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A Solid Particle Erosion of Composite Materials: Review Paper

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ABSTRACT

The effect of erosion on the economy is widely acknowledged, with solid particle erosion (SPE) being recognized as one of the most significant forms of erosion resulting from the collision of solid particles with materials. While studying and comprehending erosion can be challenging, researchers have dedicated their efforts to this field and have devised models to anticipate the erosion rate of material elimination from the surface of an object, based on the material's response to solid particle impact. Most erosion models for composite materials take into account various physical and mechanical properties of the material, such as its density, porosity, modulus, strength, and fracture toughness. They also examine the characteristics of the particles that cause erosion, such as their size, shape, and hardness. Erosion models for composite materials are used to study the impact of different factors on erosion, such as the effect of particle size, velocity, and impingement *angle. They are also used to optimize the design of composite materials and structures for specific applications and to evaluate the performance of protective coatings and erosion-resistant materials. Erosion models for composite materials can be either empirical or process-based. Empirical models use statistical relationships to predict erosion rates based on observed data, such as the size and shape of the particles, the velocity of the impacting particles, and the* impingement *angle. While the process-based models, on the other hand, use mathematical equations to simulate the physical processes that drive erosion, such as the deformation and fracture behaviour of the composite material under impact loading. Overall, erosion models for composite materials provide a valuable tool for understanding and predicting the complex processes that drive the erosion of composite materials, and for developing effective strategies to mitigate its impact on their performance and durability in various applications.*

Keywords:

Solid particle erosion; Erosion parameters; Particulate composite materials.

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1. INTRODUCTION

One of the most important wear processes for engineered materials is erosion which occurs due to the scattered particles in the fluid flowing over the material's surface. This erosion shortens the lifespan of the mechanical parts utilized in several technical and industrial applications. Based on the erodent types and impact methods, erosion could have different forms based on the erodent types and impact methods, such as cavitation erosion, solid particle erosion, liquid impact erosion, and slurry erosion [1],[2]. Erosion is the gradual degradation or harm of a solid surface due to its exposure to a fluid motion, which may be either single-phase or multi-phase. In addition, erosion is classified as a form of tribology which is defined as the science of studying the interactions between surfaces with relative motion. This field of science encompasses various phenomena, such as friction, wear, erosion, and lubrication [3],[4].

Solid particle erosion is a constantly changing phenomenon that takes place in various machine components, as a result of the impact of solid particles. The affected parts experience degradation of their surface and removal of material. Like other tribological processes, solid particle erosion is also a complex process, where mechanical stress may trigger secondary chemical, physical, and thermal reactions between the components in the tribological system. One of the most significant forms of erosion is solid particle erosion, which occurs when solid particles strike and damage the surface of a material. The erosion of solid particles is a significant contributor to the failure of centrifugal and axial compressors. This is because these particles can wear away the leading and trailing edges of the compressor blades, resulting in a deformation of the airfoil shape, and a reduction in compressor pressure ratio. Furthermore, this phenomenon can be found in other mechanical systems and lead to a decline in their overall efficiencies such as the turbine blades, machine components, combustion systems, and pipelines [2],[3],[5],[6].

2. EROSION RATE ESTIMATION

It's important to acknowledge that erosion data is reported in different ways by researchers. Erosion rates, for instance, are typically expressed as either the loss of material mass or thickness over time, in units such as kg/hr or mm/year. In contrast, certain authors report erosion data in units of mass loss, volume loss, or thickness loss per unit mass of impacting particles, utilizing measurements such as g/g, and similar units [7].

3. EROSION MECHANISM

There are two principal mechanisms for the erosion behaviour of materials: ductile erosion and brittle erosion. The ductile materials experience weight loss due to plastic deformation that arises from the cutting or displacing action of the eroding particle. Conversely, brittle materials lose material when cracks intersect and radiate out from the point of impact of the eroding particle. Materials like annealed low-carbon steel, copper, aluminium, glass, and ceramics can be easily classified into these two categories. However, other materials may not fit easily into these categories. Based on the illustration in Fig. 1, the *solid particle erosion* (SPE) behaviour of a material can be classified into two groups. The first category exhibits the most significant erosion rates when subjected to low angles of incidence (typically between 20 and 40 degrees). This category is identified by the material removed that occurs through plastic flow mechanisms like ploughing or cutting. On the other hand, brittle erosion is marked by a maximum loss of material when subjected to a normal angle of incidence. This is due to the surface absorbing the greatest amount of kinetic energy from the particle, resulting in the formation, propagation, and interaction of cracks [8].

