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Solid particle erosion wear characteristics of fiber and particulate filled polymer composites: A review

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ABSTRACT

The solid particle erosion behaviour of fiber and particulate filled polymer composites has been reviewed. An overview of the problem of solid particle erosion was given with respect to the processes and modes during erosion with focus on polymer matrix composites. The new aspects in the experimental studies of erosion of fiber and particulate filled polymer composites were emphasised in this paper. Various predictions and models proposed to describe the erosion rate were listed and their suitability was mentioned. Implementation of design of experiments and statistical techniques in analyzing the erosion behaviour of composites was discussed. Recent findings on erosion response of multi-component hybrid composites were also presented. Recommendations were given on how to solve some open questions related to the structure-erosion resistance relationships for polymers and polymer based hybrid composites.

1. Introduction

1.1. Solid particle erosion in general

Wear is damage to a solid surface usually involving progressive loss of materials, owing to relative motion between the surface and a contacting substance or substances. It is a material response to the external stimulus and can be mechanical or chemical in nature. The effect of wear on the reliability of industrial components is recognised widely and the cost of wear has also been recognised to be high. Systematic efforts in wear research were started in the 1960s 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.

Solid particle erosion, a typical wear mode, is the loss of material that results from repeated impact of small, solid particles. It 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 the fluid can change their directions of motion. The effects of solid particle erosion have been recognized for a long time. In some cases solid particle erosion 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 systems. It is a quite complex phenomenon, since it involves several processes. Although the main process is the mechanical impact, caused by the impingement of solid particles on the target material, secondary processes, like thermal, chemical and physical reactions between the counterparts are taking place during erosion. 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 in aircraft gas turbine/compressor blades, in rocket motor tail nozzles, and in boiler tubes exposed to fly ash.

It was recognized quite early that correlation is needed between the experimental conditions and the erosive response of the tested materials. Thus, Tilly [1] presented a thorough analysis of the various parameters affecting erosion, including particle properties, impact parameters, particle concentration, material temperature

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and tensile stress. He also reviewed the different mechanisms of erosion, which were categorized into brittle and ductile behaviors. Ruff and Wiederhorn [2] 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 [3] reported a more comprehensive review of the fundamentals of fluid motion and erosion by solid particles. The review included 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. Soderberg et al. [4,5] and Hutchings [6,7] reported the advantages and disadvantages of such experiments. The recent experimental study by McLaury et al. [8] 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. [9] 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. [10] 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. After many years of research Finnie [11] reviewed in 1995 the influencing parameters and dominating mechanics during solid particle erosion of metals and ceramic materials. The same year, Meng and Ludema [12] tried to approach the subject of erosion from the modelling point of view by providing information about the existing wear models and prediction equations. This article discussed all the frictional phenomena termed to wear including also the solid particle erosion. The main conclusion of this publication was that no universal predictive equation exists.

1.2. Polymer matrix composites

In the early years, priority was given on the investigation of the erosive wear of conventional materials. However, the subject of erosion of polymer matrix composites has received substantial attention over the past four 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 [13–20] where durability is a prime consideration. Typical examples of dusty environments where polymer composites are applied are pipelines carrying sand, slurries in petroleum refining, helicopter rotor blades, pump impeller blades, high-speed vehicles and aircrafts, water turbines, aircraft engine blades, missile components, canopies, radomes, wind screens and outer space applications. Resistance to rain and sand erosion is called among the major issues in all the above applications and mainly in the defence application and wind turbine performance of non-metallic materials [16,21,22,23].

Composites are rather complex materials, mainly due to the anisotropy induced by the reinforcement. When polymer matrix composites are considered this complexity increases. The viscoelastic nature of the polymer matrix can be accountable for some if not all the aforementioned secondary modes during solid particle erosion. Differences in the erosion behaviour of various types of polymer matrix composites 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. Next to that the experimental conditions (impact angle, erodent velocity, erodent shape, erodent flux rate, etc.) have a great influence on the erosive response of the tested materials. Erosion tests have been performed under various experimental conditions (erodent flux conditions, erosive particle characteristics) on different target polymers and polymer matrix composites. Compared to metals, these materials present a rather poor erosion resistance with their erosion resistance being two or three orders of magnitude lower than that of metallic materials. A full understanding of the effects of all system variables on the wear rate is necessary in order to undertake appropriate steps in the design of machine or structural component and in the choice of materials to reduce/control wear.

Barkoula and Karger-Kocsis [24] presented in 2002 a review article on the solid particle erosion of polymers and polymeric composites focusing on the dominating mechanisms, the most discussed influencing parameters and the different trends observed in the literature. A detailed analysis was given on the effect of experimental conditions (erodent velocity, erodent characteristics, erodent flux rate) and target material characteristics (morphological-, thermal-, thermomechanical-, and mechanical-properties) on the erosive response of polymers and polymer matrix composites. Also empirical relationships that attempted to correlate the erosion rate with some of the influencing parameters were reviewed. Finally, averaging rules and predictions were summarized. Furthermore, Harsha et al. [25] and Tewari et al. [26] discussed in 2003 the solid particle erosion characteristics of various polyaryletherketone as well as carbon fiber and glass fiber epoxy composites. Although the purpose of these articles was not to review the state of the art in solid particle erosion of polymer matrix composites, both articles provided a good overview, and contained details on erosion experiments carried out on polymer matrix composites by various investigators [25,26]. Finally, Arjula and Harsha [27] studied the erosion efficiency of polymers and polymer composites. The erosion efficiency of these materials was plotted as a function of their hardness in order to create an erosion map. In this map a clear demarcation of elastomers, thermoplastic, thermosetting polymers and polymer composites is reflected. However, within the same group of materials a scatter is found in the efficiency map. Therefore, the erosion efficiency can be used only as base line for estimation of the erosion resistance of these materials.

From all these studies the general conclusion is that although a great amount of work has already been devoted to the topic of erosion, many questions are still open. In summary, the key issues behind these open questions are linked with the fact that the material removal during erosion is dependent on many interrelated factors, the combination of which sometimes exceeds 20 in number. This results in erosion rates that are peculiar to the specific sets of the testing conditions. Additional difficulties arise from the fact that the different processes occur simultaneously during erosion. Next to that, it is well accepted that none of the models proposed for conventional materials can be adopted to predict reliably the erosion behaviour of polymers and polymeric composites [12]. Extensive research is therefore needed to develop various methods and theoretical models for predicting erosion behaviour and its dependence on the proportion of the components and the composite-micro-structure, since it is not straightforward to perform experiments for all different combinations of the influencing factors.

