PROCESSING, CHARACTERIZATION AND TRIBOLOGICAL EVALUATION OF PEEK-GLASS FIBER COMPOSITES

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

Master of Technology

in

Mechanical Engineering

By

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Rourkela

MAY, 2007

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CERTIFICATE

This is to certify that the thesis entitled **" PROCESSING, CHARACTERIZATION AND TRIBOLOGICAL EVALUATION OF PEEK - GLASS FIBER COMPOSITES "** submitted by **Sri S. Naga Mahendra Babu** in partial fulfillment of the requirements for the award of Master of Technology degree in Mechanical Engineering with specialization in Production Engineering to the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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Date: **S. Naga Mahendra Babu**

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ABSTRACT

This work reports the processing, characterization and tribological evaluation of a new class of composites with a polymer called poly-ether-ether-ketone as the matrix and glass fiber as the reinforcing material. Attempt is made to use red mud as filler in these fiber reinforced polymer matrix composites. Red mud is the solid waste generated in alumina plants during the production of alumina from bauxite by Bayer's process. Characterization of the resulting red mud filled glass fiber reinforced poly-ether-ether-ketone composite is done. Silicon carbide is a known hard ceramic material. SiC powders are also filled in this glass fiber reinforced poly-ether-ether-ketone matrix and mechanical characterization of the resulting new composite is done.

Solid particle erosion wear behaviour of this new class of composites is investigated. Erosion, an important material degradation mechanism encountered in a number of structural and engineering components, has been extensively investigated over the last few decades. However, the influence of factors like impact velocity, impingement angle, erodent size and stand-off distance (SOD) on erosion behavior of glass fiber reinforced polyether-ether-ketone composites is yet to be fully investigated. To this end, a design of experiment (DOE) approach based on Taguchi method is adopted in this work to evaluate effect of these factors on erosion rate of the composite. The study indicates that the rate of erosion of composites by impact of solid erodent is greatly influenced by these control factors.

This work draws the conclusions that reinforcement of glass fiber into the poly-ether-ether-ketone (PEEK) matrix improves the flexural strength quite significantly, thus making it a potential material for structural applications. Addition of red mud and silicon carbide to glass fiber reinforced poly-ether-ether-ketone composites further improves the flexural strength, flexural modulus and tensile strength of the material. Addition of these fillers is leading to reduction of density and subsequently the strength to weight ratio of the composites. Glass fiber reinforced poly-ether-ether-

ketone composites filled with red mud and silicon carbide powders exhibit much better resistance to solid particle erosion in comparison to the un-filled composite. The rate of wear of the composite material is also greatly influenced by operational variables like impact angle, velocity of impact, stand-off distance etc. and material variables like erodent size and composition of composites. These composites exhibited maximum erosion rate at an impingement angle of 60^0 under similar experimental conditions. The Taguchi experimental design approach suggests that the erodent size plays the most significant role in erosive wear of these composites. The angle of impact and the impact velocity are other major influencing factors. Stand-off distance has the least effect on the erosion rate.

This work leaves a wide scope for future investigators to explore many other aspects of such composites. Wear of polyether-ether-ketone matrix composite has been a much less studied area. Many other problems like effect of fiber orientation, loading pattern, weight fraction of ceramic fillers on erosion response of such composites require further investigation. This work is expected to introduce a new class of functional polymer composites suitable for tribological applications.

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Chapter 1

INTRODUCTION

INTRODUCTION

Composite materials (or composites for short) are engineering materials made from two or more constituent materials that remain separate and distinct on a macroscopic level while forming a single component. There are two categories of constituent materials: matrix and reinforcement. At least one portion of each type is required. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. The primary functions of the matrix are to transfer stresses between the reinforcing fibers/particles and to protect them from mechanical and/or environmental damage whereas the presence of fibers/particles in a composite improves its mechanical properties such as strength, stiffness etc. A composite is therefore a synergistic combination of two or more micro-constituents that differ in physical form and chemical composition and which are insoluble in each other. The objective is to take advantage of the superior properties of both materials without compromising on the weakness of either. The synergism produces material properties unavailable from the individual constituent materials. Due to the wide variety of matrix and reinforcement materials available, the design potentials are incredible.

Composite materials have successfully substituted the traditional materials in several light weight and high strength applications. The reasons why composites are selected for such applications are mainly their high strength-to-weight ratio, high tensile strength at elevated temperatures, high creep resistance and high toughness. Typically, in a composite, the reinforcing materials are strong with low densities while the matrix is usually a ductile or tough material. If the composite is designed and fabricated correctly it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material. The strength of the composites depends primarily on the amount, arrangement and type of fiber and /or particle reinforcement in the resin.

Merits of Composites

Advantages of composites over their conventional counterparts are the ability to meet diverse design requirements with significant weight savings as well as strength-to-weight ratio. Some advantages of composite materials over conventional ones are as follows:

- Tensile strength of composites is four to six times greater than that of steel or aluminium (depending on the reinforcements).
- Improved torsional stiffness and impact properties.
- Higher fatigue endurance limit (up to 60% of ultimate tensile strength).
- 30% - 40% lighter for example any particular aluminium structures designed to the same functional requirements.
- Lower embedded energy compared to other structural metallic materials like steel, aluminium etc.
- Composites are less noisy while in operation and provide lower vibration transmission than metals.
- Composites are more versatile than metals and can be tailored to meet performance needs and complex design requirements.
- Long life offer excellent fatigue, impact, environmental resistance and reduce maintenance.
- Composites enjoy reduced life cycle cost compared to metals.
- Composites exhibit excellent corrosion resistance and fire retardancy.
- Improved appearance with smooth surfaces and readily incorporable integral decorative melamine are other characteristics of composites.
- Composite parts can eliminate joints / fasteners, providing part simplification and integrated design compared to conventional metallic parts.

Broadly, composite materials can be classified into three groups on the basis of matrix material. They are:

a) Metal Matrix Composites (MMC)
b) Ceramic Matrix Composites (CMC)
c) Polymer Matrix Composites (PMC)

a) Metal Matrix Composites

Metal Matrix Composites have many advantages over monolithic metals like higher specific modulus, higher specific strength, better properties at elevated temperatures, and lower coefficient of thermal expansion. Because of these attributes metal matrix composites are under consideration for wide range of applications viz. combustion chamber nozzle (in rocket, space shuttle), housings, tubing, cables, heat exchangers, structural members etc.

b) Ceramic matrix Composites

One of the main objectives in producing ceramic matrix composites is to increase the toughness. Naturally it is hoped and indeed often found that there is a concomitant improvement in strength and stiffness of ceramic matrix composites.

c) Polymer Matrix Composites

Most commonly used matrix materials are polymeric. The reason for this are two fold. In general the mechanical properties of polymers are inadequate for many structural purposes. In particular their strength and stiffness are low compared to metals and ceramics. These difficulties are overcome by reinforcing other materials with polymers. Secondly the processing of polymer matrix composites need not involve high pressure and doesn't require high temperature. Also equipments required for manufacturing polymer matrix composites are simpler. For this reason polymer matrix composites developed rapidly and soon became popular for structural applications.

Composites are used because overall properties of the composites are superior to those of the individual components for example polymer/ceramic. Composites have a greater modulus than the polymer component but aren't as brittle as ceramics.

Two types of polymer composites are:

- Fiber reinforced polymer (FRP)
- Particle reinforced polymer (PRP)

Fiber Reinforced Polymer

Common fiber reinforced composites are composed of fibers and a matrix. Fibers are the reinforcement and the main source of strength while matrix glues all the fibers together in shape and transfers stresses between the reinforcing fibers. The fibers carry the loads along their longitudinal directions. Sometimes, filler might be added to smooth the manufacturing process, impact special properties to the composites, and / or reduce the product cost.

Common fiber reinforcing agents include asbestos, carbon / graphite fibers, beryllium, beryllium carbide, beryllium oxide, molybdenum, aluminium oxide, glass fibers, polyamide, natural fibers etc. Similarly common matrix materials include epoxy, phenolic, polyester, polyurethane, polyetherethrketone (PEEK), vinyl ester etc. Among these resin materials, PEEK is most widely used. Epoxy, which has higher adhesion and less shrinkage than PEEK, comes in second for its high cost.

Particle Reinforced Polymer

Particles used for reinforcing include ceramics and glasses such as small mineral particles, metal particles such as aluminium and amorphous materials, including polymers and carbon black. Particles are used to increase the modules of the matrix and to decrease the ductility of the matrix. Particles are also used to reduce the cost of the composites. Reinforcements and matrices can be common, inexpensive materials and are easily processed. Some of the useful properties of ceramics and glasses include high melting temp., low density, high strength, stiffness, wear resistance, and corrosion resistance. Many ceramics are good electrical and thermal insulators. Some ceramics have special properties; some ceramics are magnetic materials; some are piezoelectric materials; and a few special ceramics are even superconductors at very low temperatures. Ceramics and glasses have one major drawback: they are brittle. An example of particle reinforced composites is an automobile tire, which has carbon black particles in a matrix of poly-isobutylene elastomeric polymer.

Polymer composite materials have generated wide interest in various engineering fields, particularly in aerospace applications. Research is underway worldwide to develop newer composites with varied combinations of fibers and fillers so as to make them useable under different operational conditions. Against this backdrop, the present work has been taken up to develop a series of PEEK based composites with glass fiber reinforcement and with ceramic fillers and to study their response to solid particle erosion.

SCOPE OF THE THESIS

The basic aim of the present work is to develop and characterize a new class of composites with a polymer called poly-ether-ether-ketone (PEEK) as the matrix and glass fiber as the reinforcing material. Their physical and mechanical characterization is done.

Attempt is made to use red mud as filler in these fiber reinforced polymer matrix composites. Red mud is the solid waste generated in alumina plants during the production of alumina from bauxite by Bayer's process. Characterization of the resulting red mud filled glass fiber reinforced poly-ether-ether-ketone composite is done.

Silicon carbide is a known hard ceramic material. SiC powders are also filled in the glass fiber reinforced poly-ether-ether-ketone matrix and mechanical characterization of the resulting new composite is done.

Solid particle erosion wear behaviour of this new class of composites is investigated. Analysis of the experimental results is done using statistical techniques to identify significant control factors affecting the wear properties of these composites.

This work is expected to introduce a new class of functional polymer composites suitable for tribological applications.

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Chapter 2

LITERATURE SURVEY

LITERATURE SURVEY

Composite materials offer exciting advantages over traditional monolithic materials. Modern advanced composites are a success story from the view point of their widespread applications, ranging from tennis rackets to advanced space vehicles. Aggressive research is being carried out worldwide to explore new composites with improved functional properties. This chapter presents the outlines of some of the recent reports published in literature on composites with special emphasis on erosion wear behavior of glass fiber reinforced polymer composites.

Polymers and composites are extensively used in tribo-applications such as bearings, gears etc. where liquid lubricants can not always be used because of various constraints [**1**]. Apart from adhesive wear mode, some polymers and composites have exhibited excellent tribo-potential in other wear situations also such as abrasive, fretting, reciprocating and erosive [**2**]. Comparatively less is reported on erosive wear performance of polymers and composites though some polymers such as rubbers have proved their superiority over metals [**3**, **4**]. Finnie [**5**, **6**] has done pioneering work in the case of metals. But polymers and their composites are increasingly being used in applications such as radomes, surfing boats, gas and steam turbine blades gears for locomotives, conveyor belts, helicopter blades, pump-impellers in mineral slurry processing, where the components encounter impact of lot of abrasives like dust, sand, splinters of materials, slurry of solid particles and consequently the parts undergo erosive wear. Hence, it becomes imperative to study erosive wear behavior of polymeric engineering materials in various operating conditions.

In general, the operating conditions and material properties decide the erosive wear performance of the material. Pool et al. [**7**] though have summarized some general trends about the influence of various factors such as hardness, ductility, brittleness, stress levels, surface finish of materials, erodent and operating conditions on erosive wear behavior of polymers, it is not necessarily true in the case of all polymers and composites. Various researchers have correlated several properties such as hardness, brittleness index, resilience, fracture energy, etc. [**8-13**] with the erosive wear behavior of polymers and composites.