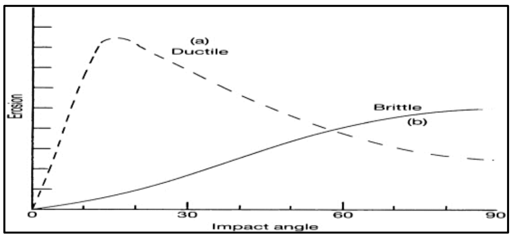


Fig.1 The behaviour of (a) ductile, and (b) brittle materials in SPE [8],[9].

4. KEY PARAMETERS IN SOLID PARTICLE EROSION

The effect of different parameters in these of composite materials is a critical area of research that aims to identify the key factors that influence the erosion resistance of these materials. Various parameters can influence the erosion behavior of composite materials, including particle velocity, particle size and shape, impact angle, temperature, and composite material properties.

Research in this area of interest involves investigating the effect of each of these parameters individually or in combination, using experimental techniques such as erosion testing and characterization, as well as numerical modelling and simulation. The goal is to identify the mechanisms that govern erosion and develop predictive models that can aid in the design of erosion-resistant composite materials.

The complexity of the erosion process represents a significant obstacle when investigating the impact of various parameters on SPE. For instance, the behavior of composite materials subjected to high velocity can be highly nonlinear and dependent on numerous factors, making it difficult to isolate the effect of a single parameter from others. However, the advances in experimental and numerical techniques have allowed researchers to progress significant in this field.

In summary, investigating the impact of various parameters on solid particle erosion of composite materials is essential in comprehending the erosion behavior of such materials and formulating approaches to enhance their erosion resistance.

Influence particle properties: Size, density, hardness, and other particle characteristics, among others, have a big impact on SPE. To gain a more comprehensive understanding of how each particle property influences erosion, it is necessary to examine the impact of each property separately [6],[10],[11].

Influence of the cumulative weight: The erosion behaviour of surface, commonly observed in polymers, when exposed to particles impingement is illustrated in Fig. (2). As depicted in the figure, the erosion process goes through four periods, i.e., the incubation, the acceleration, the steady state, and the deceleration. The incubation or induction period is distinguished by insignificant or minimal weight loss that is followed by weight gain. While the acceleration phase refers to the period when the impinging particle's cumulative weight is accumulated. In this period, the erosion rate experiences a sharp increase and reaches a maximum value, which is termed as the peak erosion rate. This is followed by the steady-state period which is characterized by remaining the erosion rate almost constant with a continuous buildup of the impinging particles' cumulative weight. In the deceleration phase, however, the erosion rate decreases rapidly from either the peak or steady-state value when the impinging particle's cumulative weight is at its maximum [12].

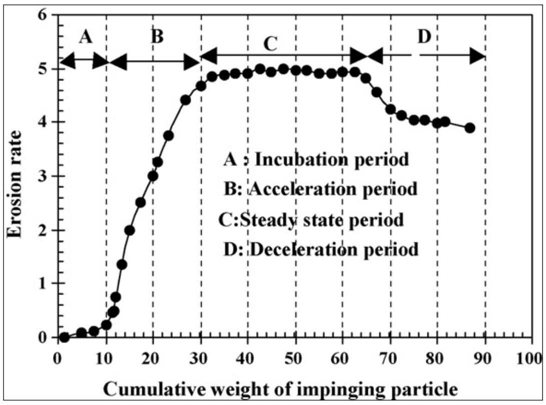
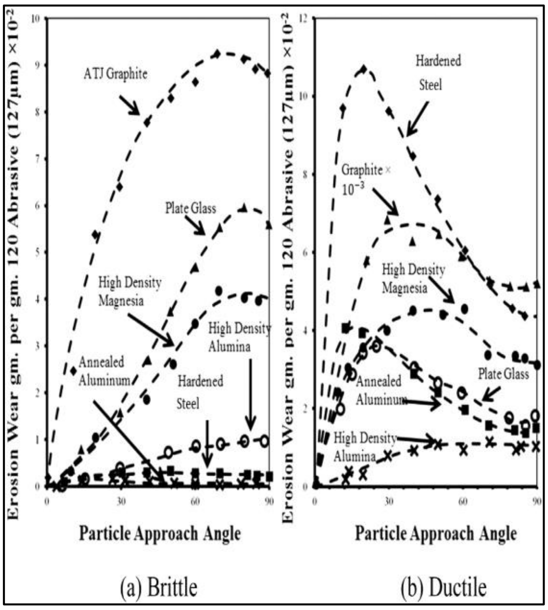


Fig. 2 The influence of the cumulative weight of the solid particles striking surface on the erosion rate [12].

