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Optimization of Solid Particle Erosion by ZrN Coating Applied Fiber Reinforced Composites by Taguchi Method

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Abstract

In this study, ZrN coatings are applied on glass and carbon fiber reinforced epoxy composite materials by magnetron sputtering method to gain an improved understanding of the solid particle erosion (SPE) wear resistance. The tests were carried out by selecting two different impact velocities (34, 53 m/s), four different impingement angles (30°, 45°, 60°, 90°) and two different abrasive (SiO_2) particle sizes (approximate 250, 500 μm). The thickness of ZrN coating material was 0.15 μm. Protective coatings produced by using Physical Vapor Deposition (PVD) method can increase the life time of the components. All test specimens regardless of their various parameter properties exhibit maximum erosion rates at 45° impingement angle and thus exhibiting similar behavior as that observed for semi ductile materials. Optic microscopic views were performed on the surfaces in order to characterize the erosion mechanism. The erodent particles of the both coating layer and composite matrix were found of main role in governing the wear progression. The measured erosion rates were sensitively correlated with the material removal process in order to explain the changes within the coated interfaces. Moreover, an erosion test facility at room temperature and Taguchi's orthogonal arrays were used for experimentation. The expression derived from the results of Taguchi experimental design is proposed as a predictive equation for estimation of erosion rate of these composites. It is demonstrated that the predicted results from this equation are consistent with the experimental observations. Finally, an optimal parameter combination was determined, which led to minimization of erosion rate (ER).

Keywords: ZrN, Magnetron Sputtering, SPE, PVD, Taguchi.

1. INTRODUCTION

The advanced science and technology world needed materials with superior features for better operational performance. In parallel with such needs, the precious and industrial use of composite materials has greatly increased. The main reason for this is that the glass and carbon fiber reinforced composite materials have high strength, better coating properties and are economical at the same time. In the meantime, advanced scientific research on these materials is being carried out gradually. Erosion wear occurs when solid particles moving at a certain speed strike a surface and some materials are removed from the top surface. The characteristics of the target material as well as the impact angle, velocity, size and shape of the particles impacting the surface are important variables affecting solid particle erosion wear. The rough and sensitive areas such as the spacecraft industry, energy conversion systems, jet engines, helicopter rotor blades, and the effects of erosion wear on coal mine sites have prompted researchers to further investigate this type of wear. In terms of lightness and strength with the increasing use of coated polymer composites in erosive working environments, it has become extremely important to investigate erosion properties intensively. Because of many variables are not able to process a single variant, alternative additives and coating materials have been derived in research aimed at actual erosion mechanism models.

Many researchers have been interested in the solid particle erosion behavior of metal, polymer and their composite materials worn by erodent. While fiber reinforced polymers take place in most of the studies conducted on erosion of composites, studies involving erosion on composites with coating materials can hardly be encountered. The poor erosion wear resistance of thermoplastic composites causes severe problems if the material is subjected to solid particle erosion. To overcome this problem, erosion wear resistant magnetron sputtered PVD coatings were deposited on glass and carbon fiber reinforced epoxy substrates. This is due to the fact that it is not easy to clearly understand wear mechanisms of these types of composites, properties of their components and their interface interactions.

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In this area of research, additive materials were generally developed for ductile and brittle materials and in case single abrasive particle or multiple abrasive particles track the surface. Bagci [1] described the development of unidirectional and multidirectional laminated composites consisting of thermoplastic epoxy resin reinforced with glass/carbon fiber, and studies their solid particle erosion behavior under different operating conditions. The erosion rates of the unidirectional carbon fiber/epoxy composites [0°, 30°, 45°, 60°, 90°] and multidirectional glass fiber/epoxy composites ([0°/-90°/0°], [30°/-60°/30°], [45°/-45°/45°], [60°/-30°/60°], [90°/0°/90°]) were especially scrutinized based on their respective fiber orientations. An optimal fiber orientation combination was determined, which led to minimization of the erosion rate.

Kumar et al. [2] investigated the application of Taguchi's experimental design methodology to determine the erosion wear behavior of in situ -formed A356-5TiB_2 composite subjected to thixo-forming. The results indicated that impact velocity is the most significant factor and accounts for 42.31% of the total effect on the erosion rate of the thixo-formed A356-5TiB2 composite. It is found that material loss during erosive wear is primarily due to micro ploughing (i.e., abrasive type) and micro fracture (i.e., impact type).

Biswas and Satapathy [3] scrutinized a mathematical model for estimating erosion damage caused by solid particle impact on red mud filled glass fiber reinforced epoxy matrix composites and also found a correlation derived from the results of Taguchi experimental design. The filler content in the composites, erodent temperature, the impact angle and velocity are found to have substantial influence in determining the rate of material loss from the composite surface due to erosion.

Jena et al. [4] investigated SPE wear behavior of bamboo fiber-reinforced epoxy composite with cenosphere filler. The present composites consisting of varying weight percentage of fibers and cenosphere fillers were prepared by hand lay-up technique. The study reveals that addition of cenosphere filler to the bamboo–epoxy composite reduces its erosion wear rate.

Deshpande and Rangaswamy [5] developed E-glass/jute fiber reinforced epoxy composites with an addition of Al_2O_3 and bone powder by using hand-lay-up technique and to compare tribological properties of these composites under similar test conditions. The wear experiments were designed according to Taguchi's (L_{27}) orthogonal array. The results indicated that the normal load for Al_2O_3 and filler content for bone powder emerged as the significant factors affecting specific wear rate of hybrid composites.

