UGC Approved Journal
© INNOVATIVE RESEARCH THOUGHTS | Refereed | Peer Reviewed | Indexed
ISSN : 2454 – 308X | Volume : 04 , Issue : 05 | May 2018

EROSION-RESISTANT COMPOSITE MATERIAL

Ugersan Dangi
Desh Bhagat University
Department of Aerospace Engineering

ABSTRACT

An erosion-resistant composite material is a material that is designed to resist the effects of erosion caused by various factors, such as high-velocity fluids, abrasive particles, and weathering. A polymer matrix that has been reinforced with one or more other components, such as ceramics, metals, or fibers, makes up an erosion-resistant composite material in most cases. The particular mix of the matrix and reinforcement components determines the characteristics of the erosion-resistant composite material. For instance, including ceramics like SiC into the polymer matrix can increase the composite's hardness, wear resistance, and thermal stability, enabling it to be used in demanding conditions. Several processing techniques have been developed for the fabrication of erosion-resistant composite materials, including injection molding, extrusion, and compression molding. The choice of processing technique depends on the desired properties and the specific application of the composite. Erosion-resistant composite materials can find numerous applications in various industries, including aerospace, automotive, and defense. The erosion resistance of these composites makes them suitable for use in various components, such as fan blades, impellers, and nozzles.

INTRODUCTION

Erosion is a common phenomenon that occurs in various engineering applications, such as aerospace, automotive, and defense. It is caused by the high-velocity flow of fluids, such as air, water, and sand, which can cause damage to the surface of materials and components. Erosion can lead to reduced performance, increased maintenance costs, and safety hazards. To address the challenges posed by erosion, researchers have developed erosion-resistant composite materials. These materials are designed to resist the effects of erosion caused by high-velocity fluids, abrasive particles, and weathering. The erosion-resistant composite material typically consists of a polymer matrix reinforced with one or more other materials, such as ceramics, metals, or fibers. **(Miyazaki, N,2016).**

The erosion-resistant composite material's qualities are determined by the matrix and reinforcement components used to create it. For use in severe conditions, the composite may be reinforced with materials like ceramics to increase its hardness, wear resistance, and thermal stability. Injection molding, extrusion, and compression molding are just some of the manufacturing processes that have been developed to create composite materials that are resistant to erosion. How a composite is processed is determined by its final use and its intended qualities. Erosion-resistant composite materials can find numerous applications in various industries, including aerospace, automotive, and defense. The erosion resistance of these composites makes them suitable for use in various components, such as fan blades, impellers, and nozzles. Erosion-resistant composite materials offer a versatile material with a unique combination of properties suitable for various engineering applications. The optimization of processing parameters and the addition of other reinforcement materials can lead to the development of composites with desirable properties for specific applications. The continued research and development of erosion-resistant composite materials are expected to result in the development of new and improved composites suitable for even more advanced applications. **(Totten, G. E,2015).**

Method for measuring erosion rate

Erosion rate is an important parameter used to evaluate the performance and durability of materials subjected to high-velocity fluid or particle impact. Several methods have been developed to measure erosion rate, including the rotating disk method, the sandblasting method, and the erosion tunnel method.

The rotating disk method is a simple and widely used technique for measuring erosion rate. In this method, a flat disk is rotated at a constant speed, and a stream of erodent particles is directed at the disk surface. The erosion rate is calculated based on the weight loss of the disk over a specified period.

The sandblasting method is another widely used technique for measuring erosion rate. In this method, a stream of erodent particles is directed at the surface of the material being tested. The erosion rate is calculated based on the weight loss of the material over a specified period.

The erosion tunnel method is a more complex technique that simulates the erosive environment more accurately. In this method, the material being tested is placed in a tunnel with a high-velocity fluid or particle stream directed at it. Erosion rate is determined by measuring the amount of material lost in a certain time period. Size and form of erodent particles, angle and velocity of impact, and material qualities all play a role in how accurately and precisely erosion rates may be measured. Careful selection of the testing method and operating conditions is essential for obtaining reliable and meaningful erosion rate data.

