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DEVELOPMENT OF A THEORETICAL MODEL TO ESTIMATE THE EROSION WEAR RATE OF POLYMER COMPOSITES

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Abstract

Nowadays Polymeric materials reinforced with synthetic fibers play an incredible role in almost all spheres of day-to-day life due to their elevated stiffness, outstanding strength-to-weight ratio, and electrical, thermal, and wear properties. The accumulation of micro-fillers or particulates in polymeric components reinforced with fibers made from synthetic materials may enhance their properties compared to fiber-reinforced composites. Solid particle erosion of engineering components made up of polymer composites is a major industrial problem, and it is significantly affected by the components' mechanical characteristics and their working environment. Therefore, it's essential to research the polymer composites' solid particle erosion properties. One area that has attracted less research attention is the impact of particle fillers and E-glass fiber reinforcing on erosion wear characteristics. Because of its significance to science and industry, research in this area is especially needed about particle fillers. Furthermore, to properly design a machine or structural component and use materials that will increase wear resistance, one must have a thorough grasp of how every system variable affects wear rate. In this research article, to estimate the erosion damage *induced by solid particle impact on composites without conducting the experiment on an air jet erosion test rig, a theoretical model is proposed. The successful implementation of this theoretical model can reduce the experimentation cost with good quantitative accuracy.*

Keywords: Erosion, Erosion Modeling, Air-jet erosion test rig, Operating Parameters, Theoretical Model.

I. Introduction

Industries are rapidly shifting toward the use of composites because of their improved properties, lower cost, environmental friendliness, and lighter weight in comparison, growing their desirability to substitute the traditional ones [XLIX]. Engineering/structural components made of polymer composites functioning in hostile environments will be subjected to various wear situations. Destruction of a solid body surface or intense diminution of material from the solid body surface because of the pertinent motion between the surface and attached substances is called wear [XLIX]. Wear is a material response to environmental changes which could be mechanical or chemical in nature. It is identified that the perfection of various industrial and technical components is decreasing due to wear and the cost of wear is also very high. Systematic research on wear was started in the 1960s in industrialized countries. To overcome the wear losses in engineering components lot of research is going on, but still related complexness exists in industrial and technical applications, which shows the complication of the wear [XXVII].
The increase or decrease in wear rate depends on:

- material properties (hardness, toughness, chemical composition and microstructure)
- operating conditions (velocity, pressure, operating optimum temperature, surface fineness, and contacting surfaces)
- Environmental and climatic conditions [XIV].

The principal modes of wear are surface fatigue, erosion, adhesion, and abrasion [V]. When two mating parts move opposite to each other the stronger particle in one cut against the other is called abrasive wear. The material removal is with the micro cutting and micro-ploughing because of the tangential motion of the two parts in opposite directions then abrasive wear will come into play [XLIX].

Adhesive wear is due to the attachment of the solid surfaces which leads to the transfer of material between two or more surfaces (or) the loss from any one surface [XIV]. Similar to this, when a surface experiences continuous loading movements such as sliding or rolling on its outermost layer, minute wear granules are created from surface fracture.

Sub-surface breakdowns improve from pre-existing flaws, mixing with other region cracks and ultimately reaching the surface removing a chunk of material [V]. In erosion wear due to a mechanical correlation between the surface and an impinging fluid stream path a high progressive material loss occurs from a solid surface

[XXXVII]. Because of the multiple impacts of tiny solid granules progressive and continuous loss of material will occur from the solid surface it is called solid particle erosion (SPE). SPE is a desirable phenomenon in some observations, such as sandblasting and high-speed abrasive water jet machining (AWJM); however, it is an important issue in many engineering and technical systems, such as pipelines and valves that transport particulate matter, steam for jet turbines, and fluidized bed combustion (FBC) systems. Solid particle erosion is to be expected once hard particles and fluid media collide with a solid surface at any significant velocity. In erosion wear, particles' motion could vary.

Polymers and composites made of them can be utilized to produce turbo-engineering materials, which have been designed for use in mechanical parts where wear is a major factor in selecting a material under non-lubricated conditions.