Studies continued with Bagci's [6] development of a multi-component composite system consisting of thermoplastic epoxy resin reinforced with E–glass fiber and (Al_2O_3+SiO_2) particles, and studies its erosion behavior under different operating conditions. With this target in mind, this empirical study investigates the solid particle erosion wear behavior of a new composite material made of glass fiber and epoxy as the main materials and (Al_2O_3+SiO_2) particles added into the structure at the amount of 30% [15% (Al_2O_3) + 15% (SiO_2)] of the resin used for the composite.

Andreska and et al. [7] investigated the erosion resistance of the galvanic coating the polymer composites examined at two different impact angles and particle impinging velocity. The coatings showed a ductile erosion mechanism under all testing conditions. A higher particle velocity did not change this mechanism, but reduced the time to coating failure. At perpendicular impact angle, the coatings failed through delamination, while this effect was not observed at 20º where failure occurred by local complete removal from the substrate.

In the present study, two different ZrN coating thickness are applied on GF/EP and CF/EP by magnetron sputtering to gain an improved understanding of the erosion resistance. All test specimens regardless of their various properties exhibit maximum erosion rates at 45° impingement angle and thus exhibiting similar behavior as that observed for semi ductile materials. Firstly, pure chrome coating is applied on the GF/EP and CF/EP composites to increase the adhesion of the zirconium nitride to the surface. An erosion test facility at room temperature and Taguchi's orthogonal arrays were used for experimentation. Moreover, the surface topography of the eroded composites was investigated by an optical microscope and a non-contact 3D digital mapping method.

2. DESCRIPTION OF THE TAGUCHI METHOD

Genichi Taguchi has developed a methodology for the application of designed experiments. This methodology has taken the design of experiments from the exclusive world of the statistician and brought it more fully into the world of manufacturing. His contributions have also made the practitioner work simpler by advocating the use of fewer experimental designs, and providing a clearer understanding of the variation nature and the economic consequences of quality engineering in the world of manufacturing [8]. Taguchi introduces his approach, using experimental design in order to obtain products or processes that are robust with respect to environmental conditions. The approach also helps to cope with component variations during development of the products/processes. In addition; the Taguchi method plays an important role in minimizing variation around a targeted value of a product/process [9].

The philosophy of Taguchi is broadly applicable. He proposed that engineering optimization of a process or product should be carried out in a three-step approach, i.e., system design, parameter design, and tolerance design.

In system design, the engineer applies scientific and engineering knowledge to produce a basic functional prototype design; this design includes the product design stage and the process design stage. In the product design stage, the selection of materials, components, tentative product parameter values, etc., are involved. As to the process design stage, the analysis of processing sequences, the selections of production equipment, tentative process parameter values, etc., are involved. Since system design is an initial functional design, it may be far from optimum in terms of quality and cost. The objective of the parameter design [10] is to optimize the settings of the process parameter values for improving performance characteristics and to identify the product parameter values under the optimal process parameter values. In addition, it is expected that the optimal process parameter values obtained from the parameter design are insensitive to the variation of environmental conditions and other noise factors.

Therefore, the parameter design is the key step in the Taguchi method to achieving high quality without increasing cost. Basically, classical parameter design, developed by Fisher [11], is complex and not easy to use. Especially, a large number of experiments have to be carried out when the number of the process parameters increases. To solve this task, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. A loss function is then defined to calculate the deviation between the experimental value and the desired value. Taguchi recommends the use of the loss function to measure the performance characteristic deviating from the desired value.

The value of the loss function is further transformed into a Signal-to-Noise (*S/N*) ratio η. There are three categories of the performance characteristic in the analysis of the *S/N* ratio, that is, the lower-the-better, the higher-the-better, and the nominal-the-better. The *S/N* ratio for each level of process parameters is computed based on the *S/N* analysis. Regardless of the category of the performance characteristic, the larger *S/N* ratio corresponds to the better performance characteristic.

Therefore, the optimal level of the process parameters is the level with the highest *S/N* ratio η. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the *S/N* and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design. In this paper, the erosion parameter design by the Taguchi method is adopted to obtain optimal erosion performance in wear.

Lower-the-better;

$$S/N_L = -10 * \log\left[\left(\frac{1}{n}\right) * \sum\left(y^2\right)\right] \tag{1}$$

Nominal-the-better;

$$S/N_N = 10 * \log\left[\left(\frac{y_A}{S_y^2}\right)\right] \tag{2}$$

Higher-the-better:

$$S/N_H = -10 * \log\left[\left(\frac{1}{n}\right) * \sum\left(\frac{1}{y^2}\right)\right] \tag{3}$$

where n is the number of observations; y is the observed data; y_A is the average of observed data; and S_y^2 is the variance of y.

Notice that these *S/N* ratios are expressed on a decibel scale. We would use S/N_N if the objective is to reduce variability around a specific target, S/N_H if the system is optimized when the response is as high as possible, and S/N_L if the system is optimized when the response is as low as possible. Factor levels that maximize the appropriate *S/N* ratio are optimal. The goal of this research is to produce minimum erosion rate (ER) in a wear operation. Lower ER values represent better or improved erosion rate. Therefore, a lower-the-better quality characteristic was implemented and introduced in this study. The use of the parameter design of the Taguchi method to optimize a process with multiple performance characteristics includes several steps [12], like identifying performance characteristics together by selecting process parameters to be evaluated, determining the number of levels for the process parameters and possible interactions between the process parameters.