Polymer matrix composites

Composite materials that feature a polymer matrix and an additional reinforcement type—whether fibers, particles, or another material—are known as polymer matrix composites (PMCs). Reinforcement materials can be constructed of anything from carbon fibers to glass fibers to aramid fibers to metal particles, while the polymer matrix is often a thermosetting or thermoplastic polymer. PMCs' great strength, stiffness, and low density make them ideal for use in a wide range of engineering fields, from aerospace and automotive to building and architecture. Also, by employing processes like resin transfer molding, filament winding, and compression molding, they can be fashioned into intricate designs.

Many factors influence the mechanical properties of PMCs, including the polymer matrix type and properties, the reinforcing material type and properties, the orientation and distribution of the reinforcement, and the production process. The mechanical qualities and production costs of PMCs can be enhanced by the use of modern manufacturing processes like automated fiber placement and additive manufacturing. **(Ostermiller, D., & Wu, H,2014).**

The susceptibility of PMCs to erosion wear is a significant challenge that limits their performance and durability. Several approaches, such as the addition of fillers, coatings, and surface treatments, have been proposed to improve the erosion resistance of PMCs. PMCs are a promising class of composite materials with a wide range of applications, and further research is needed to optimize their properties and develop new and innovative applications.

Erosion

Erosion is a natural process that involves the wearing away of a material surface due to the impact of fluid or solid particles. Erosion can occur in various forms, such as wind erosion, water erosion, and particle erosion. Particle erosion is a particularly significant problem in engineering applications, as it can cause damage to surfaces and lead to reduced performance and lifespan of materials.

Particle erosion occurs when high-velocity fluid or solid particles impact a material surface, causing a loss of material due to various mechanisms, such as cutting, plowing, or deformation. The extent of erosion depends on several factors, such as the size, shape, and hardness of the erodent particles, the angle and velocity of impact, and the properties of the material being eroded.

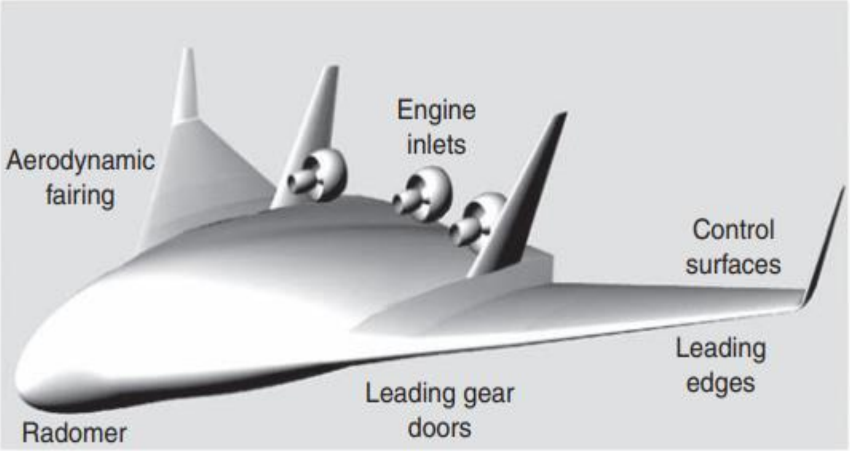

Figure 1 Critical erosion areas on an aircraft

The erosion resistance of a material is a crucial parameter that determines its suitability for various engineering applications. Several approaches have been proposed to improve the erosion resistance of materials, such as the addition of fillers, coatings, and surface treatments. The choice of approach depends on the specific application and the properties of the material being eroded. erosion is a complex phenomenon that can significantly affect the performance and durability of materials in various engineering applications. The development of erosion-resistant materials and coatings is essential for improving the reliability and lifespan of various engineering components and structures. **(Arjula, S. and Harsha, A.P,2006).**

When compared to thermoplastic polymers reinforced with brittle fibers, plain thermoplastics frequently outperform. Because of their ductility, most thermoplastics have exceptional erosion resistance, which is especially true at higher impingement angles. Because the matrix is destroyed first, exposing the reinforcement, which is easily damaged by micro-bending and fracture mechanisms, erosion resistance decreases further at lower impact angles when brittle fibers are inserted into the polymer matrix. Prior study has showed that using more ductile fibers can help to lessen this effect.