Nowadays, because of the high potential usage of polymer composites in various structural and mechanical applications: the study of solid particle or molecular erosion characteristics in polymer composites has received a lot of interest. Therefore, a key material behaviour is the composite's ability to withstand erosive wear. In picking of best suitable materials, the study of SPE of polymer composite is highly desirable.

Because of the amount, orientation, and type of reinforcement on one side and the kind and qualities of the matrix on the other, different types of composites will have different erosion wear behaviors. In the case of design and manufacturing of machine parts and to choose the material to remove the wear we should understand the consequence of all system variables [LII]. With the vast usage of composites in process industries and companies, aircraft, and transport-related industries in which they lead to fluid granule impact; research interest in SPE has been increasing day by day.

Pipelines transferring sand slurries in petroleum, aircraft rotor blades [XXXIV], rapid-speed vehicles and pump impellers, water turbines [I], canopies, missile parts, engines, windscreens [XXXV], and space applications [LI] are examples of which SPE occurs. In the defense-related applications of non-metallic parts, [XXXV] resistance to wear and sand erosion is the main issue. Although good work has been done on this topic too many doubts and questions are still exploring. A well-defined work on erosion in polymer composites has still not reached the ultimate level. The filler's addition to the matrix plays a vital role in matrix modification, compared to the reinforcement of fiber. The effect of erosion wear behaviour on fiber-reinforced polymers adding with hard particulate filler is a less studied area, so a lot of research needs to be done to realize the mechanism of attrition/ erosion, the effect of filler and fiber on erosion-wear behaviour, development of theoretical accurate models for predicting and identifying erosion wear rate, for inspect/analysis forecasting and/or optimization of technical processes of statistical methods are required. These approaches enable us to determine and evaluate the influence of minute, feasible circumstances that arise in an experiment with multiple factors or aspects. SPE is a complicated wear trend in which many control attributes or factors will be identified affecting the erosion rate and there will be much scope for execution of suitable techniques for process standardization and optimization.

II. Literature Review on erosion wear modeling

Many researchers have created various SPE models and correlations to provide designers with a quick fix in the absence of an experimental strategy for SPE estimation. The amount of substance that's eroded from a surface owing to the interference of sand particulates can be calculated using Rabinowicz's arithmetic model [XXXVI]. From the results, it has been observed that the trajectories of sand particles are governed by the secondary flows. An accurate prediction and location of the maximum SPE wear can be estimated by particulate trajectories and these trajectories can be obtained by liquid velocity profiles. In the model proposed by Rabinowicz [XXXVI], no liquid velocity profiles are present and hence the estimation of maximum SPE wear is not possible. Finnie [IX] proposed a SPE prediction correlation in which SPE is expressed as impingement velocity and particle mass. The SPE wear rate is precisely related to the square of the velocity of impact (VOI) in this correlation.

Nesic [XXVI] observed the over-prediction of SPE wear in Finnie's model and proposed a new formula to estimate the SPE wear rate in the form of critical velocity instead of impingement velocity. Bitter [II, III] suggested a model assuming the occurrence of SPE in two stages, in the first stage the repeated deformation of material takes place due to the collision of particles resulting in loose pieces of material, and in the second stage cutting of loose pieces by free moving particles. The correlation results for SPE wear are in good accord with the outcomes of the experiment. It concluded that at small impingement angles the cutting SPE wear prevails and to reduce SPE wear the selection of hard material is enough in erosive environments for application. Researchers Jordan [XVI], Laitone [XIX], Svedeman and Arnold [L], Salama and Venkatesh [XLIII], Mc Laury [XXII], Baurgoyne [IV], and Chase et al. [VI] suggested various SPE models. Recently, the prediction of multiphase SPE in elbows was done by a model developed by Shirazi and Mc Laury [LIII]. A lot of empirical information relating to physical variables like fluid properties and sand production rate is generated from various sources to develop the model.

In most of the SPE processes, the substance removal from the required surface occurs due to the impact of a large amount of irregular particles carried by the fluid system under pressure. The method of material subtraction from the exterior of the specimen is easily studied by the analysis of single particle impact of known geometry (shape and size) and these studies can be used to develop various SPE theories consisting flow of particles hitting or impinging on required surface repeatedly. The rebound kinematics of particles can be determined by impact studies of a single particle. The rebound kinematics experiments are essential to assessing the change in SPE potential owing to the impacts of impinging and rebounding particulates [XI, XXXIII].

