Journal of Bio- and Tribo-Corrosion (2025) 11:112
https://doi.org/10.1007/s40735-025-01033-5

Erosion Performance Evaluation of Coated SiC-Reinforced Polymer Composites Using Taguchi's Methodology

Parvesh Antil[1] · Manpreet Singh[2,3] · Dharmender Jangra[4] · Vinay Kumar[5] · Jayanta Boruah[6] · Pallavi Agarwal[4]

Received: 5 May 2025 / Revised: 23 August 2025 / Accepted: 31 August 2025

Abstract

The naval industry is popularizing polymer composites due to their effectiveness as propellers, turbine blades, and underwater structures. However, the marine and industrial applications expose the components of polymer composites to corrosive microbial interaction and surface erosion. The various metabolic reactions by surface microorganisms may deteriorate the substratum. On the other hand, erosion occurs when erodent particles strike over the material surface continuously. Focusing on erosion, the present paper aims at analysis of erosion performance of electroless-coated SiC-reinforced polymer composites through solid particle erosion tests. The erosion test was conducted on a developed abrasive jet erosion setup under varying conditions as per ASTM G76 standard. The reinforcement type, erodent pressure, standoff distance, and nozzle diameter were selected as process parameters, whereas weight loss was selected as a response parameter. The ANOVA demonstrates that pressure, workpiece type, and standoff distance affect erosion loss by 57.98%, 18.16%, and 17.45%, respectively. The model's R^2 value is over 90%, indicating that it performs better and can forecast erosion behavior within experimental values.

Keywords Erosion · Electroless coating · Glass fiber · Taguchi methodology

1 Introduction

Technological development is undoubtedly dependent on advances in engineering and materials science. Highly sophisticated and technologically complex aircraft or any industrial component becomes useless if the components' materials are not fit for demanding conditions and service loads. Fiber-reinforced composites have become very important among advanced materials throughout the last fifteen years. These materials' growing popularity in industrial uses has helped them to constantly enter new markets. Composites' capacity to withstand cyclic abrasive impact has been among its most crucial performance qualities for use in industry. Erosion of a surface is the continuous loss of material from that surface resulting from high-velocity abrasive particle exposure. For component performance in dusty and slurry conditions [1], surface deterioration from erosion has grown to be a major problem. Dust particles in the air help components designed in airplanes [2] to degrade their surfaces, which results in costly maintenance and security issues. Because polymer components have great stiffness and specific strength, erosion of surfaces generally occurs in industrial applications utilizing them [3]. The erosion events in glass fiber-based composites include the loss of the matrix, breaking of fibers, and the separation of the reinforcement from the matrix. The kind of impacting particles, angle of impingement, and velocity, among other process parameters, determine the degradation of fibrous composites [4]. Tewari et al. [5] found that fiber orientation significantly influences the degradation of carbon/glass fiber-reinforced polymer composites, as unidirectional fiber orientation shows semi-ductile erosion behavior. Wind turbine blades and numerous technological applications requiring a good strength-to-weight ratio and resistance to