The erosion of materials caused by impact of hard particles is one of several forms of material degradation generally classified as wear. Bitter [**14**] defined erosion as "Material damage caused by the attack of particles entrained in a fluid system impacting the surface at high speed" while Hutchings [**15**] wrote " Erosion is an abrasive wear process in which the repeated impact of small particles entrained in a moving fluid against a surface results in the removal of material from the surface". Solid particle erosion is a serious problem in gas turbines, rocket nozzles, cyclone separators, valves, pumps and boiler tubes. Polymer composite materials are finding increased application under conditions in which they may be subjected to solid particle erosion. Examples of such applications are pipe lines carrying sand slurries in petroleum refining, helicopter rotor blades [**1, 2**], pump impeller blades, high speed vehicles, air-crafts operating in desert environments, water turbines, aircraft engine blades [**3**].

Many researchers [**16-39**, **40**] have evaluated the resistance of various types of polymers and their composites to solid particle erosion. Materials that have been eroded include nylon [**21**, **22**], epoxy [**34-36**], polypropylene [**28**, **3**], polyethylene [**29**], polyetheretherketone (PEEK) [**30**, **33**], ultra high molecular weigh polyethylene (UHMWPE) [**40**] and various polymer based composites [**16**, **19**, **20**, **23-25**, **32-34**, **36**].

There are also several reports in the literature which discuss the erosion behavior of fibrous composites. These papers mainly showed, however, only the erosion behavior and performance to erosive damage [**41-51**]. Although various types of fiber are used for reinforcing plastics, no paper has been published in which the effect of types of fiber, e.g. strand mat, woven cloth, unidirectional UD fiber, etc. on sand erosion damage have been discussed systematically. And no convenient method to predict the erosion rate has been reported anywhere.

Though some efforts have been focused on evaluation of erosion behavior of bulk polymers such as PE [**8**], PP [**52**], PS [**53**], PTFE, PMMA, PC [**54**], epoxy [**55, 56**], Polyamides and their composites [**9**, **57-63**] and PEEK [**12**, **62**] very limited number of papers are available on systematic studies on erosive wear performance of a class of polymers with different mechanical properties. Arnold and Hutchings [**64**] studied the influence of hardness on erosion of three natural rubbers (NBR), styrene-butadiene rubber (SBR) and highly cross linked polybutadiene rubber (BR). Yabuki et al. [**65**] investigated seven types of polyethylene in erosive wear mode. Brandstadter et al. [**66**] studied erosive wear behavior of five types of bismaleimide polymers, formulated from different concentrations of two ingredients. Hutchings et al. [**67**] also investigated the erosive wear behavior of eight types of rubber with different chemical structures and properties. Lichtman [**68**] examined cavitation erosion of eighteen rubbers with different mechanical properties. Wally et al. [**69**], for example, studied influence of processing conditions of erosive wear of extruded and injection molded PEEK. These investigations revealed better understanding of material properties responsible for their erosive wear performance.

A crucial parameter for design with composites is the fiber content, as it controls the mechanical and thermo-mechanical responses. In order to obtain the favored 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 behavior of polymer composite systems as a function of fiber content has been studied in the past [**70-72**]. It was reported that the inclusion of brittle fibers in both thermosetting and thermoplastic matrixes in some cases leads to composite with lower erosion resistance. No definite rule is available to describe how the fiber content affects the erosion rate composite. An analytical approach was presented by Hovis et al. [**73**] which depends on the individual erosion rate of its constituents. The linear (LROM) and inverse (IROM) were proposed and evaluated for a multiphase Al-Si alloy. The same rules of mixture were adopted by Ballout et al. [**74**] for a glass fiber reinforced epoxy composite. However, the literature shows that the information on the effects of fiber content on the erosive wear behavior is scarce and its modeling is also limited.

It is often seen from the published reports that fiber reinforced composite materials compared to neat polymers present a rather poor resistance to solid particle erosion. In spite of this they are attractive for their high specific strength and are frequently used in engineering parts in automobile, aerospace, marine and energetic applications. Due to operational requirements in dusty environment, the erosion characteristics of the polymeric composites are of high relevance. As different mechanism of material removal seems to govern the erosion of polymer matrix composite, it is important to study the behavior of a specific composition in order to identify suitable application areas.

Although large numbers of research papers are available in published literature, the author has not come across any work on ceramic filled fiber-reinforced-polyetheretherketone composites. The erosion behaviour of many other polymer matrix composites is yet to be addressed to. Moreover, statistical analysis of the experimental findings has always been a very less studied area in composite research.

Against this background, the present work has been undertaken to develop, characterize and to study the erosion wear characteristics of filled and unfilled polyetheretherketone-glass-fiber-composites under various experimental conditions. Red mud and silicon carbide are the two ceramics chosen as the filler materials to be added to the fiber reinforced composites. Silicon carbide is a known hard material. Red mud is an industrial waste. Production of alumina from bauxite by the Bayer's process is associated with the generation of red mud as the major waste material. The enormous quantity of red mud discharged by industries producing alumina poses an environmental and economical problem. The treatment and disposal of this residue is a major operation in an alumina plant. Red mud, as the name suggests, is brick red in colour and slimy having average particle size of about 80 μm. It comprises of the iron, titanium and the silica part of the parent ore along with other minor constituents. It is alkaline, thixotropic and possesses high surface area in the range of 13-16 m^2/g with true density of 3.30g/cc. Residues from different bauxite have a wide range of composition: Fe_2O_3 20-60%, Al_2O_3 10-30%, SiO_2 2-20%, TiO_2 2-10% and CaO 2-8% . The leaching chemistry of bauxite suggests that the physical and chemical properties of red mud depend on the bauxite used and the manner in which the bauxite is processed.

This new class of PEEK-GF composites with red mud and silicon carbide filling has been characterized with respect to its strength and erosive wear behaviour.

OBJECTIVES OF THE PRESENT WORK

The objectives of the present work can be outlined as:

- Processing of PEEK – GF composites with multilayer fiber reinforcement.
- Processing of filled PEEK-GF composites with red mud and SiC powders
- Physical and mechanical characterization of these composites

- Study the effect of particulate filling on various composite characteristics.
- Assessment of these composites to solid particle erosion under different operational conditions.
- Analysis of experimental results by Taguchi method to identify significant control factors affecting the wear properties of the composites.

This work is expected to introduce a new class of functional polymer composite that might find applications in erosive operational situations.

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Chapter 3

MATERIALS AND METHODS

MATERIALS AND METHODS

INTRODUCTION

This chapter describes the details of processing of the composites and the experimental procedures followed for their characterization and tribological evaluation. The raw materials used in this work are

- Poly-ether-ether-ketone (PEEK)
- E-glass fiber
- Silicon Carbide Powder
- Red mud Powder

PEEK is the matrix material used in this work and is procured from Ciba Giegy Limited. Other chemicals used are cobalt acetate (Catalyst/Hardener) and an accelerator compatible to this polymer. Silicon carbide powder of average particle size 100 micron has been supplied by NICE. Red mud powder in the particle size range 70-90 micron was collected from Alumina Plant of National Aluminium Co. NALCO at Damanjodi, Orissa. The reinforcing material E-glass (360 Roving) fiber has been supplied by Saint Gobian Ltd.

PROCESSING OF THE COMPOSITES

Specimen Preparation

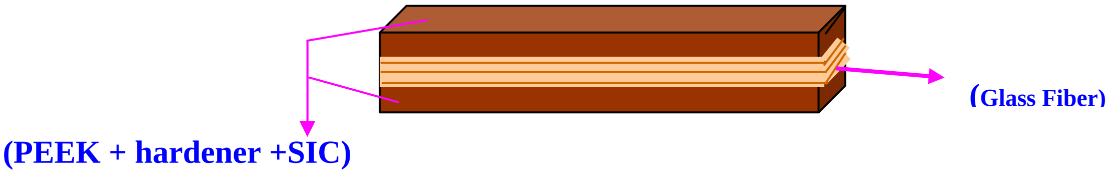
High strength E-glass fiber mat was used as reinforcement in the poly-ether-ether-ketone to prepare laminate slabs of 150 mm x 250 mm size with 40% fiber loading by weight. The mat consists of an E-glass with 72.5 GPa modulus and density of 2590 kg/m^3. The resin polymer possessing a modulus of 4 GPa and density of 1320 kg/m^3 was used in preparing the specimens with contact molding process and required number of mats were stacked in the matrix body so as to ensure that the weight fraction of fiber in the composite remained exactly 40 %.

For preparation of unfilled PEEK-GF composite clean glass plates were taken. Mould release sheets were placed on the plates. Mould release spray was applied on them. The catalyst and accelerator were added to the polymer in proportion 1.5% and 1% by weight respectively and were thoroughly mixed. For preparation of red mud filled PEEK-GF composite and silicon carbide filled PEEK-GF composite, these powders (20% by weight) were separately added to the liquid polymer-hardener solution. The mixture was sprayed on the sheets to a thickness of about 2mm followed by a piece of glass fiber mat (cut in the shape of a rectangle). Again another layer of resin was sprayed .Thus a single layer of composite is formed. Load was applied on all these preparations and these were left for 48 hours for adequate curing and solidification. Then the mould release sheets were removed and molded composites were taken out. It may be mentioned that in all these composites the fiber orientation was set at 90^0. Thus three members of a new class of fiber reinforced poly-ether-ether-ketone composites were formed which may be designated as following:

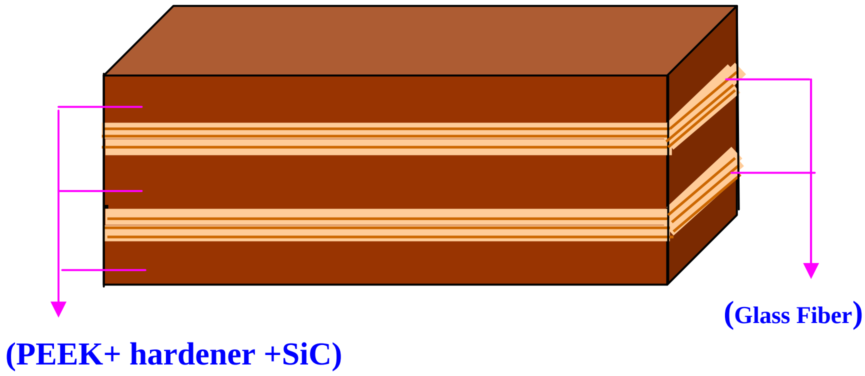
1. **GFPK** Glass Fiber Reinforced Polyetheretherketone
2. **RM-GFPK** Red Mud Filled Glass Fiber Reinforced Polyetheretherketone
3. **SiC-GFPK** Silicon Carbide Filled Glass Fiber Reinforced Polyetheretherketone

Fig 3.1 Glass Fiber Reinforced Poly-Ether-Ether-Ketone Composites

To avoid formation of bubbles by liberation of CO_2 in resin, PEEK and the filler particles were mixed thoroughly. The castings were cured at room temperature for about 48 hours. Specimens of suitable dimension were cut using a diamond cutter for further characterization and for erosion test.