1.3. Scope of current paper

Available reports on the research work carried out on erosion can be classified under three categories; experimental investigations, erosion model developments and numerical simulations. It is obvious from the analysis above that most papers focus on the first category while the second and third categories receive much less interest, most probably due to the increased complexity in developing erosion models and/or numerical simulations. In this paper the focus will be given into:

(a) Providing an overview on the problem of solid particle erosion of polymer matrix composites, with respect to the processes and modes during solid particle erosion of these materials.
(b) Reviewing the developments in the experimental investigations published after 2002 on the erosive wear of polymer matrix composites. Since the interest so far has been given on the erosive response of fiber matrix composites, this study will put effort into presenting the evolution in hybrid composites.
(c) Reviewing the developments in the model development, numerical simulations and predictions linked with erosive wear of polymer matrix composites.

2. Erosion modes and processes with focus on polymers and polymer matrix composites

Two erosion modes are often distinguished in the literature: brittle and ductile erosion depending on the variation in the erosion rate (ER) with impact angle. The impact angle is usually defined as the angle between the trajectory of the eroding particles and the sample surface. If ER goes through a maximum at intermediate impact angles, typically in the range 15°–30°, the response of the eroding material is considered ductile. In contrast, if ER continuously increases with increasing impact angle and attains a maximum at 90° (normal impact), the response of the eroding material is brittle. In addition, under ideally brittle erosion conditions the magnitude of ER is determined only by the normal component of the impact velocity, and the size of the eroding particle strongly influences the erosion rate [28].

In recent years, polyethylene (PE) has found increasing use in applications involving impact and erosion. Flat discs of the material were eroded by sieved sand accelerated by using an air blast rig in which the important variables of velocity, angle and mass flux rate are accurately controllable and measurable. Scanning electron microscopy of lightly eroded specimens enabled four basic crater types to be identified: smooth, ploughed, cut, and dented. The proportions of each were established over a range of angles. Long time erosion experiments were conducted in which the flux rate for each angle was adjusted to keep the number of impacts per unit time constant. The dimensionless erosion parameter, epsilon (mass lost per unit mass of erodent that has struck) was computed by using the rate of mass loss when steady state erosion had been established. Most erosion was found to occur at an angle of 20–30°, the mass loss becoming zero at around 80°. A range of techniques was used in this study including high-speed photography, scanning electron microscopy, and moire methods (both in-plane and out-of-plane). A deformation map was constructed for steel sphere impacts giving the type of crater to be expected at a given angle and speed. It was observed that sand grains required much lower speeds at a given angle to produce a given crater type. Transitions in the wear response of the target materials have been related into changes in the erodent characteristics, like shape, hardness or size of the erodents [24,29,30].

Different wear mechanisms can be recognized in the brittle and ductile erosion linked with material removal mechanisms ranging from tearing and fatigue for rubbers, through cutting and chip formation for ductile metals and polymers, to crack formation and brittle fracture for ceramics, glasses and brittle polymers [31]. Brittle erosion deals with material removal due to crack formation, while ductile erosion deals with material removal due to cutting and ploughing. The existing models of solid particle erosion treat ductile and brittle materials as separate and distinct, generating two basic theories. These include subsurface lateral crack propagation in brittle materials, and micro machining or damage accumulation and fatigue impact in ductile materials. Ibrahim [32] demonstrated that by separating and controlling the tangential and the normal velocity component of the erodent particles, the erosion characteristics of ductile, semi-ductile, and brittle materials appear to follow a common law. The materials respond in a similar manner under the same conditions of testing. Ibrahim [32] concluded that it is possible to unify the ductile and brittle models of solid particle erosion rates.

During this incubation period the weight of the target material first increases and then it reaches a steady state. The weight increase of the target material in the case of normal impact is related to the initial embedment of particle in the target surface. As the erosion at normal angles proceeds, these particles are removed from the surface and a steady state is reached [28,33,34]. At lower impact angles the incubation period is less associated with embedded particles, and more with the roughening process that takes places during erosion. The impact energy is mainly dissipated in roughening the target surface [35].

As stated above, solid particle erosion includes cutting, impact and fatigue processes. The local energy concentration of the erodent on the impacted surface is crucial for the erosive wear [34,36,37]. Hitting of a particle corresponds to a certain impact force imposed on the material surface. During impact, the initial energy of the particle is converted into different energy terms. This conversion has been discussed in details by Gross [37] and summarized in Ref. [24]. The occurred impact is categorized in (a) Normal, elastic impact, (b) Normal, plastic impact, (c) Normal, elastic/plastic impact and (d) Oblique, elastic/plastic impact. During normal elastic impact the entire impact energy is released to the environment in the form of kinetic energy during the rebound phase. Rubbers may show such behaviour. The relationship between mechanical properties and wear resistance for ultra-high molecular weight polyethylene (UHMWPE) is extremely complex. For polymers in general, the values of tensile strain energy at break have been considered as a measure of the abrasion resistance. Ratner et al. [38] have found independently that the abrasive wear rates of various polymers can be correlated with the reciprocal of the product of ultimate tensile strength and elongation to failure. Normal plastic impact is not a very common case, since it is next to impossible to have the entire energy converted into plastic deformation without fracture initiation. Normal elastic/plastic impact is the most frequent case, where part of the energy is elastically released in the form of kinetic rebound energy and part of it is converted into heat by internal friction. The amount of the plastic energy is determined from the properties of the target material and the erosive particle. The smaller the ductility of the impact partners, the smaller generally the number of stress cycles up to failure is, and the greater the amount of energy carrying fracture (and therefore erosive wear) is. Finally one of the most general types of impact is the oblique, elastic/plastic impact, where micro-cutting and micro-ploughing mechanisms are present especially when sharp edged erodents are used. The micro-cutting and micro-ploughing phenomena are mainly related to the hardness of the particles, which can penetrate into the target surfaces. Brittle materials are not so easily cut by the particles. The energy transfer parallel to the surface direction can take place, contrary to the ductile materials, only by friction forces. Thus the energy transfer is accordingly small. Only the perpendicular component of the velocity or the respective part of the initial energy determines the energy that goes into the material.