✉ Dharmender Jangra
dharmender1@vips.edu

1 Department of Basic Engineering, COAE&T, CCS HAU, Hisar, Haryana 125004, India

2 Punjab State Council for Science and Technology, Chandigarh 160019, India

3 Jadara University Research Center, Jadara University, Irbid 21110, Jordan

4 Vivekananda Institute of Professional Studies-Technical Campus, New Delhi 110034, India

5 Department of Statistics, Central University of Haryana, Mahendergarh, Haryana 123031, India

6 Department of Law, Central University of Karnataka, Kalaburagi, Karnataka 585367, India

Published online: 08 September 2025

erosion wear are made from fiber-reinforced polymers (FRP) [6]. A complex process, solid particle erosion is similar to other tribological events. Among the components of the tribological system, the mechanical stress may be connected to later thermal, chemical, and physical interactions [7]. It was observed that the higher glass fiber content improved composite mechanical performance [8]. Customizing and optimizing fiber-reinforced polymer composites is made possible by using particle fillers such as red mud, silicon carbide, and fly ash [9]. One may classify erosion as either ductile or brittle. After the first weight increase brought on by entrapment, a linear weight decrease usually follows in a ductile way [10]. Compared to plain composites, the results of the erosion test for filled composites showed that the fly ash-filled composites showed better erosion resistance. This results from the insufficient link between the matrix and the fiber in unfilled composites [11]. As an advancement in materials science, researchers have throughout time used many coating methods, including sputter coating, chemical vapor deposition, and physical vapor deposition for material deposition [12]. Conversely, the simple, reasonably priced electroless coating may deposit materials with desirable mechanical properties [13]. Because of the systematic autocatalytic reduction of metallic salts, the electroless coating of reinforcing materials is identified as the best suitable particle treatment [14]. Purohit et al. [15] used Taguchi's methodology to analyze erosion wear behavior of polypropylene/Linz-Donawitz sludge composites and found that filler content and impact velocity as most significant factors affecting erosion rate of composites. Prajapati et al. [16] used Taguchi's L_9 orthogonal array to assess tribological behavior of GFRE composite and found that inclusion of GNP particles enhances the tribological properties of the composite. Keeping earlier research work in mind, this work attempts to evaluate the solid particle erosion performance of SiC particle-reinforced polymer composites that are coated with a protective surface layer, employing Taguchi's design of experiments. The objective is to identify and evaluate the influence of critical operational parameters—impact angle, erodent velocity, and erodent size—on the erosion rate and determine the optimum combination of parameters for improved erosion resistance. This research improves learning by merging the Taguchi approach with coated polymer composite systems, an area with limited experimental optimization investigations, especially for SiC-reinforced matrix.

2 Material and Methodology

The various applications of reinforced PMCs includes aviation, marine, and energy generation sectors. The high resistance to sand particle erosion and thermal stress at high altitudes enables PMCs to work efficiently in aerospace applications, whereas superior resistance to saline water corrosion and sediment-induced erosion makes them suitable material for marine parts and turbine blades. However, those components which are regularly exposed to abrasive and dusty conditions, the deterioration of composite surfaces is a major challenge. Many factors affect the degradation of composite surfaces: velocity of the erodent, impact distance, erodent size, and kind. This work investigates the effects of many parameters on the degradation of composites, with particular attention to the erosion behavior of glass fiber-reinforced polymer matrix composites under a specialist abrasive jet erosion test device. Inspired by the Taguchi technique, which considers pressure, standoff distance, and nozzle size as input process parameters, experiments were set up as shown in Table 1. The experimentation was planned as per Taguchi's L_{18} orthogonal array, as shown in Table 2 [17].

Table 1 Process parameters

Machining parameters	Symbols	Level 1	Level 2	Level 3
Workpiece	W	Uncoated	Coated	–
Pressure (Psi)	P	60	75	90
Standoff distance (mm)	S	10	15	20
Nozzle diameter (mm)	N	2.0	2.5	3.0

Table 2 L_{18} Orthogonal Array

Experiment No	Workpiece (type)	Pressure (Psi)	Standoff distance (mm)	Nozzle diameter (mm)
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	1
5	1	2	2	2
6	1	2	3	3
7	1	3	1	2
8	1	3	2	3
9	1	3	3	1
10	2	1	1	3
11	2	1	2	1
12	2	1	3	2
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2

The erosion test was performed using a constructed abrasive jet erosion test setup (Fig. 1) under diverse settings in accordance with ASTM G76 standards. The configuration has three primary components: an air compressor, a mixing

