composites. As the filler content increases from 0 wt% to 10 wt% and subsequently from 10 wt% to 20 wt% the volume fraction of voids is found to be increasing. This trend is observed in both the particulate filled composites (C_2 and C_3).

Composites	Measured density (gm/cc)	Theoretical density (gm/cc)	Volume fraction of voids (%)
A_1	1.127	1.135	0.71
B_1	1.139	1.153	1.35
C_1	1.157	1.172	1.28
C_2	1.199	1.258	4.68
C_3	1.287	1.358	5.22

Table 4.1 Measured and Theoretical densities of the composites

Density of a composite depends on the relative proportion of matrix and reinforcing materials and this is one of the most important factors determining the properties of the composites. The void content is the cause for the difference between the values of true density and the theoretically calculated one. The voids significantly affect some of the mechanical properties and even the performance of composites in the workplace. Higher void contents usually mean lower fatigue resistance, greater susceptibility to water penetration and weathering [1]. The knowledge of void content is desirable for estimation of the quality of the composites. It is understandable that a good composite should have fewer voids. However, presence of void is unavoidable in composite making particularly through hand-lay-up route.

Micro-hardness

The variation of composite micro-hardness with the weight fraction of jute fiber and SiC particulates is shown in Figure 4.1. For the composite A_1 (20 wt% of JF), the micro-hardness value is recorded as 57 Hv while for C_1 (40 wt% of JF) this value is 63 Hv. It is thus seen that with the increase in fiber content in the composite, the hardness improves although the increment is marginal. Similarly, with the incorporation of filler particulates into the composites, the mean hardness is seen to have improved.

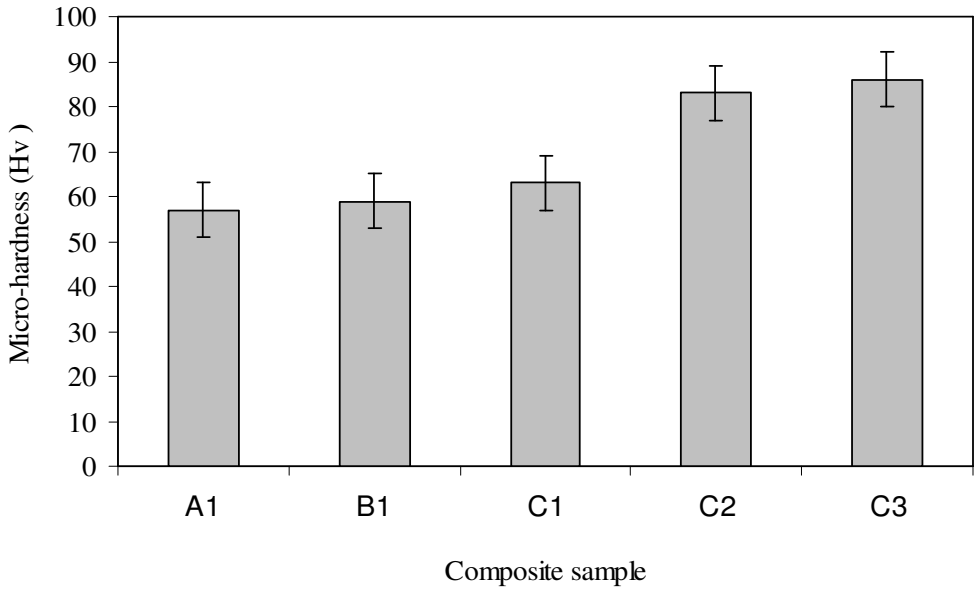


Figure 4.1 Micro-hardness values of composites with different fiber and filler content

Composites	Mean Hardness (Hv)	Tensile strength (MPa)	Flexural strength (MPa)	ILSS (MPa)
A_1	57	302.8	312.6	20.52
B_1	59	331.5	345.8	19.32
C_1	63	349.6	368.6	18.42
C_2	83	304.5	357.8	22.57
C_3	86	279.4	353.2	28.99

Table 4.2 Mechanical properties of the composites

Tensile and flexural strength

It is well known that the strength properties of composites are mainly determined by the fiber content and the fiber strength. So variation in composite strength with different fiber loading is obvious. These variations in tensile and flexural strengths of the composites A_1, B_1 and C_1 are presented in Table 4.2 and are shown in Figure 4.2. A gradual increase in both tensile strength as well as flexural strength with the fiber weight fraction is noticed. It clearly indicates that inclusion of jute fiber improves the load bearing capacity and the ability to withstand bending of the composites. Similar observations have been reported by Harsha et al. [159] for fiber reinforced thermoplastics such as poly-aryl-ether-ketone composites. It may be mentioned here that both tensile and flexural strengths are important for recommending any composite as a candidate for structural applications.

The test results for tensile and flexural strengths for the particulate filled composites C_1, C_2 and C_3 are shown in Figure 4.3. It is seen that the tensile strength of the composite decreases with increase in the filler content. The unfilled jute epoxy composite has a strength of 349.6 MPa in tension and it may be seen from Table 4.2 that this value drops to 304.5 MPa and 279.4 MPa with addition of 10 wt% and 20 wt% of silicon carbide respectively. Similar trend is observed in case of flexural strength of these composites.

There can be two reasons for this decline in the strength properties of these particulate filled composites compared to the unfilled one. One possibility is that the chemical reaction at the interface between the filler particles and the matrix may be too weak to transfer the tensile stress; the other is that the corner points of the irregular shaped

particulates result in stress concentration in the epoxy matrix. These two factors are responsible for reducing the tensile strengths of the composites so significantly. Similar property modification has been previously reported for SiC particles in polyester composites and Al_2O_3 particles reinforced in polyurethane matrix [145, 159].

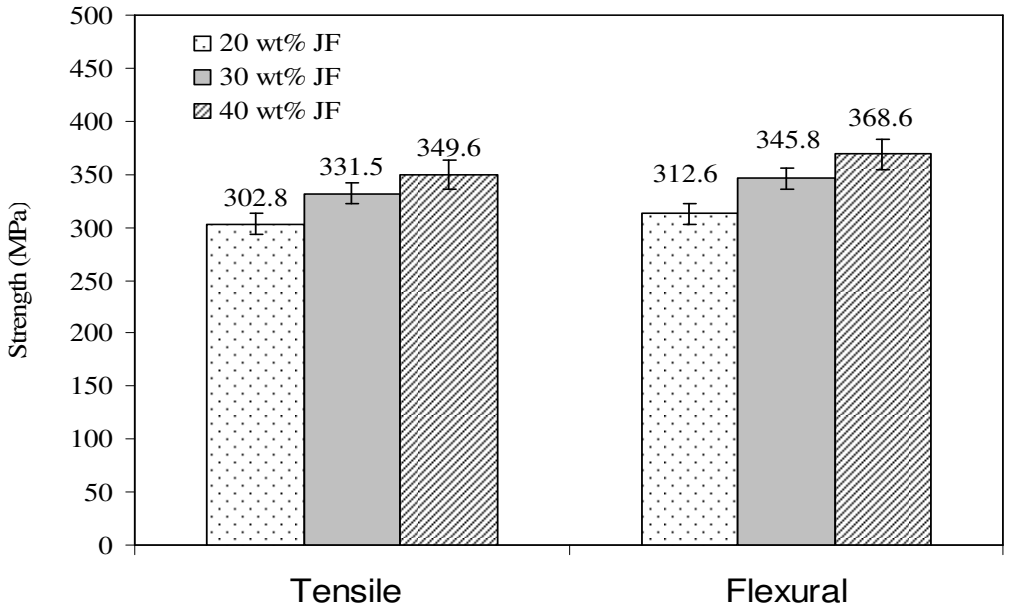


Figure 4.2 Effect of fiber loading on tensile & flexural strength of JF-epoxy composites

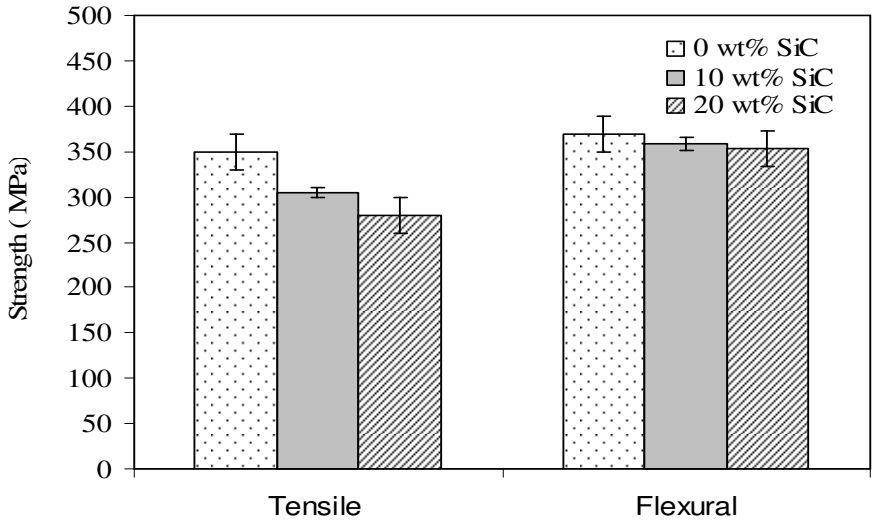


Figure 4.3 Effect of filler content on tensile & flexural strength of JF-epoxy composites

Inter laminar shear strength (ILSS)

The stresses acting on the interface of the two adjacent laminae in a layered composite are called inter-laminar stresses. These stresses cause relative deformations between the consecutive laminae and if these are sufficiently high they may cause failure along the mid-plane between two adjacent laminae. It is therefore of considerable interest to evaluate inter-laminar shear strength through tests in which failure of the laminates of the composite initiates in a shear (delamination) mode. In the present work the ILSS values are measured for unfilled jute-epoxy composites A_1, B_1 and C_1 and no improvement is recorded in the ILSS of the composites with increase in the fiber content in them. The values are illustrated graphically in Figure 4.4.

The inter-laminar shear strength values of the particulate filled composites are shown along with that of the unfilled jute epoxy composite (C_1) in the same Figure 4.4. It is seen that there is improvement of ILSS of jute-epoxy composites with particulate filling. Incorporation of silicon carbide is seen to have caused the substantial increase in the inter-laminar shear strength.

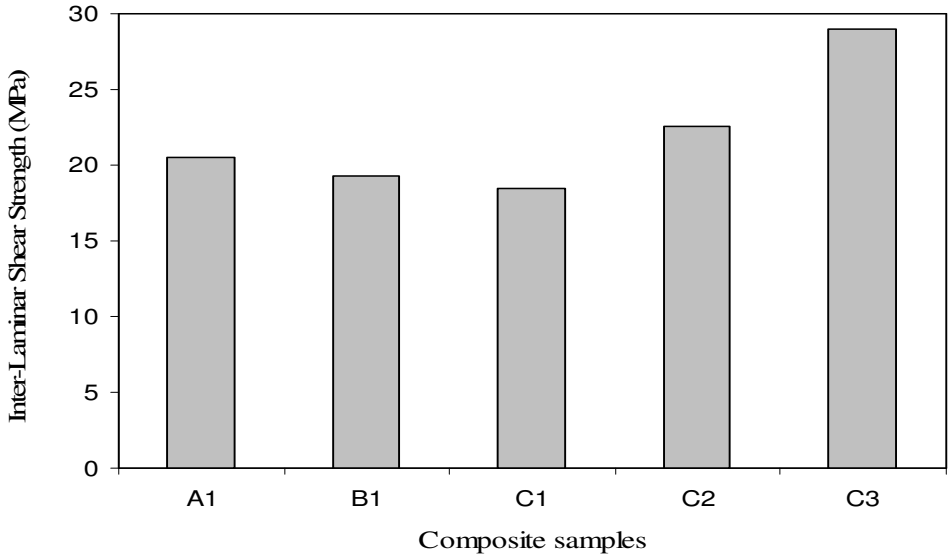


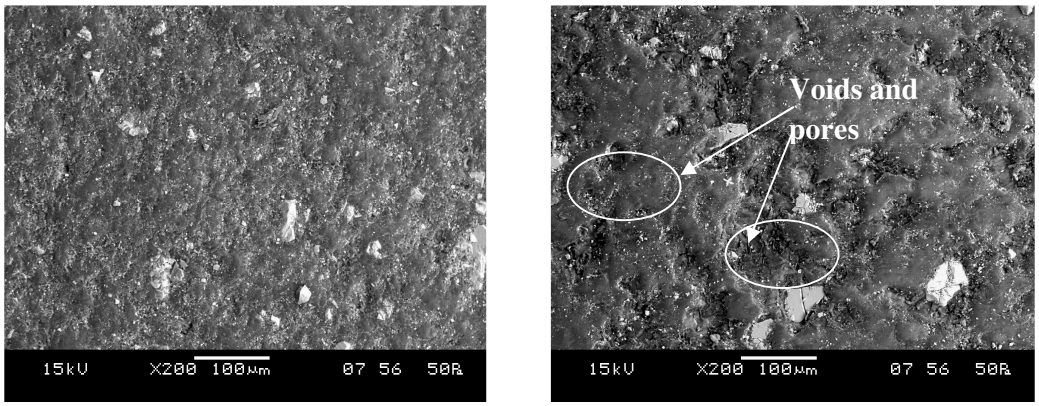
Figure 4.4 Comparison of Inter-laminar shear strength of different composites

In the present investigation, during flexural test, the span length is very short (40 mm). A large span to depth ratio in bending test increases the maximum normal stress without affecting the inter-laminar shear stress and thereby increases the tendency for

longitudinal failure. If the span is short enough, failure initiates and propagates by inter-laminar shear failure. The maximum shear stress in a beam occurs at the mid plane. So in the shear test, failure consists of a crack running along the mid plane of the beam so that crack plane is parallel to the longitudinal plane.

Surface morphology of un-eroded composite samples

The surface micro-structures of some of the composite samples are observed under scanning electron microscope to get an insight to the features.



(a) (b)

Figure 4.5 Surface morphology of un-eroded composite samples

As seen in Figures 4.5 (a) and 4.5 (b), the surfaces are reasonably homogeneous. No cracks are seen although some voids and pores are visible even at this lower magnification. SiC particles are not seen in clusters within the matrix body.

Chapter Summary

This chapter summarizes that:

- Successful fabrication of jute-epoxy composites with reinforcement of SiC derived from rice husk is possible.
- Incorporation of SiC as a filler modifies the micro-hardness, density, tensile, flexural and inter-laminar shear strengths of the jute epoxy composites.

The next chapter presents the development of a theoretical model for estimation of wear rate of polymer composites during solid particle erosion.

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Chapter 5

Development of a Theoretical Model for Erosion Wear Rate Estimation

Chapter 5

DEVELOPMENT OF A THEORETICAL MODEL FOR EROSION WEAR RATE ESTIMATION

This chapter presents the development of a mathematical model for estimating the rate of erosion wear caused by solid particle impact.

THEORETICAL MODEL

Nomenclature

The following symbols are used in this paper:

a	erodent height and base length (m)
δ	indentation depth (m)
e_v	volumetric wear loss per particle impact (m^3)
E_V	total volumetric erosion wear rate (m^3/sec)
α	angle of impingement (degree)
U	impact velocity (m/sec)
P	force on the indenter (N)
H	hardness (N/m^2)
m	mass of single erodent particle (kg)
M	mass flow rate of the erodent (kg/sec)
N	number of impact per unit time (sec^{-1})
ρ_C	density of composite (kg/m^3)
ρ	density of erodent (kg/m^3)
η_{nor}	erosion efficiency with normal impact
η	erosion efficiency
E_{rth}	erosion wear rate (kg/kg)

Solid particle erosion is a wear process in which the material is removed from a surface by the action of a high velocity stream of erodent particles entrained in a high velocity fluid stream. The particles strike against the surface and promote material loss. During flight, a particle carries momentum and kinetic energy which can be dissipated during the impact due to its interaction with a target surface. As far as erosion study of polymer matrix composites is concerned, no specific model has been developed and thus the study of their erosion behaviour has been mostly experimental. However, Mishra [160] proposed a mathematical model for material removal rate in abrasive jet machining process in which the material is removed from the work piece in a similar fashion. This model assumes that the volume of material removed is same as the volume of indentation caused by the impact. This has a serious limitation as in a real erosion process the volume of material removed is actually different from the indentation volume. Further, this model considers only the normal impact i.e. $\alpha = 90^0$ whereas in actual practice, particles may impinge on the surface at any angle ($0^0 \leq \alpha \leq 90^0$). The proposed model addresses these shortcomings in an effective manner. It considers the real situation in which the volume of material removed by erosion is not same as the volume of material displaced and therefore, an additional term "erosion efficiency (η)" is incorporated in the erosion rate formulation. In the case of a stream of particles impacting a surface normally (i.e. at $\alpha=90^0$), erosion efficiency (η_{normal}) defined by Sundararajan et. al [161] is given as

$$\eta_{normal} = \frac{2ErHv}{\rho U^2} \tag{5.1}$$

But considering impact of erodent at any angle α to the surface, the actual erosion efficiency can be obtained by modifying Eq. (5.1) as

$$\eta = \frac{2ErHv}{\rho U^2 Sin^2\alpha} \tag{5.2}$$

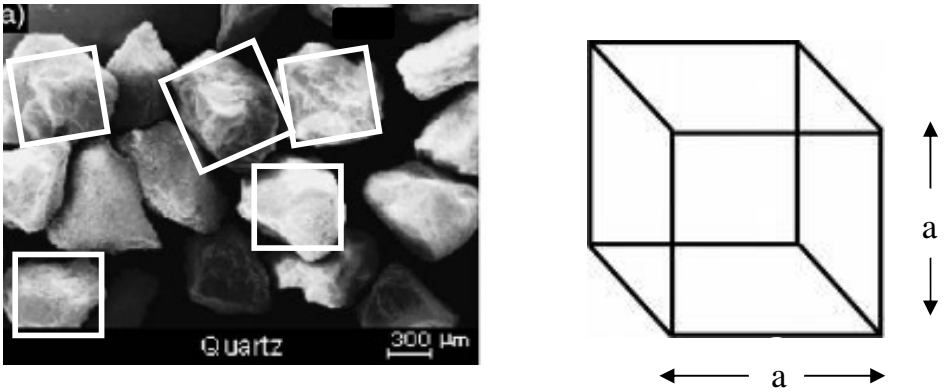

Figure 5.1 SEM Micrograph of the erodent used

Besides, while all previous models have been developed assuming the shape of erodent to be spherical, in the real situation, the erodent particles are actually bodies having sharp edges, as shown in the Figure (5.1). Therefore, considering them to be cubical shaped bodies is a more realistic assumption as compared to assuming them simply spherical. The model proposed in the present work addresses to all these shortcomings. It assumes the erodent particles to be rigid, cubical shaped bodies having side equal to the average grit size. It is further based on the assumption that the loss in kinetic energy of the impinging particles is utilized to cause micro-indentation in the composite material and the material loss is a measure of the indentation. The erosion is the result of cumulative damage of such non-interacting, single particle impacts. The model is developed with the simplified approach of energy conservation which equals the loss in erodent kinetic energy during impact with the work done in creating the indentation. It proceeds as follows.