Single layer



Double layer composite

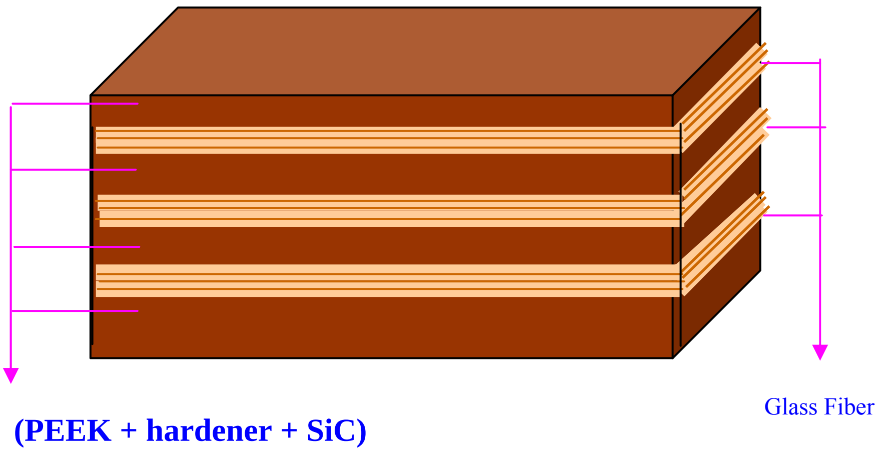


Fig. 3.2 Schematic View of the Composites

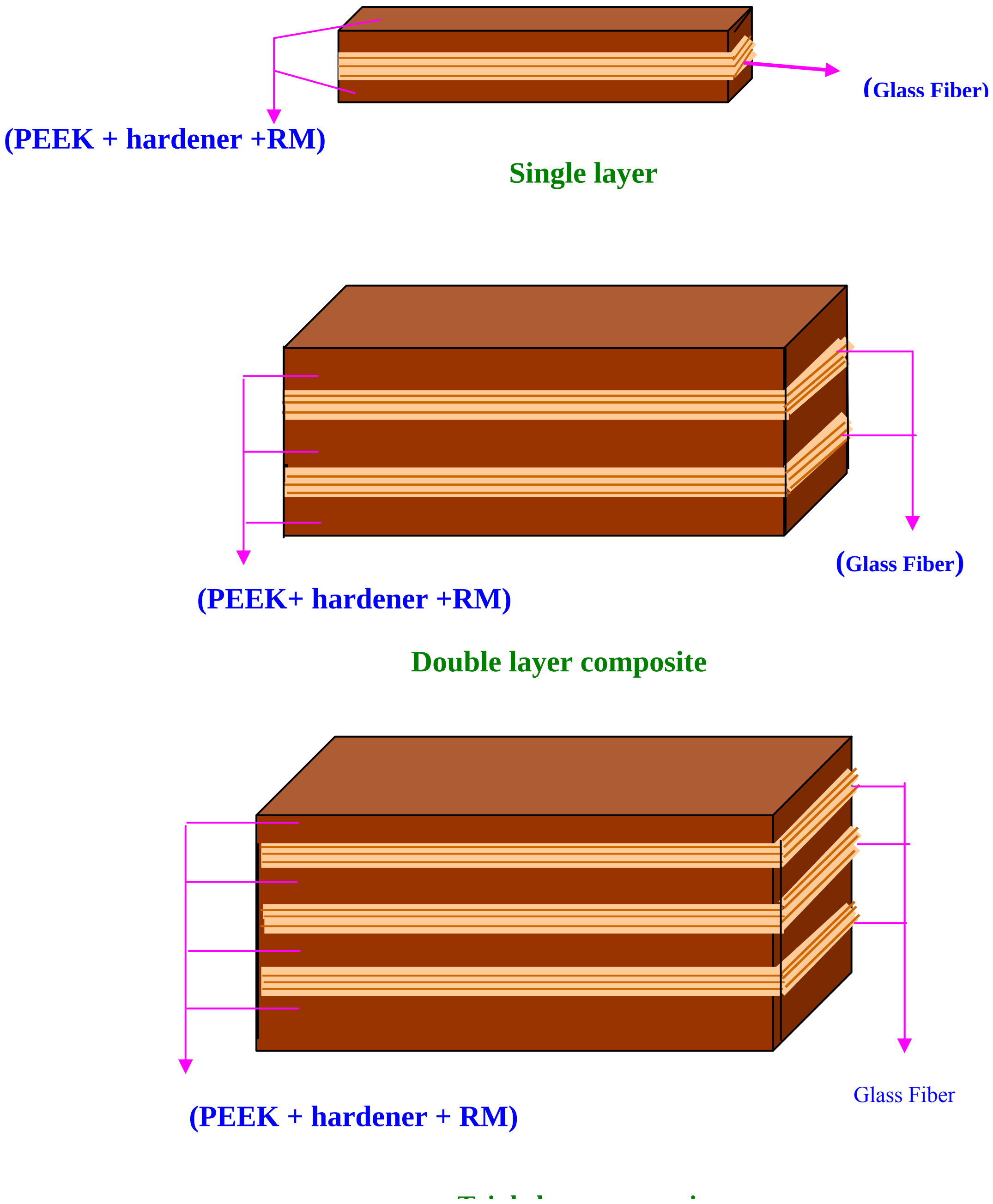


Fig. 3.3 Schematic View of the Composites

CHARACTERIZATION OF THE COMPOSITES

Density

The characterization of the newly developed composites includes the measurement of their density and evaluation of the flexural strength. From the compression moulded composite plates, test samples of approximately 70 mm × 40 mm size were cut using a diamond cutter. The thickness of the samples of different composite were measured and recorded. Each sample is weighed using a precision electronic balance with ± 0. 001 gram accuracy. The mass density of each composite sample was thus calculated by conventional method.

Tensile Strength

The tension test is generally performed on flat specimens. The most commonly used specimen geometries are the dog-bone specimen and straight-sided specimen with end tabs. A uni-axial load is applied through the ends. The ASTM standard test recommends that the specimens with fibers parallel to the loading direction should be 11.5 mm wide. Length of the test section should be 100 mm. The test-piece used here was of dog-bone type and having dimensions according to the standards. The tension test was performed on all the three samples as per ASTM D3039-76 test standards.

Flexural Strength

The determination of flexural strength is an important characterization of any structural material. It is the ability of a material to withstand the bending before reaching the breaking point. Conventionally a three point bend test is conducted for finding out this material property. In the present investigation also the composites were subjected to this test in a testing machine ***Instron 1195***. The photograph of the machine and the loading arrangement for the specimens are shown in fig 3.4 and fig 3.5 respectively. A span of 30 mm was taken and cross head speed was maintained at 10 mm/min.

The strength of a material in bending is expressed as the stress on the outermost fibers of a bent test specimen, at the instant of failure.

In a conventional test, flexural strength expressed in MPa is equal to

$$\textit{Flexural Strength} = 3PL / 2bd^2$$

Where **P= applied central load (N)**

L= test span of the sample (m)

b= width of the specimen (m)

d= thickness of specimen under test (m)

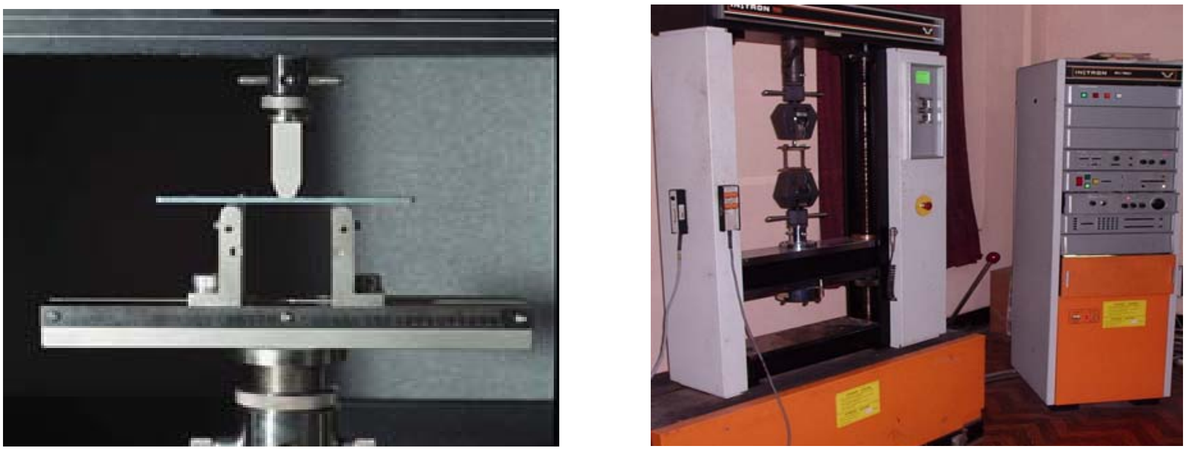


Fig 3.4 Experimental set up for three point bend test **Insron 1195**

Fig 3.5 Loading arrangement for the specimens

Micro-Hardness

Micro-hardness measurement is made using Leitz Microhardness Tester equipped with a monitor and a microprocessor based controller, with a load of 0.245N and a loading time of 20 seconds. About ten or more readings are taken on each sample and the average value is reported as the data point.

Erosion Wear Test

Solid particle erosion (SPE) is usually simulated in laboratory by one of two methods. The 'sand blast' method, where particles are carried in an air flow and impacted onto a stationary target and the 'whirling arm' method , where the target is spun through a chamber of falling particles.

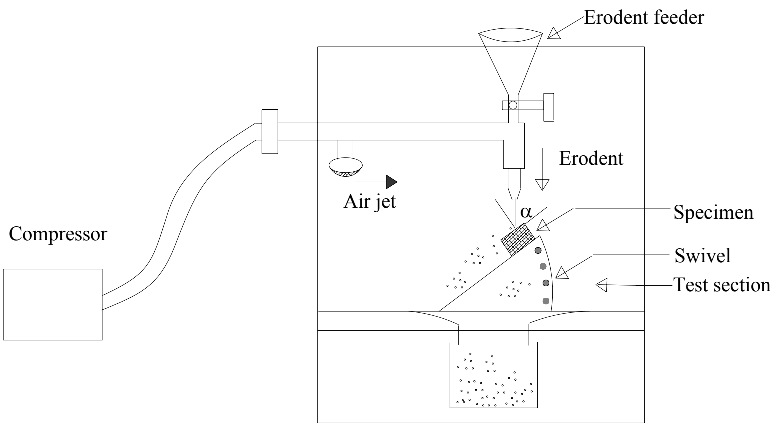


Fig. 3.6 Schematic diagram of the erosion test rig

Fig 3.7 Solid Particle Erosion Test Set Up

In the present investigation, an erosion apparatus (self-made) of the ‘sand blast’ type is used. The schematic diagram of the rig is shown in fig 3.6 and the photograph of actual set up is shown in fig. 3.7. It is capable of creating highly reproducible erosive situations over a wide range of particle sizes, velocities, particles fluxes and incidence angles, in order to generate quantitative data on materials and to study the mechanisms of damage. The test is conducted as per ASTM G76 standards.

The jet erosion test rig used in this work employs one 80 mm long nozzle of 3 mm bore. This nozzle size permits a wider range of particle types to be used in the course of testing, allowing better simulations of real erosion conditions. The mass flow rate is measured by conventional method. Particles are fed from a simple hopper under gravity into the groove. Velocity of impact is measured using double disc method. Some of the features of this test set up are:

- Vertical traverse for the nozzle: provides variable nozzle to target standoff distance, which influences the size of the eroded area.
- Different nozzles may be accommodated: provides ability to change the particle plume dimensions and the velocity range
- Large test chamber with sample mount (typical sample size 40 mm x 60 mm) that can be angled to the flow direction: by tilting the sample stage, the angle of impact of the particles can be changed in the range of 0^0 – 90^0 and this will influence the erosion process.

In this work, room temperature solid particle erosion test on filled and unfilled PEEK-GF composite samples was carried out under different operational conditions. The nozzle was kept at different stand-off distances from the target. 500 μm average size dry silica sand particles were used as erodent with three different velocities of 32m/s 45m/s and 58m/s. Amount of wear is determined on ‘mass loss’ basis. It is done by measuring the mass of the samples at the beginning of the test and at regular intervals in the test duration. A precision electronic balance with $\pm$ 0.1 mg accuracy was used for weighing. Erosion rate, defined as the coating mass loss per unit erodent mass (mg/g) was calculated.

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Chapter 4

COMPOSITE CHARACTERIZATION: RESULTS & DISCUSSION

COMPOSITE CHARACTERIZATION: RESULTS AND DISCUSSION

INTRODUCTION

This chapter presents the physical and mechanical characterization of the class of polymer matrix composites developed for the present investigation. They are --

- Glass Fiber Reinforced Polyetheretherketone (**GFPK**)
- Red Mud Filled Glass Fiber Reinforced Polyetheretherketone (**RM-GFPK**)
- Silicon Carbide Filled Glass Fiber Reinforced Polyetheretherketone (**SiC-GFPK**)

Details of processing of these composites and the tests conducted on them have been described in the previous chapter. The results of various characterization tests are reported here. They include evaluation of tensile strength, flexural strength, flexural modulus, measurement of density and micro-hardness. The effect of addition of filler materials like red mud and silicon carbide on composite characteristics has been studied and discussed.