When polymer composites are considered, it appears that the factors governing ERs are mainly influenced by (a) whether the matrix is thermosetting or thermoplastic, (b) the brittleness of the fibers and (c) the interfacial bond strength between the fibers and the matrix [39]. The following sequence in the erosion process of fiber reinforced composites has been reported [40]:

(i) Erosion and local removal of material in the resin rich zones
(ii) Erosion in the fiber zones associated with breakage of fibers
(iii) Erosion of the interface zones between the fibers and the adjacent matrix

Since the matrix is removed first, the erosion characteristics of resin materials are the prime factor for the resistance of composites. During the erosion process the fibers are exposed to the erosion environment subsequent to the removal of matrix. Thus the toughness of exposed fibers directly affects the erosion mechanisms of composites. The effect of fiber reinforcement has been classified in importance as fiber material, fiber content, reinforcement type (i.e., length, diameter etc.) and fiber orientation. Further continuation of the erosion damages the interface between the fibers and the matrix. This damage is characterised by the separation and detachment of broken fibers from the matrix. The material with the strongest interface strength showed the best erosion resistance [41,42]. The existence of interleaves in laminated composites was also beneficial (because of the better adhesion between the adjacent layers) for the erosion resistance [43]. Generally composites with thermosetting matrix erode in a brittle manner. A totally different scenario is observed in the thermoplastic matrix composites. The matrix is uniformly grooved and cratered with local material removal showing a clear tendency for ductile mode of erosion [28,41,44–47].

3. Evolution into the experimental studies of erosion

3.1. Conventional polymer matrix composites

As mentioned above an overview of the polymer matrix composites tested up to 2002 is available in the articles published by Barkoula and Karger-Kocsis [24], Harsha et al. [25] and Tewari et al. [26]. The erosion studies found in those publications focus on the following six parameters:

(1) The effect of the *fiber material*. More than 90% of the composites discussed are reinforced with either glass fibers (GF) or carbon fibers (CF). Fewer studies can be found on aramid fibers (AF) or other type of reinforcement. In most studies the fiber reinforced composites are compared with the unreinforced matrices. The trend is that the addition of the fibers, which are most commonly brittle in nature, leads to deterioration of the erosion resistance of the matrix. This holds especially when a thermoplastic matrix is used.
(2) The effect of the *fiber content*. Although this parameter cannot be isolated from other parameters like the fiber brittleness, the general conclusion is that the higher the fiber content, the lower the erosion resistance. Several studies have tried to apply modified rule of mixtures in order to correlate the ER with the fiber content. These studies have been reviewed in details in Ref. [24].
(3) The effect of the *reinforcement type* (i.e. length, diameter, weave style etc.). Most studies focus on long-continues fibers. Short-chopped fibers come next, while also woven type of reinforcement has been of interest (plain weave). Generally, short fiber reinforced composites show better resistance to erosion compared to long-continues fiber reinforced ones. Ductile fiber reinforced (even self-reinforced) polymers are also termed as self-healing polymers. Self-healing is receiving an increasing amount of interest worldwide as a method to address damage in materials. In particular, for advanced high-performance fiber-reinforced polymer (FRP) composite materials, self-healing offers an alternative to employing conservative damage-tolerant designs and a mechanism for ameliorating inaccessible and invidious internal damage within a structure. This article considers in some detail the various self-healing technologies currently being developed for FRP composite materials. Key constraints for incorporating such a function in FRPs are that it not detrimental to inherent mechanical properties and that it not impose a severe weight penalty [47].
(4) The effect of the relative *fiber orientation* during erosion. These studies focus mainly on unidirectional composites. Here the reinforcement can be parallel or perpendicular to the impingement direction, or even at 45°. The results found in the literature show different trends depending on various parameters like the angle of impingement, the fibers ductility, the fiber/matrix adhesion, the fiber content, etc. Therefore, it is a parameter that cannot be considered isolated. It is true that the fibers can be at any orientation to the erodent. Or in other words, the erodent stream may strike the fibers at any angle with respect to the longitudinal direction of the fibers. But in case of experimental works, there is always a restriction to the number of levels that can be taken for a particular factor. Most of the reported investigations are therefore confined to 0°, 45° and 90° of fiber orientations to the erodent. But the investigation can be extended to any other values as well. Brandt et al. [48] proposed that fiber type, form, and orientation (fiber architecture) comprise the main considerations when choosing reinforcements. In a part that will be carrying little or no structure loads, chopped or continuous strand mat with random fiber orientation is sufficient. However, in a part that will see primary or secondary structural loads, fiber orientation is critical and departures from the optimum can result in drastic property reduction. Fiber architecture can be tailored for specific requirements, with parallel longitudinal (0° strands carrying tension loads, circumferential (90°) strands providing compression and impact strength, and helical (commonly $\pm 33°$ or $\pm 45°$) strands handling torque stresses. This design principle is comparable to the way that civil engineers use steel-reinforcing bar in a concrete structure.
(5) Effect of *fiber treatment* and *fiber/matrix adhesion*. The improvement of the fiber/matrix adhesion leads in most cases in an improvement of the erosion resistance of the material.
(6) Effect of *testing conditions* (particle velocity, impingement angle, erodent material, erodent size, erodent shape, testing temperature etc). No clear trend can be cited on the effect of these parameters on the erosive wear of polymer composites, since it is not easy to separate there parameters from each other, or isolate them from other parameters like the target material characteristics. Furthermore, it can be concluded that it is difficult to find studies with identical experimental conditions, especially if they are not performed at the same laboratory.

Table 1 provides an overview of the studies performed on polymer matrix composites after 2002 and not included in Refs. [24–26]. This table contains details around the erosion experiments as well as the key issues addressed in each study. More specifically, one can find the matrix material, the fiber/filler type, the content and the testing conditions. It can be concluded that there is a continuation in the experimental work done in the last six years on the

Table 1
Overview of the studies performed on polymer matrix composites after 2002.