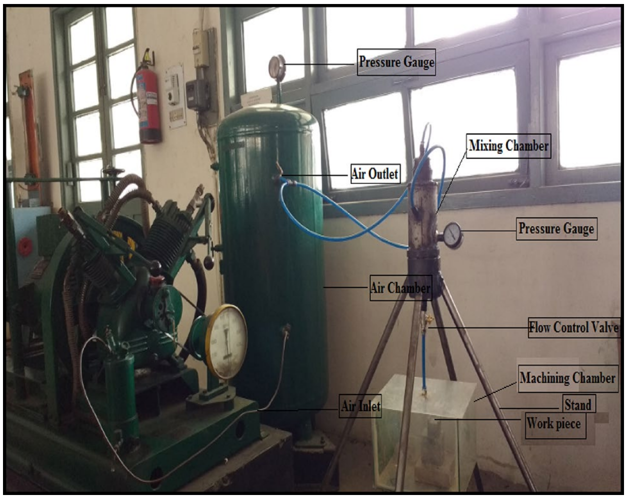


Fig. 1 Abrasive jet erosion test setup

chamber, and a machining chamber, which facilitates the impact of a mixture of dry air and abrasive particles on the workpiece surface. Two pressure gauges are fitted at the compressor and mixing chambers, respectively, to analyze pressure fluctuation. The river sand particles with an average diameter of 250 µm were used as erodent particles (Fig. 2), whereas the specimen was prepared with a size of 10 × 10 × 5 mm for experimentation. The test starts when pressurized air is introduced into the mixing chamber via polyurethane pipes with a diameter of 6.5 mm. The mixing chamber in which sand particles are pored before initiating the experiment mixes the abrasive material with compressed air until it reaches the required pressure. Upon reaching the specified pressure, the control valve is activated, allowing abrasive particles to traverse the nozzle and impact the workpiece surface inside the machining chamber for 240 s. The weight reduction in each sample was documented using an electronic scale with a minimum measurement of 0.0001 g. The polymer matrix composite, both coated and uncoated,

Fig. 2 Microscopic view of river sand particles

reinforced with E and S glass fibers and using epoxy as the matrix, was used as the workpiece for testing.

3 Electroless Coating

The effect of the copper layer on the mechanical strength of the composite is assessed by a copper coating applied to SiC particles via electroless deposition. Table 3 illustrates the design of the copper solution, which aimed to form a copper layer on top of silicon carbide particles. 5 g of $CuSO_4$, 1 g of sodium hypophosphite, 9 g of sodium citrate, 6 g of ammonium chloride, and one hundred milliliters of distilled water made up a copper solution including the sensitized particles. After 2 h of agitation and 2 h of filtration, the particles were baked at 80ºC for 6 h. Usually working at a pH over 11 and acting as a reducing agent in an electroless copper bath, formaldehyde generates dangerous gases [18]. Because of low pH and safety concerns, sodium hypophosphite was employed in place of formaldehyde, considering health hazards [19]. The schematic diagram of the process is shown in Fig. 3.

4 Result and Discussions

4.1 Taguchi's Analysis

Primarily during the tearing of elastic components, the cutting events observed in polymers, and the emergence of cracks and matrix breaks in ceramics, glass, and other brittle composites, different erosion mechanisms can be classified as brittle and ductile behaviors [20]. While ductile erosion consists in the cutting and peeling off of fibers, brittle erosion is the degradation of a surface brought about by the proliferation of cracks. Still, it is possible to combine the features of ductile and brittle surfaces by controlling the tangential and normal velocity components of abrasive particles [21]. The degraded surfaces of the composites showed during experimentation that the erosion behavior clearly resulted from abrasive actions. Starting with the development of many microcracks on the surface, the degradation of composite surfaces developed with the elimination of the surrounding matrix. Table 4 shows the