COMPOSITE CHARACTERIZATION

Measurement of density

Composites offer many advantages over other materials. In applications like aerospace and marine units, where exceptional performance is required but weight is critical, composites continue to grow in importance because of their low density and high strength. The density measurement therefore is an important characterization of any newly developed composite. In the present work, the mass densities of all the three composites are found out and the values are reported in table 4.1. The density of composite GFPK is 1.608 gm/cc while those of the

Composite	Mass Density (gm/cc)
o **GFPK** o **RM-GFPK** o **SiC-GFPK**	o 1.608 o 1.547 o 1.498

Table 4.1 Density of unfilled and filled PEEK-GF composites

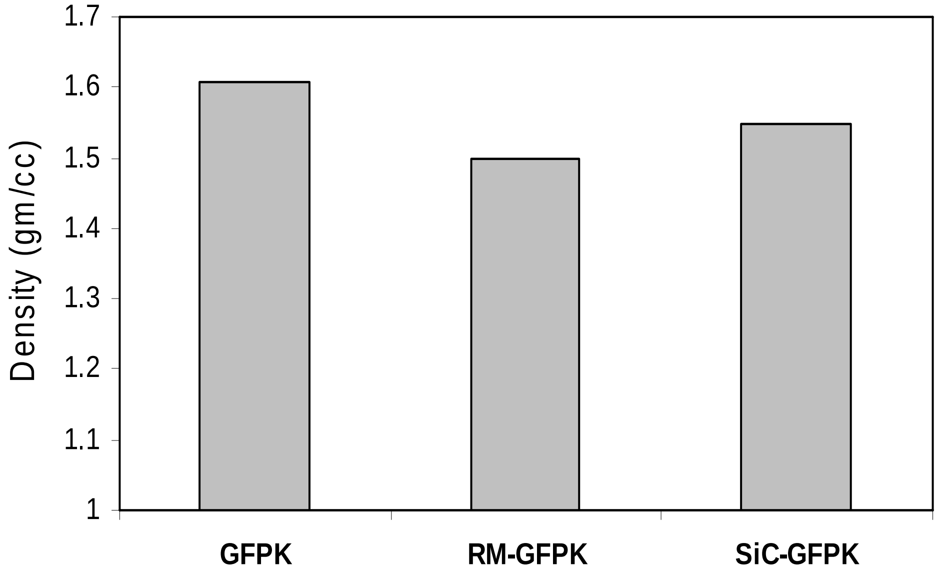

Fig 4.1 Comparison of density of unfilled and filled PEEK-GF composites

composites RM-GFPK and SiC-GFPK are found out to be 1.498 gm/cc and 1.547 gm/cc respectively. Fig. 4.1 presents the density comparison plot for the unfilled and filled PEEK-GF composites.

Evaluation of Tensile Strength

The tension test was performed on all the three composite samples following the ASTM D3039-76 test standards. A tension test is probably the most fundamental type of mechanical test that can be performed on the material under study. This test is simple, relatively inexpensive and fully standardized. By pulling on the composite, it can be known how the material would react to forces being applied in tension. In this work, the tensile strength values obtained for various composite specimens are presented in figure 4.2.

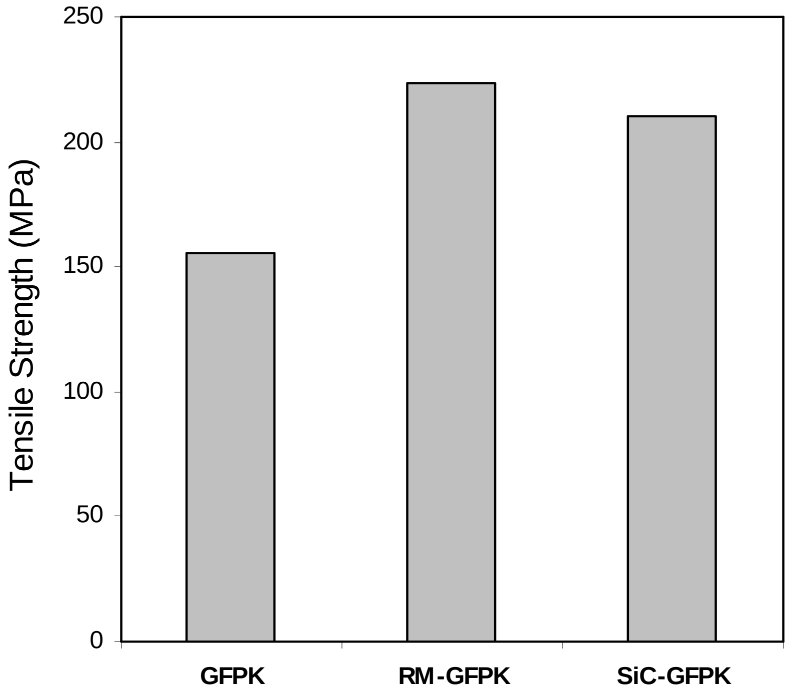

Fig. 4.2 Tensile strength of unfilled and filled PEEK-GF composites

It is seen that composite GFPK has a tensile strength of 155.5 MPa while composites RM-GFPK and SiC-GFPK have strength 223.5 MPa and 210.5 MPa respectively. The composite with red mud filling is found to have the maximum tensile strength among all types.

Evaluation of Flexural Strength

The flexural strength is a measure of resistance of the composite to bending. It is the ability of the material to withstand bending before reaching the breaking point. And the flexural modulus is the ratio, within the elastic limit, of the applied stress on a test specimen in flexure, to the corresponding strain in the outermost fibers of the specimen.

In the present work, three point bend test was conducted for all the three composites samples following the ASTM D3039-76 test standards. The flexural strength and flexural modulus for each of them was evaluated. The flexural strength and the flexural modulus values obtained for various composite specimens are shown in figure 4.3 and 4.4.

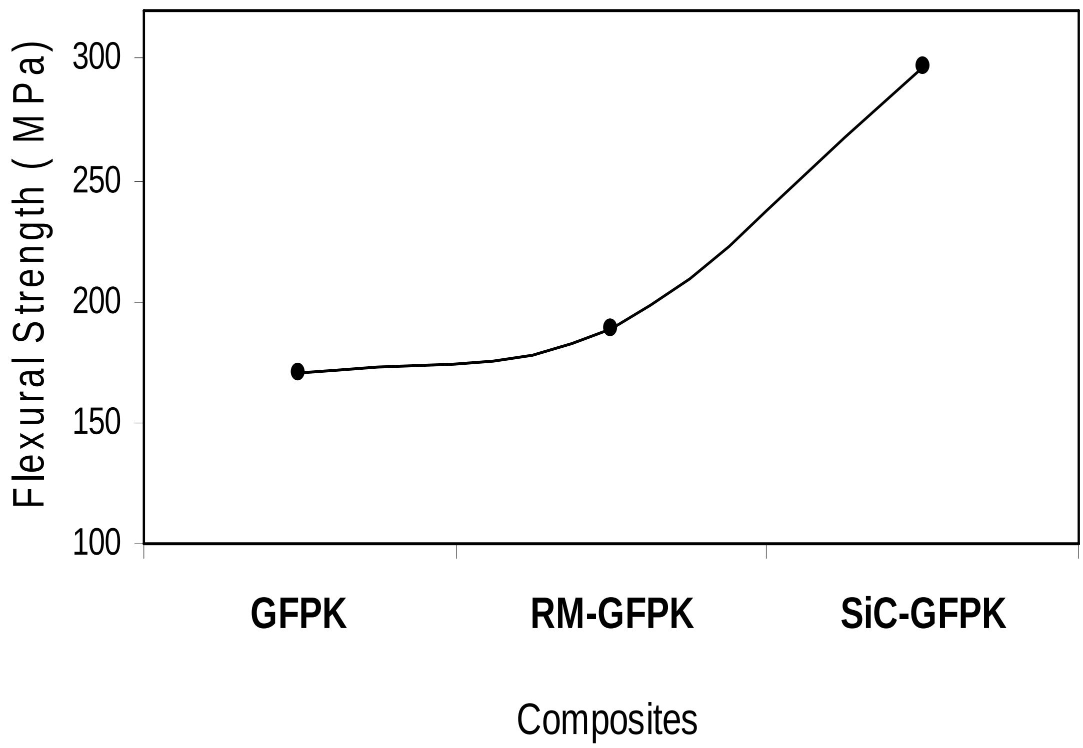

Fig. 4. 3 Flexural strength of unfilled and filled PEEK-GF composites

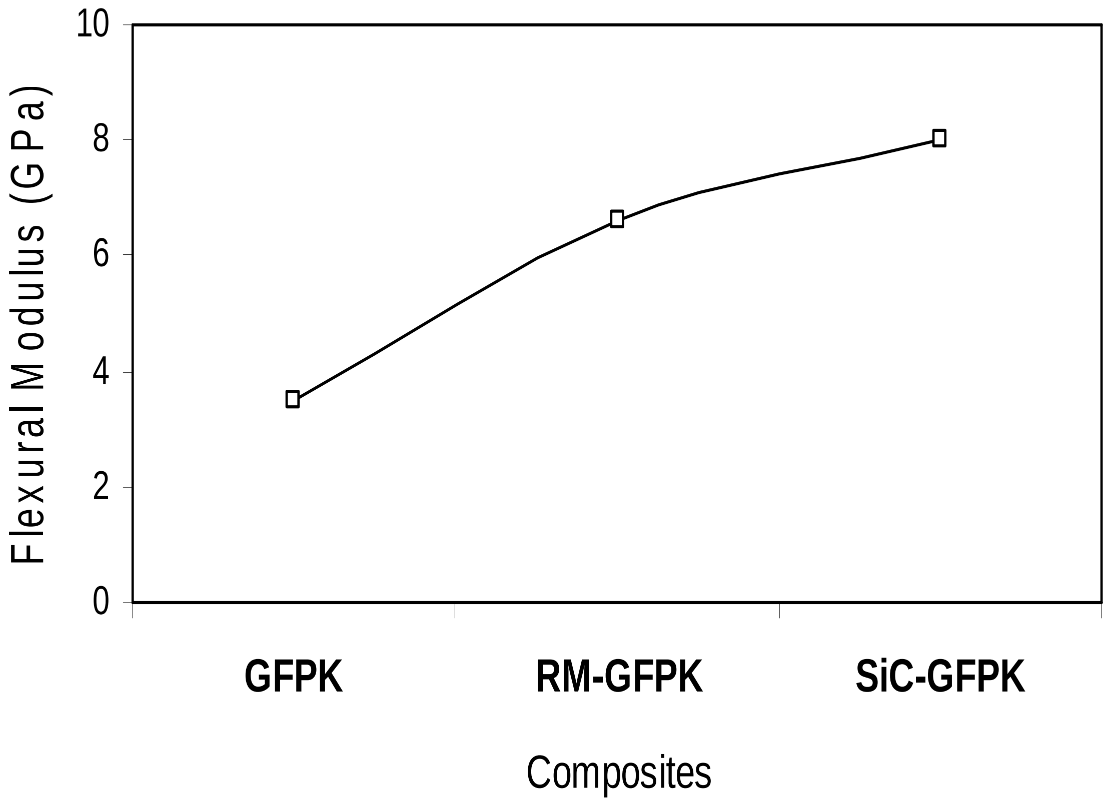

Fig. 4. 4 Flexural Modulus of unfilled and filled PEEK-GF composites

Microhardness Measurement

Micro-hardness measurement was made using Leitz Micro-hardness Tester equipped with a monitor and a microprocessor based controller, with a load of 0.25N and a loading time of 20 seconds. About ten or more readings were taken on each sample and the average value is reported as the data point.