At time t after initial contact, the particle of mass m will have indented the surface to a depth x; the cross-sectional area of the indentation at the surface will be A(x), where A(x) normally determined by the shape of the erodent particle. The upward force decelerating the particle will be that due to the plastic flow pressure acting over A(x); and the equation of motion of the particle can therefore be written as:

$$m\frac{d^2x}{dt^2} = -HA(x) \tag{5.3}$$

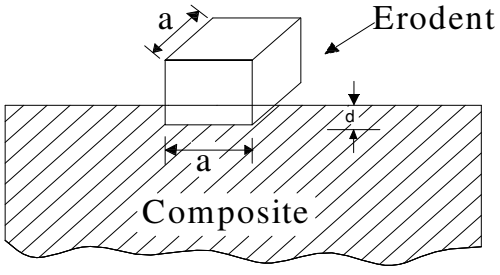

Figure 5.2 Scheme of material removal mechanism

For simple particle shapes, this equation can readily be solved analytically. But to know the final volume of indentation when the particle comes to rest at a depth δ at time t= T, the work done by the retarding force will equal to the sum of the kinetic energy and the loss of thermal energy of the particle.

The conservation of energy can be represented by the equation

$$\int_0^{\delta} HA(x)dx = \frac{1}{2}mU^2 \tag{5.4}$$

The impact velocity will have two components; one normal to the composite surface and one parallel to it. At zero impact angles, it is assumed that there is negligible wear because eroding particles do not practically impact the target surface [162]. Consequently, there will be no erosion due to the parallel component and the indentation is assumed to be caused entirely by the component normal to the composite surface as shown in Figure 5.3.

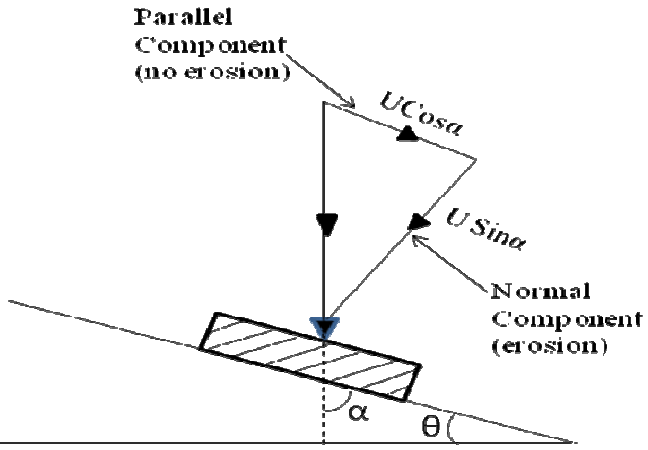

Figure 5.3 Resolution of impact velocity in normal and parallel directions.

Now applying conservation of energy to the single impact erosion process, kinetic energy associated with the normal velocity component of a single erodent particle is equal to the work done in the indentation of composite. The energy of impact introduces a force P on the indenter to cause the indentation in the composite. Thus, in case of

oblique impact, the kinetic energy corresponding to the normal component of velocity is considered and Eq. (5.4) becomes:

$$\text{So, } \int_0^{\delta} HA(x)dx = \frac{1}{2} mU^2 Sin^2\alpha \tag{5.5}$$

$$\text{Now, } \int_0^{\delta} A(x)dx = \int_0^{\delta} a^2 dx = a^2\delta$$

So, the volumetric wear loss per particle impact is given by

e_v = Volume of indentation $\times \eta$

$$= \eta\ a^2\delta$$

Considering N number of particle impacts per unit time, the volumetric erosion wear loss will be

$$Ev = a^2 N\eta\delta$$

$$\text{Now, } \frac{1}{2}.P.\delta = \frac{1}{2}.m.U^2.Sin^2\alpha$$

$$\frac{1}{2}a^2\delta\ .H = \frac{mU^2.Sin^2\alpha}{2}$$

$$e_v = \eta.\left[\frac{m.U^2.Sin^2\alpha}{H}\right]$$

For multiple impact

$$E_V = \eta.mN\left[\frac{U^2.Sin^2\alpha}{H}\right]$$

$$\text{Or, } E_V = \eta.M\left[\frac{U^2.Sin^2\alpha}{H}\right]$$

The non-dimensional erosion rate, defined as the composite mass lost per unit time due to erosion divided by the mass of the erodent causing the loss, is now expressed as

$$E_R = \frac{\eta \rho_C}{H}\left[U^2 Sin^2 \alpha\right] \tag{5.6}$$

The mathematical expression in Eq. 5.6 can possible be used for predictive purpose to make an approximate assessment of the erosion damage from the composite surface.

Chapter summary

- This chapter has provided a theoretical model for estimation of wear rate in an erosion process. But since, material removal by impact erosion wear involves complex mechanisms; a simplified theoretical model for such a process may appear inadequate unless its assessment against experimental results is made. So for the validation of the proposed model, erosion tests on the composites are to be conducted at various operating conditions.

The next chapter presents the erosion test results of the jute-epoxy-SiC composites under this study.

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Chapter 6

Erosion Wear Characteristics of Jute-Epoxy Composites

Chapter 6

EROSION WEAR CHARACTERISTICS OF JUTE-EPOXY COMPOSITES

The objective of this chapter is to validate the theoretical erosion model proposed in the previous chapter through systematic experimental investigation. The test results of erosion trials carried out on the three unfilled jute-epoxy composites A_1, B_1 and C_1 and three particulate filled jute-epoxy composites C_1, C_2 and C_3 are given in this part of the thesis. The Taguchi analysis of the experimental results is also presented.

EROSION TEST RESULTS

PART I For Unfilled Jute-Epoxy Composites (A_1, B_1 and C_1)

Steady state erosion

Erosion wear behaviour of materials can be grouped as ductile and brittle categories although this grouping is not definitive. Thermoplastic matrix composites usually show ductile behaviour and have the peak erosion rate at around 30^0 impingement angle because cutting mechanism is dominant in erosion. While the thermosetting ones erode in a brittle manner with the peak erosion occurring at normal impact. However, there is a dispute about this failure classification as the erosive wear behaviour depends strongly on the experimental conditions and the composition of the target material [159]. In the present work, erosion curves are plotted in from the results of erosion tests conducted for different impingement angle keeping all other parameters constant (impact velocity = 32m/sec, stand-off distance = 100 mm and erodent size =200 μm). Figure 6.1 shows the dependence of the erosion rate of epoxy composites with different fiber content on the impingement angle. It can be seen that the peaks of erosion rates are located at an angle of 60^0 for all the samples irrespective of fiber content. This shows semi-ductile erosion behaviour of the composite. It is further noted that with increased fiber content the erosion rate of the composites is greater.

Surface morphology

To identify the mode of material removal, the morphologies of eroded surfaces are studied under scanning electron microscope. Figure 6.2 presents the microstructure of the

composite eroded at high impact velocity (58m/sec) and at an impingement angle of 60^0. It shows local removal of resin material from the impacted surface resulting in exposure of the fibers to the erodent flux. This micrograph also reveals that due to sand particle impact on fibers there is formation of transverse cracks that break these fibers. The propagation of crack along transverse as well as longitudinal direction is well visualized.

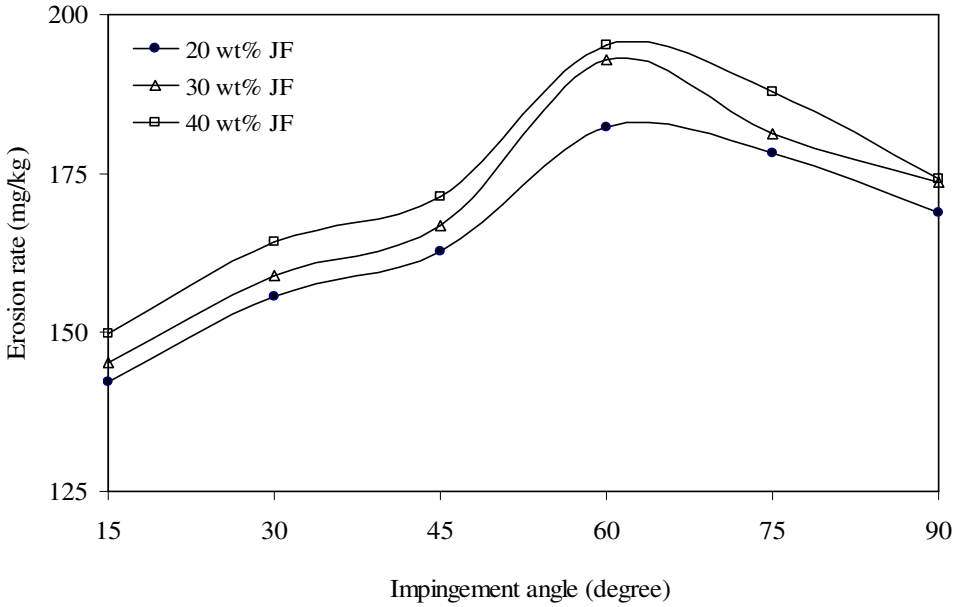


Figure 6.1 Erosion rate vs. angle of impingement for different fiber loading

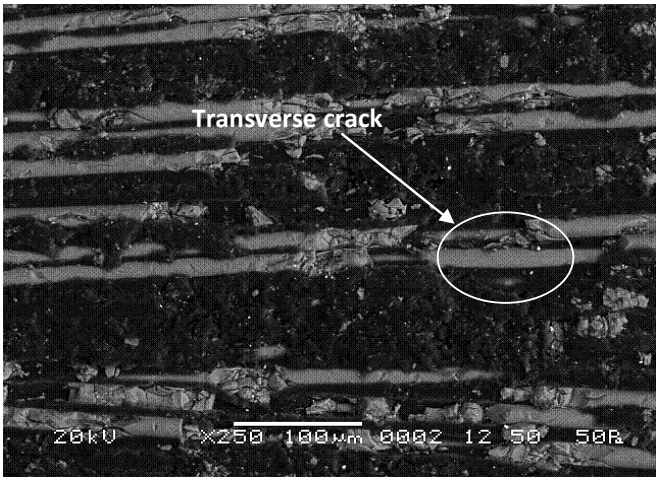


Figure 6.2 SEM micrograph of eroded jute-epoxy composite surface (impact velocity 58m/sec, fiber loading 40 wt%, S.O.D 100mm, impingement angle 60^0 and erodent size 200µm).

A possible reason for the semi-ductile erosion behaviour exhibited by the epoxy based composites in the present investigation is that the erosion of jute fibers 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. According to Hutchings et al. [162], kinetic energy loss is a maximum at normal impact, where erosion rates are highest for brittle materials. In the present study, however, the peak erosion rate shifts to an impingement angle of 60^0 and it is clearly due to the incorporation of jute fibers. So although neat epoxy exhibits a ductile erosion response, the presence of fibers makes the composite relatively more sensitive to impact energy which increases when the impact mode pattern changes from tangential ($\alpha = 0^0$) to normal ($\alpha = 90^0$). This explains the semi-ductile nature of the jute-epoxy composites with respect to solid particle erosion.

Taguchi Analysis of the Erosion Test Results

The erosion wear rates of jute fiber reinforced epoxy matrix composites under various test conditions are given in Table 6.1. The theoretical erosion wear rates (E_{rth}) of all the three unfilled composites are calculated using Eq. 5.6. These values are compared with those obtained from experiments (E_r) conducted under similar operating conditions and the comparison curve has been given in Figure 6.3. Table 6.1 also presents the comparison between the theoretical and experimental results for the composites eroded under different test conditions. The errors associated with each comparison are found to lie in the range 0-12 %.

Test Run	Erodent Velocity (m/s)	Impingement Angle (Degrees)	Erodent size (μm)	Fiber Content (wt %)	Theoretical ER (mg/kg)	Experimental ER (mg/kg)	Error (%)
1	32	30	200	20	172.38	155.710	10.70
2	32	60	300	30	189.76	172.564	9.96
3	32	90	400	40	174.46	188.543	7.46
4	44	30	300	40	218.95	202.765	7.98
5	44	60	400	20	196.88	176.987	11.23
6	44	90	200	30	216.48	197.643	9.53
7	58	30	400	30	235.97	211.987	11.3
8	58	60	200	40	257.98	234.980	9.78
9	58	90	300	20	217.89	199.768	9.07

Table 6.1 Erosion Test Results for Jute-Epoxy Composites

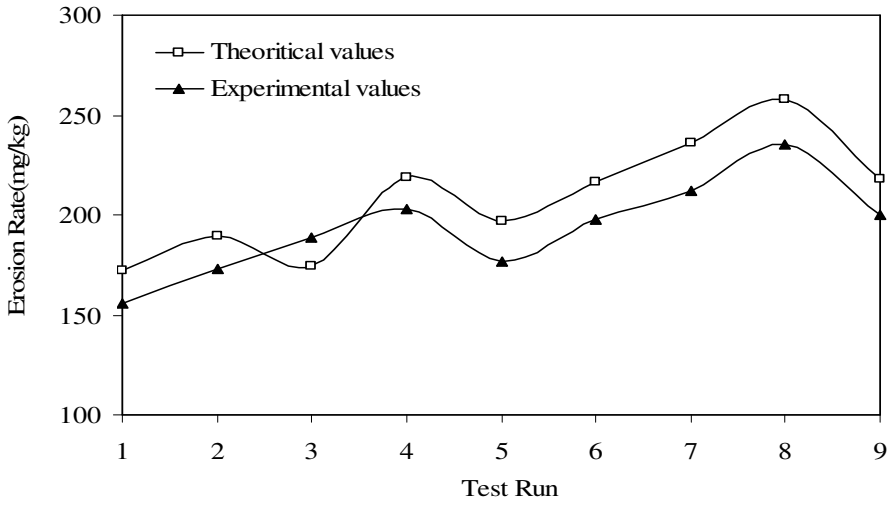


Figure 6.3 Comparisons of Theoretical and Experimental Values of Erosion Rate

The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum erosion rate coming under *smaller-is-better* characteristic, which can be calculated as logarithmic transformation of the loss function as shown below.

Smaller is the better characteristic: $\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right)$ (6.1)

where n the number of observations, and y the observed data. "Lower is better" (LB) characteristic, with the above S/N ratio transformation, is suitable for minimization of erosion rate.

Test Run	A	B	C	D	E	S/N Ratio
1	32	30	200	20	155.710	-43.8463
2	32	60	300	30	172.564	-44.7390
3	32	90	400	40	188.543	-45.5082
4	44	30	300	40	202.765	-46.1399
5	44	60	400	20	176.987	-44.9588
6	44	90	200	30	197.643	-45.9176
7	58	30	400	30	211.987	-46.5262
8	58	60	200	40	234.980	-47.4206
9	58	90	300	20	199.768	-46.0105

Table 6.2 S/N ratio and Erosion Rate for Different Test conditions

In Table 6.2, the last column represents S/N ratio of the erosion rate which is in fact the average of three replications. The overall mean for the S/N ratio of the erosion rate is found to be -45.674 db.

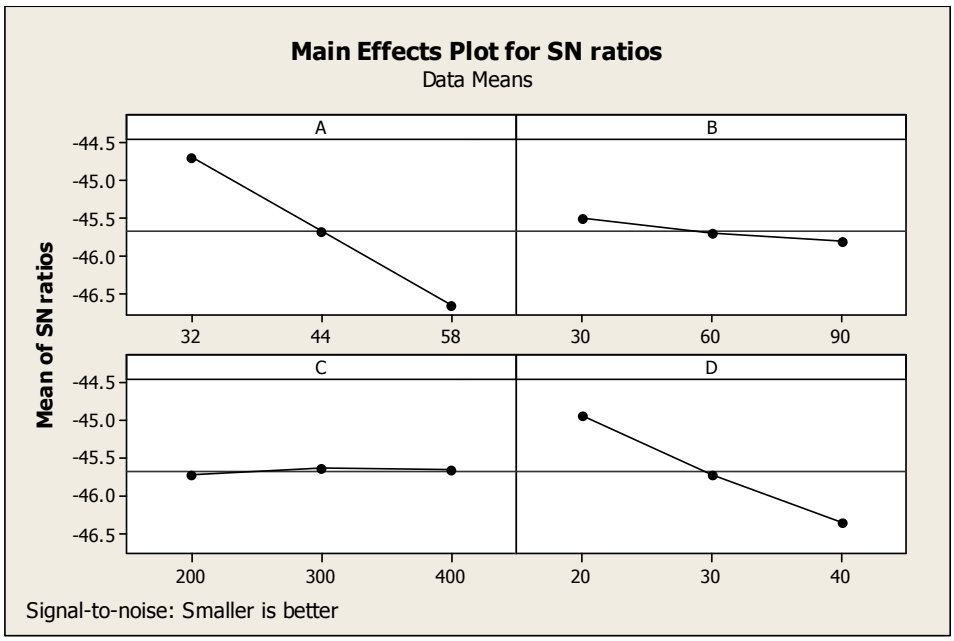


Figure 6.4 Effect of control factors

Level	A	B	C	D
1	-44.70	-45.50	-45.73	-44.94
2	-45.67	-45.71	-45.63	-45.73
3	-46.65	-45.81	-45.66	-46.36
Delta	1.95	.31	0.10	1.42
Rank	**1**	**3**	**4**	**2**

Table 6.3 Response Table for Signal to Noise Ratio (Smaller is better)

The analysis is made using the popular software specifically used for design of experiment applications known as MINITAB 14.