Another step is to select an appropriate orthogonal array and assignment of process parameters to the array. This also involves conducting the experiments based on the arrangement of the orthogonal array. On top of that, it is important that the total loss function and *S/N* ratio are calculated. The calculated *S/N* ratio together with ANOVA can be used for analysis of the experimental results. Another important step is to select optimal levels of process parameters and finally; the selected optimal process parameters should be verified through a confirmation experiment.

3. EXPERIMENTAL PROCEDURE

3.1 Test Materials

In this experimental study, the unidirectional CF/EP and multidirectional GF/EP composites were used as substrate materials and industrially produced at Izoreel Composite Insulating Materials, a Turkish Materials Company where “hand lay-up” technique is used to fabricate the composites.

Fibers with diameter of 17 µm, thickness of 0.20 mm and mass per unit area of 200 g/m^2 arranged in a uni/multi directional location provide homogeneously distributed fibers in the matrix form.

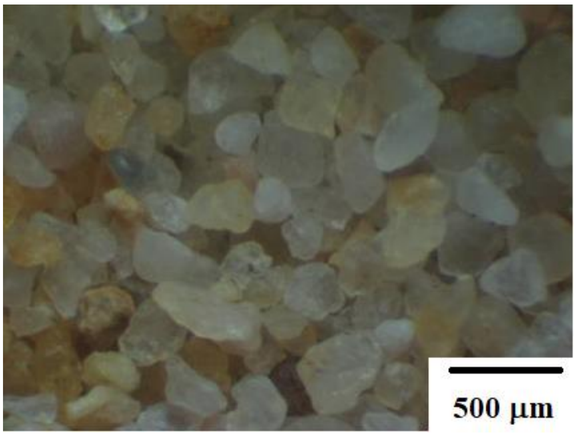
All test specimens were produced as plates by “hand lay-up” technique (110 Bar pressure, 120 °C temperature and a time of 3 top of the hour) with a thickness of 3 mm and dimensions of (1x1m^2). Then, to enable the attachment of specimens to the holder, a diamond-impregnated slitting saw was used to cut notches on the samples with size of 30×30×3mm^3 from the manufactured composite plate for the erosion tests.

Mechanical properties were evaluated as per the ASTM standards and given in Table 1 and abbreviations are used. In Figure 1 and Table 2, respectively, optic microscope views of SiO_2 erodent and chemical compositions of these particles are shown.

As the test specimens are deformed due to particle bombardments, the abrasive particles also undergo some deformations and fractures. To prevent this condition from affecting the tests conducted, fresh particles were used in each test.

Table 1. Mechanical properties of the test specimens.

Material	ρ g/cm^3	σ_t MPa	H HB	E MPa
GF/EP (uncoated)	1.683	533	87	144
GF/EP (ZrN coated)	1.726	597	106	167
CF/EP (uncoated)	1.497	1713	133	869
CF/EP (ZrN coated)	1.553	1824	117	921



(a)

(b)

Figure 1. Optic microscopic views of SiO_2 abrasive particles; (a) 250 µm and (b) 500 µm.

Table 2. Chemical compositions of SiO_2 abrasive particles (% weight).

Content	Minimum	Maximum
% Humidity	3	8
% Clay	0.1	0.5
% SiO_2	98	99
% Fe_2O_3	0.18	0.4
% Al_2O_3	0.5	1.2

In addition to all these details which define the test specimens, as shown in Figure 2, the X-ray diffraction patterns were obtained in order to prove the presence of the glass/carbon fibre and epoxy. A sharp peak at 2θ=17.6° for glass fibre and at 2θ=26.9° for carbon fibre can be distinguished. However; a different diffraction pattern is observed for epoxy resin in which a broad peak appears around 2θ=21.5°. The observed peaks for GF, CF and EP indicate that all the layers have been sufficiently disordered.

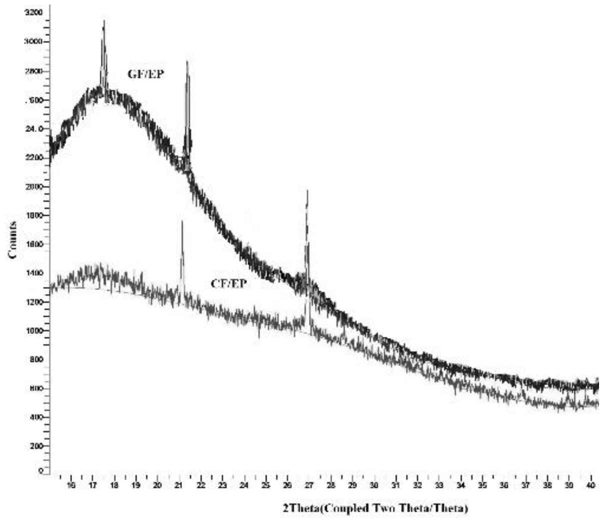


Figure 2. XRD patterns of test specimens.

3.2 ZrN Coating Process

Physical Vapor Deposition (PVD) is a collective set of processes used to deposit thin layers of material, typically in the range of few nanometers to several micrometers [13]. PVD processes are environmentally friendly vacuum deposition techniques consisting of three fundamental steps;

- Vaporization of the material from a solid source assisted by high temperature vacuum or gaseous plasma.
- Transportation of the vapor in vacuum or partial vacuum to the substrate surface.
- Condensation onto the substrate to generate thin films.