Influence of impingement angle: Several studies have focused on exploring the effect of particle impingement angle on the SPE behavior for different materials and found that it plays a big role. Based on the relationship between a material's erosion rate and impingement angle, the materials have been divided into ductile, brittle, and semi-ductile categories. The studies show that the maximum erosion in brittle material happens at normal impingement angles (90°). While the maximum erosion in semi-ductile material occurs at impingement angles between 45° and 60°. However, for ductile materials, the highest erosion typically takes place at low impingement angles ranging from 15° to 30° [13].

The impact angle of particles affects erosion differently depending on the surface material. Figure (3) illustrates the correlations between erosion rate and particle impact angle for ductile and brittle materials. Clearly, brittle materials have distinct erosion rate patterns than ductile ones. Consequently, higher erosion rates for ductile materials happen at smaller impact angles. This is because particles cutting platelets at lower angles produce them and cut them more effectively [14].

In contrast, due to cracking being the main factor leading to erosion in brittle materials, the highest erosion in such materials is observed at impact angles close to normal. It is worth noting that most materials used in the oil and gas industry exhibit both ductile and brittle characteristics [14].



(a) Brittle (b) Ductile

Fig. 3 The variation of erosion rate for various materials vs. the particle impact angle, for a particle impact velocity of 153 m/s and using the Silicon Carbide Grit [14].

Influence of impact velocity: Harsha and Thakre [12] conducted a study on erosion for polyetherimide and its composites by varying the impact velocity of particles between 30 and 88 m/s, and the impingement angles ranging from 15° to 90°. Figure 4 depicts the erosion rate of polyetherimide and its composites in a steady state, which increases as the impact velocity of particles increases at different impingement angles, i.e., 60° and 90°. Their results showed that the erosion rate of the materials is significantly influenced by the velocity of the erosive particles. Accordingly, they suggested a correlation equation of the power law form ($E=KV^n$) was used to fit their data points obtained from the tests. In this equation, the variables E, V and n represent respectively the steady-state erosion rate, the impact velocity of particles, and the velocity exponent, while k is a constant [12].

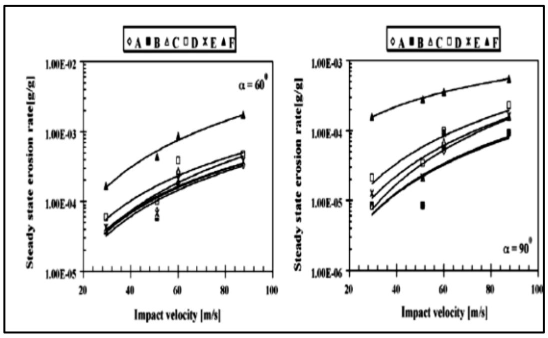


Fig. 4 The effect of impact velocity on steady state erosion rate for PEI and its composites [12].

Influence of solid particle size: Desale et al. [15] in (2009) investigated how the erosion performance of an aluminum alloy (AA 6063) was affected by the particle size of the silica sand employed in their study for eight different sizes, ranging from 37.5-655 µm. They maintained a sand concentration of 20 wt% and a carrier fluid velocity of 3 m/s for investigating the effect of the impingement angles of 30 and 90°. Their findings indicated that, despite a decrease in the number of particles and their impacts, increasing the particle size at a constant sand concentration (wt %) increases the erosion rate. Figure (5) illustrates the influence of particle size on the particle impact velocity and kinetic energy per impact [14],[15].