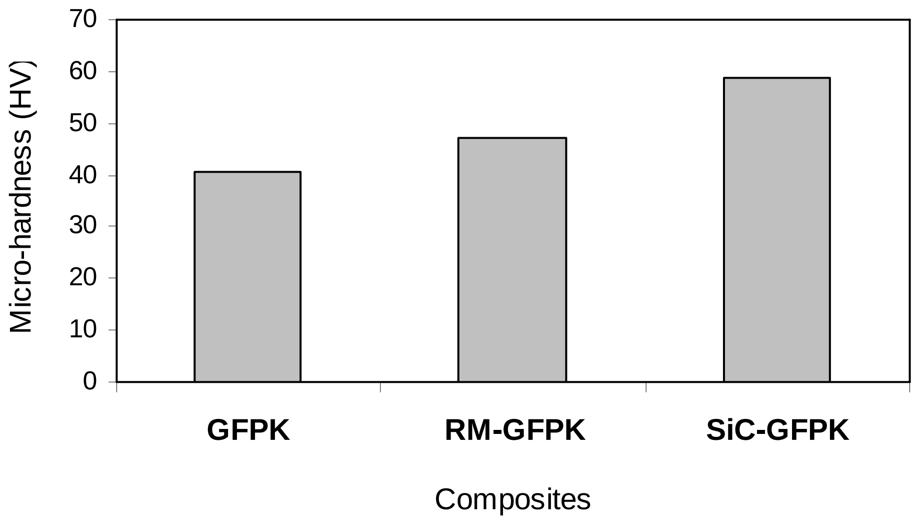

Fig. 4. 5 Micro-hardness of unfilled and filled PEEK-GF composites

The hardness values of different composites under investigation in the present work are shown in fig 4.5.

DISCUSSION:

The composites GFPK, RM-GFPK and SiC-GFPK are found to have different density. The fiber content and the ceramic filler content in the composites affect their density which is obvious. The composite with red mud filling is the lightest among them and the unfilled PEEK-GF composite has the maximum density. It is evident that addition of filler material (low density ceramics) is beneficial as it makes the composite lighter and more suitable for applications like aerospace and marine units, where exceptional performance is required but weight is critical.

Tensile strength measures the force required to pull something such as a structural beam to the point where it breaks. The addition of fillers enhances the tensile strength of the composites. Flexural modulus is the ratio, within the elastic limit, of the applied stress on a test specimen in flexure, to the corresponding strain in the outermost fibers of the specimen. The Flexural test measures the force required to bend a beam under three point loading conditions. The data is often used to select materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material's stiffness when flexed. Since the physical properties of many materials (especially thermoplastics) can vary depending on ambient temperature, it is sometimes appropriate to test materials at temperatures that simulate the intended end use environment.

In composite making, formation of air bubbles and voids is practically unavoidable. The voids not only reduce the stress bearing area but also act as stress raisers, which initiate the cracks. This affects the hardness of the composite. In this work, it is seen that addition of red mud and silicon carbide improves the micro-hardness of unfilled PEEK-GF. This improvement may be attributed to the high hardness values of filler materials and also to the possible reduction in number of voids with filling of these solid particulates. The micro-hardness of filled GFPK is also by the degree of crystallinity, since crystalline phases are harder than glassy phases.

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Chapter 5

TRIBOLOGICAL EVALUATION: RESULTS & ANALYSIS

CHAPTER 5

TRIBOLOGICAL EVALUATION: RESULTS AND ANALYSIS

INTRODUCTION

Polymers and their composites have generated wide interest in various engineering fields, particularly in aerospace applications, in view of their good strength and low density as compared to monolithic metal alloys. Still, the erosion wear characteristics of polymers and their composites have not been investigated to the same extent as for metals or ceramics. The erosion behavior of polymer matrix composites is of great importance in many applications rather than their mechanical properties. Hence, needs arise to study erosion behavior of polymer matrix composites exhaustively before recommending for use.

Solid particle erosion is defined as the progressive loss of original material from a solid surface due to mechanical interaction between that surface and solid particles.

This chapter reports the experimental findings obtained during the erosion test on the composites under study. Erosion trials were made under various test conditions and the resulting erosion wear rates were recorded. The experimental results are analyzed using Taguchi method and the significant parameters affecting material erosion have been identified. The results of the Taguchi analysis are also presented here.

TRIBOLOGICAL EVALUATION: EROSION TEST RESULTS

Different composites respond to solid particle erosion differently. They are affected largely by the reinforcing material, main matrix resin, the erodent material and also by the operational variables like impact angle, velocity, stand-off distance etc.

Influence of Erodent Dose on Wear Rate

With the advancement of exposure time, the cumulative mass of eroding particles hitting the target (composite surface) increases and the resulting mass loss from the composite material also increases. This causes a variation in the rate of wear. This variation is shown in figures 5.1 to 5.5 for different erosion trials for the erodent (500 micron size) impacting the composite surface with a velocity of 58 m/s at different impact angles (30^0, 45^0, 60^0,75^0 and 90^0) . It is seen that the erodent dose to achieve steady state value varies with the target material. Moreover, the nature of the erosion curves also varies from material to material. For a particular composite the wear rate shows either an increasing or a decreasing trend initially but with increase in the cumulative weight of erodent it finally attains an almost steady value.

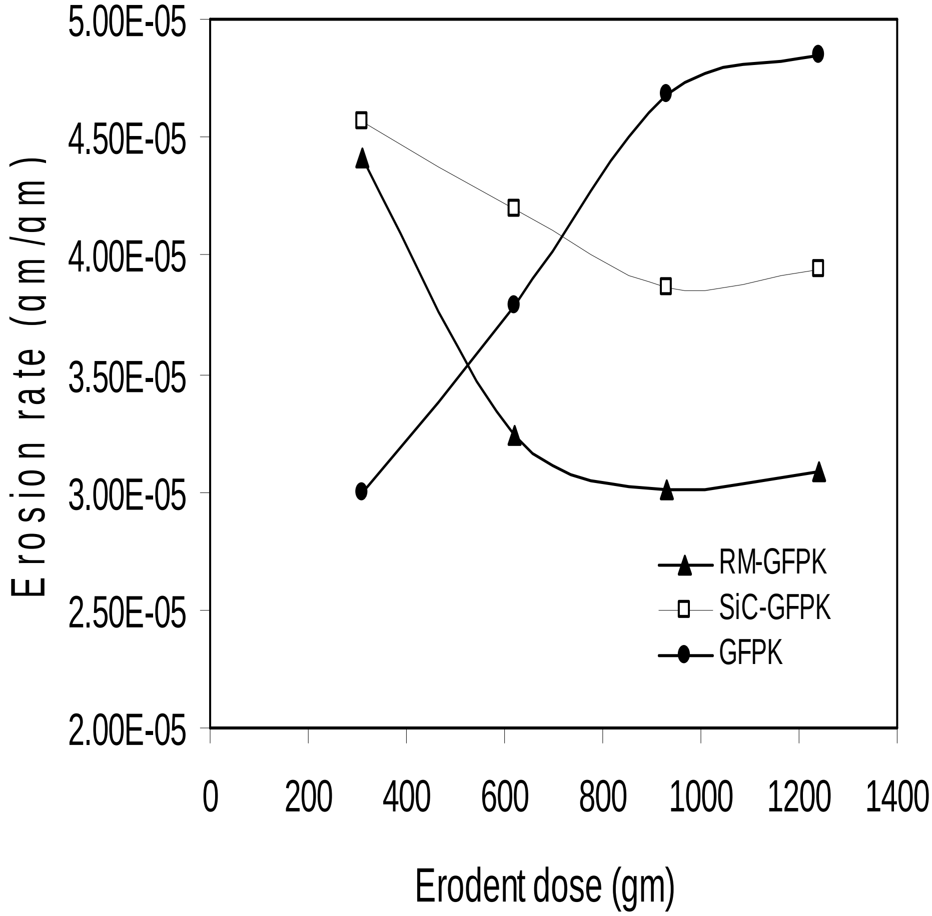


Fig. 5.1 Variation of erosion rate with erodent dose (impact angle 30^0 and velocity 58 m/s)

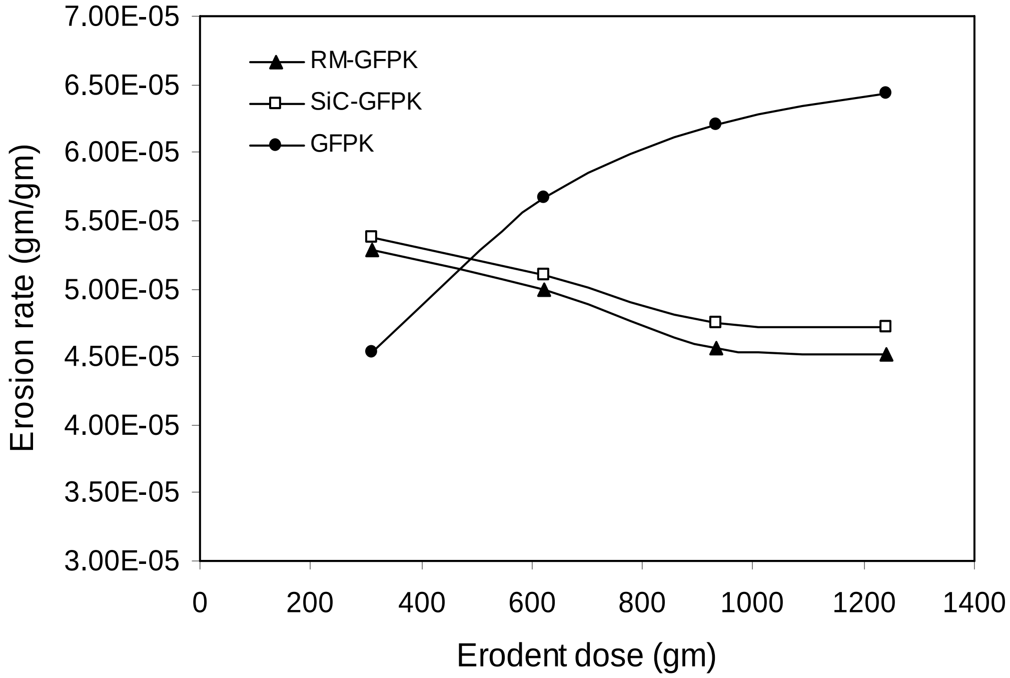


Fig. 5.2 Variation of erosion rate with erodent dose (impact angle 45^0 and velocity 58 m/s)

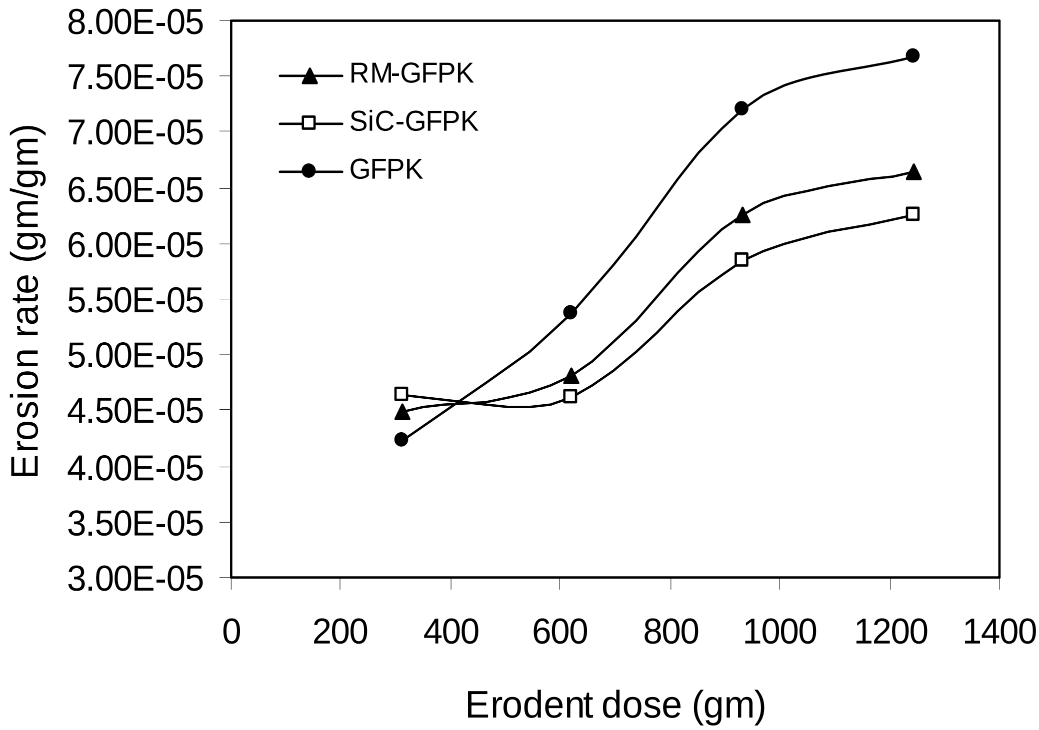


Fig. 5.3 Variation of erosion rate with erodent dose (impact angle 60^0 and velocity 58 m/s)