The effects of individual control factors are shown in Figure 6.2. The S/N ratio response are given in Table 6.3, from which it can be concluded that among all the factors, impact velocity is the most significant factor followed by fiber content and impingement angle while the erodent size has the least or almost no significance on erosion of the reinforced composite. It also leads to the conclusion that factor combination of A_1, B_1, and D_1 gives minimum erosion rate.

Factor Settings for Minimum Erosion Rate

In this study, an attempt is made to derive a predictive equation in terms of the significant control factors for determination of erosion rate. The single-objective function requires quantitative determination of the relationship between erosion rates with combination of control factors. In order to express, erosion rate in the form of a mathematical model in the following correlation is suggested.

$$E = K_0 + K_1 \times A + K_2 \times B + K_3 \times D \quad (6.2)$$

Here, E is the performance output terms and K_i (i = 0, 1…3) are the model constants. The constant are calculated using non-linear regression analysis with the help of SYSTAT 7 software and the following relations are obtained.

$$E = 66.984 + 1.665 \times A + 0.086 \times B + 1.564 \times D \quad (6.3)$$

$r^2 = 0.99$

The correctness of the calculated constants is confirmed as high correlation coefficients (r^2) in the tune of 0.99 are obtained for Eq. (6.3).

PART II For Jute-Epoxy Composites Filled with SiC particulates (C_1, C_2 & C_3)

Steady state erosion

Erosion behaviour of the composites is generally ascertained by correlating erosion rate with impingement angle, erodent velocity and composition of the material. Composites usually respond to solid particle erosion in two broad ways: ductile and brittle. The ductile response is characterized by maximum erosion rate occurring at 15–30^0 impingement angle and brittle behaviour is characterized by the peak erosion rate at 90^0. Similarly, semi-ductile behaviour is characterized by the maximum erosion rate taking place at 45–60^0. But as already mentioned, this grouping is not definitive because the erosion characteristics equally depend on the experimental conditions as on composition of the target material.

The erosion wear rates of jute-SiC-epoxy composites as a function of impingement angle (α) are shown in Figure 6.5. It can be seen that filling of composite with SiC particles reduces the wear rate of the jute-epoxy composites quite significantly. The unfilled composite, shows maximum erosion occurring at $\alpha = 60^0$ while for both the filled composites (with 10wt% and 20wt% SiC content) the value of α where the peak erosion occurs is found to be 75^0. In the present study, the location of peak erosion has shifted to 60^0 from the usual 15^0-30^0 (for purely ductile case) as it is reinforced with jute fiber (curve A). This shift in the erosion behaviour is an indication of loss of ductility and is obviously attributed to the presence of fibers. Further shifting of α from 60^0 to 75^0 (curve B and C) proves that the composites tend to become still more brittle with incorporation of SiC particles. The trend is similar for both the composites with SiC filler. It is also important to note that the sample with higher filler content exhibits better erosion resistance. Thus it can be concluded that erosion performance of jute-epoxy composites improves with SiC filling and this improvement is a function of filler content within the limit of the present study.

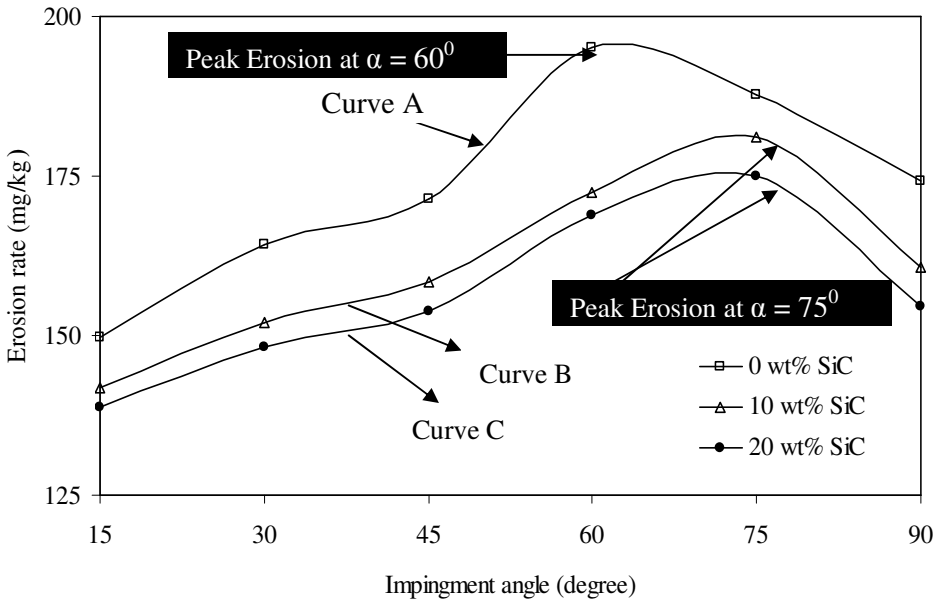
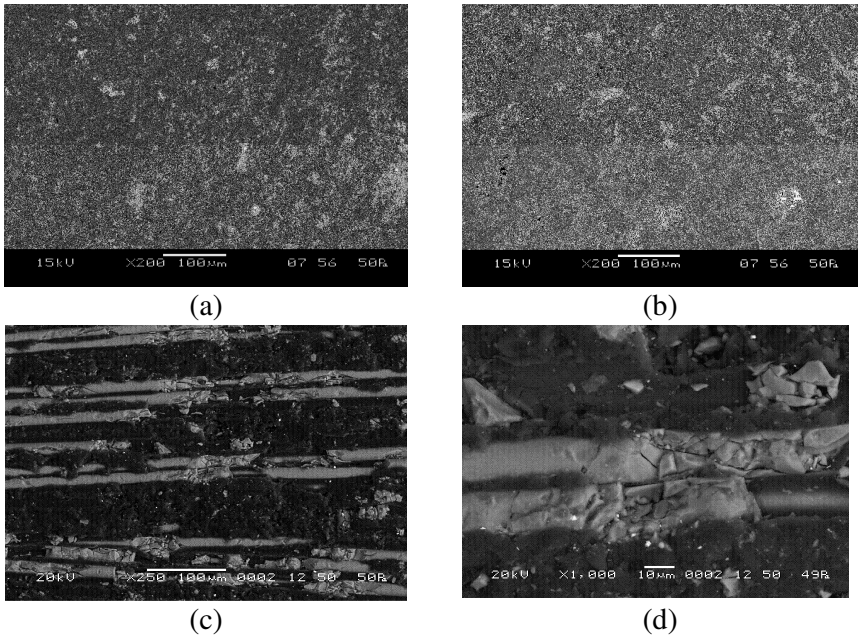


Figure 6.5 Erosion rate vs. Angle of impingement for different weight fraction of SiC

Surface morphology

To identify the mode of material removal, the morphologies of eroded surfaces are studied under scanning electron microscope. The surface micro-structures of some of the un-eroded composite samples are observed under scanning electron microscope basically

to get an insight to the features. As seen in Figures (6.6a) and (6.6b), the surfaces are reasonably homogeneous. No cracks are seen although some voids and pores are visible even at lower magnification. SiC particles are not seen in clusters within the matrix body. To identify the mode of material removal, the morphologies of eroded surfaces are studied under scanning electron microscope. Figure (6.6c) presents the microstructure of the composite eroded at high impact velocity (58m/sec) and at an impingement angle of 60^0. It shows local removal of resin material from the impacted surface resulting in exposure of the fibers to the erodent flux. This micrograph also reveals that due to sand particle impact on fibers there is formation of transverse cracks that break these fibers. The propagation of crack along transverse as well as longitudinal direction is well visualized.



(a) (b)

(c) (d)

Figure 6.6 SEM micrograph of SiC filled jute-epoxy composite surface

Figure (6.6d) presents the microstructure of the SiC filled composite eroded with high impact velocity (58m/sec) at an impingement angle of 60^0. It shows local removal of resin material from the impacted surface resulting in exposure of the fibers to the erodent flux. This micrograph also reveals that due to sand particle impact on jute-fibers, there is formation of transverse cracks that break these fibers. The propagation of crack along transverse as well as longitudinal direction is well visualized. It appears that cracks have

grown on the fibers giving rise to breaking of the fibers into small fragments. Figure (6.6d) also shows the dominance of micro-chipping and micro-cracking phenomena. It can be seen that multiple cracks originate from the point of impact, intersect one another and form wear debris due to brittle fracture in the fiber body as well as in the silicon carbide particles present in the matrix body. After repetitive impacts, the debris in platelet form is removed and account for the measured wear loss.

Taguchi Analysis of the Erosion Test Results

The erosion wear rates of jute fiber reinforced epoxy matrix composites filled with different proportions of silicon carbide under various test conditions are given in Table 6.4. The theoretical erosion wear rates (E_{rth}) of all the three unfilled composites are calculated using Eq. 5.6. These values are compared with those obtained from experiments (E_r) conducted under similar operating conditions and the comparison curve has been given in Figure 6.7. Table 6.4 also presents the comparison between the theoretical and experimental results for the composites eroded under different test conditions. The errors associated with each comparison lie in the range 0-12 %.

Test Run	Erodent Velocity (m/s)	Impingement Angle (Degrees)	Erodent size (μm)	Filler Content (wt %)	Theoretical ER (mg/kg)	Experimental ER (mg/kg)	Error (%)
1	32	30	200	0	142.83	135.170	5.66
2	32	60	300	10	144.68	133.980	7.89
3	32	90	400	20	114.46	106.667	7.30
4	44	30	300	20	121.95	131.320	7.13
5	44	60	400	0	226.81	204.778	10.75
6	44	90	200	10	199.40	189.874	5.01
7	58	30	400	10	235.297	211.493	11.25
8	58	60	200	20	217.297	197.765	9.87
9	58	90	300	0	247.892	258.370	4.05

Table 6.4 Erosion Test Results for particulate filled Jute-Epoxy Composites

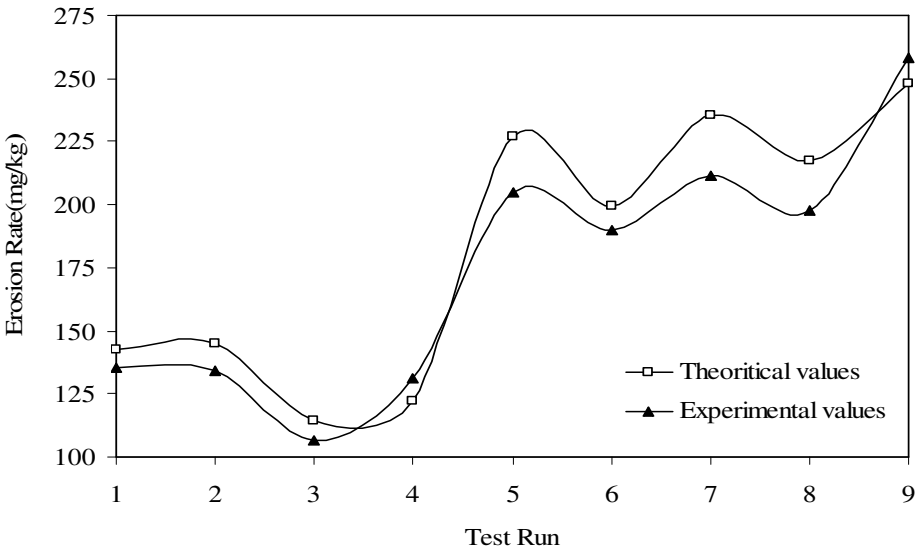


Figure 6.7 Comparison of Theoretical and Experimental Values of Erosion Rate

The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum erosion rate coming under *smaller-is-better* characteristic, which can be calculated as logarithmic transformation of the loss function as shown below.

Smaller is the better characteristic: $\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right)$ (6.4)

where n the number of observations, and y the observed data. "Lower is better" (LB) characteristic, with the above S/N ratio transformation, is suitable for minimization of erosion rate.

Test Run	**A**	**B**	**C**	**D**	**E**	**S/N Ratio**
1	32	30	200	0	135.170	-42.6176
2	32	60	300	10	133.980	-42.5408
3	32	90	400	20	106.667	-40.5606
4	44	30	300	20	131.320	-42.3666
5	44	60	400	0	204.778	-46.2257
6	44	90	200	10	189.874	-45.5693
7	58	30	400	10	211.493	-46.5059
8	58	60	200	20	197.765	-45.9230
9	58	90	300	0	258.370	-48.2448

Table 6.5 S/N ratio and Erosion Rate for Different Test conditions

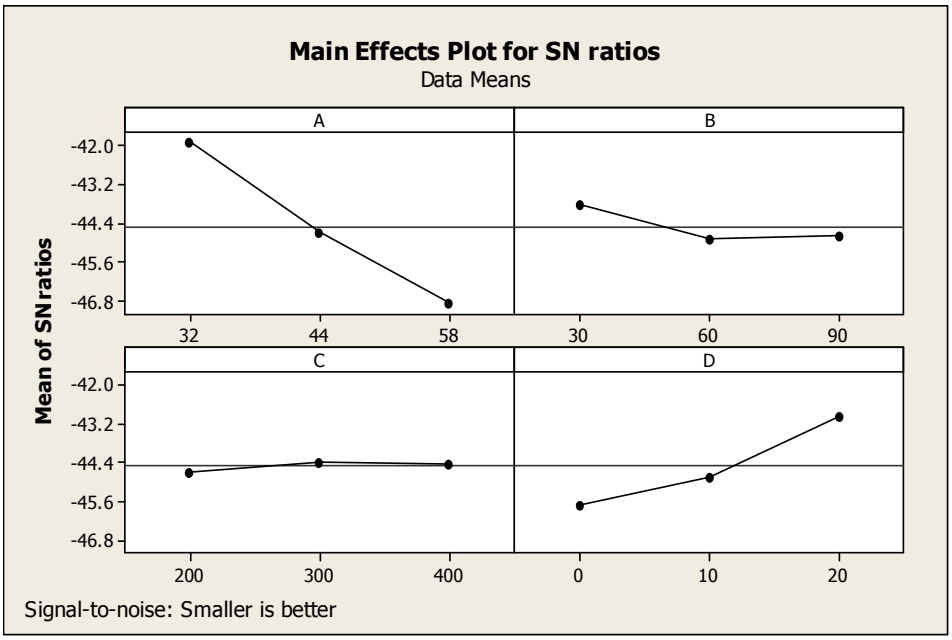


Figure 6.8 Effect of control factors on erosion rate

In Table 6.5, the last column represents S/N ratio of the erosion rate which is in fact the average of three replications. The overall mean for the S/N ratio of the erosion rate is found to be - 44.506 db.

Level	**A**	**B**	**C**	**D**
1	-41.91	-43.83	-44.70	-45.70
2	-44.72	-44.90	-44.38	-44.87
3	-46.89	-44.79	-44.43	-42.95
Delta	4.98	1.07	0.32	2.75
Rank	**1**	**3**	**4**	**2**

Table 6.6 Response Table for Signal to Noise Ratios (Smaller is better)

The analysis is made using the popular software specifically used for design of experiment applications known as MINITAB 14.

The effects of individual control factors are shown in Figure 6.8. The S/N ratio response are given in Table 6.6, from which it can be concluded that among all the factors, impact velocity is the most significant factor followed by filler content and impingement angle while the erodent size has the least or almost no significance on erosion of the reinforced composite. It also leads to the conclusion that factor combination of A_1, B_1, and D_3 gives minimum erosion rate.

Factor Settings for Minimum Erosion Rate

In this study, an attempt is made to derive a predictive equation in terms of the significant control factors for determination of erosion rate. The single-objective function requires quantitative determination of the relationship between erosion rates with combination of control factors. In order to express, erosion rate in the form of a mathematical model in the following correlation is suggested.

$$E = K_0 + K_1 \times A + K_2 \times B + K_3 \times D \tag{6.5}$$

Here, E is the performance output terms and K_i (i = 0, 1…3) are the model constants. The constant are calculated using non-linear regression analysis with the help of SYSTAT 7 software and the following relations are obtained.

$$E = 9.179 + 3.731 \times A + 0.427 \times B - 2.709 \times D \tag{6.6}$$

$r^2 = 0.989$

The correctness of the calculated constants is confirmed as high correlation coefficients (r^2) in the tune of 0.989 are obtained for Eq. (6.6).

Chapter summary:

This chapter has provided the findings that lead to the following conclusions:

1. Successful fabrication of multi-component hybrid jute-epoxy composites with reinforcement of SiC derived from rice husk by plasma processing route is possible.
2. It is demonstrated that if supported by an appropriate magnitude of erosion efficiency, the proposed theoretical model can perform well for epoxy based hybrid composites for normal as well as oblique impacts.

3. The presence of particulate fillers (silicon carbide) in these composites improves their erosion wear resistance and this improvement depends on the weight content of the filler.
4. Erosion characteristics of these composites have been successfully analyzed using Taguchi experimental design. Significant control factors affecting the erosion rate have been identified through successful implementation of this technique. Impact velocity, fiber/filler content and impingement angle in declining sequence are found to be significant for minimizing the erosion rate of all the composites. Erodent size is identified as the least influencing control factor for erosion rate.

The next chapter presents the executive summary and conclusions along with recommendations for future work.

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Chapter 7

Summary and Conclusions

Chapter 7

SUMMARY AND CONCLUSIONS

Summary

The research reported in this thesis consists of two parts: the first part has provided the description of the experimental program and has presented the mechanical characteristics of the jute-epoxy composites under this study; the second part has reported the effect of SiC filler on the solid particle erosion characteristics of these composites.

By incorporating these particulate fillers into the jute-fiber reinforced epoxy, synergistic effects, as expected were achieved in the form of modified mechanical properties and improved erosion wear resistance. Inclusion of jute fiber in neat epoxy improved the load bearing capacity (tensile strength) and the ability to withstand bending (flexural strength) of the composites. But with the incorporation of silicon carbide fillers, the tensile strengths of the composites were found to be less. There can be two reasons for this decline in tensile strength of these particulate filled composites compared to the unfilled one. One possibility is that the chemical reaction at the interface between the filler particles and the matrix may be too weak to transfer the tensile stress; the other is that the corner points of the irregular shaped particulates result in stress concentration in the epoxy matrix.