Table 3 Copper bath constituents

Sr. No	Chemical name	Chemical formula	Concentration (g/l)
1	Copper sulfate	$CuSO_4$	5
2	Sodium hypophosphite	$NaH_2PO_2H_2O$	1
3	Sodium citrate	$Na_3C_6H_5O_7$	9
4	Ammonium chloride	NH_4Cl	6

results from the erosion experiments. Scholars use three kinds of signal-to-noise ratio criteria based on the required response characteristics: lower is better, nominal is better, and greater is better [22–26]. In the present evaluation, we choose and compute the criteria for a smaller S/N ratio, as detailed below:

$$\eta_{ij} = -10\log\{\frac{1}{n}\sum_{i=1}^{n} y_{ij}^2\} \tag{1}$$

here y_{ij} is the ith experiment at jth test and n is the total number of tests [27]. The analysis of variance for the wear test as shown in Table 5 provides significance of each parameter. The analysis of obtained results during erosion test was carried out to examine statistical importance of each parameter. As per ANOVA results, pressure is the most significant parameter having 57.98% contribution followed by workpiece type, standoff distance, and nozzle diameter with 18.16%, 17.45%, and 0.33%, respectively. Figure 4 shows the S/N ratio response plots for erosion behavior of composite. As per higher S/N ratio value, the optimum parametric combination for erosion test is obtained as $W_2P_1S_1N_3$. The residual plots for erosion are shown in Fig. 5.

The SEM images shown in Fig. 6 indicate that the uncoated composite exhibits uneven orientation and significant gaps between subsequent fibers. The blowholes generated on the matrix surface decrease interfacial strength and

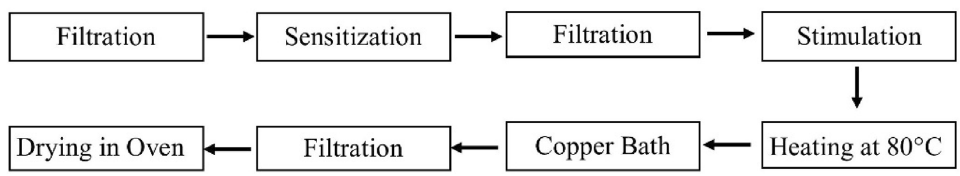


Fig. 3 Schematic diagram of electroless coating procedure

Table 4 Erosion results

Experiment No	Workpiece	Pressure (Psi)	Standoff distance (mm)	Nozzle diameter (mm)	Avg. erosion (mg/min)
1	Uncoated	60	10	2.0	6.8
2	Uncoated	60	15	2.5	8.4
3	Uncoated	60	20	3.0	9.8
4	Uncoated	75	10	2.0	9.3
5	Uncoated	75	15	2.5	10.6
6	Uncoated	75	20	3.0	9.7
7	Uncoated	90	10	2.5	11.3
8	Uncoated	20	15	3.0	11.8
9	Uncoated	20	20	2.0	13.0
10	Coated	60	10	3.0	5.8
11	Coated	60	15	2.0	7.2
12	Coated	60	20	2.5	7.3
13	Coated	75	10	2.3	7.8
14	Coated	75	15	3.0	9.2
15	Coated	75	20	2.0	9.8
16	Coated	90	10	3.0	8.6
17	Coated	90	15	2.0	10.1
18	Coated	90	20	2.5	10.9

Table 5 Analysis of variance

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value	% Contribution
Workpiece	1	10.8889	10.8889	29.96	0.000	18.16
Pressure	2	34.7700	17.3850	47.83	0.000	57.98
SOD	2	10.4633	5.2317	14.39	0.001	17.45
Nozzle Dia	2	0.2033	0.1017	0.28	0.762	0.33
Error	10	3.6344	0.3634			6.08
Total	17	59.9600				100

$R^2 = 93.94\%$; R^2 (adj.) = 89.70%

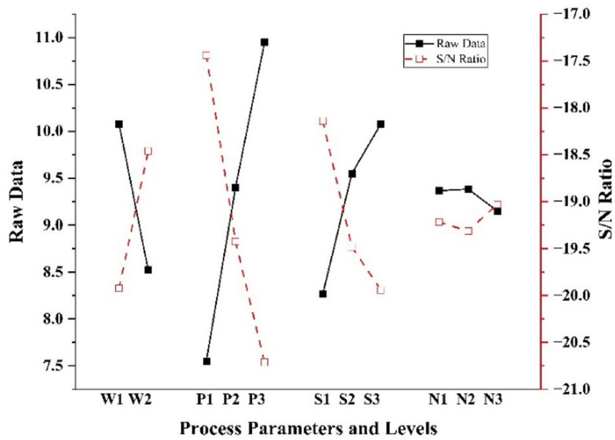


Fig. 4 Raw data and S/N ratio plots

trigger fiber pullout under tensile stress, leading to composite fracture [28]. During the fracture phenomena, glass fibers detached from the matrix and experienced longitudinal penetration. However, the coated composite showed better resistance against erosion as the fibers are closely packed and matrix suffered lesser cracks and blowholes.