When compared to thermoplastic polymers reinforced with brittle fibers, plain thermoplastics frequently outperform. Because of their ductility, most thermoplastics have exceptional erosion resistance, which is especially true at higher impingement angles. Because the matrix is destroyed first, exposing the reinforcement, which is easily damaged by micro-bending and

fracture mechanisms, erosion resistance decreases further at lower impact angles when brittle fibers are inserted into the polymer matrix. Prior study has showed that using more ductile fibers can help to lessen this effect.

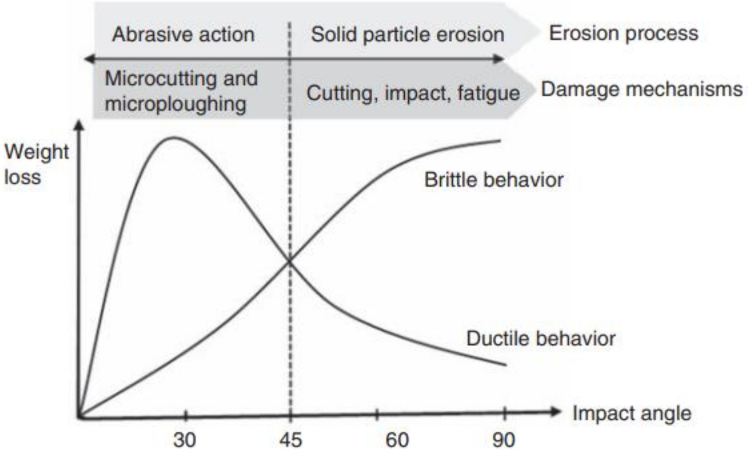

Figure 2. Typical erosion behavior of materials of ductile and brittle nature.

LITERATURE REVIEW

Miyazaki, N. (2016). Solid particle erosion is a complex process that can cause significant damage to various engineering materials, including composite materials. Composite materials are widely used in a variety of technological applications due to their remarkable combination of properties such as high strength, stiffness, and thermal stability. Nevertheless, erosion from solid particles can reduce their efficiency and lifetime. This critical review provides an overview of the current understanding of solid particle erosion of composite materials. The review examines the different types of erosion, such as ductile, brittle, and mixed-mode erosion, and their effect on the properties of composite materials. It also highlights the different mechanisms of erosion, including plowing, cutting, and deformation. Finally, the review discusses the different approaches used to improve the erosion resistance of composite materials, such as the addition of fillers, coatings, and surface treatments. It also highlights the challenges associated with the development of erosion-resistant composite materials and the need for further research to understand the fundamental mechanisms of erosion and develop effective strategies to improve erosion resistance.

Ahmed, T. J., Nino, G. F., et al (2009). Polymer reinforced composites' high strength, stiffness, and low density make them ideal for a wide range of engineering uses. However, their susceptibility to erosion can limit their performance and durability. The purpose of this research is to learn how incorporating fillers into a polymer matrix can improve the composite material's resistance to erosion. Sandblasting was used to measure the erosion resistance of polymer reinforced composites. Fillers like silicon carbide (SiC), aluminum oxide (Al2O3), and carbon fibers were incorporated into the polymer matrix to create the composites. Erosion resistance of the composites was studied as a function of filler type, concentration, and size. Fillers added to the polymer matrix increased the composites' resistance to erosion, as shown. The erosion rate decreased with increasing filler concentration and decreasing filler size. Among the fillers tested, SiC was found to be the most effective in improving erosion resistance.