Different PVD technologies utilize the same three fundamental steps but differ in the methods used to generate and deposit material (for example TiN, ZrN, CrN, CrCN, TiAlN). The two most common PVD processes are thermal evaporation and magnetron sputtering. Thermal evaporation is a deposition technique that relies on vaporization of source material by heating the material using appropriate methods in vacuum. Magnetron sputtering is a plasma-assisted technique (Figure 3) that creates a vapor from the source target through bombardment with accelerated gaseous ions (typically Argon).

In both evaporation and sputtering, the resulting vapor phase is subsequently deposited onto the desired substrate through a condensation mechanism [14]. Deposited films can span a range of chemical compositions based on the source material(s).

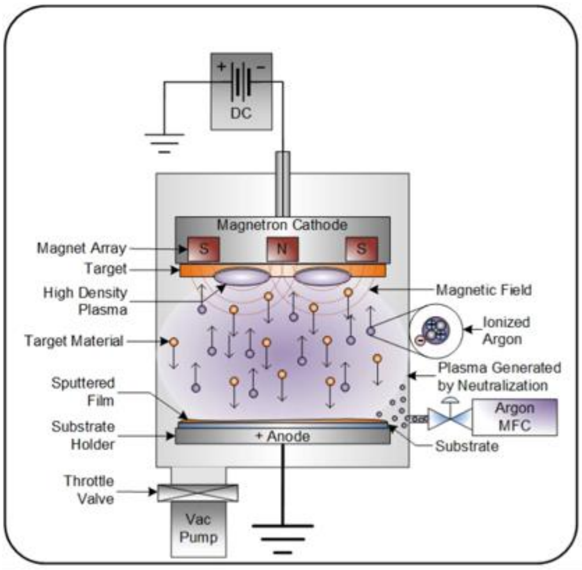


Figure 3. Schematic view of the magnetron sputtering system.

Further compositions are accessible through reactive deposition processes. Relevant examples include co-deposition from multiple sources, reaction during the transportation stage by introducing a reactive gas (nitrogen, oxygen or simple hydrocarbon containing the desired reactant), and post-deposition modification through thermal or mechanical processing [15]. PVD is used in a variety of applications, including fabrication of microelectronic devices, interconnects, battery and fuel cell electrodes, diffusion barriers, optical and conductive coatings, and surface modifications [16-18].

Zirconium nitride (ZrN) is an inorganic compound used in a variety of ways due to its properties. ZrN grown by PVD is a light gold color similar to elemental gold. The hardness of single-crystal ZrN is 22.7±1.7 GPa, elastic modulus is 450 GPa and density is 7.09 g/cm3. Zirconium nitride is a hard ceramic material similar to titanium nitride and is a cement-like refractory material. Thus it is used in refractories, cermets and laboratory crucibles. When applied using the physical vapor deposition coating process it is commonly used for coating medical devices, industrial parts, automotive and aerospace components and other parts subject to high wear and corrosive environments.

In this study, ≈0.15 m thickness ZrN coatings are applied on glass and carbon fiber reinforced epoxy (CF/EP) composites by magnetron sputtering were produced at Ionbond Turkey where PVD, CVD and PACVD techniques are used to fabricate the coating materials.

3.3 SPE Test Equipment

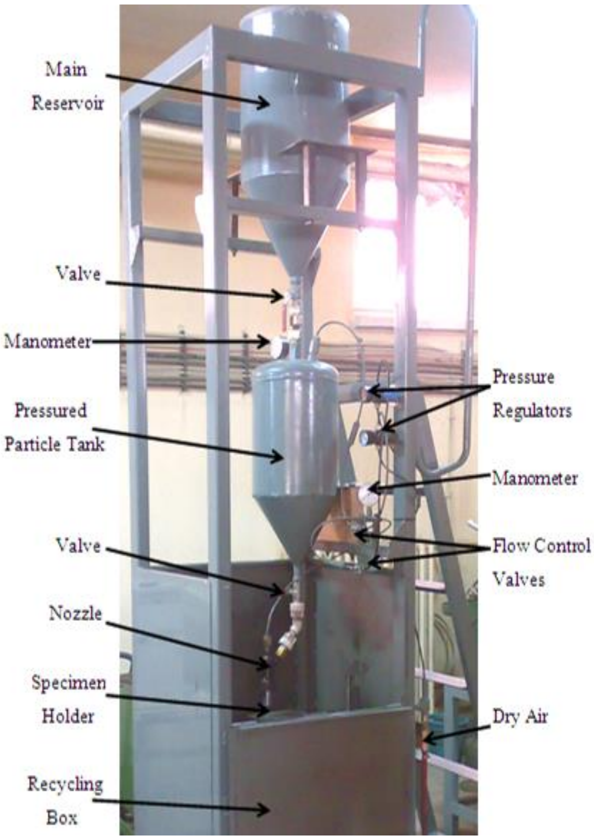
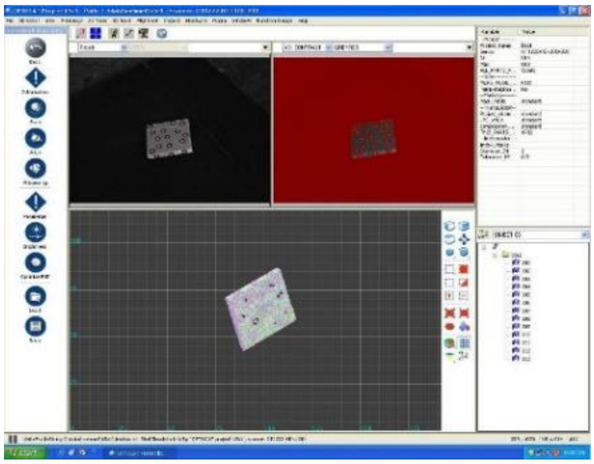


Figure 4. Test device for solid particle erosion wear.