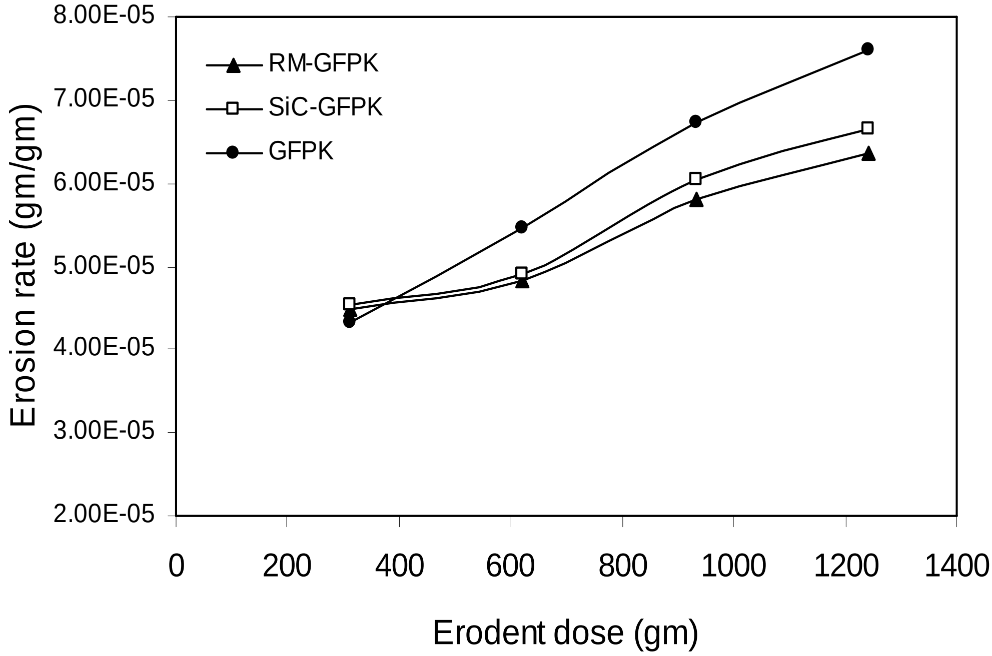


Fig. 5.4 Variation of erosion rate with erodent dose (impact angle 75^0 and velocity 58 m/s)

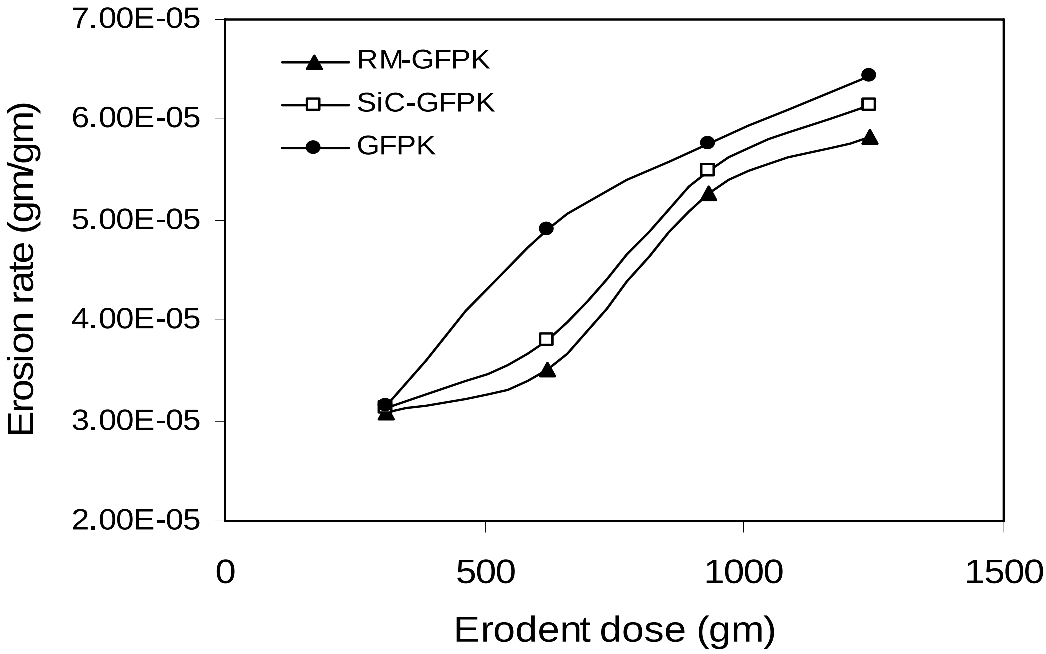


Fig. 5.5 Variation of erosion rate with erodent dose (impact angle 90^0 and velocity 58 m/s)

The erosion response of the composites to the weight of erodent is seen to be sigmoidal in nature in most of the cases. The curves show regimes of acceleration, peaking, deceleration and stabilization. Most of the curves have the trend similar to the behaviour of a typical brittle material in which the erosion rate increases with increase in the erodent dose.

It is interesting to note that the erosion rate of unfilled composite is higher than those in case of filled ones. Further it is seen that red mud filled composite suffers less erosion wear compared to silicon carbide filled composite under similar test conditions. Silicon carbide being harder than red mud, this trend is unexpected. This result needs a detailed investigation.

Influence of Angle of Impingement on Wear Rate

The influence of impact angle on erosion rate is evident in fig. 5.6. It is seen that as the angle of impact increases the wear rate also increases and reaches the maximum when the angle of impact is 60^0 . For all the three composites the variation of erosion rate with impact angle is showing similar trend. Initially with increase in the impingement angle the rate of erosion increases, reaches a peak value and with further increase in angle the wear rate decreases. In all the cases the minimum erosion was recorded at impact angle 30^0 followed by that at normal impact (90^0).

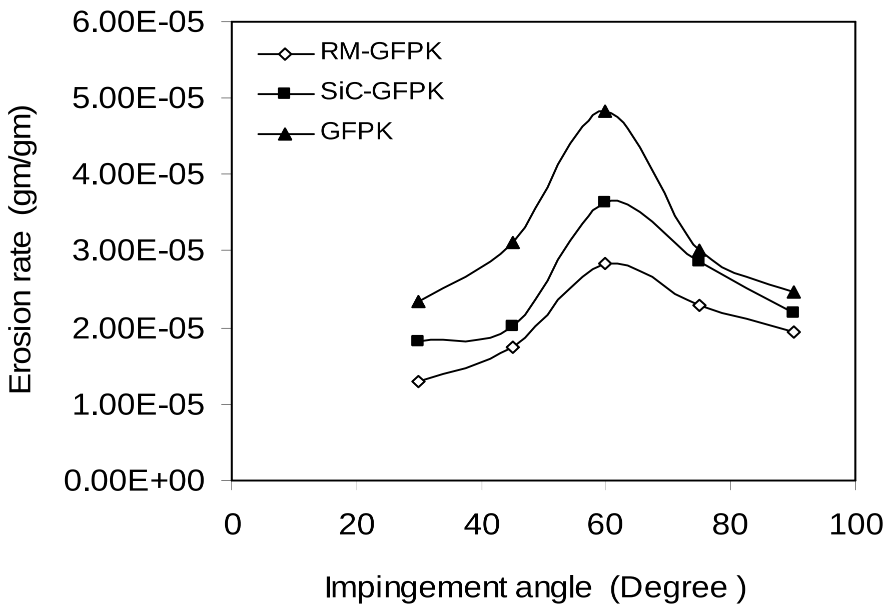


Fig. 5.6 Variation of erosion rate with impingement angle at velocity 58 m/s.

It is known that impingement angle is one of the most important parameters influencing the erosion of materials subjected to solid particle impact. In the erosion literature, materials are broadly classified as ductile or brittle based on the dependence of their erosion rate on impingement angle. The behaviour of ductile materials is characterized by maximum erosion rate occurring at low impingement angles (15^0 to 30^0). Brittle materials on the other hand show maximum erosion under normal impact angle (90^0). The unfilled and filled glass fiber reinforced PEEK composites considered in this work are exhibiting a somewhat semi-ductile behaviour with the peak erosion occurring at 60^0. This may be attributed to the ductile nature of the matrix material poly-ether-ether-ketone and brittle nature of glass and reinforcing ceramics.

The angle of impact is a major operational parameter influencing the erosion rate of the target material. This angle determines the relative magnitude of the two velocity component; one normal to the surface and the other, 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 contact time (t_c) and the tangential 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 as does the nature and magnitude of the stress system. Both of these aspects influence the way a material wears. These changes imply that different types of material would exhibit different angular dependency.

Effect of Impact Velocity

The velocity of the erosive particles has a very strong effect on erosion rate. In order to study the effect of particle impact velocity on erosion rate, tests were performed by varying the particle velocity from 32 to 58 m/s at impingement angles of 30^0 - 90^0. Fig. 5.7 presents the dependence of erosion wear rate of the composites on impact velocity.

It is observed that with increase in the velocity of impact the erosion rate is also increasing in an exponential fashion. The trend is similar for all the three types of composites under study. It is further seen that the wear rate is least for red mud filled glass reinforced poly-ether-

ether-ketone composite. The unfilled composite suffers the maximum erosion. This leads to the conclusion that ceramic fillers improve the erosion resistance of polymer matrix composites to a reasonable extent.

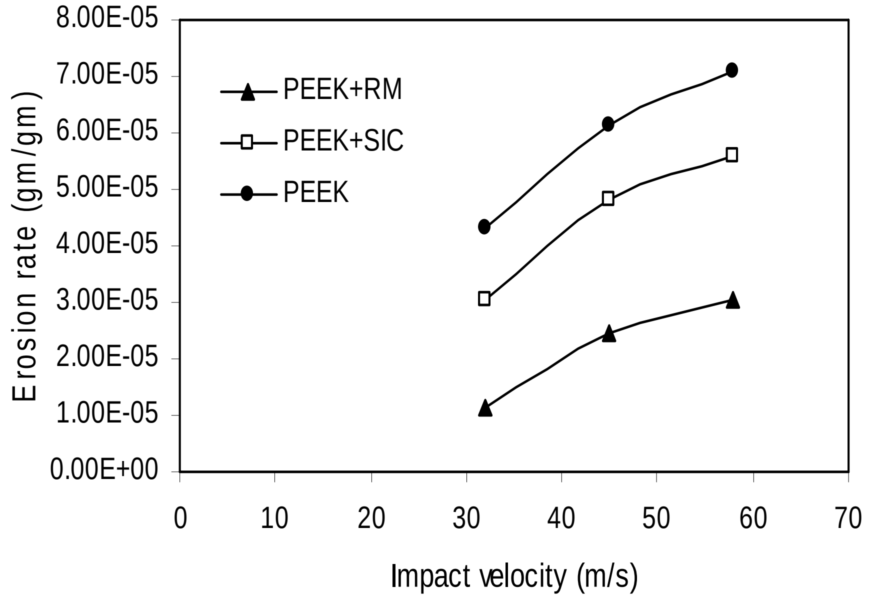


Fig. 5.7 Variation of erosion rate with impact velocity at impingement angle 60^0

The experimental findings suggest that the velocity of the erosive particles has a very strong effect on erosion rate. It was found that the erosion rate follows power law behaviour with particle velocity. This relationship can be written as follows:

$$E = kV^n$$

E is the steady-state erosion rate,

V the impact velocity of particles,

n a velocity exponent , and

k a constant.

The velocity exponent in the present work was found out to be in the range of 1.50–1.70 .

Surface Morphology of Eroded Surface

In general, thermoplastic matrix composites exhibit a ductile erosive wear with plastic deformation, ploughing and ductile tearing being the usual damage mechanism.

Thermosetting matrix composites erode in a brittle manner (generation and propagation of surface lateral cracks). However, this failure classification is not definitive because the erosion behaviour of composites depends strongly on their compositions as well as on the experimental conditions. The impingement angle is also one of the most important parameters in deciding the erosion behaviour. Study of microstructure of the eroded surfaces gives an insight to the wear mechanism.