Hardness values have been found to have improved for the particulate filled composites. The reduction in tensile strength and the improvement in hardness with the incorporation of fillers can be explained as follows: under the action of a tensile force the filler-matrix interface is vulnerable to debonding depending on interfacial bond strength and this may lead to a break in the composite. But in case of hardness test, a compression or pressing stress is in action. So the polymeric matrix phase and the solid filler phase would be pressed together and touch each other more tightly. Thus, the interface can transfer pressure more effectively although the interfacial bond may be poor. This might have resulted in an enhancement of hardness.

The presence of pores and voids in the composite structure significantly affect some of the mechanical properties and even the performance of the composites. Higher void contents usually mean lower fatigue resistance, greater susceptibility to water penetration

and weathering. However, presence of void is unavoidable in composite making particularly through hand-lay-up route. In the present investigation, it was noticed that the composites with particulate fillers have higher void fraction compared to the unfilled jute epoxy composites.

The possible wear mechanism during solid particle erosion of jute-epoxy composites, as evident from test results and scanning electron microscopy, can be characterized as follows.

- First, there is local removal of resin material from the impacted surface which results in exposure of the fibers to the erosive environment.
- Sand particles impact on the fibers and cause fibers to break because of the formation of cracks perpendicular to their length. These cracks are presumably caused by fibers-bending stresses due to the impact of erodent particles on the unsupported fibers.
- Further damage results when the interfaces between the broken fibers and the matrix resin are degraded until the fibers are removed by subsequent impacts.

The erosion wear rates of particulate filled jute-epoxy composites are found to be lower than those of the unfilled jute-epoxy composites under similar test conditions. This has led to the conclusion that the presence of silicon carbide particulates improves the erosion wear resistance of fiber reinforced epoxy. The reduction in material loss in these particulate 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 jute fiber phase. These two factors together lead to the enhancement of erosion wear resistance of the composites. This study thus, shows that the filler content in the composite is significant in combating erosive wear.

The erosion wear rates of the composites were found to be dependent on the impingement angle. The findings of this research further suggest that, this dependency is also influenced by the weight percentage of the filler material. In fact, the angle of impact determines the relative magnitude of the two components of the impact velocity

namely, the component normal to the surface and parallel to the surface. The normal component will determine how long the impact will last (i.e. contact time) and the load. The product of this contact time and the tangential (parallel) velocity component determines the amount of sliding that takes place. The tangential velocity component also provides a shear loading to the surface, which is in addition to the normal load that the normal velocity component causes. Hence as this angle changes the amount of sliding that takes place also changes the nature and magnitude of the stress system. Both of these aspects influence the way a composite wears out.

Conclusions

This analytical and experimental investigation on jute-epoxy composites (with and without SiC fillers) has led to the following specific conclusions:

1. Successful fabrication of multi-component hybrid jute-epoxy composites with reinforcement of SiC derived from rice husk by plasma processing route is possible.

2. Incorporation of these fillers modifies the tensile, flexural and inter-laminar shear strengths of the jute epoxy composites. The micro-hardness and density of the composites are also greatly influenced by the content of fillers. Hence, while fabricating a composite of specific requirements, there is a need for the choice of appropriate filler material and for optimizing its content in the composite system.

3. A mathematical model based on conservation of particle kinetic energy during multiple impact erosion process has been developed. To overcome the shortcomings of the existing theoretical models an 'erosion efficiency' term has been introduced. It is demonstrated that if supported by an appropriate magnitude of erosion efficiency, the model can perform well for polymer based hybrid composites for normal as well as oblique impacts.

4. The presence of particulate fillers (silicon carbide) in these composites improves their erosion wear resistance and this improvement depends on the weight content of the filler.

5. Erosion characteristics of these composites have been successfully analyzed using Taguchi experimental design. Significant control factors affecting the erosion rate have been identified through successful implementation of this technique. Impact velocity, fiber/filler content and impingement angle in declining sequence are found to be significant for minimizing the erosion rate of all the composites. Erodent size is identified as the least influencing control factor for erosion rate.

Recommendation for future work

The present work leaves a wide scope for future investigators to explore many other aspects of particulate filled FRP composites. Some recommendations for future research include:

- The response of these composites to other wear modes such as sliding and abrasion.
- Possible use of other ceramic/metallic fillers, polymeric resins other than epoxy and natural fibers other than jute in the development of new hybrid composites.

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Appendices

Papers Communicated to Journals:

1. **Processing and Characterization of Jute-Epoxy Composites Reinforced with SiC Derived from Rice Husk** --- Alok Satapathy, **Alok Kumar Jha**, Sisir Mantry, S.K. Singh --- Communicated to *Journal of Reinforced Plastics and Composites* (Sage Publications) Appendix I

2. **Wear Performance Analysis of Jute-Epoxy-SiC Hybrid Composites** -- **Alok Kumar Jha**, Sisir Mantry, Alok Satapathy and Amar Patnaik --- Communicated to *Journal of Composite Materials* (Sage Publications) Appendix II

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Processing and Characterization of Jute-Epoxy Composites Reinforced with Silicon Carbide Derived from Rice Husk

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Abstract:	ABSTRACT This paper depicts the processing and mechanical characterization of a new class of multi-phase composites consisting of epoxy resin reinforced with jute fiber and filled with silicon carbide (SiC) particulates. The SiC used as filler material in this work has been prepared from rice husk through plasma processing technique. The effect of filler in modifying the physical and mechanical properties of jute-epoxy composites has been studied. It is found that the incorporation of rice husk derived SiC modifies the tensile, flexural and inter-laminar shear strengths of the jute-epoxy composites. The micro-hardness and density of the composites are also greatly influenced by the content of these fillers. Rice husk is considered as an agricultural waste and it is thus interesting to explore the utilization potential of SiC derived from rice husk in composite making. Moreover, being cheap, inexhaustible and easily available, it would hopefully provide a cost effective solution to composite manufacturers.

Processing and Characterization of Jute-Epoxy Composites Reinforced with SiC Derived from Rice Husk

Alok Satapathy, Alok Kumar Jha, Sisir Mantry, S.K. Singh

ABSTRACT

This paper depicts the processing and mechanical characterization of a new class of multi-phase composites consisting of epoxy resin reinforced with jute fiber and filled with silicon carbide (SiC) particulates. The SiC used as filler material in this work has been prepared from rice husk through plasma processing technique. The effect of filler in modifying the physical and mechanical properties of jute-epoxy composites has been studied. It is found that the incorporation of rice husk derived SiC modifies the tensile, flexural and inter-laminar shear strengths of the jute-epoxy composites. The micro-hardness and density of the composites are also greatly influenced by the content of these fillers. Rice husk is considered as an agricultural waste and it is thus interesting to explore the utilization potential of SiC derived from rice husk in composite making. Moreover, being cheap, inexhaustible and easily available, it would hopefully provide a cost effective solution to composite manufacturers.

KEYWORDS: Silicon carbide; Rice husk; Jute-Epoxy; Mechanical characterization;

INTRODUCTION

Fiber reinforced polymer composites are now considered as an important class of engineering materials. They offer outstanding mechanical properties, unique flexibility in design capability and ease of fabrication. Additional advantages include light weight, corrosion and impact resistance and excellent fatigue strength. Today, fiber composites are routinely used in such diverse applications as automobiles, aircraft, space vehicles, off-shore structures, containers and piping, sporting goods, electronics and appliances. A fiber reinforced composite is not simply a mass of fibers dispersed within a polymer. It consists of fibers embedded in or bonded to a polymer matrix with distinct interfaces between the two constituent phases. The fibers are usually of high strength and modulus and serve as the principal load carrying members. The matrix acts as the load transfer medium between fibers and in less ideal cases where loads are complex, the matrix may even have to partly bear loads. The matrix also serves to protect the fibers from environmental damage before, during and after composite processing. In a composite, both fibers and matrix largely retain their identities and yet result in many properties that cannot be achieved with either of the constituents acting alone. A wide variety of fibers are available for use in composites. The most commonly used fibers are various types of carbon, glass and aramid fibers. Besides, natural fibers such as: jute, sisal and ceramic fibers like alumina, silicon carbide, mullite and silicon nitride are also used in composite making. The unique combinations of properties available in these fibers provide the outstanding functional and structural characteristics such as: high specific strength and specific stiffness to the fiber reinforced composites.

A key feature of fiber composites that makes them so promising as engineering materials is the opportunity to tailor the materials properties through the control of fiber and matrix combinations and the selection of processing techniques. In principle, an infinite range of

composite types exists, from randomly oriented chopped fiber based materials at the low property end to continuous, unidirectional fiber composites at the high performance end. 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 [1]. The physical and mechanical characteristics can further be modified by adding a solid filler phase to the matrix body during the composite preparation. It has been observed that by incorporating filler particles into fiber reinforced composites, synergistic effects may be achieved in the form of higher modulus and reduced material cost, yet accompanied with decreased strength and impact toughness [2, 3]. Garcia at al. [4, 5] suggested this kind of multi-phase composite technique for improving the matrix dominated properties of continuous fiber reinforced composites. In this technique a supplementary reinforcement such as particulates, whiskers, or micro fibers is added to the matrix prior to resin impregnation. Jang et al. [6,7] found a significant improvement in impact energy of hybrid composites incorporating either particulates or ceramic whiskers. Hard particulate fillers consisting of ceramic or metal particles and fiber fillers made of glass are being used these days to dramatically improve the wear resistance of composites, even up to three orders of magnitude [8].

The improved performance of polymers and their composites in industrial and structural applications by the addition of filler materials has shown a great promise and so has lately been a subject of considerable interest. Various kinds of polymers and polymer matrix composites reinforced with metal particles have a wide range of industrial applications such as heaters, electrodes [9], composites with thermal durability at high temperature [10] etc. These engineering composites are desired due to their low density, high corrosion resistance, ease of fabrication, and low cost [11, 12, 13]. Similarly,

ceramic filled polymer composites have been the subject of extensive research in last two decades. The inclusion of inorganic fillers into polymers for commercial applications is primarily aimed at the cost reduction and stiffness improvement [14,15]. Along with fiber-reinforced composites, the composites made with particulate fillers have been found to perform well in many real operational conditions.

However, such multi-component hybrid composites form complex systems and there is inadequate data available about phenomena behind the properties changes due to the addition of particulate fillers to the fiber reinforced thermoplastic components. Hence the objective of this paper is to know how the incorporation of silicon carbide (derived from rice husk) particulates affects the mechanical properties of jute fiber reinforced epoxy composites. Silicon carbide (SiC) is a ceramic material that has the potential to be used as filler in various polymer matrices. It is an excellent abrasive used in grinding wheels and other abrasive products for over one hundred years. Today the material has been developed into a high quality technical grade ceramic with very good mechanical properties. It is used in abrasives, refractories, ceramics, and numerous high-performance applications. The high thermal conductivity coupled with low thermal expansion and high strength gives this material exceptional thermal shock resistant qualities. Moreover, silicon carbide has low density, low thermal expansion, high elastic modulus, high strength, high hardness, and superior chemical inertness. Although the effect of SiC (produced from mineral sources) as a filler material has been investigated earlier [16] in glass-polyester composites, there is no report available on the potential of SiC particles derived from a bio-resource like rice husk in jute fiber reinforced polymer composites. In this investigation, SiC produced from rice husk by plasma processing route has been used. The details of formation of SiC from rice husk by this route are described elsewhere [17].

EXPERIMENTAL DETAILS

Matrix Material

Epoxy LY 556 is the resin which is used as the matrix material. Its common name is Bisphenol-A-Diglycidyl-Ether and it chemically belongs to the 'epoxide' family. The epoxy resin and the hardener are supplied by Ciba Geigy India Ltd.

Fiber Material

Jute is a long, soft, shiny vegetable fiber that can be spun into coarse, strong threads. It is produced from plants in the genus *Corchorus*, family Tiliaceae. Jute is one of the cheapest natural fibres and is second only to cotton in amount produced and variety of uses. Jute fibres are composed primarily of the plant materials cellulose (major component of plant fibre) and lignin (major components wood fibre). It is thus a ligno-cellulosic fibre that is partially a textile fibre and partially wood. It falls into the bast fibre category (fibre collected from bast or skin of the plant) along with kenaf, industrial hemp, flax (linen), ramie, etc. Cross plied woven mats of this jute-fiber have been used as the reinforcing phase in the composites used in this work.

Composite fabrication

Cross plied jute fibers are reinforced in epoxy resin in three different weight proportions (20 wt%, 30 wt% and 40 wt%) to prepare the composites A_1, B_1 and C_1 respectively. Jute fibers and epoxy resin have modulus of about 55 GPa and 3.42 GPa respectively and possess density of 1300 kg/m^3 and 1100 kg/m^3 respectively. No particulate filler is used in these composites.

The other composite samples C_2 and C_3 with silicon carbide fillers of fixed weight percentage are fabricated by the same technique. The low temperature curing epoxy resin and corresponding hardener (HY951) are mixed in a ratio of 10:1 by weight as

recommended. The mix is stirred manually to disperse the particulate fillers in the matrix. The mixing is done thoroughly before the jute-fiber mats (40 wt%) are reinforced in the matrix body. Composites C_2 and C_3 contain SiC particles in 10 wt% and 20 wt% proportions respectively. Each ply of jute-fiber is of dimension 200 mm× 200 mm. The composite slabs are made by conventional hand-lay-up technique followed by light compression moulding technique. A stainless steel mould having dimensions of 210 × 210 × 40 mm^3 is used. A releasing agent (Silicon spray) is used to facilitate easy removal of the composite from the mould after curing. Care is taken to ensure a uniform sample since particles have a tendency to clump and tangle together when mixed. The cast of each composite is cured under a load of about 25kg for 24 h before it removed from the mould. Then this cast is post cured in the air for another 24 h after removing out of the mould. Specimens of suitable dimension are cut using a diamond cutter for physical characterization and mechanical testing. Utmost care has been taken to maintain uniformity and homogeneity of the composite. The designation and detailed composition of the composites are given in Table 1.

MECHANICAL CHARACTERIZATION

Density and Void Fraction

The theoretical density of composite materials in terms of weight fraction can easily be obtained as for the following equations given by Agarwal and Broutman [18].

$$\rho_{ct} = \frac{1}{\left(W_f / \rho_f\right) + \left(W_m / \rho_m\right)} \quad (1)$$

Where, W and ρ represent the weight fraction and density respectively. The suffix *f, m* and *ct* stand for the fiber, matrix and the composite materials respectively.

The composites under this investigation consists of three components namely matrix, fiber and particulate filler. Hence the modified form of the expression for the density of the composite can be written as

$$\rho_{ct} = \frac{1}{\left(W_f / \rho_f\right) + \left(W_m / \rho_m\right) + \left(W_p / \rho_p\right)} \quad (2)$$

Where, the suffix '*p*' indicates the particulate filler materials.

The actual density (ρ_{ce}) of the composite, however, can be determined experimentally by simple water immersion technique. The volume fraction of voids (V_v) in the composites is calculated using the following equation:

$$V_v = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}} \quad (3)$$

The theoretical and measured densities of the composites along with the corresponding volume fraction of voids are presented in Table 2. It may be noted that the composite density values calculated theoretically from weight fractions using Eq.(2) are not equal to the experimentally measured values. This difference is a measure of voids and pores present in the composites. It is clearly seen that with the increase in fiber content from 20 wt% to 40 wt%, there is an increase in the void fraction. However, in all the three composites A_1, B_1 and C_1, the volume fractions of voids are reasonably small (< 1.5%) and this can be attributed to the absence of particulate fillers in these composites. With the addition of silicon carbide as the filler material, more voids are found in the composites. As the filler content increases from 0 wt% to 10 wt% and subsequently from 10 wt% to 20 wt% the volume fraction of voids is found to be increasing. This trend is observed in both the particulate filled composites (C_2 and C_3).

Density of a composite depends on the relative proportion of matrix and reinforcing materials and this is one of the most important factors determining the properties of the

composites. The void content is the cause for the difference between the values of true density and the theoretically calculated one. The voids significantly affect some of the mechanical properties and even the performance of composites in the workplace. Higher void contents usually mean lower fatigue resistance, greater susceptibility to water penetration and weathering [18]. The knowledge of void content is desirable for estimation of the quality of the composites. It is understandable that a good composite should have fewer voids. However, presence of void is unavoidable in composite making particularly through hand-lay-up route.

Micro-hardness

Micro-hardness measurement is done using a Leitz micro-hardness tester. A diamond indenter, in the form of a right pyramid with a square base and an angle 136^0 between opposite faces, is forced into the material under a load of 24.54N. The variation of composite micro-hardness with the weight fraction of jute fiber and SiC particulates is shown in Figure (1). For the composite A_1 (20 wt% of JF), the micro-hardness value is recorded as 57 Hv while for C_1 (40 wt% of GF) this value is 63 Hv. It is thus seen that with the increase in fiber content in the composite, the hardness improves although the increment is marginal. Similarly, with the incorporation of filler particulates into the composites, the mean hardness is seen to have improved.

Tensile, Flexural and Inter-laminar shear strength

The tensile test is generally performed on flat specimens. The commonly used specimens for tensile test are the dog-bone type and the straight side type with end tabs. During the test a uniaxial load is applied through both the ends of the specimen. The ASTM standard test method for tensile properties of fiber resin composites has the designation D 3039-76. The length of the test section should be 200 mm. The tensile test is

performed in the universal testing machine (UTM) Instron 1195 and results are analyzed to calculate the tensile strength of composite samples.