In recent years, several studies on the rebounding mechanics of angular or spherical particulates [XXII, LVI, XVII, XXIV, XVIII, XV] have been conducted, and these research investigations have disclosed the path of the impacting particles on the surface of the material to forecast material loss and crater formation. A ductile SPE model has been developed by Sundararajan et al. [XLIV, LIII, XLVI], and rebound kinematics of the particles of spherical shape has been studied.

The studies on the detailed mechanism of SPE of composite material are required to develop a theoretical or mathematical expression or model for the evaluation of SPE wear. The material removal from the composite surface in the SPE model depends on the particle size of the erodent, the shape of the erodent, the velocity of the impact of particles, mechanical characteristics of both the erodent material and composite material (target), the volume of the erodent, size, composition, and properties of reinforcing material and bond strength in between the matrix and reinforcing phases. It is very difficult to investigate the SPE mechanism of composites experimentally by considering all the above factors. To overcome such difficulties to determine the SPE mechanisms computer simulations are used and these simulation techniques are very effective and economical. The proposed computer models to simulate the SPE process are categorized into two categories:

- Macro-scale models or MS Models
- Atomic-Scale models or AS Models

Many theories or assumptions like cutting mechanism [IX] and mechanism of platelet [XV] were considered to propose MS models.

Each erodent particulate hits a target surface or material to cut out a swath of the material from the target surface and this mechanism is observed in ductile materials. Only ductile materials are appropriate for the platelet mechanism, which takes into account deformation due to plasticity (PD) and work-hardened before fracture. Few researchers have utilized the FEA for the SPE model [X, XLV], Molecular dynamic simulation (MDS) [LIV, XIII] and the first principle technique [LIX] etc., are some of the wear modeling techniques developed based on fundamental laws of physics. Micro-scale dynamic modeling (MSD model) was also presented for wear modeling to better comprehend the abrasive wear in materials [XXI, VIII]. Afterward, it is utilized for simulating the SPE of homogenous materials [VII]. Some studies have examined the relationships between the resistance to wear and distinctive features of PMCs using a variety of semi-empirical methods [XXXVIII, XX].

Wear depends on numerous mechanical and other characteristic parameters, so it can be treated as a very complicated one. The empirical equations are very much useful to determine the wear response of PMC's in some specialized cases. The prediction of wear response is done using an Artificial Neural Network (ANN) by 'Velten et al.' [LV] and 'Zhang et al.' [LVII]. Almost in all research works related to PMC's the wear behaviour is predicted by a multi-layered neural network [LVIII, XXIII]. Recently, Patnaik et al. [XXVIII-XXXII] and Sandhya Rani Biswas [XXXIX-XLII, XXV] developed mathematical expressions to determine or estimate the SPE wear rate of PMC's underneath several impingement conditions depending on the conservation of energy of the eroding particles.

This section presents the evolution of a model for calculating the theoretical wear rate because of erosion induced by the impact of hard particles on the composite surface. It also focuses on the concerns connected to material removal processes from the surface of the polymer matrix composite due to erosive wear. This study paper uses Newton's second law of motion to build a theoretical model to predict the erosion wear rate, which is based on earlier literature.

III. Materials and Methods

Newton's second law of motion, different air-jet erosion test rig operating parameters, and impinging slurry particle characteristics are taken into consideration in order to obtain the equation for the theoretical erosion wear rate model.

IV. Development of a Theoretical/ Mathematical model to estimate the Erosion wear behaviour

The following Nomenclature/ symbols are used in the development of theoretical model:

M	Erodent's mass flow rate in Kg/Sec
H	standoff distance from nozzle tip to target surface (m) (SOD)
α	Angle of impingement/angle of impingement in degrees (AOI)
V	Velocity of impingement/Velocity of impact in meters per sec (VOI)
η	Erosion efficiency
E_{rexp}	Experimental erosion wear rate in mg/kg
E_{rth}	Theoretical erosion wear rate in mg/kg
d	Diameter of erodent particle (m)
2r	Chord length of indentation/diameter of spherical segment (m)
N	Number of impacts /sec
Pexp	Experimental density of composite in kg/m^3
ρ_{th}	Theoretical density of composite (kg/m^3)
ρ	Erodent density in kg/m^3
Hv	Vickers microhardness number of the composite (N/m^2)
e_v	Volumetric wear loss/particle impact in m^3
Ev	Total volumetric wear loss (m^3/sec)
m	Mass of single particle (Kg)
F	Force of jet/ Indenter (N)
δ	Depth of Indentation (m)