Matrix	Fiber/Filler/V_f/W_f (%)	Temp (°C)	Erodent material	Erodent size (μm)	Erodent shape	Angle (°)	Velocity (m/s)	Key issues addressed	Year of publication	Ref
PEEK	65% CF, (V_f), unidirectional fibers	RT	Steel balls	300–500	Round	15, 30, 45, 60, 75, 90	45, 85	Effect of fiber orientation, (0°, 90/0), (45°, 90/45), (90°, 90/90)	2002	[48]
PEEK, PEK, PEKK	0%, 20% GF, 30% GF,(10% CF +10% PTFE +10% Graphite) (W_f), short fibers	RT	Silica sand	150–212	Angular	15,30, 60, 90	30, 68, 90	Effect of fiber content, influence of ketone/ether ratio, correlation of tensile strength, ultimate elongation, hardness with erosion rate	2003	[25]
EP	56% CF, 53% GF, (V_f), unidirectional fibers	RT	Steel balls	300–500	Round	15, 30, 45, 60, 75, 90	45	Effect of fiber orientation, (0°, 90/0), (45°, 90/45), (90°, 90/90)	2003	[26]
EP, uncoated & two layer coated	Carbon-Kevlar	93	Al_2O_3	10	N/S	20, 90	229	Effect of coating type/thickness, impingement angle on erosion rate	2003	[20]
PUR	Al_2O_3 (0-64%), (W_f)	RT	SiO_2	40–70	Irregular	45	24.8	Effect of filler content, coupling agents on the erosion rate	2005	[49]
Resin	Mat GF (9.4%, 17.1%, 24.5%), Cloth GF (12%, 27.9%, 32.4%), UD GF 27.8%, (V_f), chopped strand mats, plain weave, unidirectional (UD)	RT	Crashed glass powder	350	N/S	20-90	24.5	Effect of fiber weave style on the erosion rate, proposal of general way for predicting the erosion rate	2006	[50]
EP	55.8% AF, 53.8% PBO, (V_f), cross ply	RT	SiC	100–150	N/S	15-90	57.8	After impact erosion	2006	[51]
EP, EP + Flyash (1:4)	GF, cross ply	RT	Silica sand	150–250	N/S	30, 45, 60, 90	24, 35, 52	Effect of flyash content, impingement angle, particle velocity, calculation of the erosion efficiency	2006	[52]
EP, EP + wheat flour (1-4%) (W_f)	46.5% GF (V_f), cross ply	RT	Silica sand	150–250	N/S	30, 45, 60, 90	24, 35, 52	Effect of what flour content, impingement angle, particle velocity	2006	[53]
Used data produced by other works	Two tables with data from previous studies (material, testing conditions etc)	Compiled data,calculated erosion efficiency as a function of impact velocity, erosion rate, hardness, created erosion efficiency map	2006	27						
PI, uncoated & coated	Coatings: PI + WC-Co powder, PI +WC-Co powder + zinc “binding” layer, Fiber: CF	RT, 250	Al_2O_3	50	Angular	20, 90	100	Effect of coating system, coating spraying technique, angle of impingement, erosion temperature, erosion time on the erosion rate	2006	[13]

Table 1 (*Continued*)

Matrix	Fiber/Filler/V_f/W_f (%)	Temp (°C)	Erodent material	Erodent size (μm)	Erodent shape	Angle (°)	Velocity (m/s)	Key issues addressed	Year of publication	Ref
PPS	40% GF + 25% $CaCO_3$, (W_f), short fiber	RT	Silica sand	150–200	Angular	15, 30, 45, 60, 75, 90	20, 40, 60	Effect of particle velocity, fiber orientation, mineral particles	2007	[54]
EP	55% GF, (V_f), [45/−45/0/45/−45/0]s	RT	SiC	400–500	N/S	30, 60, 90	42.5	Definition of: erosion damage parameter to determine the residual tensile strength after erosion,modified Basquin equation to predict the fatigue life	2007	[55]
PEI	40% CF, (V_f), plain weave	RT	Silica sand	N/S	N/S	15, 30, 45, 60, 75, 90	26.88	Effect of impingement angle	2007	[56]
PEEK	CF, unidirectional fibers	RT, 260	Arizona Test Dust, Sieved Runway Sand	10, 100	Irregular, slighly rounded	15, 30, 45, 60, 90	61, 97.5, 152.4	Effect of erosion temperature, impingement angle, particle velocity, particle size, particle type, fiber orientation, used non linear regression analysis to predict erosion rate	2007	[57]
PEI	CF, unidirectional fibers	RT	Silica sand	150-200	N/S	15, 30, 45, 60, 75, 90	1.96, 2.88	Effect of particle velocity (low speed), impingement angle, correlation of erosion rate with surface roughness	2007	[58]
PEI	0%, 20% GF, 30% GF, 40% GF, 25% CF, 25% GF +15% PTFE +15% (MoS_2 +graphite), (W_f), short fibers	RT	Silica sand	150–300	Irregular, slighly rounded	15, 30, 60, 90	30, 52, 60, 88	Effect of fiber content, presence of solid lubricants (PTFE, graphite, MoS_2), correlation of tensile strength, ultimate elongation, hardness, Izod impact strength, shear strength with erosion rate	2007	[59]
PPS	51% CF, (V_f), cross ply	RT	Silica sand	150–200	Angular	15-90	20, 40, 60	effect of particle velocity on erosion rate & residual flexural properties, effect of impingement angle	2008	[60]
PEI	60% CF, (V_f), unidirectional fibers	RT	Silica sand	150–250	Angular	15, 30, 60, 90	25-66	Effect of fiber orientation, (0°, 90/0),(90°, 90/90)	2008	[61]
EP	55% GF, (V_f), [45/−45/0/45/−45/0]s	RT	SiC	400–500	N/S	30, 60, 90	42.5	Non-destructive experimental protocol to estimate the residual tensile strength after erosion effect of	2008	[62]