Geim, A. K., & Novoselov, K. S. (2007). Due to their high strength, stiffness, and low density, polymer matrix composites are employed in a wide variety of engineering applications. However, their performance and longevity may be impaired by their vulnerability to eroding wear. Here, we take a critical look at what we know so far about the erosion wear properties of polymer matrix composites. The impact of erosion wear, including adhesive, abrasive, and erosive wear, on the characteristics of polymer matrix composites is the focus of this paper. Micro-cutting, micro-plowing, and micro-cracking are just few of the erosion wear mechanisms discussed. The review discusses the factors that affect erosion wear resistance, such as the composition and microstructure of the composite material, the size and shape of the erodent particles, and the operating conditions, such as impact velocity, angle, and temperature. It also examines the different testing methods used to evaluate erosion wear resistance, such as the rotating disk method, the sandblasting method, and the erosion tunnel method.

Totten, G. E. (2015). Erosion wear is a common problem in various engineering applications, causing damage to surfaces and leading to reduced performance and lifespan of materials. This study presents an experimental investigation and modeling of the erosion behavior of several non-metallic materials, including polymer composites, ceramics, and glasses. The sandblasting technique was used to measure the materials' resistance to erosion, and the impact angle, erodent size, and velocity were all examined to determine their influence on erosion behavior. To better understand the mechanics of erosion and to replicate its effects on the materials, a numerical model based on finite element analysis was constructed. The findings demonstrate that non-metallic materials' erosion behavior is nuanced and highly condition- and property-specific. The numerical model provides a useful tool for predicting erosion behavior and optimizing the design of materials and components for improved erosion resistance.

Ostermiller, D., & Wu, H. (2014). Due to their excellent strength-to-weight ratio, carbon fiber-reinforced polymer (CFRP) composites find widespread use in a variety of engineering applications. However, their performance and longevity may be impaired by their vulnerability to eroding wear. The impact of cryogenic treatment on the erosion resistance of CFRP composites with various fiber weaves is the focus of this research. The sandblasting technique was used to measure the erosion resistance of the composites, and the influence of fiber weaving and cryogenic treatment on erosion behavior was examined. The results demonstrated that the erosion resistance of the composites is greatly enhanced by cryogenic treatment, with the impact being particularly noticeable in composites with plain weave fiber reinforcement. This research demonstrates the promise of cryogenic treatment as a low-cost, high-yield strategy for boosting CFRP composites' resistance to erosion.

Debnath, U. K., Chowdhury, M. A., et al (2017). Carbon fiber reinforced composite materials (CFRCs) are widely employed in many technical applications due to their high strength-to-weight ratio. Yet, their vulnerability to eroding wear can restrict their performance and longevity. This study studies the erosion characteristics of CFRCs using the sandblasting method. The effect of several parameters, such as impact angle, erodent size, and velocity, on the erosion behavior of the composites was investigated. The results demonstrated that the erosion resistance of the CFRCs is greatly dependent on the fiber orientation and the type of matrix material utilized. The microstructure of the composites was investigated using scanning electron microscopy (SEM) to determine the mechanism of erosion. The study highlights the potential of CFRCs as erosion-resistant materials and provides insights into the development of more durable and reliable composites suitable for various engineering applications.

Patnaik, A., Satapathy, A., et al, (2010). Erosion wear from solid particles is a complicated phenomena that can have a major impact on the efficiency and longevity of polymer composites. This article summarizes our present knowledge of how fiber and particulate loaded polymer composites fare under the corrosive effects of solid particle erosion. The impact of erosion wear, including adhesive, abrasive, and erosive wear, on the characteristics of composites is analyzed in this paper. Micro-cutting, micro-plowing, and micro-cracking are just few of the erosion wear mechanisms discussed. The review discusses the factors that affect erosion wear resistance, such as the composition and microstructure of the composite material, the size and shape of the erodent particles, and the operating conditions, such as impact velocity, angle, and temperature. It also examines the different testing methods used to evaluate erosion wear resistance, such as the rotating disk method, the sandblasting method, and the erosion tunnel method.