4.2 Regression Equation

The linear regression model was developed using Minitab 17. The obtained regression model equation for material removal rate during erosion of GFRP composite is shown in Eq. (2)

Fig. 5 Residual plots for erosion

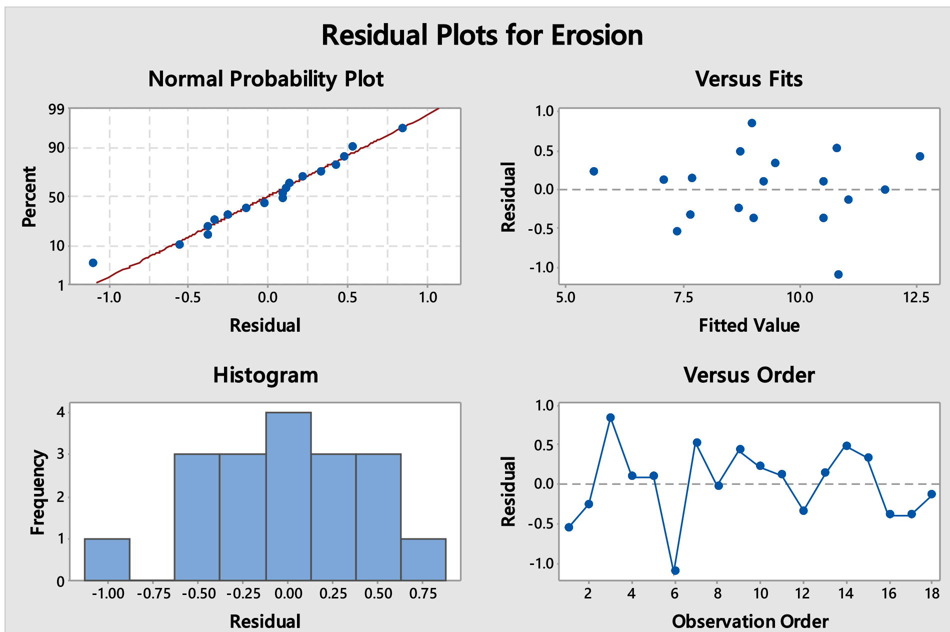
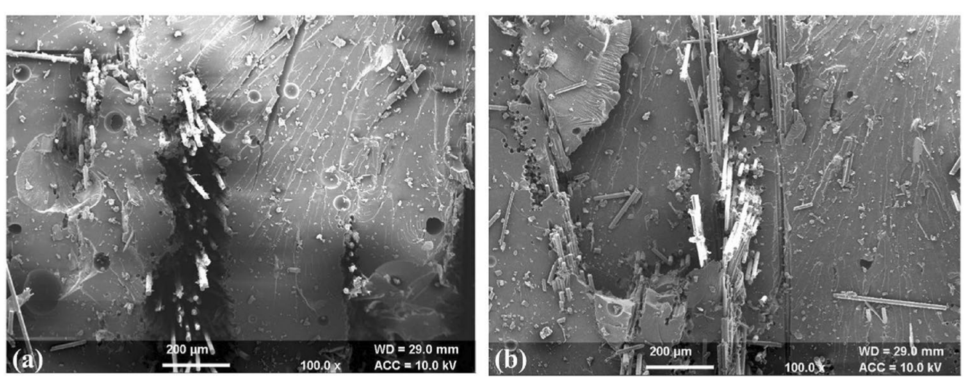