Solid particle erosion (SPE) is the process or operation wherein a composite surface loses its content due to the impact of high-speed erodent particles. The loss of material from the upper surface is owing to the striking of particles against the surface. A solid particle will have kinetic energy and momentum during its flight; it can be dissipated because of the interaction of particles with the target material during the impact. The study of the erosion wear occurrence of polymer matrix composites is mostly experimental as there is no specific expression to know the erosion wear volume.

In the AJM process to estimate the material removal rate Mishra [XXIII] developed a theoretical or mathematical model in which the removal of material volume from the surface is equal to the volume of indentation (VoI) caused due to the impingement of hard particulates but in an actual erosion procedure the volume of material removal will not be equal to volume of indentation and hence the term erosion efficiency (η) is incorporated to estimate the wear rate in erosion process.

The expression for erosion efficiency defined by Sundarajan et.al [XLVII] is represented as:

$$\eta_{normal} = \frac{2E_r.H_v{}^1}{\rho.v^2} \tag{4.1}$$

But the expression for erosion efficiency due to the impingement of erodent at α angle to the surface can be acquired by modifying equation 4.1 as

$$\eta = \frac{2E_r.H_v{}^1}{\rho.v^2.Sin^2\alpha} \tag{4.2}$$

A model was prepared by Amar Patnaik et.al [XXX] to estimate the erosion wear rate when erodent particles of spherical shape impinge on the target material surface with high velocity causing indentation and loss of material from the surface is a measure of indentation. The estimation of erosion wear rate was done by the principle of energy conversion. It is assumed that the erodent and material of the target/ Composite are at identical temperatures or room temperature. The expression for the theoretical erosion wear rate proposed by Amar Patnaik is:

$$Erth = \frac{\rho_c.v^2.Sin^2\alpha.\eta}{2H_v{}^2} \tag{4.3}$$

The above expression (5.3) may be true when the erosion process is taking place at room temperature but when the eroding material is at an elevated temperature like in pipelines (Target material) hot air carrying pulverized coal (erodent) there will be debauchery of thermal energy as well as kinetic energy from erodent to composite surface/target material. In these situations, to estimate the wear rate a theoretical model was prepared by Sandhyarani Biswas in 2010 [XL], in which the erodent particles of irregular shape having sharp edges and the material removal takes place due to the indentation of erodent particles which are at high temperatures. This model was also developed based on energy preservation in which the loss in kinetic energy and thermal energy of the erodent during the impact is equal to the amount of work done for the notch.

The mathematical expression for erosion wear rate estimation by Sandhyarani Biswas is:

$$Erth = \frac{\rho_c.\eta.[v^2.Sin^2\alpha + 2S(T - T0)}{2H_v{}^2} \tag{4.4}$$

In this work, a theoretical model is derived to estimate the erosion wear rate based on the second law of motion in which an erodent particle is assumed to be spherical as shown in Figure 4.1, and considers the ductile manner of erosion. The development of a numerical model for erosion wear rate is as follows:

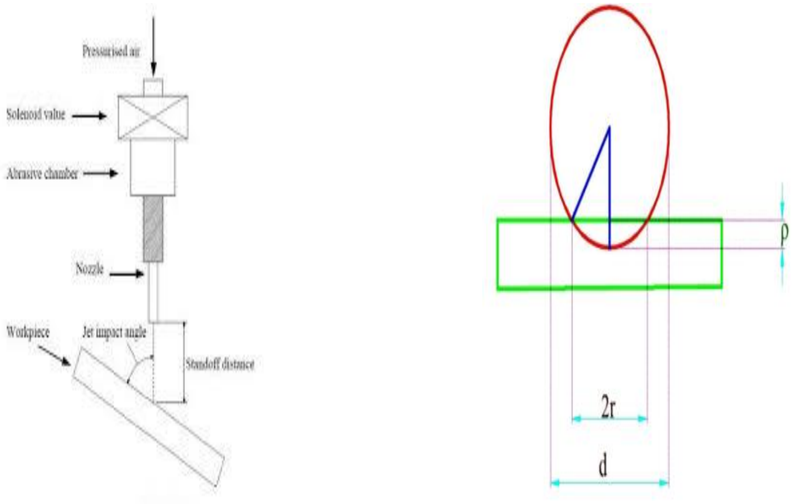

Fig. 4.1. Scheme of the mechanism of material removal from the composite surface with the impingement of erodent particle spherical in shape
Source: Drawn by Autocad software

From Figure 4.1 it is observed that

$$r^2 = d\delta \tag{4.5}$$

Volume of Indentation

$$= \frac{1}{3}\pi\delta^2[3R-\delta]$$

$$= \frac{1}{3}\pi\delta^2\left[\frac{3d}{2}-\delta\right]$$

$$= \frac{\pi d\delta^2}{2} - \frac{\pi\delta^3}{3}$$

δ^3 Term can be neglected as δ represents the negligible depth of indentation.

So, Indentation volume $= \frac{\pi d\delta^2}{2}$

Volumetric wear loss/particle (e_v)

$$= \text{Indentation volume} \times \eta$$

$$= \frac{\pi d\delta^2}{2} \times \eta$$

Where (η =erosion efficiency)

Volumetric erosion wear loss for 'N' number of particles

$$E_v = N \times \frac{\pi d\delta^2}{2}\eta \tag{4.6}$$

By considering Newton's second law of motion

$$v^2 - u^2 = 2as$$

$$v^2 Sin^2\alpha = 2as$$

$$v^2 Sin^2\alpha = 2\left(\frac{F}{m}\right)h$$

$$v^2 Sin^2\alpha = \frac{2(\pi r^2 Hv)}{\left(\frac{\pi d^3}{6}\right)\rho}h$$

$$v^2 Sin^2\alpha = \frac{12(\pi d\delta H_v h)}{\pi d^3 \rho}$$

$$\delta = \frac{v^2 sin^2\alpha d\rho}{12H_v h} \tag{4.7}$$

The total number of erodent pieces impacting the target material is calculated using the known value of the erodent's mass flow rate, M.
Number of particles

$$N = \frac{M}{\left(\frac{\pi d^3}{6}\right)\rho} \tag{4.8}$$

Where $\rho = \frac{mass}{volume}$

Equations (4.7) and (4.8) substituted in equation (4.6)

$$E_v = \frac{6.M}{\pi d^3.\rho} \times \frac{\pi d}{2}.\eta \times \frac{v^4.Sin^4\alpha.d^3.\rho^2}{144.H^2v.h^2}$$

Total Volume (E_v) $= \frac{\rho.v^4.Sin^4\alpha.\eta}{48.H_v{}^2.h^2}.M$

Mass lost from the material $= \frac{\rho_c.\rho.v^4.Sin^4\alpha.\eta}{48.H_v{}^2.h^2}.M$

Erosion rate (E_{rth}) $= \frac{mass\ lost}{mass\ of\ erodent}$

$= \frac{\rho_c.\rho.v^4.Sin^4\alpha.\eta}{48.H_v{}^2.h^2} \times \frac{M}{M}$

$$(\boldsymbol{E_{rth}}) = \frac{\boldsymbol{\rho_c.\rho.v^4.Sin^4\alpha.\eta}}{\boldsymbol{48.H_v{}^2.h^2}} \tag{4.9}$$

The above mathematical expression (4.9) is used to estimate the wear rate in SPE process from the surface of the composite and assessment against experimental results.

V. Conclusions

The key findings from the development of the theoretical model are as follows:

- This article proposes a hypothetical approach for estimating the composite wear rate in SPE.
- By utilizing the above theoretical model one can reduce the erosion wear rate experimentation cost to a large extent.
- To confirm the proposed theoretical model, erosion wear rate experiments are to be conducted using an air jet erosion wear test rig in a variety of functioning circumstances. (will be discussed in the next article)

Conflict of Interest:

There was no relevant conflict of interest regarding this paper.

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