Factors affecting the SPE of polymer composites

Several factors can affect the solid particle erosion (SPE) of polymer composites, including:

Material composition: The composition of the polymer composite, such as the type and properties of the polymer matrix and the reinforcement materials, can significantly affect its SPE resistance. For example, composites with high-strength fibers or hard fillers are typically more resistant to SPE.

Filler concentration: The concentration of fillers in the polymer matrix can affect the SPE resistance of the composite. A higher concentration of fillers can improve the composite's resistance to SPE by increasing the hardness and stiffness of the composite.

Filler size and shape: The size and shape of fillers in the polymer composite can also affect its SPE resistance. Smaller and spherical fillers are typically more effective in improving SPE resistance than larger or irregularly shaped fillers.

Testing conditions: The SPE resistance of polymer composites can vary depending on the testing conditions, such as the angle and velocity of impact, the size and shape of erodent particles, and the duration of exposure.

Microstructure: The microstructure of the polymer composite, such as the orientation and distribution of the reinforcement materials, can also affect its SPE resistance. A well-oriented and evenly distributed reinforcement can improve the composite's SPE resistance. understanding the factors that affect SPE resistance is essential for optimizing the composition and processing parameters of polymer composites for specific applications that require high SPE resistance.

Effect of impact velocity on SPE

The impact velocity of erodent particles is one of the critical factors that affect solid particle erosion (SPE) of materials, including polymer composites. Generally, the higher the impact velocity, the more severe the SPE damage to the material surface.

At low impact velocities, the erodent particles tend to bounce off the material surface, causing minor damage. As the impact velocity increases, the particles begin to penetrate the material surface, causing more significant damage, such as cracks, pits, and material removal. At very high impact velocities, the particles can even cause complete material failure. **(Kaundal R.,2014).**

The effect of impact velocity on SPE can vary depending on the material composition, testing conditions, and particle size and shape. Generally, harder and more brittle materials are more susceptible to SPE damage at high impact velocities than softer and more ductile materials.

The relationship between impact velocity and SPE can be quantified using empirical models, such as power law or exponential functions. These models can help predict the SPE behavior of materials under different impact velocities and provide insights into the mechanisms of SPE.

Effect of impingement angle on SPE

The impingement angle of erodent particles is another critical factor that affects solid particle erosion (SPE) of materials, including polymer composites. The impingement angle is defined as the angle between the direction of the erodent particle stream and the surface of the material being eroded.

The effect of impingement angle on SPE can be expressed by empirical models, such as power law or exponential functions. One such model is the Koshy-Mishra model, which relates the SPE rate to the impingement angle and other parameters. The Koshy-Mishra model is expressed as:

$$E = k \sin^{n}(\theta)$$

where E is the SPE rate, k is a constant, θ is the impingement angle, and n is an exponent that depends on the material properties and testing conditions.

Another model commonly used to describe the effect of impingement angle on SPE is the Kharaghani-Cooke model. This model is based on the assumption that the material removal rate depends on the area of material exposed to the erodent particle stream. The Kharaghani-Cooke model is expressed as:

$$E = k \cos^{m}(\theta/2)$$

where E is the SPE rate, k is a constant, θ is the impingement angle, and m is an exponent that depends on the material properties and testing conditions.

Both the Koshy-Mishra and Kharaghani-Cooke models indicate that the SPE rate increases as the impingement angle approaches 90 degrees (normal incidence). The models also suggest that the SPE rate is minimum at a specific angle, depending on the material properties and testing conditions.