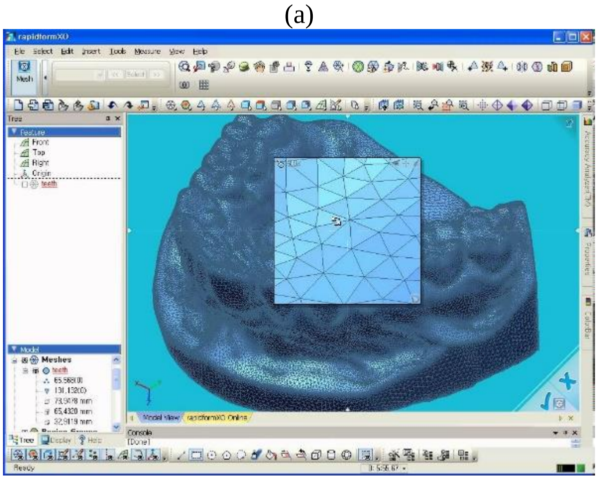
The erosion test equipment used in this scientific study (Figure 4) which was specifically designed for the tests consists of upper and lower particle tanks, universal valves, manometers, flow and pressure regulators, nozzle, specimen holder, particle collecting basin and a compressor. The impact velocity of the particles can be varied by varying the pressure of the compressed air. In order to determine the velocity of the eroding particles, the most common method [19] was used previously. The particles impact velocities used in the tests (34 and 53 m/s) were adjusted by using the double disc method.

Dry compressed air is mixed with the particles, which are fed at a constant rate from the sand hopper into the pressurized particle tank and then accelerated by a compressor thereby forcing the mixture through a WC converging nozzle of 8 mm diameter. These accelerated particles impact the specimen, which can be held at various angles with respect to the impacting particles using an adjustable sample holder. A diamond-impregnated slitting saw was used to cut test specimens with size of 30×30×3 mm^3 from the manufactured composite plate for the erosion tests. All edges cut were finished using a fine SiC paper. The distance from specimen surface to nozzle end was 10±1 mm as described in ASTM G76-95 standards [20].

The standard test process was performed in accordance with ASTM G76-95 for each erosion test. Erosion wear losses in the test specimen with an electronic balance on accuracy of 0.1 mg was measured. Then 25 kg of erodent particles were spurted on the specimen and then, the latter was weighed again to determine its weight loss. At the same time, these measurements as well as volumetric losses occurring in the test sample for detecting the digital map method of the surfaces is simulated using the point cloud and the mesh modeling. In addition, volumetric losses occurring in the test sample was determined. Surface mapping of the numerical method for three-dimensional (3D) scanning has been used on the Figure 5. Weight loss and volumetric loss changes of a similar trend has emerged in terms of the comparison of results.



(a)



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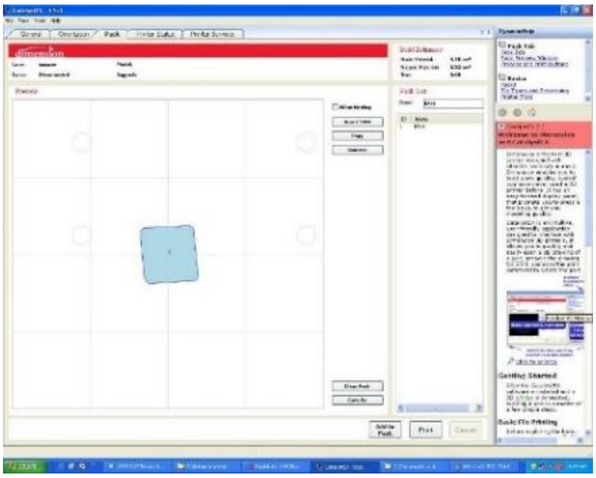

(c)

Figure 5. The digital map method of the surfaces; (a) Point cloud with OPTOCAT, (b) Mesh modeling with Rapidform XOR/ Redesign, (c) Volumetric loss with CatalystEX.

3.4 Taguchi Method

The design parameters of the system to be studied are known as the control factors or design variables, which mainly affect the output of the objective function [21–22]. In this study, four parameters, namely coating material, impact velocity, impingement angle and erodent size are determined as the control factors which significantly affect the performance of ER. Moreover, an L_{16} (4^2 2^2) orthogonal array was used in this study and the results of the experiments are reported in the completed design layout as seen in Table 3.Analysis of the influence of each solid particle erosion parameter was performed by using MINITAB 17. Based on Eq.(1), having obtained the S/N_L ratios, the effect of each factor level on the quality characteristic is studied.

Table 3. Experimental layout and results using an L_{16} (4^2 2^2) orthogonal array.