Fig. 5.8 shows the worn surface of the composite GFPK eroded at an impingement angle of 60^0 and an impact velocity of 58 m/s. It can be seen from the micrograph that, when impacting at certain angle to the normal direction, the hard erodent particles can penetrate the surfaces of the samples and cause material removal by micro-cutting and microploughing. This indicates plastic deformation and micro cracking as the dominant wear mechanisms.

Figures 5.9 (a), (b) and (c) show micrographs of eroded composites GFPK, RM-GFPK and of SiC-GFPK respectively under similar experimental conditions. Repeated impact of the erodent caused roughening of the surface of the material. In the unfilled polymer composite, fig.5.9 (a), the erosion seems to have occurred mostly due to plastic deformation. While in the filled composites, fig.5.9 (b) and (c), signs of fracture are visible. In these micrographs, erosion along the fibers and clean removal of the matrix to expose the fibers is also seen. The matrix shows multiple fractures and material removal. The exposed fibers are seen to have broken into fragments.

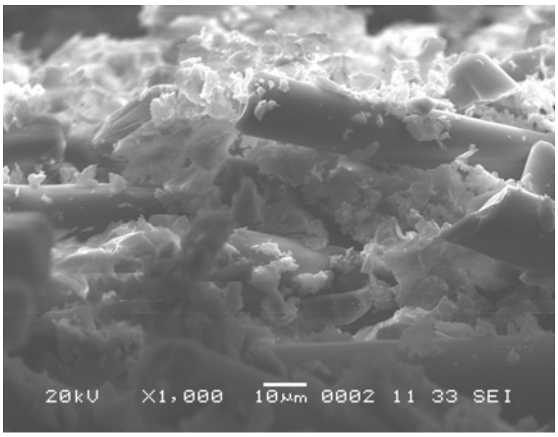
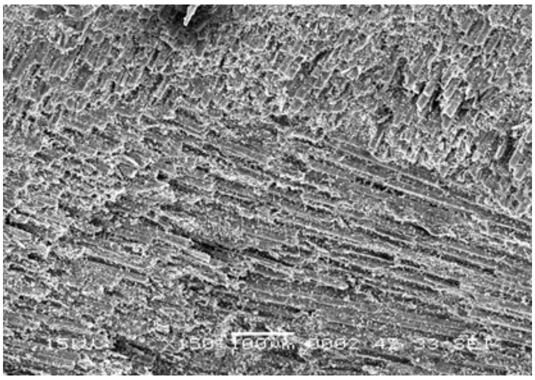
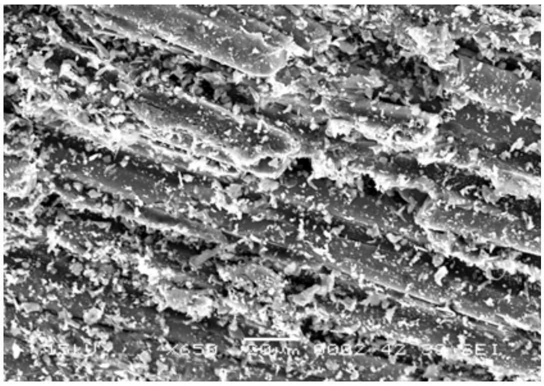


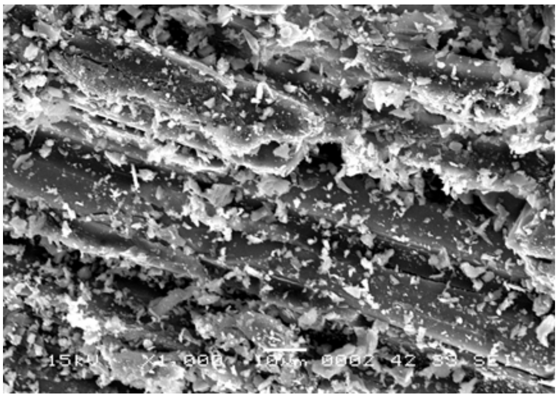
Fig. 5.8 SEM microstructure of eroded GFPK surface (impact angle 60^0, velocity 58 m/s)



(a)

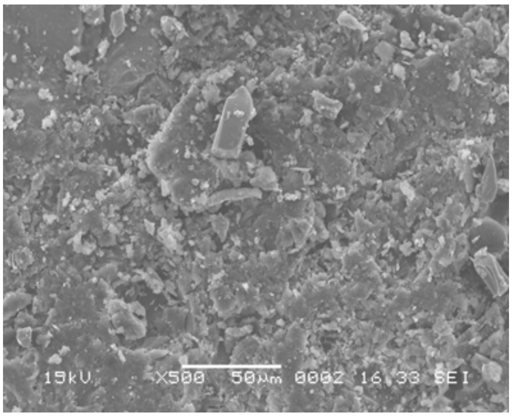


(b)

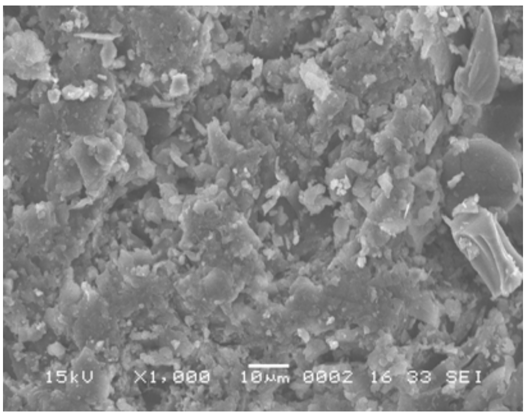


(c)

Fig. 5. 9 SEM microstructures of eroded composite surfaces
(impact angle 60^0, velocity 58 m/s)



(a)



(b)

Fig. 5.10 SEM microstructure of eroded SiC-GFPK surface
(impact angle 60^0, velocity 58 m/s)

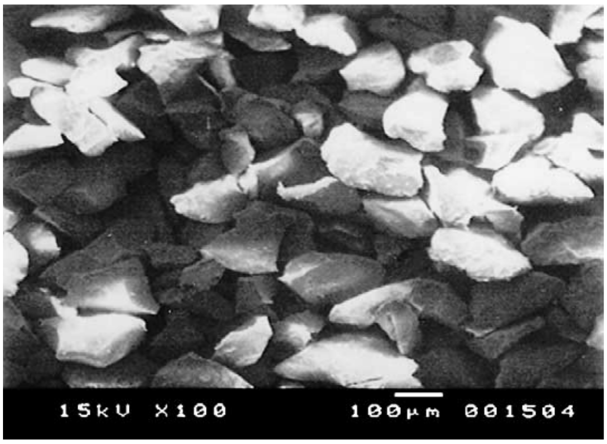


Fig. 5.11 Scanning electron micrograph of dry silica sand, the erodent

Fig. 5.10 (a) and (b) show micrographs of surfaces of SiC-GFPK composite eroded at an impingement angle of 60^0 and with an impact velocity of 58 m/s. The micrographs show micro cracking as the dominant failure mechanism. PEEK is a ductile polymer. However, the failure mechanism does not reflect any ductility; instead a brittle failure appearance is reflected in the micrographs. Fig. 5.11 shows the SEM micrograph of the erodent particles. The angular shape of the sand particles penetrate very easily in to the soft polymer matrix. The continuous impact of sand particles on the composite surface resulted in local removal of matrix and hence fibers protruded out of the matrix phase.

TAGUCHI EXPERIMENTAL DESIGN

Taguchi method of experimental design is a simple, efficient and systematic approach to optimize designs for performance and cost. In the present work, this method is applied to the process of erosion of unfilled and filled poly-ether-ether-ketone-glass fiber composites for identifying the significant process variables influencing solid particle erosion rate. The levels of these factors are also found out so that the variables can be optimized within the test range.

Experimental Design

Design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors over the performance output. The most important stage in the design of experiment lies in the selection of the control factors. As many factors as possible should be included, so that it would be possible to identify non-significant variables. Since the erosion tests, in the present work, were performed under room conditions, the temperature and humidity effects on wear rate were not studied. Four parameters and three levels for each parameter were chosen. From the consideration of these experimental conditions, a pre-designed orthogonal array developed by Taguchi was used in this study. Each row represents the test conditions and the column represents test parameters and their levels for each. A full factorial experiment would have required at least $3^4 = 81$ runs. On the other hand, the Taguchi experimental design approach reduces the requirement to just 27 runs and hence offers a great advantage in terms of experimentation time and cost. Experiments were carried out to investigate the influence of the four selected control parameters. The code and levels of control parameters are shown in table 5.1. This table shows that the experimental plan has three levels. A standard Taguchi experimental plan with notation L_9 is chosen as outlined in table-5.2. In this method, experimental results are transformed into a signal-to-noise (S/N) ratio. It uses the S/N ratio as a measure the quality characteristics deviating from or nearing to the desired values. There are three categories of quality characteristics in the analysis of the S/N ratio, i.e. the lower-the-better, the higher-the-better, and the nominal-the-better. The three categories are given by equations 1- 3.

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

Nominal the better characteristics: $$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum \frac{\bar{Y}}{S_Y^2}\right) \quad (2)$$

Larger the better characteristics : $$\frac{S}{N} = -10 \log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \quad (3)$$

where $\bar{Y}$ is the average of observed data, S_Y^2 the variation of y, n the number of observations, and y the observed data. "smaller is better" characteristic with the above S/N ratio transformation is suitable for minimization of erosion rate.

Control factor		**Level I**	**Level II**	**Level III**	**Units**
A	Impact velocity	32	45	58	m/sec
B	Impact angle	30	60	90	degree
C	Erodent size	300	500	800	micron
D	Stand-off Distance	120	180	240	mm

Table 5.1 Control factors and selected test levels

The plan of the experiments is as follows: the first column was assigned to impact velocity (A), the second column to impingement angle (B), the third column to erodent size (C) and fourth column to stand-off distance (D). The analysis was made using the popular software ***MINITAB 14*** specifically used for DOE.

Run	A (Vel)	B (Angle)	C (Size)	D (SOD)	E (Ero.Rate)	S/N Ratio
1	32	30	300	120	7.218	-17.1683
2	32	60	500	180	8.749	-18.8392
3	32	90	800	240	36.070	-31.1429
4	45	30	500	240	8.455	-18.5423
5	45	60	800	120	6.492	-16.2476
6	45	90	300	180	5.937	-15.4713
7	58	30	800	180	11.870	-21.4890
8	58	60	300	240	4.607	-13.2684
9	58	90	500	120	12.350	-21.8333

Table 5.2 Experimental layout (L_9 Array) and results with calculated S/N ratios for erosion rate of composite GFPK

Level	A	B	C	D
	Velocity	Angle	Erodent Size	SOD
1	-22.38	-19.07	-15.30	-18.42
2	-16.75	-16.12	-19.74	-18.60
3	-18.86	-22.82	-22.96	-20.98
Delta	5.63	6.70	7.66	2.57
Rank	**3**	**2**	**1**	**4**

Table 5.3 The S/N ratio response table for composite GFPK

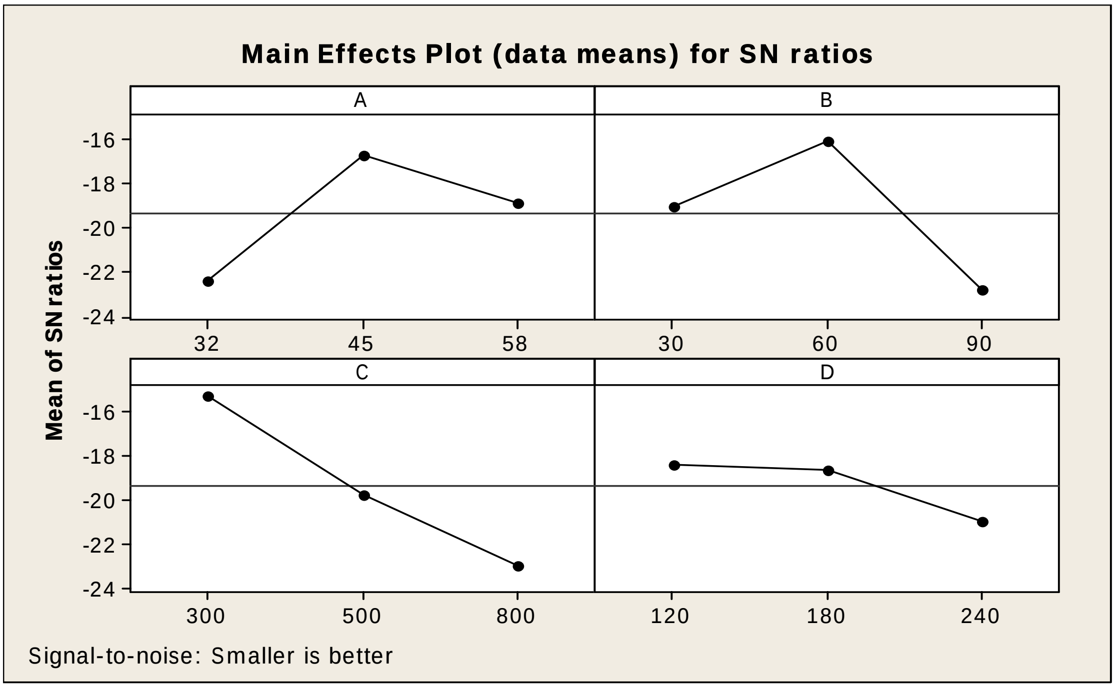


Fig. 5.13 The S/N ratio response graphs for erosion rate of composite GFPK

The S/N ratio response table for erosion rate of composite GFPK and the corresponding response graphs are shown in table 5.3 and Fig.5.13 respectively.