The short beam shear (SBS) tests are performed on the composite samples at room temperature to evaluate the value of inter-laminar shear strength (ILSS). It is a 3-point bend test, which generally promotes failure by inter-laminar shear. The SBS test is conducted as per ASTM standard (D2344-84) using the same UTM. Span length of 40 mm and the cross head speed of 10 mm/min are maintained. The ILSS values are calculated as follows,

$$ILSS = \frac{3P}{4b.t} \tag{4}$$

Where, P is maximum load,

b the width of specimen, and

t the thickness of specimen

The data recorded during the 3-point bend test is used to evaluate the flexural strength also. The flexural strength (F.S.) of any composite specimen is determined using the following equation.

$$F.S = \frac{3PL}{2bt^2} \tag{5}$$

Where, L is the span length of the sample.

It is well known that the strength properties of composites are mainly determined by the fiber content and the fiber strength. So variation in composite strength with different fiber loading is obvious. These variations in tensile and flexural strengths of the composites A_1, B_1 and C_1 are presented in Table 2 and are shown in Figure (2). A gradual increase in both tensile strength as well as flexural strength with the fiber weight fraction is noticed. It clearly indicates that inclusion of jute fiber improves the load

bearing capacity and the ability to withstand bending of the composites. Similar observations have been reported by Harsha et al. [19] for fiber reinforced thermoplastics such as poly-aryl-ether-ketone composites. It may be mentioned here that both tensile and flexural strengths are important for recommending any composite as a candidate for structural applications.

The test results for tensile and flexural strengths for the particulate filled composites C_1, C_2 and C_3 are shown in Figure (3). It is seen that the tensile strength of the composite decreases with increase in the filler content. The unfilled jute eopxy composite has a strength of 349.6 MPa in tension and it may be seen from Table 4.2 that this value drops to 304.5 MPa and 279.4 MPa with addition of 10 wt% and 20 wt% of silicon carbide respectively. Similar trend is observed in case of flexural strength of these composites.

By incorporating these particulate fillers into the jute-fiber reinforced epoxy, synergistic effects, as expected were achieved in the form of modified mechanical properties and improved erosion wear resistance. Inclusion of jute fiber in neat epoxy improved the load bearing capacity (tensile strength) and the ability to withstand bending (flexural strength) of the composites. But with the incorporation of silicon carbide fillers, the tensile strengths of the composites were found to be less. There can be two reasons for this decline in tensile strength of these particulate filled composites compared to the unfilled one. One possibility is that the chemical reaction at the interface between the filler particles and the matrix may be too weak to transfer the tensile stress; the other is that the corner points of the irregular shaped particulates result in stress concentration in the epoxy matrix.

Hardness values have been found to have improved for the particulate filled composites. The reduction in tensile strength and the improvement in hardness with the incorporation

of fillers can be explained as follows: under the action of a tensile force the filler-matrix interface is vulnerable to debonding depending on interfacial bond strength and this may lead to a break in the composite. But in case of hardness test, a compression or pressing stress is in action. So the polymeric matrix phase and the solid filler phase would be pressed together and touch each other more tightly. Thus, the interface can transfer pressure more effectively although the interfacial bond may be poor. This might have resulted in an enhancement of hardness.

The stresses acting on the interface of the two adjacent laminae in a layered composite are called inter-laminar stresses. These stresses cause relative deformations between the consecutive laminae and if these are sufficiently high they may cause failure along the mid-plane between two adjacent laminae. It is therefore of considerable interest to evaluate inter-laminar shear strength through tests in which failure of the laminates of the composite initiates in a shear (delamination) mode. In the present work the ILSS values are measured for unfilled jute-epoxy composites A_1, B_1 and C_1 and no improvement is recorded in the ILSS of the composites with increase in the fiber content in them.

The inter-laminar shear strength values of the particulate filled composites are shown along with that of the unfilled jute epoxy composite (C_1) in the same Figure (4). It is seen that there is improvement of ILSS of jute-epoxy composites with particulate filling. Incorporation of silicon carbide is seen to have caused the substantial increase in the inter-laminar shear strength. In the present investigation, during flexural test, the span length is very short (40 mm). A large span to depth ratio in bending test increases the maximum normal stress without affecting the inter-laminar shear stress and thereby increases the tendency for longitudinal failure. If the span is short enough, failure initiates and propagates by inter-laminar shear failure. The maximum shear stress in a

beam occurs at the mid plane. So in the shear test, failure consists of a crack running along the mid plane of the beam so that crack plane is parallel to the longitudinal plane.

Surface morphology of composite samples

The surfaces of the specimens are examined directly by scanning electron microscope JEOL JSM-6480LV. The composite samples are mounted on stubs with silver paste. To enhance the conductivity of the samples, a thin film of platinum is vacuum-evaporated onto them before the photomicrographs are taken. The surface micro-structures of some of the composite samples are observed under scanning electron microscope basically to get an insight to the features. As seen in Figures (5a) and (5b), the surfaces are reasonably homogeneous. No cracks are seen although some voids and pores are visible even at this lower magnification. SiC particles are not seen in clusters within the matrix body.

CONCLUSIONS

Successful fabrication of jute-epoxy composites with reinforcement of SiC derived from rice husk is possible. Incorporation of these fillers modifies the tensile, flexural and inter-laminar shear strengths of the jute epoxy composites. The micro-hardness and density of the composites are also greatly influenced by the content of fillers. Hence, while fabricating a composite of specific requirements, there is a need for the choice of appropriate filler material and for optimizing its content in the composite system.

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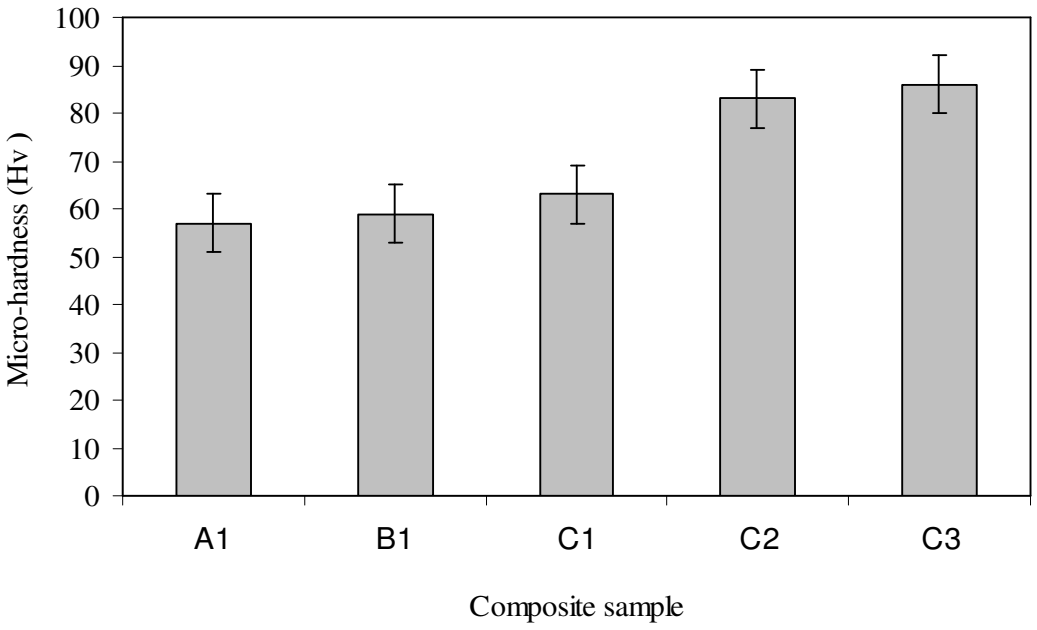


Figure 1 Micro-hardness values of composites with different fiber and filler content

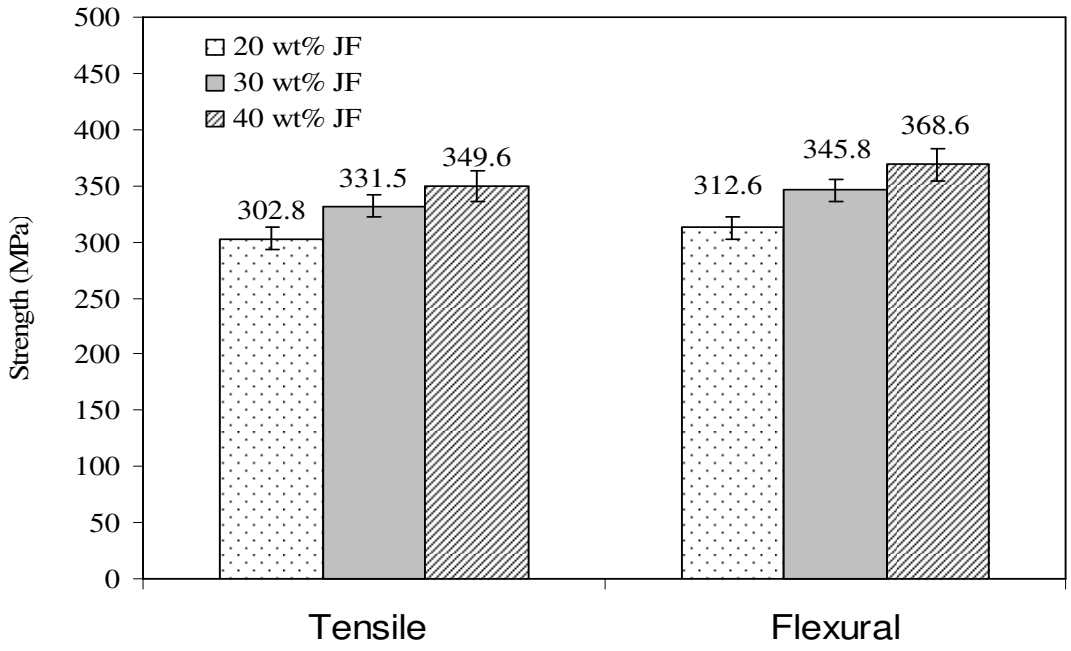


Figure 2 Effect of fiber loading on tensile & flexural strength of JF-epoxy composites

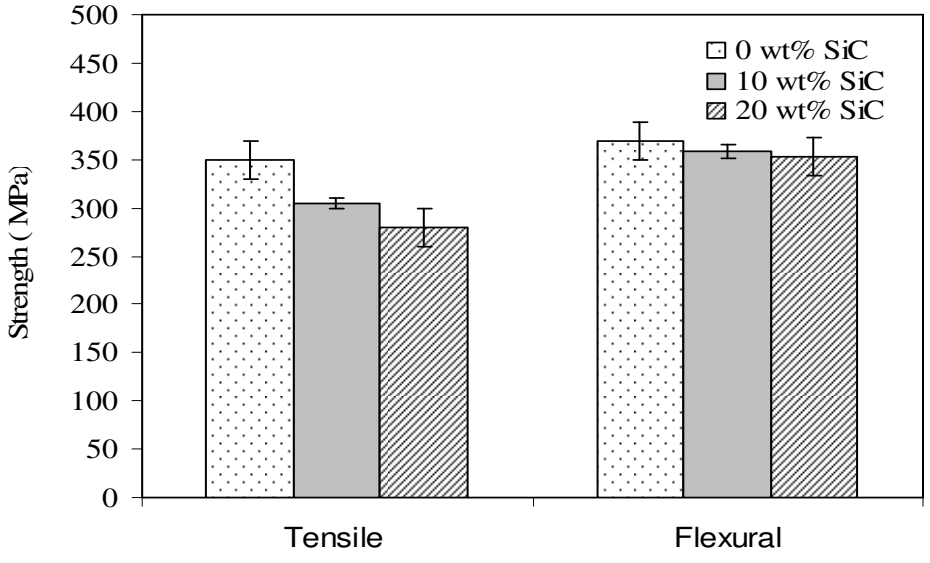


Figure 3 Effect of filler content on tensile & flexural strength of JF-epoxy composites

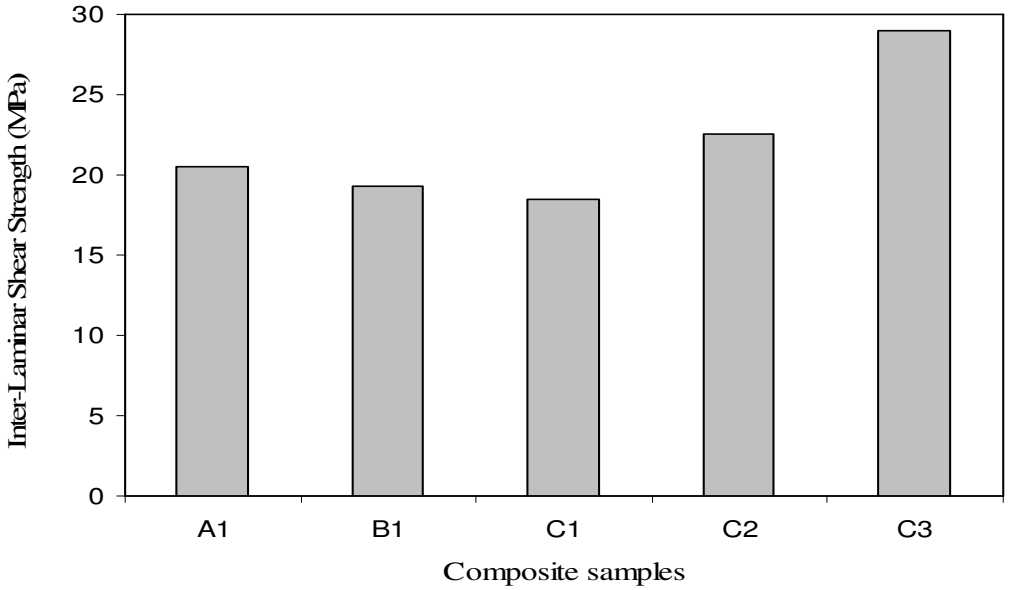
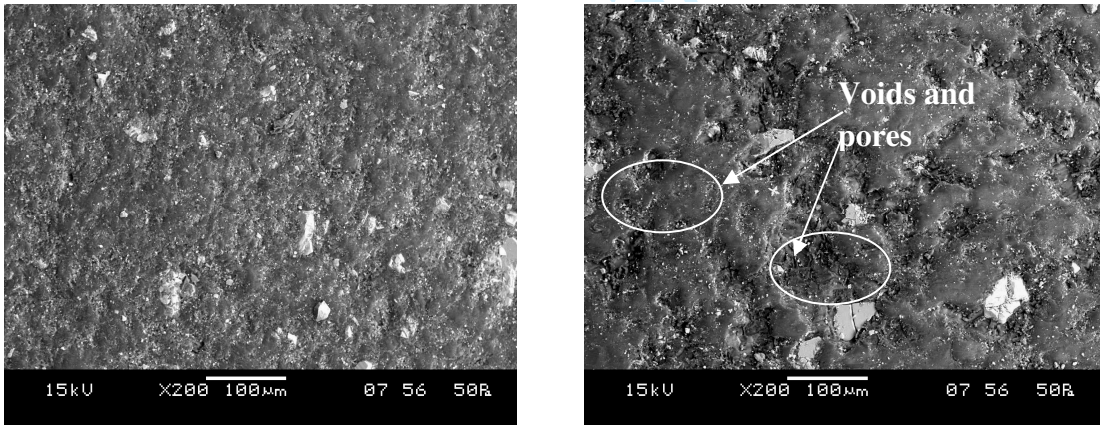


Figure 4 Comparison of Inter-laminar shear strength of different composites



(a) (b)

Figure 5 Surface morphology of composite samples

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Designation	Composition
A_1	Epoxy + 20 wt% jute fiber
B_1	Epoxy + 30 wt% jute fiber
C_1	Epoxy + 40 wt% jute fiber
C_2	Epoxy + 40 wt% jute fiber + 10wt% SiC
C_3	Epoxy + 40 wt% jute fiber + 20wt% SiC

Table 1 Designation and detailed composition of the composites

Composites	Measured density (gm/cc)	Theoretical density (gm/cc)	Volume fraction of voids (%)
A_1	1.127	1.135	0.71
B_1	1.139	1.153	1.35
C_1	1.157	1.172	1.28
C_2	1.199	1.258	4.68
C_3	1.287	1.358	5.22

Table 2 Measured and Theoretical densities of the composites

Composites	Mean Hardness (Hv)	Tensile strength (MPa)	Flexural strength (MPa)	ILSS (MPa)
A_1	57	302.8	312.6	20.52
B_1	59	331.5	345.8	19.32
C_1	63	349.6	368.6	18.42
C_2	83	304.5	357.8	22.57
C_3	86	279.4	353.2	28.99

Table 3 Mechanical properties of the composites

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Wear Performance Analysis of Jute-Epoxy-SiC hybrid composites

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Keywords:	Jute-fiber, Epoxy, SiC filler, Hybrid composites, Theoretical model, Erosion wear
Abstract:	Fiber reinforced polymer composites are now considered as an important class of engineering materials. With the increased use of these materials in erosive work environments, it has become extremely important to investigate their erosion characteristics intensively. In view of this, the present article reports the solid particle erosion response of a new class of multi-component composite system consisting of epoxy resin reinforced with jute-fiber and SiC particles derived from a bio-resource like rice husk. Erosion trials are carried out at various test conditions. For this, an air jet type erosion test rig and Taguchi's orthogonal arrays are used. Significant control factors influencing the erosion wear rate are identified. This paper also presents the development of a theoretical model for estimating erosion damage caused by solid particle impact on the composites. The model is based upon conservation of particle kinetic energy and relates the erosion rate with some of the material properties and test conditions. The theoretical results are compared and are found to be in good agreement with the experimental values.

Wear Performance Analysis of Jute-Epoxy-SiC Hybrid Composites

Alok Kumar Jha, Sisir Mantry, Alok Satapathy and **Amar Patnaik**

ABSTRACT

Fiber reinforced polymer composites are now considered as an important class of engineering materials. With the increased use of these materials in erosive work environments, it has become extremely important to investigate their erosion characteristics intensively. In view of this, the present article reports the solid particle erosion response of a new class of multi-component composite system consisting of epoxy resin reinforced with jute-fiber and SiC particles derived from a bio-resource like rice husk. Erosion trials are carried out at various test conditions. For this, an air jet type erosion test rig and Taguchi's orthogonal arrays are used. Significant control factors influencing the erosion wear rate are identified. This paper also presents the development of a theoretical model for estimating erosion damage caused by solid particle impact on the composites. The model is based upon conservation of particle kinetic energy and relates the erosion rate with some of the material properties and test conditions. The theoretical results are compared and are found to be in good agreement with the experimental values.