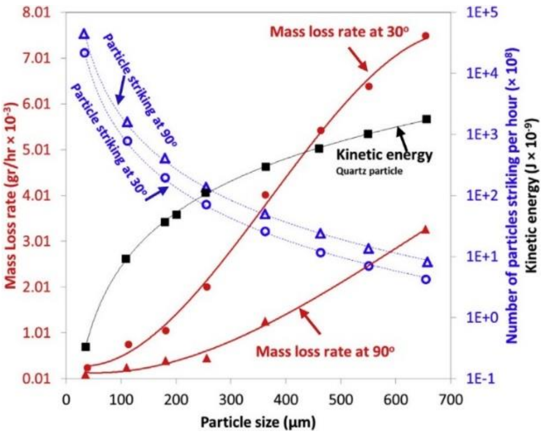


Fig. 5 Impact of sand size on the erosion rate, the number of impacting particles, and the kinetic energy of impact on AA 6063 target material in the presence of 20 wt% silica sand [14].

Generally, it has been shown that as the particle size rises, the erosive also increases. Using appropriate particle size is one of the main challenges in creating or using these connections. A number of studies proposed a power-law correlation equation, as shown below, for connecting the mean size of the particles gathered across a small size range with the erosion rate:

$$Erosion\ rate\ \alpha\ particle\ size^{n}.$$

The range of values for exponent 'n' has been reported to be between 0.3 and 2.0, which can be explained by differences in experimental conditions, material properties, particle size, and size distributions. Gandhi and Borse [15] proposed to use the mass mean particle size to evaluate wear for the cases where solid particle size in a solid-liquid mixture varies significantly. At a constant solid concentration, an increase in particle size leads to a decrease in the number of suspended particles in the mixture. However, an increase in the kinetic energy per impacting particle, results in an increase in overall wear. The effect of particle size on striking efficiency and impact velocity was investigated by Clark, who measured the craters formed by particle impacts on wear specimens. He observed a significant decrease in striking efficiency and impact velocity with a decrease in particle size. Additionally, it mentions that Lynn et al. [18] also conducted a similar study on this phenomenon [15].

Influence of solid particle shape: The shape of particles has a significant impact on the erosion rate, as demonstrated by Salik et al. [19], who showed that it can cause a tenfold change in the erosion rate. A similar behavior observed by Levy and Chik [11], who noted that the sharpness of the particles had a significant impact on the rate of erosion. They used two distinct particle forms, i.e., the spherical and sharp angular particles. The erosion caused by sharp angular particles was four times greater than that caused by spherical particles. Moreover, it has been noted that particle shape and particle angularity both influence the impact angle at which the most erosion occurs. The various particle sizes used in previous experimental studies are shown in Fig. (6) [14],[16].

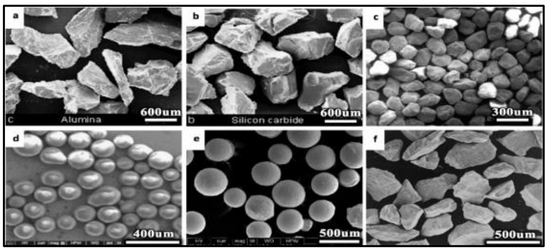


Fig. 6 Particle materials and shapes used in experimental studies: (a) alumina, (b) silicon carbide, (c) quartz, (d) glass beads, (e) round steel grit, and (f) tungsten carbide [5].

Influence of temperature: Numerous theories have been proposed to elucidate the impact of temperature on the erosion process. According to Smeltzer et al. [20], the erosion rate reduces as the temperature rises. Subsequently, Levy [11] proposed that rising temperature causes metal ductility to rise. Therefore, a higher proportion of the kinetic energy of impacting particles is dissipated through plastic deformation. The influence of temperature on erosion is not well-understood, but it is believed to have a minor impact [14].

For the three particle sizes taken into consideration and under typical impact velocity at 200 m/s, the variation in erosion rate with temperature is depicted in Fig. 7. It is evident that the rate of erosion accelerates as the temperature rises. The erosion rate for the three particle sizes showed a moderate increase up to 815 °C, but exhibited a dramatic rise at 1200 °C. At 815 °C, the erosion rate was nearly 1.4-2.4 times higher compared to ambient temperature, while at 1200 °C, it was 2–4 times higher [17].

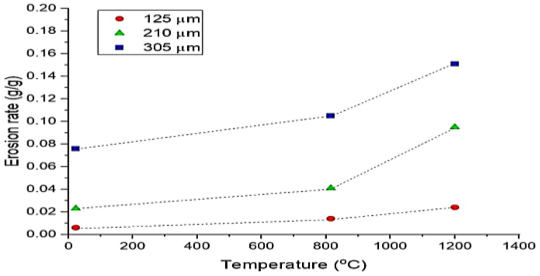


Fig. 7 The impact of temperature on the erosion rate for three different particle sizes [17].