EP	66.4% GF, 59.4% GF, 64% CF, (V_f), unidirectional & bidirectional fibers	RT	Silica sand	150–200	Irregular, slighly rounded	90	25, 37, 47, 60	Reinforcement orientation, comparison between bidirectional and unidirectional composites	2008	[63]
PET	30% GF, 40% GF, 50% GF, (W_f), cross ply	RT	Silica sand	300, 500, 800	N/S	30, 60, 90	32, 45, 58	Use of the Taguchi method under various testing conditions, create a genetic algorithm to determine optimal factor settings for erosion rate reduction	2008	[64]
PET	50% GF + 0%, 10%, 20% Alumina, (W_f), cross ply	RT	Silica sand	300, 500, 800	Spherical	45, 60, 90	32, 45, 58	Effect of alumina particles at different contents and operation conditions, determination of optimal parameter settings for minimum erosion rate using Taguchi method	2008	[65]
PET	50% GF + 0%, 10%, 20% SiC (W_f), cross ply	RT	Silica sand	300, 500, 800	Spherical	45, 60, 90	32, 45, 58	Effect of SiC particles at different contents and operation conditions, determination of optimal parameter settings for minimum erosion rate using Taguchi method	2008	[66]
PET	30% GF, 40% GF, 50% GF, (W_f), cross ply	RT	Silica sand	300, 500, 800	N/S	30, 60, 90	32, 45, 58	Use of the Taguchi method under various testing conditions, create a genetic algorithm to determine optimal factor settings for erosion rate reduction, propose two predictive models based on ANN	2008	[67]
PET	50% GF + 0%, 10%, 20% Alumina, (W_f), cross ply	RT	Silica sand	300, 500, 800	Spherical	45, 60, 90	32, 45, 58	A mathematical model for damage assessment in erosion is developed, using Taguchi's orthogonal arrays	2008	[68]

solid particle erosion of polymer matrix composites, as most of the studies focus on the aforementioned parameters. The new aspects of the studies reviewed in Table 1 can be summarized as follows:

(1) Matrix materials like PET, PEEK, PPS and PEI, which have not been discussed in details before [13,25,54,56–61,65–68]. In most cases a semi-ductile erosive response of the composite systems can be observed with maximum erosion rates at 60°, while the unreinforced polymers exhibited a ductile response with maximum erosion at 30°, which is typical for thermoplastic materials. Furthermore, the inclusion of the brittle fibers led into lower erosion rates compared with the unreinforced polymers.
(2) Use of coatings for reduction of the solid particle erosion. The effects of (a) the coating system, (b) the coating spraying technique and (c) the coating thickness are new elements in these studies [13,20]. In Ref. [20] tungsten carbide-cobalt (WC-Co) with metal bondcoat was applied on EP- CF/AF composites.

The two-layered coating was found to reduce the erosion volume loss by a factor of 10. Two different coating thicknesses were tested (0.06 and 0.09 mm). It was found that the coating thickness does not influence the resistance to erosion. Furthermore in [13] functionally graded coatings with varying volume fractions of WC-Co were tested. Two techniques were used to apply the coatings, i.e. the high velocity oxy-fuel (HVOF) combustion spraying process and the flame sprayed process. The erosion resistance of three HVOF and/or flame sprayed polyimide WC-Co coatings were tested, and compared to the uncoated substrate. The HVOF led to dense and adherent WC-Co coatings while the flame sprayed process led to porous, poorly cohesive topcoats. As a result the first improved the erosion resistance of the polymer composite, while the second did not influence the erosion resistance.

(3) Study of the erosive wear of hybrid systems [25,52,54,59,65,66,68]. Section 3.2 is devoted into reviewing this new aspect.
(4) Erosion studies at high temperatures [13,20,57]. Very few studies can be found in this area, mainly due to the increased cost and difficulty to construct suitable equipment for such experiments. However, this subject is very relevant since many high temperature applications (for example turgofan engines) need to withstand erosive wear loadings. High temperatures lead to higher erosion rates compared to room temperature exposure. This holds especially when the matrix is of thermoplastic nature and the temperature during erosion at the impact site is close to the melting temperature of the matrix. Additional processes can be attributed to high temperatures, i.e. melting and degradation of the ductile phase, as well as particle deposition effects. When the ductile phase is near its high heat distortion temperature, some of the impacting particles get embedded into the ductile phase. This melting and deposition lead to the next process which is fiber breakage [57].

3.2. Hybrid polymer matrix composites

Studies made on the erosive wear of composites refer more on fiber-reinforced polymer 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. There is no clear understanding of the mechanism of erosion and how the properties of the constituents and the interface affect the erosion behaviour of these composites. A possibility that the incorporation of both particles and fibers in polymer could provide a synergism in terms of improved properties and wear 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 and impact toughness [69–74]. Such multi-component composites consisting of a matrix phase reinforced with a fiber and filled with particulate matters are termed as hybrid composites.

Some recent publications by Patnaik et al. [64–68] have reported extensively on erosion wear characteristics of glass-polyester hybrid composites filled with different particulate fillers such as fly ash, aluminium oxide (Al_2O_3) and silicon carbide (SiC). These reports suggested that in fiber reinforced particulate filled hybrid composites, the rate of material loss due to solid particle erosion reduced significantly with the addition of hard particulate fillers into the matrix. This improvement in the wear resistance depends on the type and content of filler. The composites with Al_2O_3 filling showed better erosion resistance than the composites filled with SiC and fly ash. The reduction in material loss in these particle filled composites can be attributed to two reasons. One is the improvement in the bulk hardness of the composite with addition of these hard ceramic particles. Second, 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 fiber phase. These two factors together lead to enhancement of erosion wear resistance of the composites.

Figs. 1 and 2 are two typical SEM observations of the eroded surfaces of SiC filled glass polyester hybrid composites. It appears that the composites exhibit several stages of erosion and material removal process. The matrix covering the fiber seems to be chipped off due to repeated impact of hard silica sand particles. Craters thus formed, as in Fig. 1 show array of glass fibers. After the local removal of matrix this array of fibers is exposed to erosive environment. Fig. 2 shows fragments of SiC particles and the fibers which are result of continued sand impact. The broken fiber and carbide filler fragments are mixed with the matrix micro-flake debris and the damage of the composite is characterized by separation and detachment of this debris.