	C1 Coat. Mat.	C2 Imp. Ang.	C3 Imp. Vel.	C4 Erod. Size	C5	C6 SNRA1
1	1	1	1	1	17,424	-24,8230
2	1	2	1	1	19,567	-25,8305
3	1	3	2	2	8,862	-18,9506
4	1	4	2	2	4,606	-13,2665
5	2	1	1	2	26,558	-28,4839
6	2	2	1	2	29,872	-29,5053
7	2	3	2	1	6,831	-16,6897
8	2	4	2	1	3,257	-10,2564
9	3	1	2	1	23,689	-27,4909
10	3	2	2	1	25,164	-28,0156
11	3	3	1	2	7,258	-17,2163
12	3	4	1	2	5,369	-14,5979
13	4	1	2	2	29,357	-29,3542
14	4	2	2	2	32,159	-30,1461
15	4	3	1	1	7,943	-17,9997
16	4	4	1	1	6,843	-16,7049
17						

Figure 6 shows the effects of all four control factors with their corresponding levels. This figure clearly indicates how coating material, impingement angle, impact velocity and erodent size change. This experimental study has shown that the most effective influence on erosion rate appears due to variations on the impingement angle used for the specimens. The variation of coating materials follows suit after this parameter. It was found that any changes in these angles caused significant variations on erosion rates. These first two parameters were followed by erodent size and impact velocity which played a determining role in increasing erosion rates.

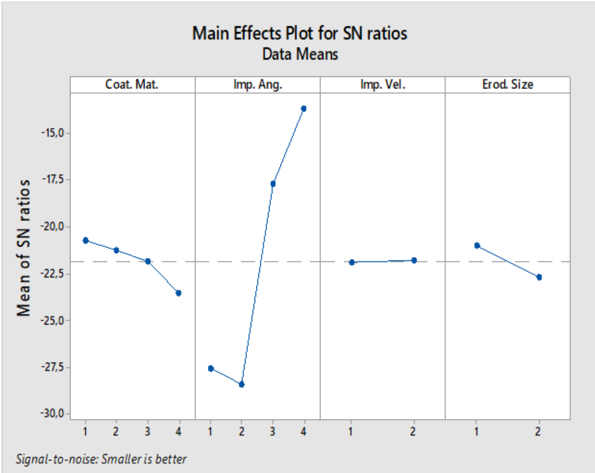

Figure 6. Main effects of control factors on ER.

The best erosion rate value is at the higher S/N_L ratios on the response graph. Optimal testing conditions of these control factors can be very easily determined from the S/N_L response table. The table of the erosion rate for test specimens is presented in Table 4.

Table 4. Response table for S/N_L ratios.

Level	Coat. Mat.	Imp. Ang	Imp. Vel.	Erod. Size
1	-20,72	-27,54	-21,90	-20,98
2	-21,23	-28,37	-21,77	-22,69
3	-21,83	-17,71		
4	-23,55	-13,71		
Delta	2,83	14,67	0,12	1,71
Rank	2	1	4	3

The final step was to verify the improvement of the quality characteristic using the optimal levels of the design parameters (A1B4C2D1).

Using the optimal level of the erosion parameters, the estimated S/N_L ratio, η can be calculated as;

$$\eta = \eta_m + \sum_{i=1}^{q}(\eta_i - \eta_m) \quad (4)$$

where η_m is the total mean of the S/N_L ratio, η_i is the mean S/N_L ratio at the optimal level and q is the number of the main design parameters that significantly affect the performance characteristic.

Table 5 shows a comparison of the predicted erosion rate with the experimental ER using the optimal wear values. The increase in the S/N_L ratio from initial wear values to optimal wear values was about 13.15 dB, which meant that the erosion rate was increased by about 4.38 times. Therefore, based on the S/N_L ratio analysis, the optimal wear values for the erosion rate with ZrN coating materials added GF/EP composites were in this order, the coating material (A) at level 1, the impingement angle (B) at level 4, the impact velocity (C) at level 2 and the fiber direction (D) at level 1.

Table 5. Results of the confirmation experiment

	Initial Wear values	Optimal wear values	
		Experiment	Prediction
Level	A1B1C1D1	A1B4C2D1	A1B4C2D1
ER	17,424	3,978	3,83
S/N_L	-24,82	-11,99	-11,67

*Improvement of S/N_L ratio = 13.15 dB

4. RESULTS AND DISCUSSION

To ensure a sufficient lifetime of glass/ carbon fiber reinforced epoxy components which are exposed to solid particle erosion, protective coatings are needed. Metallic coatings on composites are mainly produced by electro plating, thermal spraying, or PVD.

When deposited on GF/CF, electro plated coatings require extensive pre-treatment processes to create conductivity and to ensure adhesion. Coatings produced by thermal spraying can increase the surface roughness and an additional post-treatment may be needed to guarantee adequate flow conditions at the surface. In contrast, simple processing can be realized by PVD methods.

When the tests are analyzed it is seen that regardless of the fact the results is at different materials, the specimens in both sets of results seem to undergo much erosion rates at impingement angle of 45°. Together with this, it has also been observed that, parallel to the increase of the impingement angles (60°–90°), the erosion rates tend to reduce abruptly.

This situation shows that, a similar erosion trend is observed as that seen in literature for semi ductile materials [23-24]. It was determined that beside the remarkable effects of ZrN coating material also have considerable effects on solid particle erosion wear. From the experimental result data, it is seen that the effects of the GF/EP composites with ZrN coated on SPE wear are more evident than those of the CF/EP composites with ZrN coated

When the results and optical microscope views based on the tests done are studied, it is seen that GF/EP and CF/EP of the ZrN coating material have had positive and negative effects respectively on erosion.

This condition though can be perfectly recognized from the results, the microscope views also indicate extensive surface resistivity for the specimens with GF/EP. ZrN coating material adhered to the GF/EP substrate surface and reacted to the attack of abrasive particles. But CF/EP composites could not match with ZrN coating materials and the surface resistance is weakened.

The optical microscope views in Figure 7 show variations of erosion rates with test specimens (uncoated and ZrN coated composites) at impingement angles of 45° with an impact velocity of 53 m/s where the slightly rounded SiO_2 abrasive particles used had average diameters of 400 µm.