Keywords: Jute-fiber; Epoxy; SiC filler; Composites; Erosion wear; Theoretical model;

INTRODUCTION

Fiber-reinforced polymer (FRP) composites have many applications in automobile, marine and aerospace industries. They offer outstanding mechanical properties, unique flexibility in design capability and ease of fabrication. Additional advantages include light weight, corrosion and impact resistance and excellent fatigue strength. A fiber reinforced composite is not simply a mass of fibers dispersed within a polymer. It consists of fibers embedded in or bonded to a polymer matrix with distinct interfaces between the two constituent phases. The fibers are usually of high strength and modulus and serve as the principal load carrying members. The matrix acts as the load transfer medium between fibers and in less ideal cases where loads are complex, the matrix may even have to partly bear loads. The matrix also serves to protect the fibers from environmental damage before, during and after composite processing. In a composite, both fibers and matrix largely retain their identities and yet result in many properties that cannot be achieved with either of the constituents acting alone. A wide variety of fibers are available for use in composites. The most commonly used fibers are various types of carbon, glass and aramid fibers. Besides, natural fibers such as: jute, sisal and ceramic fibers like alumina, silicon carbide, mullite and silicon nitride are also used in composite making. The unique combinations of properties available in these fibers provide the outstanding functional and structural characteristics such as: high specific strength and specific stiffness to the fiber reinforced composites.

Fiber reinforced polymer composites are now considered as an important class of engineering materials. Due to operational requirements in dusty environments, the erosion characteristics of these composites are of vital importance. Since erosive wear of engineering components caused by abrasive particles is a major industrial problem, 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 components, and to choose the materials to reduce/control this wear mode. In recent years much research has been devoted to exploring the potential advantages of thermoplastic polymers for composite materials. Some of the commonly used thermoplastics are polyetheretherketone (PEEK), polyetherketone (PEK), polyetherketoneketone (PEKK), polyester, polypropylene (PP), etc. Several investigations on friction and wear properties of PEEK and its composites filled with fibers, organic and inorganic fillers have been carried out [1,2]. Cirino et al. [1, 3] reported the sliding as well as the abrasive wear behavior of continuous carbon and aramid fiber-reinforced PEEK. Lhymn et al. [4] have studied the abrasive wear of short carbon fiber-reinforced PEEK. Voss and Friedrich [5] investigated the sliding and abrasive wear behavior of short fiber-reinforced PEEK composites at room temperature. Briscoe et al. [6] described the friction and wear of PEEK-PTFE blends over a wide composition range under several testing conditions. Bahadur and Gong [7] investigated the action of various copper compounds as fillers on the tribological behavior of PEEK. Wang et al. [2, 8, 9] investigated friction and wear properties of nanometric ZrO_2 and SiC-filled PEEK composites with different filler proportions. However, most of the above studies are confined to dry sliding wear of various polymers and their composites. The erosive wear behavior of polymer composites reinforced with any fiber and/or particulate has not adequately been reported in the literature.

Hard particulate fillers consisting of ceramic or metal particles and fiber fillers made of glass are being used these days to dramatically improve the wear resistance of composites, even up to three orders of magnitude [10]. The improved performance of polymers and their composites in tribological applications by the addition of filler materials has shown great promise and so has lately been a subject of considerable interest. Various kinds of polymers and polymer matrix composites reinforced with metal particles have a wide

range of industrial applications, such as heaters, electrodes [11], composites with thermal durability at high temperature [12], etc. These engineering composites are desired due to their low density, high corrosion resistance, ease of fabrication, and low cost [13–15]. Similarly, ceramic-filled polymer composites have been the subject of extensive research in the last two decades. The inclusion of inorganic fillers into polymers for commercial applications is primarily aimed at cost reduction and stiffness improvement. Along with fiber-reinforced composites, the composites made with particulate fillers have been found to perform well in tribological conditions.

Silicon carbide (SiC) is one such ceramic material that has the potential to be used as filler in various polymer matrices. It is an excellent abrasive and has been produced and made into grinding wheels and other abrasive products for over 100 years. It is the only chemical compound of carbon and silicon. It was originally produced by a high temperature electro-chemical reaction of sand and carbon. Today the material has been developed into a high quality technical grade ceramic with very good mechanical properties. It is used in abrasives, refractories, ceramics, and numerous high performance applications. The material can also be made an electrical conductor and has applications in resistance heating, flame igniters, and electronic components. Structural and wear applications are constantly developing. Silicon carbide is composed of tetrahedral of carbon and silicon atoms with strong bonds in the crystal lattice. This produces a very hard and strong material. It is not attacked by any acids, alkalis, or molten salts up to 800^0C. The high thermal conductivity coupled with low thermal expansion and high strength gives this material exceptional thermal shock resistant qualities. Silicon carbide has low density of about 3.1 g/cm^3, low thermal expansion, high elastic modulus, high strength, high thermal conductivity, high hardness, excellent thermal shock resistance, and superior chemical inertness. Although the effects of SiC (produced from mineral sources) as a filler

material on the wear behavior have been investigated earlier [16] for glass-polyester composites, there is no report available on the potential of SiC particles derived from a bio-resource like rice husk in jute fiber reinforced composite system. In this investigation, SiC produced from rice husk by plasma processing route has been used. The details of formation of SiC from rice husk by this route are described elsewhere [17].

Erosion rate (E) depends on velocity by a power law, given as $E = kV^n$, where k is a material constant. However, the exponent n is found to be material independent and is governed by test condition including particle characteristics and the erosion test apparatus [18]. In addition to velocity, solid particle erosion is also governed by impact angle, particle size, particle shape and hardness [19]. The impact of the above parameters has been studied independently, keeping all parameters at fixed levels. Therefore, visualization of impact of various factors in an interacting environment really becomes difficult. To this end, an attempt has been made to analyze the impact of more than one parameter on solid particle erosion because, in actual practice, the resultant erosion rate is the combined effect of impact of more than one interacting variable. An inexpensive and easy-to-operate experimental strategy based on Taguchi's parameter design has been adopted to study the effect of various parameters and their interactions. This experimental procedure has already been successfully implemented for parametric appraisal in erosion of polyester based composites [20-25]. The Taguchi method helps to ease the process of analyzing the experimental results and get insight into the physical phenomenon of experimentation.

MATHEMATICAL MODEL

Nomenclature

The following symbols are used in this paper:

a	erodent height and base length (m)
δ	indentation depth (m)
e_v	volumetric wear loss per particle impact (m^3)
E_V	total volumetric erosion wear rate (m^3/sec)
α	angle of impingement (degree)
U	impact velocity (m/sec)
P	force on the indenter (N)
H	hardness (N/m^2)
m	mass of single erodent particle (kg)
M	mass flow rate of the erodent (kg/sec)
N	number of impact per unit time (sec^{-1})
ρ_C	density of composite (kg/m^3)
ρ	density of erodent (kg/m^3)
η_{nor}	erosion efficiency with normal impact
η	erosion efficiency
E_{rth}	erosion wear rate (kg/kg)

Solid particle erosion is a wear process in which the material is removed from a surface by the action of a high velocity stream of erodent particles entrained in a high velocity fluid stream. The particles strike against the surface and promote material loss. During flight, a particle carries momentum and kinetic energy which can be dissipated during the impact due to its interaction with a target surface. As far as erosion study of polymer matrix composites is concerned, no specific model has been developed and thus the study of their erosion behaviour has been mostly experimental. However, Mishra [26] proposed a mathematical model for material removal rate in abrasive jet machining process in which the material is removed from the work piece in a similar fashion. This model assumes that the volume of material removed is same as the volume of indentation caused by the impact. This has a serious limitation as in a real erosion process the volume of material removed is actually different from the indentation volume. Further, this model considers only the normal impact i.e. $\alpha = 90^0$ whereas in actual practice, particles may impinge on the surface at any angle ($0^0 \le \alpha \le 90^0$). The proposed model addresses these shortcomings in an effective manner. It considers the real situation in which the volume of material removed by erosion is not same as the volume of material displaced and therefore, an additional term "erosion efficiency (η)" is incorporated in the erosion rate formulation. In the case of a stream of particles impacting a surface normally (i.e. at $\alpha=90^0$), erosion efficiency (η_{normal}) defined by Sundararajan et. al [27] is given as

$$\eta_{normal} = \frac{2ErHv}{\rho U^2} \quad (1)$$

But considering impact of erodent at any angle α to the surface, the actual erosion efficiency can be obtained by modifying Eq. (1) as

$$\eta = \frac{2ErHv}{\rho U^2 Sin^2 \alpha} \quad (2)$$

Besides, while all previous models have been developed assuming the shape of erodent to be spherical, in the real situation, the erodent particles are actually bodies having sharp edges, as shown in the Figure (1). Therefore, considering them to be cubical shaped bodies is a more realistic assumption as compared to assuming them simply spherical. The model proposed in the present work addresses to all these shortcomings. It assumes the erodent particles to be rigid, cubical shaped bodies having side equal to the average grit size. It is further based on the assumption that the loss in kinetic energy of the impinging particles is utilized to cause micro-indentation in the composite material and the material loss is a measure of the indentation. The erosion is the result of cumulative damage of such non-interacting, single particle impacts. The material removal mechanism is shown schematically in Figure (2). The model is developed with the simplified approach of energy conservation which equals the loss in erodent kinetic energy during impact with the work done in creating the indentation. It proceeds as follows.

At time t after initial contact, the particle of mass m will have indented the surface to a depth x; the cross-sectional area of the indentation at the surface will be A(x), where A(x) normally determined by the shape of the erodent particle. The upward force decelerating the particle will be that due to the plastic flow pressure acting over A(x); and the equation of motion of the particle can therefore be written as:

$$m\frac{d^2x}{dt^2} = -HA(x) \quad (3)$$

For simple particle shapes, this equation can readily be solved analytically. But to know the final volume of indentation when the particle comes to rest at a depth δ at time t= T,

the work done by the retarding force will equal to the sum of the kinetic energy and the loss of thermal energy of the particle.

The conservation of energy can be represented by the equation

$$\int_0^{\delta} HA(x)dx = \frac{1}{2}mU^2 \tag{4}$$

The impact velocity will have two components; one normal to the composite surface and one parallel to it. At zero impact angles, it is assumed that there is negligible wear because eroding particles do not practically impact the target surface [28]. Consequently, there will be no erosion due to the parallel component and the indentation is assumed to be caused entirely by the component normal to the composite surface as shown in Figure (3).

Now applying conservation of energy to the single impact erosion process, kinetic energy associated with the normal velocity component of a single erodent particle is equal to the work done in the indentation of composite. The energy of impact introduces a force P on the indenter to cause the indentation in the composite. Thus, in case of oblique impact, the kinetic energy corresponding to the normal component of velocity is considered and Eq. (4) becomes:

$$\text{So, } \int_0^{\delta} HA(x)dx = \frac{1}{2}mU^2 Sin^2\alpha \tag{5}$$

$$\text{Now, } \int_0^{\delta} A(x)dx = \int_0^{\delta} a^2 dx = a^2\delta$$

So, the volumetric wear loss per particle impact is given by

e_v = Volume of indentation $\times \eta = \eta\ a^2\delta$

Considering N number of particle impacts per unit time, the volumetric erosion wear loss will be

$$Ev = a^2 N \eta \delta$$

Now, $\frac{1}{2}.P.\delta = \frac{1}{2}.m.U^2.Sin^2\alpha$

$$\frac{1}{2}a^2\delta \ .H = \frac{mU^2.Sin^2\alpha}{2}$$

$$e_v = \eta.\left[\frac{m.U^2.Sin^2\alpha}{3H}\right]$$

For multiple impact

$$E_V = \eta.mN\left[\frac{U^2.Sin^2\alpha}{3H}\right]$$

Or, $E_V = \eta.M\left[\frac{U^2.Sin^2\alpha}{H}\right]$

The non-dimensional erosion rate, defined as the composite mass lost per unit time due to erosion divided by the mass of the erodent causing the loss, is now expressed as

$$E_R = \frac{\eta\rho_C}{H}\left[U^2 Sin^2\alpha\right] \quad (6)$$

The mathematical expression in Eq. (6) can possible be used for predictive purpose to make an approximate assessment of the erosion damage from the composite surface.

EXPERIMENTAL DETAILS

Composite fabrication

Cross plied jute fibers are reinforced in epoxy resin in three different weight proportions (20 wt%, 30 wt% and 40 wt %) to prepare the composites A_1, B_1 and C_1 respectively. Jute fibers and epoxy resin have modulus of about 55 GPa and 3.42 GPa respectively and possess density of 1300 kg/m^3 and 1100 kg/m^3 respectively. No particulate filler is used in these composites.

The other composite samples C_2 and C_3 with silicon carbide fillers of fixed weight percentage are fabricated by the same technique. The low temperature curing epoxy resin and corresponding hardener (HY951) are mixed in a ratio of 10:1 by weight as recommended. The mix is stirred manually to disperse the particulate fillers in the matrix. The mixing is done thoroughly before the jute-fiber mats (40 wt %) are reinforced in the matrix body. Composites C_2 and C_3 contain SiC particles in 10 wt% and 20 wt% proportions respectively. Each ply of jute-fiber is of dimension 200 mm× 200 mm. The composite slabs are made by conventional hand-lay-up technique followed by light compression moulding technique. A stainless steel mould having dimensions of 210 × 210 × 40 mm^3 is used. A releasing agent (Silicon spray) is used to facilitate easy removal of the composite from the mould after curing. Care is taken to ensure a uniform sample since particles have a tendency to clump and tangle together when mixed. The cast of each composite is cured under a load of about 25kg for 24 h before it removed from the mould. Then this cast is post cured in the air for another 24 h after removing out of the mould. Specimens of suitable dimension are cut using a diamond cutter for physical characterization and mechanical testing. Utmost care has been taken to maintain

uniformity and homogeneity of the composite. The designation and detailed composition of the composites are given in Table 1.

Erosion Test Apparatus

The set up used in this study for the solid particle erosion wear test is capable of creating reproducible erosive situations for assessing erosion wear resistance of the prepared composite samples. It consists of an air compressor, an air particle mixing chamber and accelerating chamber. The schematic diagram of the erosion test rig is given in Figure (4). Dry compressed air is mixed with the erodent particles which are fed at constant rate from a sand flow control knob through the nozzle tube and then accelerated by passing the mixture through a convergent brass nozzle of 3mm internal diameter. These particles impact the specimen which can be held at different angles with respect to the direction of erodent flow using a swivel and an adjustable sample clip. The velocity of the eroding particles is determined using standard double disc method [25]. The parameters (confirming to ASTM G 76 test standards) which are considered for erosion tests are listed in Table 2. In the present study, dry silica sand of different particle sizes (200µm, 300 µm and 400µm) are used as erodent. The samples are cleaned in acetone, dried and weighed to an accuracy of ± 0.1 mg before and after the erosion trials using a precision electronic balance. The weight loss is recorded for subsequent calculation of erosion rate. The process is repeated till the erosion rate attains a constant value called *steady state erosion rate*. The ratio of this weight loss to the weight of the eroding particles causing the loss is then computed as a dimensionless incremental erosion rate. The erosion rate is defined as the weight loss of the specimen due to erosion divided by the weight of the erodent causing the loss.

Parametric Appraisal and Taguchi Method

Statistical methods are commonly used to improve the quality of a product or process. Such methods enable the user to define and study the effect of every single condition possible in an experiment where numerous factors are involved. Solid particle erosion is such a process in which a number of control factors collectively determine the performance output i.e. the erosion rate. Hence, in the present work a technique called Taguchi method is used to optimize the process parameters leading to minimum erosion of the polymer composites under study. This part of the chapter presents the Taguchi experimental design methodology in detail.

Taguchi Experimental Design

Every single discipline has researchers carrying out experiments to observe and understand a certain process or to discover the interaction and effect of different variables. From a scientific viewpoint, these experiments are either one or a series of tests to either confirm a hypothesis or to understand a process in further detail. Experiments from a manufacturing point of view, however, are concerned with finding the optimum product and process, which is both cost effective and of a high quality. In order to achieve a meaningful end result, several experiments are usually carried out. The investigator needs to know the factors involved, the range these factors are varied between, the levels assigned to each factor as well as a method to calculate and quantify the response of each factor. This *one-factor-at-a-time* approach will provide the most favorable level for each factor but not the optimum combination of all the interacting factors involved. Thus, experimentation in this scenario can be considered as an iterative process. Although it will provide a result, such methods are not time or cost effective. But the design of experiments is a scientific approach to effectively plan and perform experiments, using statistics. In

such designs, the combination of each factor at every level is studied to determine the combination that would yield the best result. The advantage of such design schemes is that it will always determine the effect of factors and possible interactions (between factors) on the performance output.

Taguchi design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors on performance output. The most important stage in the design of experiment lies in the selection of the control factors. Therefore, initially a large number of factors are included so that non-significant variables can be identified at earliest opportunity. Exhaustive literature review on erosion behavior of polymer composites reveal that parameters viz., impact velocity, impingement angle, fiber loading, filler content, erodent size etc largely influence the erosion rate of polymer composites [20-25]. In the present work, the impact of four such parameters are studied using L_9 (3^4) orthogonal design. The operating parameters and the selected levels are given in Table 3. The tests are conducted at room temperature as per experimental designs given in Table 4 (for A_1,B_1,C_1) and Table 5 (for C_1,C_2 ,C_3) which gives the operating conditions under which each erosion test has been carried out.

Four parameters viz., impact velocity, impingement angle, erodent size, and fiber/filler loading, each at three levels, are considered in this study. In Tables 4 and 5, each column represents a test parameter and a row gives a test condition which is nothing but combination of parameter levels. Four parameters each at three levels would require 3^4 = 81 runs in a full factorial experiment. Whereas, Taguchi's factorial experiment approach reduces it to 9 runs only offering a great advantage in terms of cost and time.

The plan of the experiments is as follows: the first column is assigned to impact velocity (A), the second column to impingement angle (B), third column to erodent size (C), and the last column to fiber/filler loading (D).

The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum erosion rate coming under *smaller-is-better* characteristic, which can be calculated as logarithmic transformation of the loss function as shown below.