4. Erosion wear modelling

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 predic-

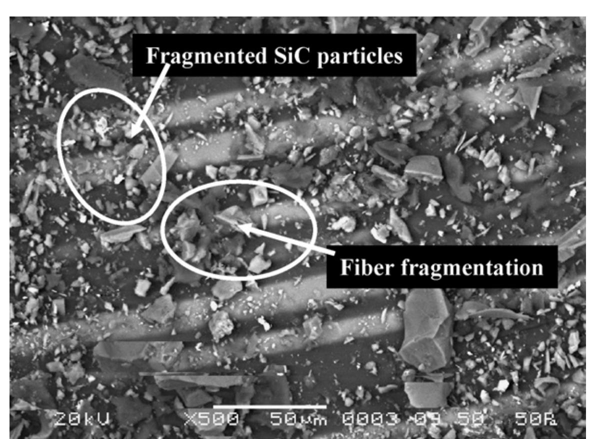

Fig. 1. SEM image of the eroded surface of glass-polyester-SiC hybrid composite showing fiber and filler fragmentation.

Fig. 2. SEM image of the eroded surface of glass-polyester SiC hybrid composite showing fiber and matrix micro-flake debris.

tion. The theoretical model developed by Rabinowicz [75] 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 [76] 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 [77] 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 [78,79] 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. Glaeser and Dow [80] 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 [81], Salama and Venkatesh [82], Bourgoyne [83], Chase et al. [84], McLaury [85], Svedeman and Arnold [86], and Jordan [87]. Recently, Shirazi and McLaury [88] presented a model for predicting multiphase erosion in elbows. The model was developed based on extensive empirical information gathered from many sources, and it accounts for the physical variables affecting erosion, including fluid properties, sand production rate and size, and the fluid-stream composition. An important different feature of this model was the use of the characteristic impact velocity of the particles. The method used for obtaining this characteristic velocity for an elbow was an extension of a previous method introduced by the same authors for the case of a single-phase flow.

The use of computational methods in erosion prediction constitutes a combination of flow modelling, Lagrangian particle-tracking, and the use of erosion correlations. The flow model is used to determine the flow field for a given geometry while the particle-tracking model is used to determine the particle trajectories for solid particles released in the flow. The particle impingement information extracted from the trajectories is used along with the empirical erosion equations to predict the erosion rates. Wang et al. [89] developed a computational model for predicting the rate of erosive wear in a 90° elbow for the two cases of sand in air and sand in water. The flow field was first obtained and then the particle trajectory and impacting characteristics were then determined by solving the equation of particle motion taking into consideration all the forces including drag, buoyancy, and virtual mass effects with the assumption of a uniform distribution of the solid particles at the starting section. In a recent study by Edwards et al. [90], an erosion prediction procedure was developed and verified based on a CFD code combining flow field analysis and particle-tracking for obtaining particle impingement data. The erosion rate was then computed using the empirical relations of Ahlert [91] and applied to predict erosion in a pipe bend fitting made of carbon steel.

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 [92,93]. Andrews and Horsfield [94] explained particle collisions in the vicinity of a eroding surface which is being eroded there is a region where particles arriving at and departing from the surface can collide. The frequency of collisions and the resulting motion of spherical particles have been investigated theoretically and experimentally. An expression is derived for the flux of spheres necessary for a high frequency of collisions. The directions and velocities of particles after collision have also been calculated, assuming elastic collisions. In the low-flux limit collisions do not reduce the number of particles reaching the surface. Long-exposure (ca. 1 s) and high-speed (5000 frames s^{-1}) photography confirms these findings for the case of 0.6+ or −0.1 mm diameter glass spheres travelling at 13+ or $-1\ m\,s^{-1}$. These conclusions conflict with the ideas of many authors who suggest that collisions help protect the eroded surface. The present paper shows that collisions degrade the incident beam of particles by increasing the angular divergence of the beam and creating a spectrum of velocities. Stray particles have also been observed entering the region of interest, increasing the frequency of collisions. Stray particles and changes in the incident beam are probably the causes of the observed reduction in erosion rate at high levels of flux.

A number of recent papers contain investigations of the rebound kinematics of spherical/angular particles [95–98]. These are concerned with the identification and modelling of mechanisms of ductile target material removal due to the impact of single hard, angular particles. These works have demonstrated that, in this case, the trajectory of the particle while impacting the material surface is of prime interest in predicting the material loss, since this determines the manner in which a crater is carved out. In much of this work, the target material is assumed to be perfectly plastic (i.e.

elastic rebound effects are ignored), with the impacting particle assumed to be non-deforming, and the theory has thus come to be known as 'rigid-plastic'. Finnie's analysis [99] of the cutting action of a single particle launched against a ductile target was the first such model capable of predicting material removal rate. In his model, the particles were assumed to be rigid and impact a target which reached a constant flow pressure immediately upon impact. Under the assumption that the particle did not rotate during the impact process, the particle was subjected to a resisting force vector of constant direction, and Finnie was able to solve for the trajectory of the particle in closed form as it cut the surface, and thus predict the size of the impact crater. An extension of Finnie's work, the rigid-plastic theory developed by Hutchings and co-workers [100–102] predicted the collision kinematics and crater dimensions for single impacts of square and spherical particles on ductile targets. The theory predicted the kinematics of the particle as it ploughed or cut through the target, under the assumption that the instantaneous resisting force could be calculated by multiplying a constant plastic flow pressure (i.e. the dynamic hardness) by the instantaneous contact area. In contrast to the constant direction force vector assumed in Finnie's work, in Hutchings' analysis, the particle was free to rotate, and the resisting force vector could thus vary in both direction and magnitude. By examining the single impacts of the square and spherical particles, Hutchings identified two fundamental mechanisms of cutting erosion, and a ploughing erosion mechanism, depending on both the particle shape and its orientation at the moment of impact [101]. In general, comparisons of experimentally measured crater volume, energy loss, and particle kinematics yielded acceptable agreement. For impacts involving spherical particles, the rigid-plastic theory was later improved by Rickerby and Macmillan and Hutchings et al. [103,104], to include a more accurate calculation of contact area. Sundararajan and co-workers [105–107] also used a similar theory to model ductile erosion, and investigated the effect of material pile-up at the edge of the crater on the rebound kinematics of the spherical particles, and the size of the resulting plastic zone below the impact. In the case of the rigid-plastic impact of single angular particles, however, very little literature exists. A rigid-plastic theory developed by Papini and co-workers [108–111] generalized Hutchings' [101,102] rigid-plastic theory for square particles, so that particles of any shape impacting targets of arbitrary dynamic hardness and dynamic friction coefficient could be analysed. The specific case of two dimensional particles having rhomboidal shape (i.e. 'diamond shaped') of varying angularity was studied in detail by constructing a computer program capable of describing the trajectory of the particles as they formed impact craters, so that their size and shape could be predicted [110]. Dimensionless parameters were identified so that the results of a parametric study could be presented in a generally applicable form, fundamental erosion mechanisms were predicted, and it was postulated that for a given angle of attack, there was an optimum particle shape for the most efficient material removal [111]. Due to the difficulties associated with performing repeatable experiments involving the impact of angular particles, this model remained without experimental verification of any kind until very recently. Of particular difficulty was the design of the launching apparatus, so that the impacts all would occur in one plane. Very recently, an experimental apparatus capable of reliably launching two-dimensional rhomboidal particles was constructed, and used to show that the model of Papini et al. could reasonably predict the rebound kinematics of particles launched at aluminium alloy targets [112]. Along with the erosion mechanisms identified by Hutchings, a previously unreported mechanism was also identified. While the agreement between measured and predicted results was encouraging, the experimental data were limited to measurements of rebound kinematics and not crater volume, and particles of only one angularity were used.