The impingement angle of erodent particles is a critical factor that affects the SPE behavior of materials, and empirical models can be used to describe this effect and provide insights into the mechanisms of SPE.

Effect of erodent characteristics

Polymer composites, like any other material, can have their solid particle erosion (SPE) behavior considerably altered by the size, shape, and hardness of the erodent particles. Power law and exponential functions are two examples of empirical models that can be used to characterize the impact of eroding features on SPE.

One such model is the Archard's wear law, which is commonly used to describe the effect of erodent characteristics on SPE. The Archard's wear law states that the material removal rate due to SPE is proportional to the product of the normal load and the sliding distance, as well as a constant that depends on the erodent properties. The equation is expressed as:

$E = k H^\alpha d^\beta v^\gamma$

where E is the SPE rate, k is a constant, H is the hardness of the erodent particle, d is the particle diameter, v is the impact velocity, and α, β, and γ are exponents that depend on the material properties and testing conditions.

Another model commonly used to describe the effect of erodent characteristics on SPE is the Park's model. This model is based on the assumption that the material removal rate depends on the ratio of the erodent particle size to the material grain size. The Park's model is expressed as:

$E = k (d/D)^m v^n$

where E is the SPE rate, k is a constant, d is the particle diameter, D is the material grain size, v is the impact velocity, and m and n are exponents that depend on the material properties and testing conditions.

Both the Archard's wear law and the Park's model indicate that the SPE rate increases with increasing erodent hardness, size, and velocity. The models also suggest that the SPE rate is minimum at a specific erodent size or hardness, depending on the material properties and testing conditions.

Effect of fiber orientation during Erosion

Fiber orientation is an important factor that can significantly affect the solid particle erosion (SPE) behavior of fiber-reinforced polymer composites. The orientation of the fibers can influence the direction and extent of the erosion damage to the composite material.

When the fibers are aligned parallel to the direction of the erodent particle stream, they can act as channels that direct the particles into the material, resulting in more significant damage. In contrast, when the fibers are oriented perpendicular to the erodent particle stream, they can resist the particle impact and provide a barrier that reduces the erosion damage.

The effect of fiber orientation on SPE can be described by empirical models, such as power law or exponential functions. For example, the Koshy-Mishra model can be modified to account for the effect of fiber orientation on SPE by introducing an orientation factor, K. The modified model is expressed as:

$E = K k \sin^n (\theta)$

where E is the SPE rate, k is a constant, θ is the impingement angle, n is an exponent that depends on the material properties and testing conditions, and K is the orientation factor that accounts for the effect of fiber orientation.

The orientation factor, K, can be calculated using micromechanical models that consider the fiber distribution and orientation in the composite material. These models can predict the orientation factor for different fiber distributions and orientations and provide insights into the SPE behavior of fiber-reinforced polymer composites.

Erosion Tests

Since sand is a common erodent in the literature on erosion of composites and poses a significant threat to outdoor composite structures, it was chosen as the erodent in this study. The eroding particles were made from two sizes of Australian (garnet) sand: 150-30 mm (fine) and 200-60 mm (rough). As can be seen in Figure 3, the erosion experiments were conducted in a conventional sandblast chamber. The specimen holder was immovable, while the nozzle holder was height and angle adjustable. The range of angle adjustments was from 158 to 908. Except for the 908 angle experiments, where the distance was lowered to 25 mm due to equipment constraints, the nozzle was always positioned 45 mm from the sample. The impact time was held constant at 45s, and the and velocity was set at 70 m/s using the same rotating disc technique as described by Ruff and Ives. The mass flow rate at this speed for coarse sand was 6.6 g/s, whereas that for fine sand was 11.2 g/s. **(Patnaik A, Satapathy A,2010).**

Figure 3. Erosion test equipment (a) Sandblasting chamber, and (b) Nozzle and specimen arrangement.