Smaller is the better characteristic: $\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right)$ (7)

where n the number of observations, and y the observed data. "Lower is better" (LB) characteristic, with the above S/N ratio transformation, is suitable for minimizations of erosion rate.

RESULTS AND DISCUSSION

Steady state erosion

Erosion wear behavior of materials can be grouped as ductile and brittle categories although this grouping is not definitive. Thermoplastic matrix composites usually show ductile behavior and have the peak erosion rate at around 30^0 impingement angle because cutting mechanism is dominant in erosion. While the thermosetting ones erode in a brittle manner with the peak erosion occurring at normal impact. However, there is a dispute about this failure classification as the erosive wear behavior depends strongly on the experimental conditions and the composition of the target material. In the present work, erosion curves are plotted in from the results of erosion tests conducted for different impingement angle keeping all other parameters constant (impact velocity = 32m/sec,

stand-off distance = 100 mm and erodent size =200 μm). Figure (5) shows the dependence of the erosion rate of unfilled jute-epoxy composites with different fiber content on the impingement angle. It can be seen that the peaks of erosion rates are located at an angle of 60^0 for all the samples irrespective of fiber content. This shows semi-ductile erosion behavior of the composite. It is further noted that with increased fiber content the erosion rate of the composites is greater.

Erosion behaviour of the composites is generally ascertained by correlating erosion rate with impingement angle, erodent velocity and composition of the material. Composites usually respond to solid particle erosion in two broad ways: ductile and brittle. The ductile response is characterized by maximum erosion rate occurring at 15-30^0 impingement angle and brittle behaviour is characterized by the peak erosion rate at 90^0. Similarly, semi-ductile behaviour is characterized by the maximum erosion rate taking place at 45–60^0. But as already mentioned, this grouping is not definitive because the erosion characteristics equally depend on the experimental conditions as on composition of the target material.

The erosion wear rates of SiC filled jute-epoxy composites as a function of impingement angle (α) are shown in Figure (6). It can be seen that filling of composite with SiC particles reduces the wear rate of the jute-epoxy composites quite significantly. The unfilled composite, shows maximum erosion occurring at $\alpha = 60^0$ while for both the filled composites (with 10wt% and 20wt% SiC content) the value of α where the peak erosion occurs is found to be 75^0. In the present study, the location of peak erosion has shifted to 60^0 from the usual 15^0-30^0 (for purely ductile case) as it is reinforced with jute fiber (curve A). This shift in the erosion behavior is an indication of loss of ductility and is obviously attributed to the presence of fibers. Further shifting of α from 60^0 to 75^0 (curve B and C)

proves that the composites tend to become still more brittle with incorporation of SiC particles. The trend is similar for both the composites with SiC filler. It is also important to note that the sample with higher filler content exhibits better erosion resistance.

Surface morphology

The surface micro-structures of some of the un-eroded composite samples are observed under scanning electron microscope basically to get an insight to the features. As seen in Figures (7a) and (7b), the surfaces are reasonably homogeneous. No cracks are seen although some voids and pores are visible even at lower magnification. SiC particles are not seen in clusters within the matrix body.

To identify the mode of material removal, the morphologies of eroded surfaces are studied under scanning electron microscope. Figure (7c) presents the microstructure of the composite eroded at high impact velocity (58m/sec) and at an impingement angle of 60^0. It shows local removal of resin material from the impacted surface resulting in exposure of the fibers to the erodent flux. This micrograph also reveals that due to sand particle impact on fibers there is formation of transverse cracks that break these fibers. The propagation of crack along transverse as well as longitudinal direction is well visualized.

A possible reason for the semi-ductile erosion behavior exhibited by the epoxy based composites in the present investigation is that the erosion of jute fibers 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. According to Hutchings et al. [29], kinetic energy loss is a maximum at normal impact, where erosion rates are highest for brittle materials. In the present study, however, the peak erosion rate shifts to an impingement angle of 60^0 and it is clearly due to the incorporation of jute fibers. So

although neat epoxy exhibits a ductile erosion response, the presence of fibers makes the composite relatively more sensitive to impact energy which increases when the impact mode pattern changes from tangential ($\alpha = 0^0$) to normal ($\alpha = 90^0$). This explains the semi-ductile nature of the jute-epoxy composites with respect to solid particle erosion.

Figure (7d) presents the microstructure of the SiC filled composite eroded with high impact velocity (58m/sec) at an impingement angle of 60^0. It shows local removal of resin material from the impacted surface resulting in exposure of the fibers to the erodent flux. This micrograph also reveals that due to sand particle impact on jute-fibers, there is formation of transverse cracks that break these fibers. The propagation of crack along transverse as well as longitudinal direction is well visualized. 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. Figure (7d) also shows the dominance of micro-chipping and micro-cracking phenomena. It can be seen that multiple cracks originate from the point of impact, intersect one another and form wear debris due to brittle fracture in the fiber body as well as in the silicon carbide particles present in the matrix body. After repetitive impacts, the debris in platelet form is removed and account for the measured wear loss.

Taguchi Analysis of the Erosion Test Results

The erosion wear rates of unfilled jute fiber reinforced epoxy matrix composites under various test conditions are given in Table 6. The theoretical erosion wear rates (E_{rth}) of all the three unfilled composites are calculated using Eq. (7).These values are compared with those obtained from experiments (E_r) conducted under similar operating conditions and the comparison curve has been given in Figure (8). Table 6 also presents the values of theoretical and experimental results for the composites eroded under different test

conditions. The errors associated with each comparison are found to lie in the range 0-12 %. Similarly, the erosion wear rates of jute fiber reinforced epoxy matrix composites filled with different proportions of silicon carbide under various test conditions are given in Table 9. These values are compared with those obtained from experiments (E_r) conducted under similar operating conditions and the comparison curve has been given in Figure (9). The errors associated with each comparison, in this case also lie in the range 0-12 %.

The experimental observations are transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The S/N ratio for minimum erosion rate coming under *smaller-is-better* characteristic, which can be calculated as logarithmic transformation of the loss function as shown below.

Smaller is the better characteristic: $\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum y^2\right)$ (8)

where n the number of observations, and y the observed data. “Lower is better” (LB) characteristic, with the above S/N ratio transformation, is suitable for minimization of erosion rate.

In Tables 7 and 10, the last columns represents S/N ratio of the erosion rate which is in fact the average of three replications. The overall mean for the S/N ratio of the erosion rate is found to be -45.674 db in case of unfilled composites (Table 7) and- 44.506 db in case of silicon carbide composites (Table 10). The analysis is made using the popular software specifically used for design of experiment applications known as MINITAB 14.

The effects of individual control factors influencing the erosion wear rates of unfilled jute-epoxy composites are shown in Figure (10). The S/N ratio response is given in Table 8, from which it can be concluded that among all the factors, impact velocity is the most significant factor followed by fiber content and impingement angle while the erodent size

has the least or almost no significance on erosion of the reinforced composite. It also leads to the conclusion that factor combination of A_1, B_1, and D_1 gives minimum erosion rate.

Similarly, the effects of individual control factors influencing the erosion wear rates of SiC filled jute-epoxy composites are shown in Figure (11). The S/N ratio response is given in Table 11, from which it can be concluded that among all the factors, impact velocity is the most significant factor followed by filler content and impingement angle while the erodent size has the least or almost no significance on erosion of the reinforced composite. It also leads to the conclusion that factor combination of A_1, B_1, and D_3 gives minimum erosion rate.

Factor Settings for Minimum Erosion Rate

In this study, an attempt is made to derive predictive equations in terms of the significant control factors for determination of erosion rate of both the filled and unfilled composites. The single-objective function requires quantitative determination of the relationship between erosion rates with combination of control factors. In order to express, erosion rate in the form of a mathematical model in the following correlation is suggested.

$$E = K_0 + K_1 \times A + K_2 \times B + K_3 \times D \quad (9)$$

Here, E is the performance output terms and K_i (i = 0, 1…3) are the model constants. The constants are calculated using non-linear regression analysis with the help of SYSTAT 7 software and the following relations are obtained

$$E = 66.984 + 1.665 \times A + 0.086 \times B + 1.564 \times D \quad (10)$$
(r^2=0.99)

$$E = 9.179 + 3.731 \times A + 0.427 \times B - 2.709 \times D \quad (11)$$
(r^2=0.989)

The correctness of the calculated constants is confirmed as high correlation coefficients (r^2) in the tune of 0.99 and 0.989 are obtained for Eq. (10) and for Eq. (11) respectively.

CONCLUSIONS

Successful fabrication of multi-component hybrid jute-epoxy composites with reinforcement of SiC derived from rice husk by plasma processing route is possible. It is demonstrated that if supported by an appropriate magnitude of erosion efficiency, the proposed theoretical model can perform well for epoxy based hybrid composites for normal as well as oblique impacts. The presence of particulate fillers (silicon carbide) in these composites improves their erosion wear resistance and this improvement depends on the weight content of the filler. Erosion characteristics of these composites have been successfully analyzed using Taguchi experimental design. Significant control factors affecting the erosion rate have been identified through successful implementation of this technique. Impact velocity, fiber/filler content and impingement angle in declining sequence are found to be significant for minimizing the erosion rate of all the composites. Erodent size is identified as the least influencing control factor for erosion rate.

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List of Figures:

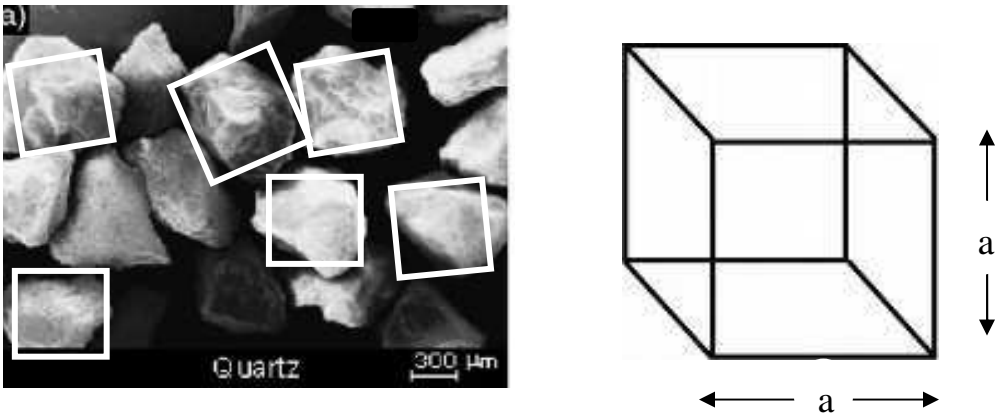


Figure 1 SEM Micrograph of the erodent used

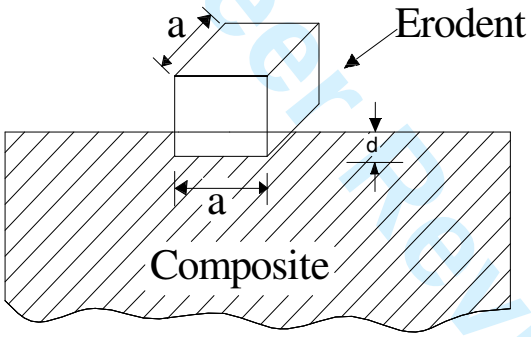


Figure 2 Scheme of material removal mechanism

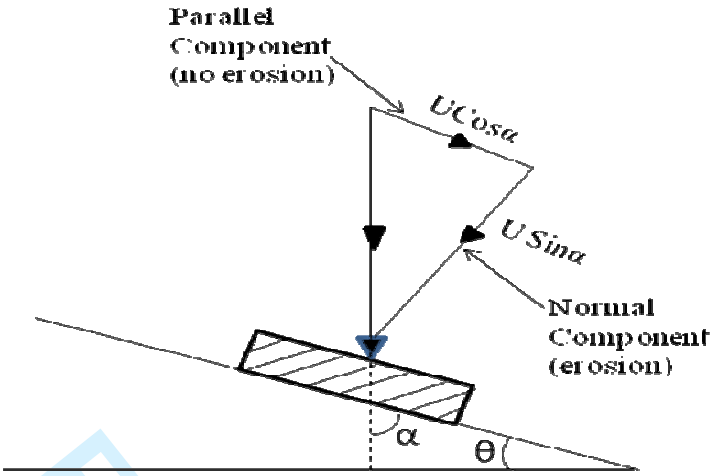


Figure 3 Resolution of impact velocity in normal and parallel directions.