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 [76] and the platelet mechanism [113]. 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 microcutting does not often occur [114]. Regarding the platelet mechanism, plastic deformation and work hardening prior to fracture are taken into account and this makes it closer to reality. However, this mechanism is also only suitable for ductile materials. Since there are many parameters influencing erosion, computer models based on the platelet mechanism are often used to treat special cases [115,116]. Furthermore, it is difficult to establish the relationship between erosion and micro-structure based on these theories. Another method, finite element analysis (FEM), is also used for erosion simulation [117–119]. 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.

Another group of models developed based on fundamental physics laws are promising for wear modelling, such as the molecular dynamics simulation [120,121] and the first-principle technique [122]. The molecular dynamic technique (MD) is one of the most powerful approaches for materials studies. However, the limited capability of current computing facilities makes it difficult to simulate an erosion process involving microstructural effects, which requires handling a large number of atoms. Such simulation needs an unacceptable long computing time. A micro-scale dynamic model (MSDM) was recently proposed for wear simulation, which has been applied to investigate abrasive wear [123,124]. This model was later applied to simulation of solid-particle erosion of homogeneous materials [125].

The correlations between wear resistance and characteristic properties of polymers have been discussed in terms of various semi-empirical equations by some pioneers. These include, e.g. the Ratner–Lancaster equation [126,127], i.e. the relationship of the single pass abrasion rate with the reciprocal of the product of ultimate tensile stress and strain, or an equation used by Friedrich [128] to correlate the erosive wear rate of polymers with the quotient of their hardness to fracture energy. Although these equations are quite helpful to estimate the wear behaviour of polymers in some special cases, wear normally is very complicated, and it therefore depends on many more mechanical and other parameters. This means that simple functions cannot always cover all the prevailing mechanisms under wear. For predictive purposes, an artificial neural network (ANN) approach has, therefore, been introduced recently into the field of wear of polymers and composites by Velten et al. [129] and Zhang et al. [130]. An ANN is a computational system that simulates the micro-structure (neurons) of biological nervous system. The most basic components of ANN are modelled after the structure of the brain. Inspired by these biological neurons, ANN is composed of simple elements operating in parallel. ANN is the simple clustering of the primitive artificial neurons. This clustering occurs by creating layers, which are then connected to one another. How these layers connect may also vary. Basically, all ANN have a similar structure of topology. Some of the neurons interface the real world to receive its input, and other neurons provide the real world with the network's output. All the rest of the neurons are hidden from view. As in nature, the network function is determined largely by the interconnections between neurons, which are not simple connections, but some non-linear functions. Each input to a neuron has a weight factor of the function that determines the strength of the interconnection and thus the contribution of that interconnection to the following neurons. ANN can be trained to perform a particular function by adjusting the values of these weight factors between the neurons, either from the information of outside the network or by the neurons themselves in response to the input. This is the key to the ability of ANN to achieve learning and memory. The multi-layered neural network is the most widely applied neural network, which has been utilized in the most of the research works for materials science reviewed by Zhang and Friedrich [131]. This approach has been specifically applied to predict the erosive wear response of polymers and modified polymers by the same group of researchers [132]. Back propagation algorithm can be used to train these multi-layer feed-forward networks with differentiable transfer functions to perform function approximation, pattern association, and pattern classification. The term back propagation refers to the process by which derivatives of network error, with respect to network weights and biases, can be computed. The training of an ANN by back propagation involves three stages: (a) the feed-forward of the input training pattern, (b) the calculation and back propagation of the associated error, and (c) the adjustment of the weights. This process can be used with a number of different optimization strategies.

Recently, Patnaik et al. [67] developed a theoretical model to estimate the erosion wear rate of polymer composites under multiple impact condition. The model is based on the assumption that the 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 further assumes the erodent particles to be rigid, spherical bodies of diameter equal to the average grit size. It considers the ductile mode of erosion and assumes the volume of material lost in a single impact is less than the volume of indentation. It further considers that the hardness alone is unable to provide sufficient correlation with erosion rate, largely because it determines only the volume displaced by each impact and not really the volume 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. The 'erosion efficiency' is obviously one such parameter. In case of a stream of particles impacting a surface at any angle α, the erosion efficiency defined by Patnaik et al. [68] is given as

$$\eta = \frac{2ErH\nu}{\rho V^2 \mathrm{Sin}^2\alpha} \tag{1}$$

And according to the model proposed by them, the non-dimensional erosion wear rate of a composite material is given by

$$E_{\mathrm{rth}} = \frac{\rho_{\mathrm{c}}\, \eta\, V^2\, \mathrm{Sin}^2\alpha}{2H\nu} \tag{2}$$

where: α: angle of impingement (degree), V: impact velocity (m/s), $H\nu$: hardness (N/m^2), ρ_{c}: density of composite (kg/m^3), ρ: density of erodent (kg/m^3), η: erosion efficiency, E_{r}: actual erosion wear rate (kg/kg), E_{rth}: theoretical erosion wear rate (kg/kg)

The magnitude of η can be used to characterize the nature and mechanism of erosion. For example, ideal micro-ploughing involving just the displacement of the material from the crater without any fracture (and hence no erosion) will results in $\eta = 0$. In contrast, if the material removal is by ideal micro-cutting, $\eta = 1.0$ or 100%. If erosion occurs by lip or platelet formation and their fracture by repeated impact, as is usually the case in ductile materials, the magnitude of η will be very low, i.e η 100%. In the case of brittle materials, erosion occurs usually by spalling and removal of large chunks of materials resulting from the interlinking of lateral or radial cracks and thus η can be expected to be even greater than 100% [27].