The amount of material lost during erosion testing was calculated by air blasting the laminate and aluminum plate specimens to remove extra particles and then weighing them. It is evident that a direct comparison of the erosion rate in the classical sense, i.e., the mass loss per unit mass of erodent particles generating the loss, was insufficient because materials of varying densities were studied. For this reason, a second erosion rate was calculated by calculating the volume lost relative to the mass lost of the erodent particles. The erosion rates are denoted by w and v, where w represents the weight-based rate and v represents the volume-based rate. To make the calculations for volume loss easier, it was assumed that just the top layer of mesh-polymer was eroded and the underlying glass layers were unaffected. This presumption turns out to be correct, as we shall see. Table 2 displays the densities used to determine erosion rates for the various materials studied. The damage was quantified by looking at optical micrographs of the specimen surfaces and cross-sections.

Results

The eroding effect of the fine particles on all tested specimens was found to be substantially less than with the rough particles. This was expected since for the same erosion time and speed, the kinetic energy was less for the fine particles. The erosion rates of the Plain laminate relative to the aluminium plate were similar with that of the rough sand, at roughly 11 times at 908, however the erosion rates at the lower impingement angles were substantially lower. In this situation, the kinetic energy of the erodent particles may not have been significant enough to cause a considerable quantity of material removal as with the rough sand.

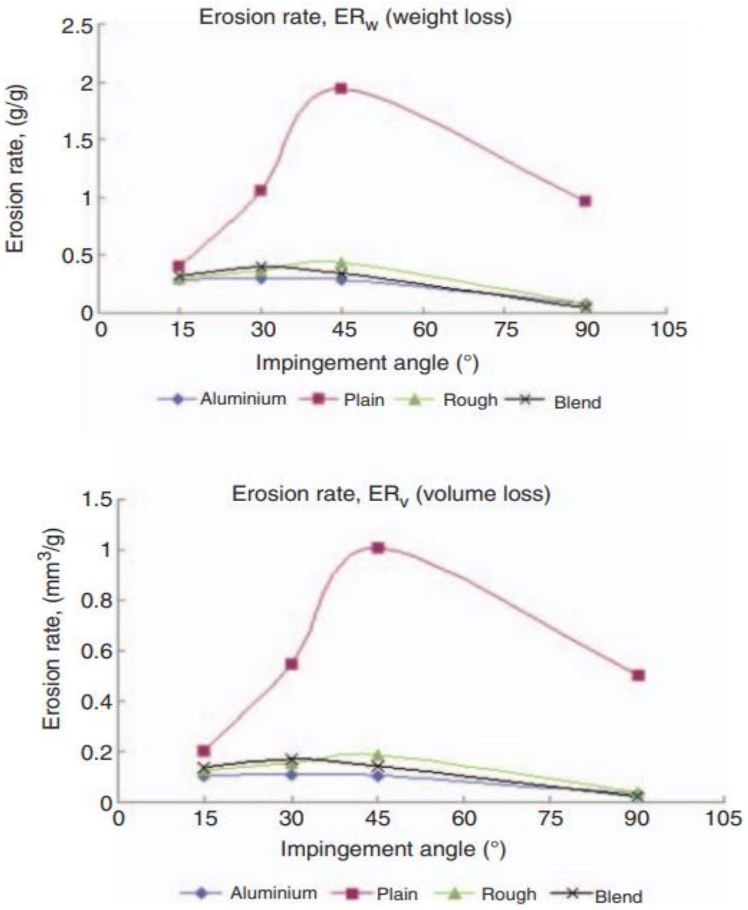

Figure 4. Effect of sand impact angle on the erosion rate using fine sand particles.

The semi-ductile character of damage to the materials was not affected by reducing the erodent particle size, since peak erosion rates occurred at 458 for all save the Blend laminates. In all cases, the erosion rates were comparable to or somewhat higher than those obtained with the aluminum plate after meshes were incorporated. In spite of identical material removal to the laminates reinforced with the rough mesh, the Blend laminates' peak erosion rate of 308 indicates a switch to more ductile damage.