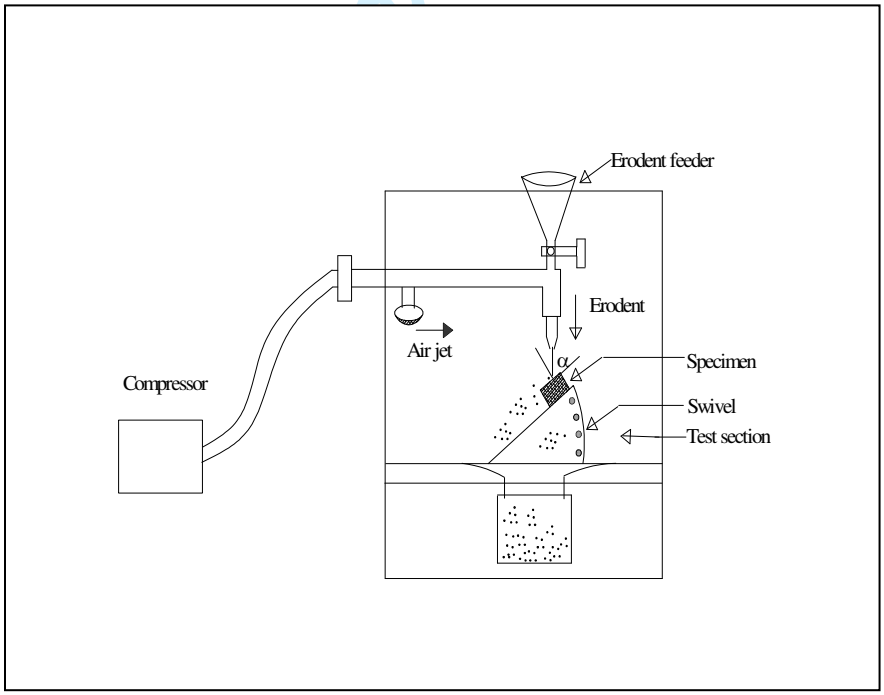


Figure 4 A schematic diagram of the erosion test rig

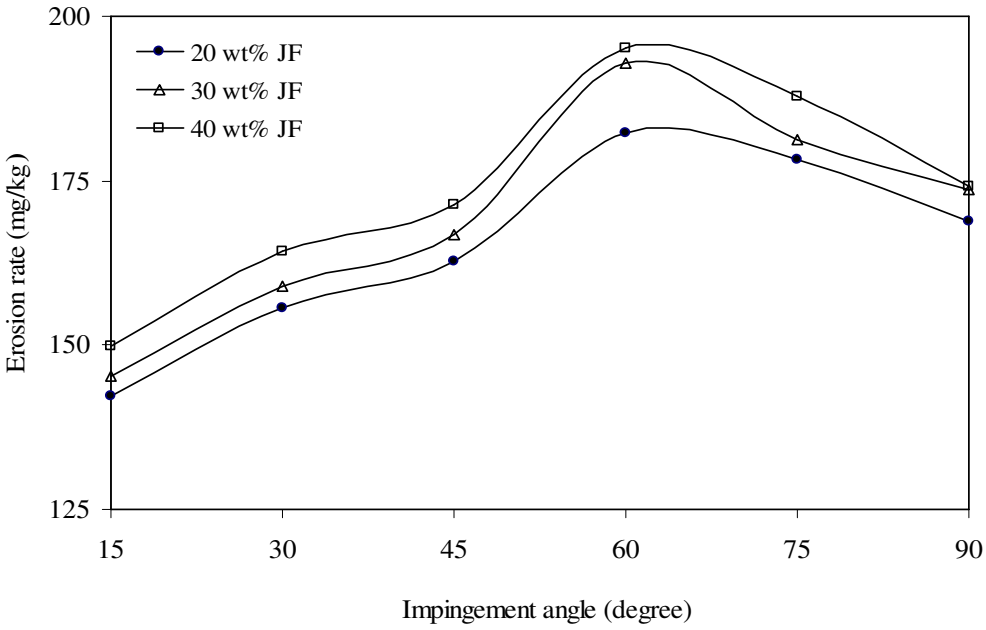


Figure 5 Erosion rate vs. angle of impingement for different fiber loading

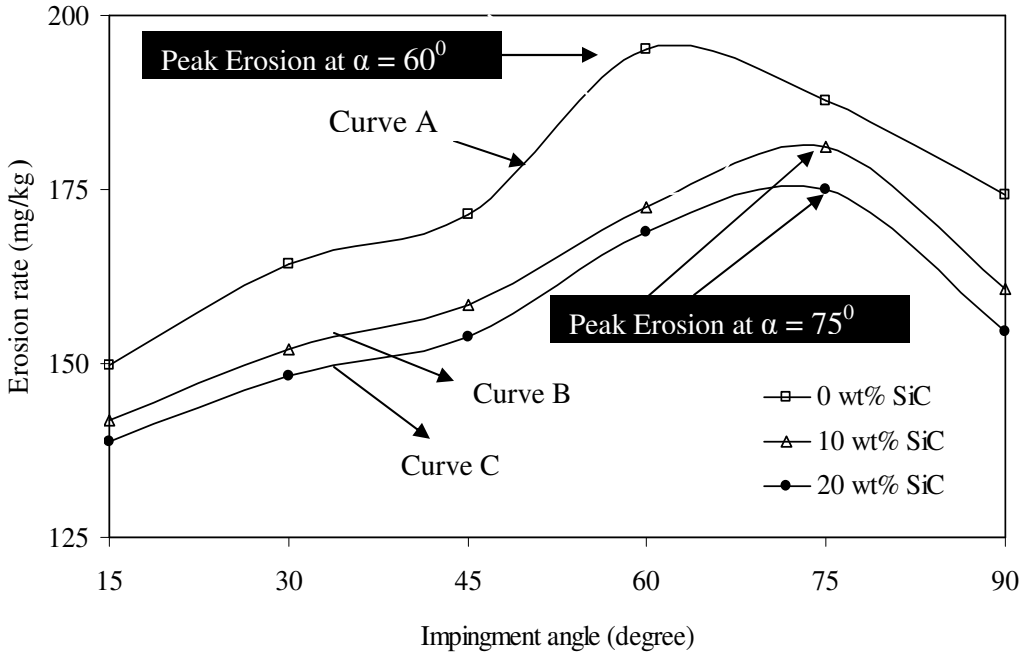
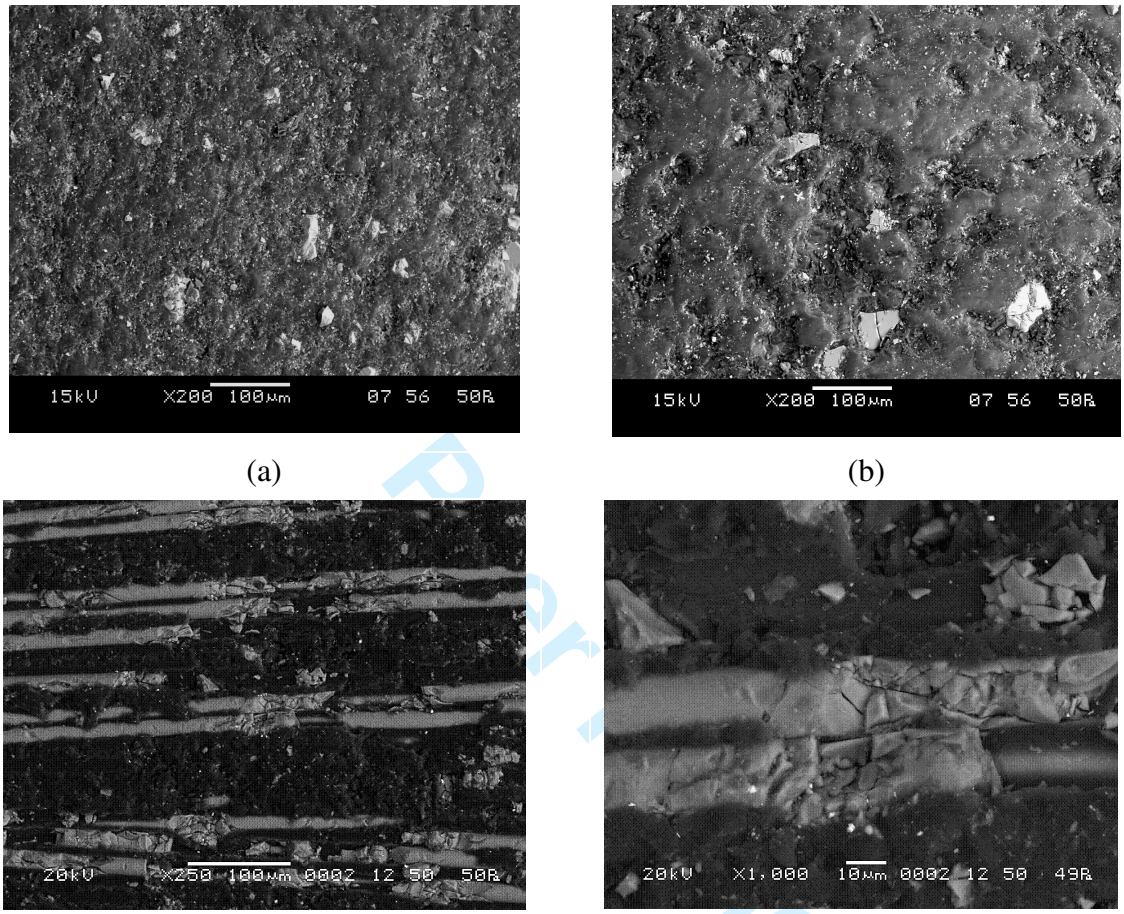


Figure 6 Erosion rate vs. angle of impingement for different weight fraction of SiC



(a) (b)

(c) (d)

Figure 7 SEM micrograph of SiC filled jute-epoxy composite surface

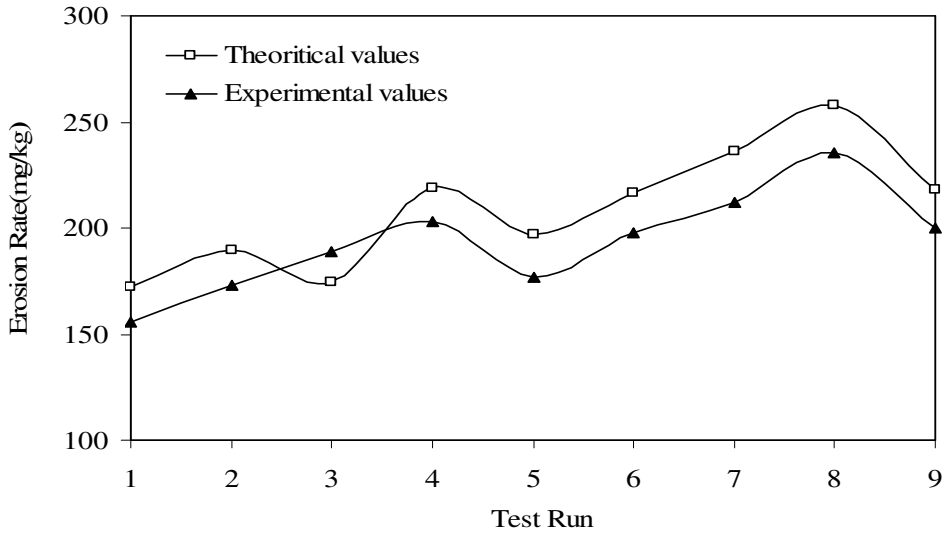


Figure 8 Comparison of theoretical and experimental values of erosion rate for unfilled jute-epoxy composites

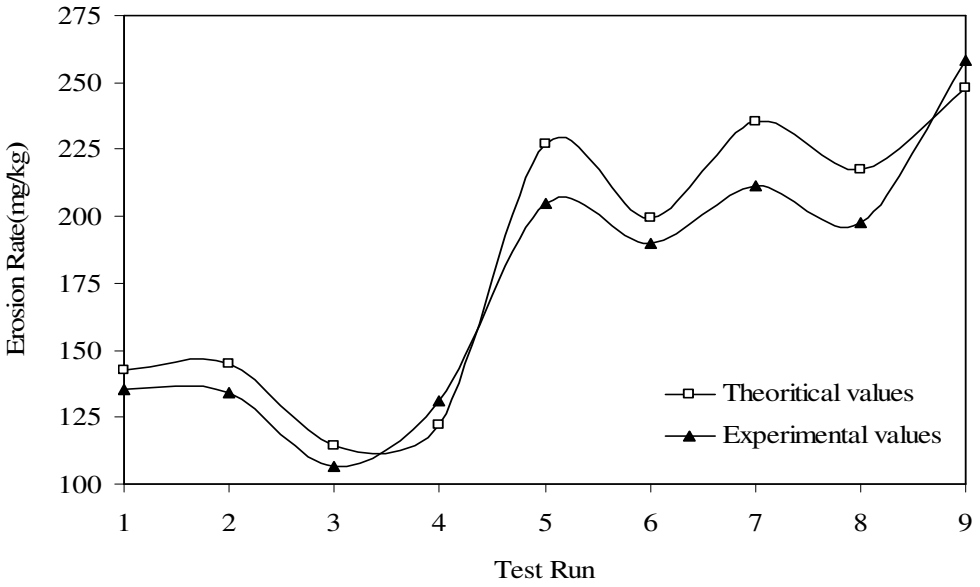


Figure 9 Comparison of theoretical and experimental values of erosion rate for SiC filled jute-epoxy composites

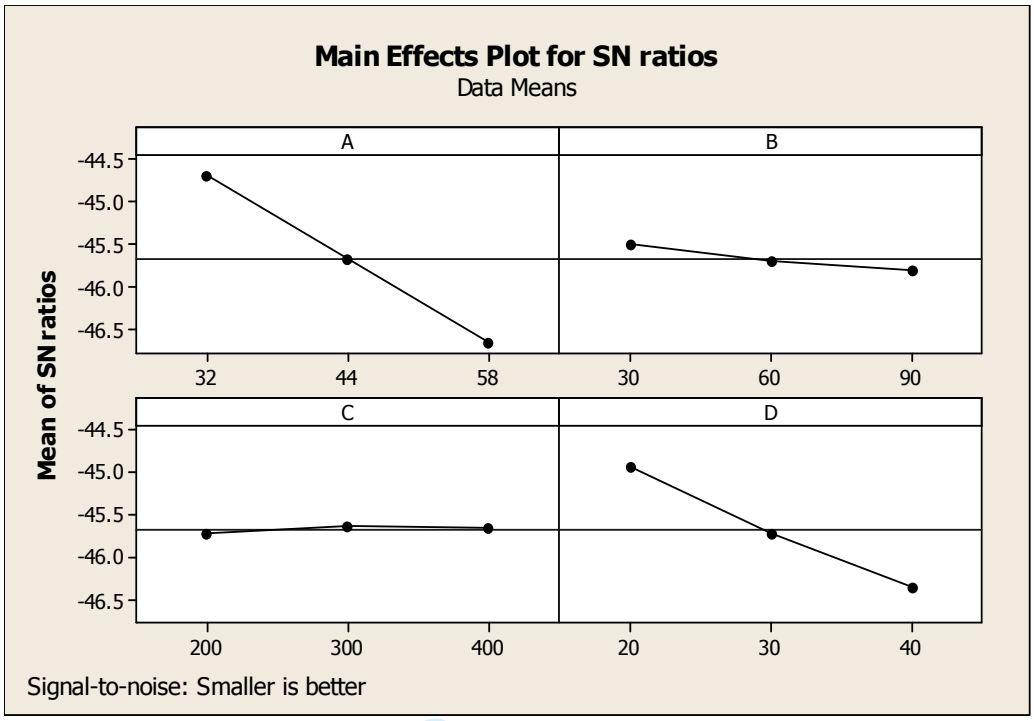


Figure 10 Effect of control factors on erosion rate (for unfilled composites)

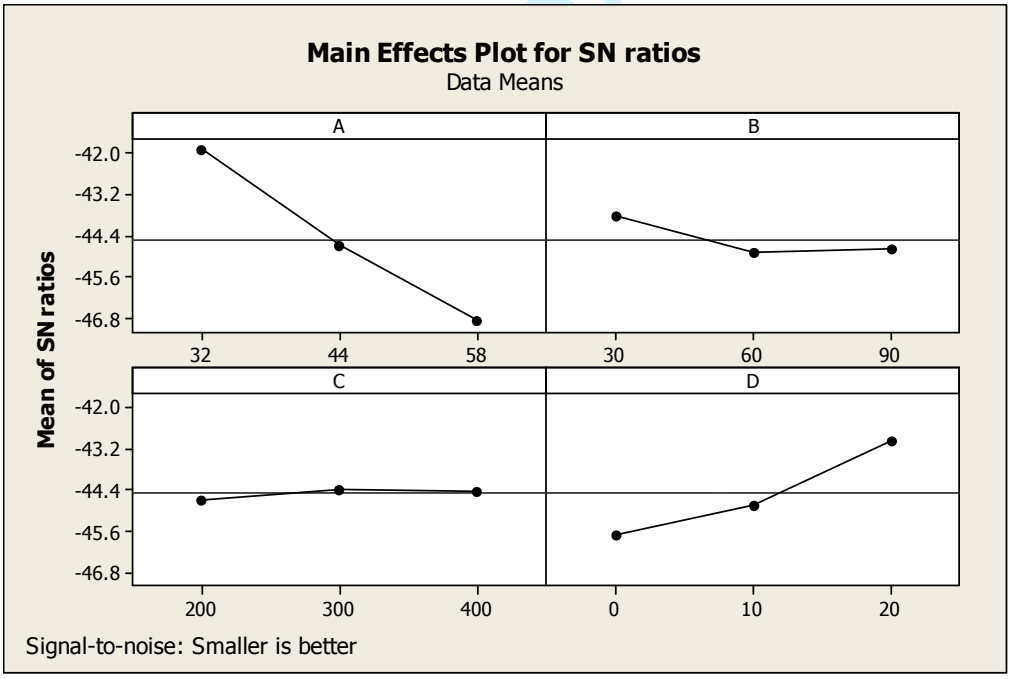


Figure 11 Effect of control factors on erosion rate (for particulate filled composites)

List of Tables

Designation	Composition
A_1	Epoxy + 20 wt% jute fiber
B_1	Epoxy + 30 wt% jute fiber
C_1	Epoxy + 40 wt% jute fiber
C_2	Epoxy + 40 wt% jute fiber + 10wt% SiC
C_3	Epoxy + 40 wt% jute fiber + 20wt% SiC

Table 1. Designation and detailed composition of the composites

Control Factors	Symbols	Fixed parameters	
Velocity of impact	Factor A	Erodent	Silica sand
Impingement angle	Factor B	Erodent feed rate (g/min)	10.0 ± 1.0
Erodent size	Factor C	Test temperature	RT
Fiber/Filler loading	Factor D	Nozzle diameter (mm)	3
		Length of nozzle (mm)	80
		Stand-off distance (mm)	100

Table 2 Parameters considered during erosion test

Control factor	Level I	II	III	Units
A: Velocity of impact	32	44	58	m/sec
B: Impingement angle	30	60	90	degree
C: Erodent size	200	300	400	µm
D: Fiber loading (for composites A_1,B_1,C_1)	20	30	40	wt%
Filler content (for composites C_1,C_2 ,C_3)	0	10	20	wt%

Table 3 Levels for various control factors

Test Run	Erodent Velocity (m/s) A	Impingement Angle (Degrees) B	Erodent Size (µm) C	Fiber Content (wt %) D
1	32	30	200	20
2	32	60	300	30
3	32	90	400	40
4	44	30	300	40
5	44	60	400	20
6	44	90	200	30
7	58	30	400	30
8	58	60	200	40
9	58	90	300	20

Table 4 Orthogonal array for L_9 Taguchi Design for composites A_1,B_1,C_1

Test Run	Erodent Velocity (m/s) A	Impingement Angle (Degrees) B	Erodent size (μm) C	Filler Content (wt %) D
1	32	30	200	0
2	32	60	300	10
3	32	90	400	20
4	44	30	300	20
5	44	60	400	0
6	44	90	200	10
7	58	30	400	10
8	58	60	200	20
9	58	90	300	0

Table 5 Orthogonal array for L_9 Taguchi Design composites C_1, C_2, C_3

Test Run	Erodent Velocity (m/s)	Impingement Angle (Degrees)	Erodent size (μm)	Fiber Content (wt %)	Theoretical ER (mg/kg)	Experimental ER (mg/kg)	Error (%)
1	32	30	200	20	172.38	155.710	10.70
2	32	60	300	30	189.76	172.564	9.96
3	32	90	400	40	174.46	188.543	7.46
4	44	30	300	40	218.95	202.765	7.98
5	44	60	400	20	196.88	176.987	11.23
6	44	90	200	30	216.48	197.643	9.53
7	58	30	400	30	235.97	211.987	11.3
8	58	60	200	40	257.98	234.980	9.78
9	58	90	300	20	217.89	199.768	9.07

Table 6 Erosion Test Results for Jute-Epoxy Composites

Test Run	A	B	C	D	E	S/N Ratio
1	32	30	200	20	155.710	-43.8463
2	32	60	300	30	172.564	-44.7390
3	32	90	400	40	188.543	-45.5082
4	44	30	300	40	202.765	-46.1399
5	44	60	400	20	176.987	-44.9588
6	44	90	200	30	197.643	-45.9176
7	58	30	400	30	211.987	-46.5262
8	58	60	200	40	234.980	-47.4206
9	58	90	300	20	199.768	-46.0105

Table 7 S/N ratio and Erosion Rate for Different Test conditions (for unfilled composites)

Level	A	B	C	D
1	-44.70	-45.50	-45.73	-44.94
2	-45.67	-45.71	-45.63	-45.73
3	-46.65	-45.81	-45.66	-46.36
Delta	1.95	.31	0.10	1.42
Rank	**1**	**3**	**4**	**2**

Table 8 Response Table for Signal to Noise Ratio (Smaller is better) for unfilled composites

Test Run	Erodent Velocity (m/s)	Impingement Angle (Degrees)	Erodent size (μm)	Filler Content (wt %)	Theoretical ER (mg/kg)	Experimental ER (mg/kg)	Error (%)
1	32	30	200	0	142.83	135.170	5.66
2	32	60	300	10	144.68	133.980	7.89
3	32	90	400	20	114.46	106.667	7.30
4	44	30	300	20	121.95	131.320	7.13
5	44	60	400	0	226.81	204.778	10.75
6	44	90	200	10	199.40	189.874	5.01
7	58	30	400	10	235.297	211.493	11.25
8	58	60	200	20	217.297	197.765	9.87
9	58	90	300	0	247.892	258.370	4.05

Table 9 Erosion Test Results for particulate filled jute-epoxy Composites

Test Run	**A**	**B**	**C**	**D**	**E**	**S/N Ratio**
1	32	30	200	0	135.170	-42.6176
2	32	60	300	10	133.980	-42.5408
3	32	90	400	20	106.667	-40.5606
4	44	30	300	20	131.320	-42.3666
5	44	60	400	0	204.778	-46.2257
6	44	90	200	10	189.874	-45.5693
7	58	30	400	10	211.493	-46.5059
8	58	60	200	20	197.765	-45.9230
9	58	90	300	0	258.370	-48.2448

Table 10 S/N ratio and erosion rate for different test conditions for particulate filled jute-epoxy composites

Level	**A**	**B**	**C**	**D**
1	-41.91	-43.83	-44.70	-45.70
2	-44.72	-44.90	-44.38	-44.87
3	-46.89	-44.79	-44.43	-42.95
Delta	4.98	1.07	0.32	2.75
Rank	**1**	**3**	**4**	**2**

Table 11 Response Table for Signal to Noise Ratios (Smaller is better) for particulate filled jute-epoxy Composites