5. CONCLUSIONS

An SPE of composite materials is a complex and challenging area of research that has attracted significant attention from materials scientists and engineers. Overall, the study of SPE of composite materials is important for a wide range of applications, including aerospace, automotive, and energy industries, where materials are often exposed to harsh environments that can cause erosion. This research can help to identify new composite materials with improved erosion resistance and to optimize the design of components and structures to reduce erosion and extend their lifespan. In summary, an SPE of composite materials is an important area of research that requires a multidisciplinary approach, combining experimental techniques with theoretical modeling and materials design. Continued research in this field is expected to generate additional insights into erosion behaviour and drive innovation in materials science and engineering. Based on the current study, the following conclusions can be drawn:

i. Solid particles erosion is considered one of the most dangerous types.
ii. Two main types of material erosion behaviour mechanisms have been identified: one for ductile materials and another for brittle materials.
iii. The erosion behaviour of materials varies depending on their properties. Ductile materials exhibit maximum erosion at low impingement angles (15°- 30°), while brittle materials show maximum erosion at normal impingement angles, i.e., 90°. Semi-ductile materials, on the other hand, exhibit maximum erosion at impingement angles of 45°- 60°.
iv. Particle properties such as size, density, hardness, and shape have significant influence on SPE.
v. The erosion rates of samples increase with increasing particle velocity for all particle sizes. However, the erosion behaviour of materials remains unaltered with an increase in the particle impingement velocity.
vi. Even when striking a target at the same velocity, larger particles have greater kinetic energies than smaller particles.
vii. The maximum erosion rate is influenced by the shape of the particles and can vary depending on their angularity.
viii. As the number of particles increases, they tend to rebound and deviate from their trajectory, resulting in sliding over the surface without causing any erosion.

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عملية التعرية بالجسيمات الصلبة للمواد المتراكبة: بحث مراجعة

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الملخص

إن تأثير التعرية على الاقتصاد معترف به على نطاق واسع ، حيث يتم التعرف على التعرية بواسطة الجسيمات الصلبة كأحد أهم انواع التعرية الناتج عن اصطدام الجسيمات الصلبة بالمواد. في حين أن دراسة التعرية وفهمه يمكن أن يمثل تحديًا ، فقد كرس الباحثون جهودهم لهذا المجال وابتكروا نماذج لتوقع معدل تعرية إزالة المواد من سطح الجسم ، بناءً على استجابة المادة لتأثير الجسيمات الصلبة. تأخذ معظم نماذج التعرية للمواد المتراكبة في الاعتبار الخصائص الفيزيائية والميكانيكية المختلفة للمادة ، مثل كثافتها ومساميتها ومعاملها وقوتها وصلابة الكسر. كما يأخذون في الاعتبار خصائص الجسيمات التي تسبب التعرية ، مثل حجمها وشكلها وصلابتها. تُستخدم نماذج التعرية للمواد المتراكبة لدراسة تأثير العوامل المختلفة على التعرية ، مثل تأثير حجم الجسيمات والسرعة وزاوية التأثير. كما أنها تستخدم لتحسين تصميم المواد المتراكبة والهياكل لتطبيقات محددة ولتقييم أداء الطلاءات الواقية والمواد المقاومة للتعرية. يمكن أن تكون نماذج التعرية إما تجريبية أو قائمة على العمليات. تستخدم النماذج التجريبية العلاقات الإحصائية للتنبؤ بمعدلات التعرية بناءً على البيانات المرصودة ، مثل حجم وشكل الجسيمات وسرعة الجسيمات المؤثرة وزاوية التأثير. من ناحية أخرى ، تستخدم النماذج القائمة على العمليات المعادلات الرياضية لمحاكاة العمليات الفيزيائية التي تؤدي إلى التعرية ، مثل التشوه وسلوك الكسر للمادة المتراكبة تحت تأثير التصادم. بشكل عام ، توفر نماذج التعرية للمواد المتراكبة أداة قيمة لفهم الاليات التعر والتنبؤ بها ، ولتطوير استراتيجيات فعالة للتخفيف من تأثيرها على أدائها ومتانتها في مختلف التطبيقات.

الكلمات الدالة:

التعرية بواسطة الجسيمات الصلبة، متغيرات التعرية، المواد المتراكبة.