CONCLUSION

Erosion-resistant composite materials offer a versatile solution for engineering applications that require resistance to high-velocity fluids, abrasive particles, and weathering. These materials typically consist of a polymer matrix reinforced with ceramics, metals, or fibers to improve hardness, wear resistance, and thermal stability. The use of erosion-resistant composite materials can result in improved performance, reduced maintenance costs, and increased safety in various applications, such as aerospace, automotive, and defense. The choice of processing technique depends on the desired properties and specific application of the composite, with several methods available, including injection molding, extrusion, and compression molding. The continued research and development of erosion-resistant composite materials are expected to lead to the development of new and improved composites suitable for even more advanced applications. Further optimization of processing parameters and the addition of other reinforcement materials could lead to composites with even more desirable properties. the use of erosion-resistant composite materials is a promising field of study and innovation, providing a solution to the challenges posed by erosion and opening up opportunities for new and improved engineering applications.

REFERENCES

1. Miyazaki, N. (2016). Solid particle erosion of composite materials: A critical review. *Journal of Composite Materials*, *50*(23), 3175-3217.
2. Ahmed, T. J., Nino, G. F., Bersee, H. E. N., & Beukers, A. (2009). Improving erosion resistance of polymer reinforced composites. *Journal of Thermoplastic Composite Materials*, *22*(6), 703-725.
3. Debnath, U. K., Chowdhury, M. A., Kowser, M. A., & Mia, M. S. (2017, June). Study of erosion characterization of carbon fiber reinforced composite material. In *AIP Conference Proceedings* (Vol. 1851, No. 1, p. 020098). AIP Publishing LLC.
4. Patnaik, A., Satapathy, A., Chand, N., Barkoula, N. M., & Biswas, S. (2010). Solid particle erosion wear characteristics of fiber and particulate filled polymer composites: A review. *Wear*, *268*(1-2), 249-263.
5. Sinmazc¸ elik, T., Fidan, S. and Gu¨nay, V. (2008). Residual Mechanical Properties of Carbon/Polyphenylenesulphide Composites after Solid Particle Erosion, Materials and Design, 29: 1419–1426.
6. Arjula, S. and Harsha, A.P. (2006). Study of Erosion Efficiency of Polymers and Polymer Composites, Polymer Testing, 25: 188–196.
7. Nino, G.F., Bergsma, O.K. and Bersee, H.E.N. (2006). Design and Evaluation Tool for Thermoplastic Composites, In: 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, USA
8. Patnaik A, Satapathy A, Chand N, et al. Solid particle erosion wear characteristics of fiber and particulate filled polymer composites: a review. Wear 2010; 268: 249–263.
9. Kaundal R. Role of process variables on the solid particle erosion of polymer composites: a critical review. Silicon 2014; 6: 5–20.
10. Ballout YA, Hovis SK and Talia JE. Erosion in glassfiber reinforced epoxy composite. Scripta Metall Mater 1990; 24: 195–200.
11. Ballout YA, Hovis SK and Talia JE. Erosion in glassfiber reinforced epoxy composite. Scripta Metall Mater 1990; 24: 195–200.
12. Totten, G. E. (2015). Handbook of Aluminum: Volume 2: Alloy Production and Materials Manufacturing. CRC Press. This book includes a chapter on aluminum matrix composites, which are erosion-resistant.
13. Ostermiller, D., & Wu, H. (2014). Investigation of erosion resistance of glass fiber-reinforced polymer composites. Journal of Materials Engineering and Performance, 23(8), 3039-3046. This article examines the erosion resistance of GFRP composites.
14. Geim, A. K., & Novoselov, K. S. (2007). The rise of graphene. Nature Materials, 6(3), 183-191. This influential article introduces the properties and potential applications of graphene, which is erosion-resistant.