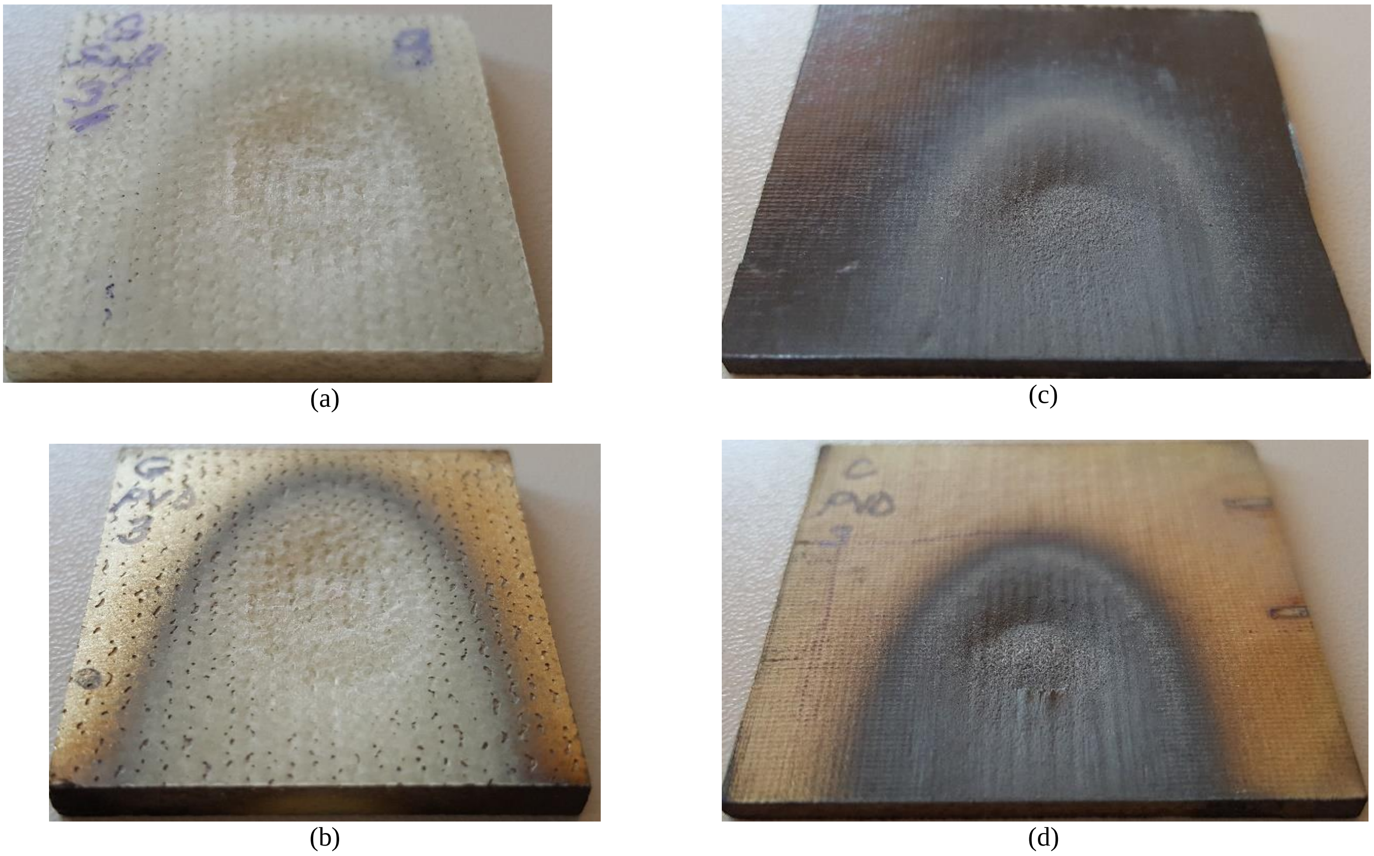

Figure 7. Optical microscope view of test specimens; (a) GF/EP (uncoated), (b) GF/EP (ZrN coated), (c) CF/EP (uncoated), (d) CF/EP (coated).

5. CONCLUSIONS

This paper has presented the parameter design of the Taguchi method provides a simple, systematic and efficient methodology for the optimization of the erosion wear parameters. Taguchi's robust orthogonal array design method is suitable for analyzing the erosion rate as described in this paper.

It was found that material removal from the surfaces of the test specimens as a result of solid particle erosion wear took place at several different stages. First of all, micro cracking appeared on the surfaces as the particles stroked the surface and as the particle bombardments continued material delamination took place over the affected areas.

The structural bonds got damaged as the particles kept striking the surfaces. Due to this damage, the rate of material delamination off the surfaces increased. Consequently; the cracks and grooves on the surfaces became more vivid. It has been observed that the application of coating to the materials caused the differentiation of these processes.