But this model proposed by Patnaik et al. [67] assumes that both the erodent material and the target material are at same temperature and therefore there is no exchange of any thermal energy between them during the impact. This may be true for a room temperature erosion situation, but when the erodent is at an elevated temperature, as in the case of hot air carrying pulverised coal powders in a pipe, there will be dissipation of the kinetic energy as well as the thermal energy from the erodent body to the target. Research on erosion of composite materials by high temperature erodent particles has been rare but very recently Biswas and Satapathy [133] have proposed another model which takes into account this approach of energy dissipation. 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 irregular shaped bodies having sharp edges (Fig. 3). Considering them to be 36 square pyramidal shaped bodies is a more realistic assumption as compared to assuming them simply spherical. The model proposed by Biswas and Satapathy [133] addresses to this shortcoming as well. It assumes the erodent particles to be rigid, square pyramidal shaped bodies of height and base length equal to the average grit size. As already mentioned, it also assumes that the loss in both kinetic as well as thermal 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 and thermal 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 material removal mechanism has been schematically shown in Fig. 4.

Now applying conservation of energy to the single impact erosion process, the sum of the kinetic energy associated with the normal velocity component and the loss of thermal energy of the a single erodent particle is equal to the work done in the indentation of composite. And finally, according to this model, 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 expressed as

$$E_r = \frac{\eta\, \rho_{\mathrm{c}}}{3H}[U^2 \mathrm{Sin}^2\alpha + 2S(\theta - \theta_0)] \tag{3}$$

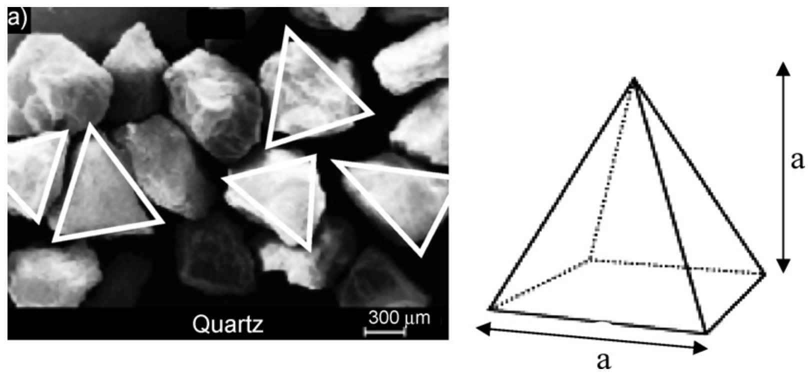

Fig. 3. Shape of the erodent used.

where: U: impact velocity (m/s), θ: erodent temperature (°C) and, θ_0: room temperature (°C).

The mathematical expression in Eq. (3) can be used for predictive purpose to make an approximate assessment of the erosion damage from the composite surface. Biswas and Satapathy [133] conducted erosion trials on a set of particulate filled epoxy composites and demonstrated that if supported by an appropriate magnitude of erosion efficiency, the model performed well for normal as well as oblique impacts.

Patnaik and co-workers [134–141] conducted erosion trials on a number of polyester based composites and demonstrated that if supported by an appropriate magnitude of erosion efficiency, the above model performed well for polyester matrix composites for normal as well as oblique impacts.

5. Implementation of design of experiment (DOE) and optimization techniques

Statistical methods have commonly been used for analysis, prediction and/or optimization of a number of engineering processes. 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 a complex wear phenomenon in which a number of control factors collectively determine the performance output i.e. the erosion rate and there is enormous scope in it for implementation of appropriate statistical techniques for process optimization. But unfortunately, such studies have not been adequately reported so far. The present work addresses to this aspect by adopting a systematic statistical approach called Taguchi method to optimize the process parameters leading to minimum erosion of the polymer composites under study.

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 [142–147]. 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 [148] advocated the use of orthogonal arrays and Taguchi [149] devised a new experiment design that applied signal-to-

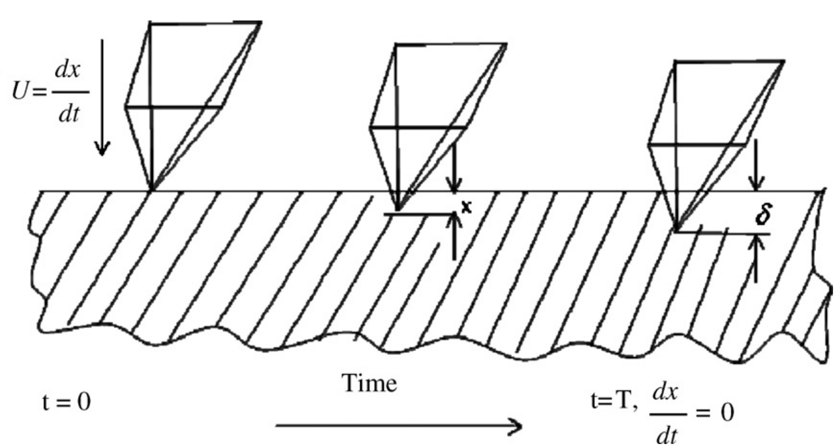

Fig. 4. Scheme of material removal mechanism.

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 [150], Wu and Moore [151] and others [152–154] 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 wire electrical discharge machining (WEDM) process, drilling of metal matrix composites, and erosion behaviour of metal matrix composites such as aluminium reinforced with red mud [133–141].

6. Conclusions

The exhaustive literature survey presented above reveals that though much work has been reported on erosion wear characteristics of polymers and their 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. 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. Studies carried out worldwide on erosion behaviour of composites have largely been experimental and use of statistical techniques in analyzing wear characteristics is rare. It appears that the effect of fiber reinforcement and ceramic particulate filling on erosion characteristics of polyester composites has still remained a less studied area. 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. Behaviour of hybrid composites under solid particle erosion is another open-ended area in which a lot of meaningful research can be done.

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