Run	A	B	C	D	E	S/N Ratio
	(Vel)	(Angle)	(Size)	(SOD)	(Ero.Rate)	
1	32	30	300	120	0.22346	13.0160
2	32	60	500	180	5.44410	-14.7185
3	32	90	800	240	5.59200	-14.9513
4	45	30	500	240	4.68050	-13.4058
5	45	60	800	120	9.24010	-19.3135
6	45	90	300	180	0.12317	18.1899
7	58	30	800	180	6.07340	-15.6686
8	58	60	300	240	9.65920	-19.6988
9	58	90	500	120	4.91200	-13.8252

Table 5.4 Experimental layout (L_9 Array) and results with calculated S/N ratios for erosion rate of composite RM-GFPK

Level	A	B	C	D
	Velocity	Angle	Erodent Size	SOD
1	-5.551	-5.353	3.836	-6.708
2	-4.843	-17.910	-13.983	-4.066
3	-16.998	-3.529	-16.645	-16.019
Delta	11.954	14.381	20.480	11.253
Rank	**3**	**2**	**1**	**4**

Table 5.5 The S/N ratio response table for composite RM-GFPK

Nine test trials were made and the erosion rate for each trial was found out. This was repeated for all the three composites GFPK, RM-GFPK and SiC-GFPK. The experimental layout (L_9 Array) and results with calculated S/N ratios for erosion rate of composite

RM-GFPK and SiC-GFPK are shown in table 5.4 and 5.6 respectively. Similarly, the S/N ratio response tables and the corresponding S/N ratio response graphs for erosion rate of composites RM-GFPK and SiC-GFPK GFPK are given in table 5.5, table 5.7 and fig. 5.14 and fig.5.15 respectively.

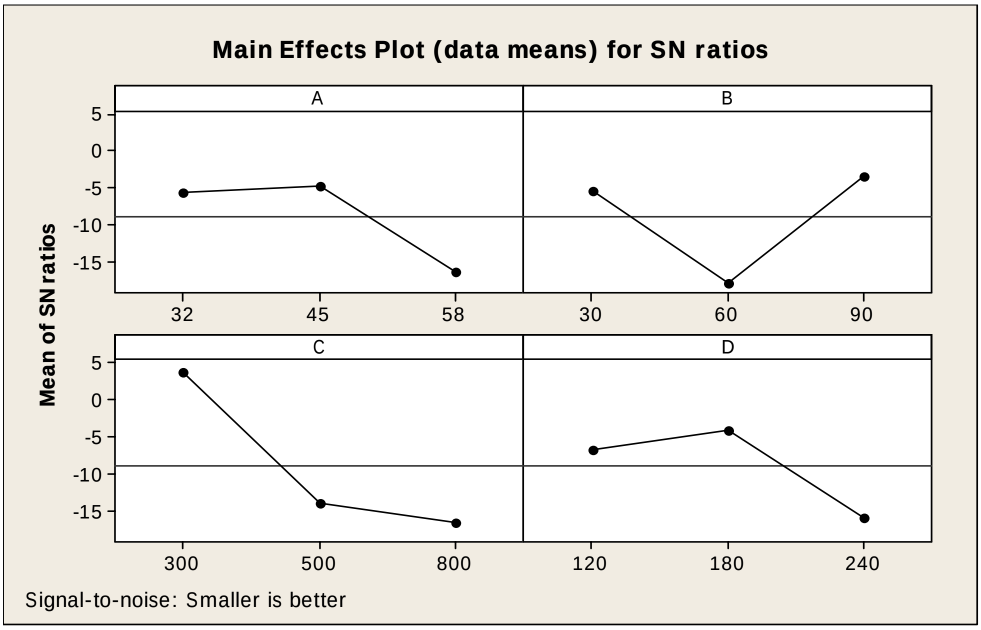


Fig. 5.14 The S/N ratio response graphs for erosion rate of composite RM-GFPK

Run	A (Vel)	B (Angle)	C (Size)	D (SOD)	E (Ero.Rate)	S/N Ratio
1	32	30	300	120	0.21640	13.2949
2	32	60	500	180	5.22400	-14.3601
3	32	90	800	240	5.43200	-14.6992
4	45	30	500	240	4.61200	-13.2778
5	45	60	800	120	9.12300	-19.2028
6	45	90	300	180	0.11360	18.8924
7	58	30	800	180	6.01230	-15.5808
8	58	60	300	240	9.64521	-19.6862
9	58	90	500	120	4.91230	-13.8257

Table 5.6 Experimental layout (L_9 Array) and results with calculated S/N ratios for erosion rate of composite SiC-GFPK

Level	A Velocity	B Angle	C Erodent Size	D SOD
1	-5.050	-5.188	4.167	-6.578
2	-4.529	-17.750	-13.821	-3.683
3	-16.964	-3.211	-16.494	-14.888
Delta	11.910	14.539	20.661	11.205
Rank	**3**	**2**	**1**	**4**

Table 5.7 The S/N ratio response table for composite SiC-GFPK

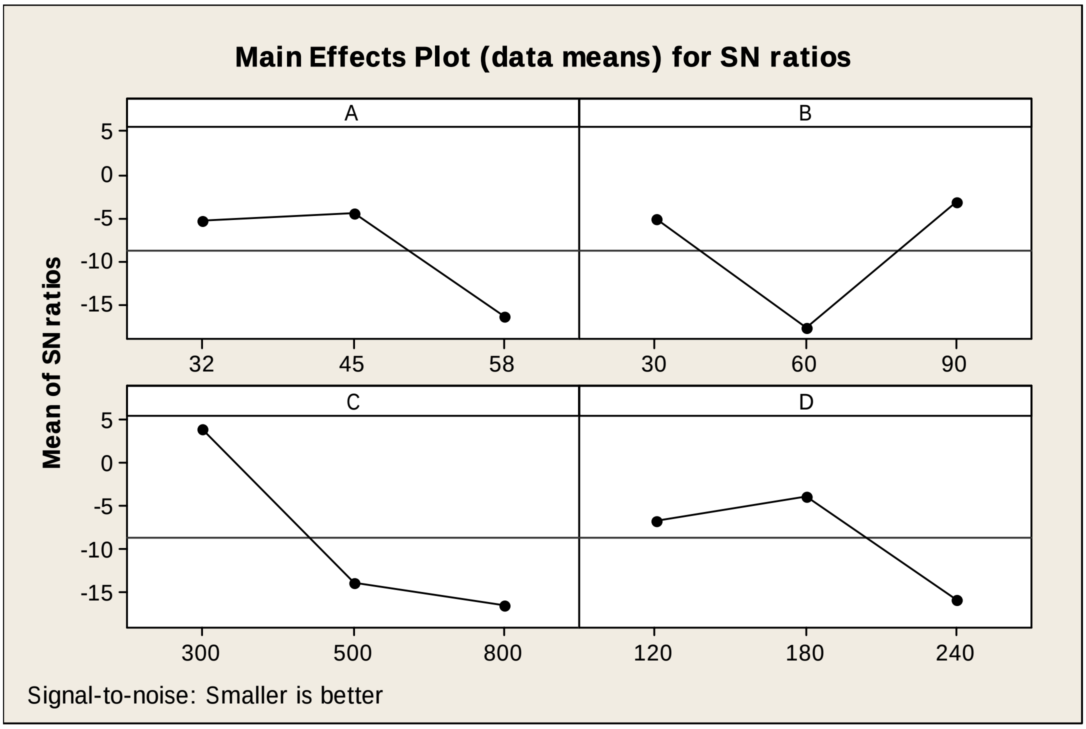


Fig. 5.15 The S/N ratio response graphs for erosion rate of composite SiC-GFPK

ANALYSIS

The S/N ratio response tables rank the control parameters as per their individual influence on a particular performance output in a Taguchi experimental scheme. The control factor with the strongest influence is determined by the difference (delta) values. The higher the difference, the more influential is the control factor.

As indicated in response table 5.3, the strongest influence on erosion wear rate of glass reinforced poly-ether-ether-ketone composite GFPK is of the erodent size (C) followed by angle of impact (B) and impact velocity (A). Out of the four control factors selected for this analysis, the fourth one i.e. the stand-off-distance (D) comes out to be the least significant factor.

It is interesting to note that when this analysis is done for the other two particulate filled composites, the results are found to be surprisingly similar to those obtained for unfilled composite. The erodent size, here also, emerged as the most significant factor affecting the erosion rates of the red mud and silicon carbide filled glass reinforced poly-ether-ether-ketone composites. The impact angle and impact velocity, in that order, are found to be the other two significant control factors. Although stand-off distance is identified as the least significant factor, it cannot be neglected because it may show significant interaction with other factors. However, the influence of interactions (among the control factors) is not included within the scope of this analysis.

Functional composites have to fulfill various requirements. The erosion response is one the main requirements of these materials when they are used as structural members or in engineering components. It represents the workability and the durability of the composite in operation. In order to optimize the operational life and for component design improvement the influence parameters of the process are to be known. Apart from Taguchi approach, methods like neural computation can also be employed for precise identification of significant control parameters for optimization and prediction within a parameter space larger than the domain of experimentation.

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Chapter 6

CONCLUSIONS

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Based on the analysis of experimental results and findings the following conclusions can be drawn:

1. Reinforcement of glass fiber into the poly-ether-ether-ketone (PEEK) matrix improves the flexural strength quite significantly, thus making it a potential material for structural applications.

2. Addition of red mud and silicon carbide to glass fiber reinforced poly-ether-ether-ketone composites further improves the flexural strength, flexural modulus and tensile strength of the material.

3. Addition of these fillers is leading to reduction of density and subsequently the strength to weight ratio of the composites.

4. Glass fiber reinforced poly-ether-ether-ketone composites filled with red mud and silicon carbide powders exhibit much better resistance to solid particle erosion in comparison to the un-filled composite.

5. The rate of wear of the composite material is also greatly influenced by operational variables like impact angle, velocity of impact, stand-off distance etc. and material variables like erodent size and composition of composites.

6. All the filled as well as unfilled glass fiber reinforced poly-ether-ether-ketone composites exhibited maximum erosion rate at an impingement angle of 60^0 under similar experimental conditions.

7. An analysis using Taguchi experimental design approach suggests that the erodent size plays the most significant role in erosive wear of these composites. The angle of impact

and the impact velocity are other major influencing factors. Stand-off distance has the least effect on the erosion rate.

SCOPE FOR FUTURE WORK

Tribological evaluation of polyether-ether-ketone matrix composite has been a much less studied area. There is a very wide scope for future scholars to explore this area of research. Many other aspects of this problem like effect of fiber orientation, loading pattern, weight fraction of ceramic fillers on erosion response of such composites require further investigation.

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