According to the experimental results,

- The L_{16} (4^2 2^2) orthogonal arrays were adopted to investigate the effects of impingement angle, impact velocity and erodent size on the solid particle erosion wear of four different fiber reinforced epoxy composites. According to S/N_L response table, the most significant factor in affecting the erosion rate is the impingement angle, followed by the coating materials, erodent size and impact velocity.
- ZrN coated and uncoated composites exhibit maximum erosion rates at 45º impingement angle and thus exhibiting similar behavior as that observed for semi ductile materials. Parallel to the increase of a impinging angle, the values of erosive wear rates dropped.
- Inclusion of ZrN coating material in GF/EP composites considerably increases the value of hardness, tensile strength, modulus of elasticity and density. The erosion rate of ZrN coated GF/EP gives the lower value as it restricts surface delamination.
- GF/EP composites without any coated show the upper erosion rate due to weak bonding strength. In CF/EP composites, it decreased the erosion resistance due to the thermal and physical effects applied to the surface.
- The difference in erosion of GF/EP and CF/EP materials should be even higher. The difference in fiber orientations has been influential in this case. Experience

shows that every tribological system can be optimized by selecting the right coating.
- The remarkable increase in the erosion rate is correlated to the impact velocities used in the tests. Moreover, large erodent size lead to an increase in wear.
- The confirmation experiments are conducted to verify the optimal wear parameters. The improvement of erosion rate from the initial wear values to the optimal wear values is about 438%.
- As a future study, inclusion of new composites using different coating material and concentration combinations can be taken into consideration and the resulting experimental findings can be similarly analyzed.

REFERENCES

[1] M. Bagci, "Influence of fiber orientation on solid particle erosion of uni/multidirectional carbon fiber/glass fiber reinforced epoxy composites", Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, vol. 231, no. 5, pp. 594-603, 2017.
[2] S.D. Kumar, P.R. Vundavilli, A. Mandal, S. Mantry & M. Chakraborty, "Erosion response of thixoformed A356-5TiB_2 in situ composite using Taguchi's experimental design", Tribology Transactions, vol. 60, no. 1, pp. 39-46, 2017.
[3] S. Biswas, A. Satapathy, "Tribo-performance analysis of red mud filled glass-epoxy composites using Taguchi experimental design", Material & Design, vol. 30, no. 8, pp. 2841-2853, 2009.
[4] H. Jena, A.K. Pradhan, and M.K. Pandit, "Study of Solid Particle Erosion Wear Behavior of Bamboo Fiber Reinforced Polymer Composite with Cenosphere Filler", Advances in Polymer Technology, 2016.
[5] S. Deshpande, T. Rangaswamy, "A comparative study on dry sliding wear characteristics of Al2O3 and bone powder filled hybrid composites", Journal of Minerals and Materials Characterization and Engineering, vol. 4, pp. 164-180, 2016.
[6] M. Bagci, "Determination of solid particle erosion with Taguchi optimization approach of hybrid composite systems", Tribology International, vol. 94, pp. 336-345, 2016.
[7] J. Andreska, C. Maurer, J. Bohnet, U. Schulz, "Erosion resistance of electroplated nickel coatings on carbon-fibre reinforced plastics", Wear, vol. 319, pp. 138-144, 2014.
[8] G. Taguchi, S. Konishi, "Taguchi methods, orthogonal arrays and linear graphs, tools for quality engineering". American Supplier Institute, pp. 35-38, 1987.
[9] P.J. Ross, "Taguchi techniques for quality engineering–loss function, orthogonal experiments, parameter and tolerance design", McGraw–Hill, New York, pp. 10-50, 1988.
[10] D.C. Montgomery, "Design and analysis of experiments", 4th edition Wiley, New York, 1997.
[11] R.A. Fisher, "Statistical methods for research worker", Oliver&Boyd, London, 1925
[12] G.S. Peace, "Taguchi methods: a hand-on approach", Addison-Wesley, MA, 1993.
[13] C.F. Powell, J.H. Oxley, J. H. and Jr.J.M. Blocher, "Vapor Deposition", Wiley, New York, 1967.
[14] W.D. Westwood, "Sputter Deposition", AVS education committee book series, vol. 2, Education Committee, New York, 2003.
[15] D.M. Mattox, "Handbook of Physical Vapor Deposition (PVD) Processing: Film Formation, Adhesion, Surface Preparation and Contamination Control", Noyes Publications, New Jersey, 1998.
[16] H. Geng, "Semiconductor Manufacturing Handbook", McGraw-Hill, New York, 2004.
[17] U. Helmersson, M. Lattemann, J. Bohlmark, A.P. Ehiasarian, J.T. Gudmundsson, "Ionized physical vapor deposition (IPVD): A review of technology and applications", Thin Solid Films", vol. 513, no. 1, pp. 1-24, 2006.
[18] S. Uhlenbruck, R. Nedelec, D. Sebold, H.P. Buchkremer, D. Stoever, "Heißer ist besser-Kraftwerke umweltschonender machen, ECS Transactions, vol. 35, pp. 2275, 2011.
[19] A.W. Ruff, L.K. Ives, "Measurement of solid particle velocity in erosive wear", Wear, vol. 35, pp. 195-199, 1975.
[20] ASTM G76–95, "Standard test method for conducting erosion tests by solid particle impingement using gas jets", ASTM Annual Book of Standards, 03.02, West Conshohocken, PA, 2000.
[21] G. Taguchi, "Introduction to Quality Engineering", Asian Productivity Organization, Tokyo, 1990.
[22] P. Sahoo, S.K. Pal, "Tribological performance optimization of electroless Ni–P Coatings using the Taguchi method and grey relational analysis", Tribology Letters, vol. 28, pp. 191–201, 2007.
[23] I.M. Hutchings, "Ductile-brittle transitions and wear maps for the erosion and abrasion of brittle material", Journal of Physics D: Applied Physics, vol. 25, pp. 212-221, 1992.
[24] I. Finnie, "Some reflections on the past and future of erosion", Wear, vol. 186-187, no. 1, pp. 1-10, 1995.