Fig. 6 SEM of **a** uncoated composite, **b** coated composite



$$\text{Erosion} = 9.300 + 0.778\text{W}_1 - 0.778\text{W}_2 - 1.750\text{P}_1 + 0.100\text{P}_2 + 1.650\text{P}_3 - 1.033\text{S}_1 + 0.250\text{S}_2 + 0.783\text{S}_3 + 0.067\text{N}_1 + 0.083\text{N}_2 - 0.150\text{N}_3 \quad (2)$$

here *W*, *P*, *S*, and *N* refer to workpiece, pressure, standoff distance, and nozzle diameter respectively. The erosion obtained was calculated in mg/minute during erosion of GFRP composite. R^2 value specifies the coefficient of determination of particular equation. The R^2 value is more than 90%, which confirms that developed model provides better results and can be helpful in predicting erosion behavior within experimental values.

5 Conclusions

The following conclusions were drawn from the present investigation:

- The electroless copper coating was successfully completed, and the results show that the coating has improved the erosion resistance of the composite.
- Treatment and electroless coating of SiC result in improved adhesion properties, which strengthen the composite against erosion.
- During erosion testing, it was found that pressure is the most influential parameter in controlling erosion.
- The ANOVA shows that after pressure, the workpiece type and standoff distance were also found to be significant.
- The R^2 value is more than 90%, which confirms that the developed model provides better results and can be helpful in predicting erosion behavior within experimental values.

Author Contributions Parvesh Antil: methodology, concept, analysis, original manuscript writing, resource. Manpreet Singh: data curation, formal analysis. Vinay Kumar: data curation, formal analysis. Dharmender Jangra: review manuscript, supervision, resource. Jayanta Boruah: review manuscript, resource, language improvement. Pallavi Agarwal: formal analysis, review manuscript, language improvement.

Funding The author(s) received no financial support for the research, authorship, and/or publication of this article.

Data Availability Data will be made available on request.

Declarations

Conflict of interest The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

1. Dallaire S (2013) Slurry erosion resistance of boride-based over lays containing boride crystal oriented perpendicularly to the wearing surface. Wear 297:1006–1015
2. Qian DN, Bao LM, Takatera M, Kemmochi K, Yamanaka A (2010) Fiber-reinforced polymer composite materials with high specific strength and excellent solid particle erosion resistance. Wear 26:637–642
3. Harsha AP, Thakre AA (2007) Investigation on solid particle erosion behavior of poly etherimide and its composites. Wear 262:807–818
4. Drensky G, Hamed A, Tabakoff W, Abot J (2011) Experimental investigation of polymer matrix reinforced composite erosion characteristics. Wear 270:146–151
5. Tewari US, Harsha AP, Hager AM, Friedrich K (2003) Solid particle erosion of carbon fibre- and glass fibre-epoxy composites. Compos Sci Technol 63:549–557
6. Yarlagaddaa J, Ramakrishna M (2019) Fabrication and characterization of S glass hybrid composites for tie rods of aircraft. Mater Today Proc 19:2622–2626
7. Vigneshwaran S, Uthayakumar M, Arumugaprabu A (2017) A review on erosion studies of fiber-reinforced polymer composites. J Reinf Plast Compos 36(14):1019–1027
8. Mohammed R, Reddy BR, Shaik AS, Manoj A (2019) Effect of fillers on erosion wear rate of polymer matrix composites. Int J Eng Adv Technol 8(6):1905–1912
9. Nayak SK, Satapathy A (2002) Erosion response analysis of waste marble dust reinforced kenaf-polyester composites. J Braz Soc Mech Sci Eng 44(9):1–15
10. Amaro AM, Loureiro AJR, Neto MA, Reis PNB (2020) Residual impact strength of glass/epoxy composite laminates after solid particle erosion. Compos Struct 238:112026
11. Shahapurkar K, Soudagar MEM, Shahapurkar P, Mathapathi M, Khan TY, Mujtaba MA, Ali MA (2022) Effect of crump rubber on the solid particle erosion response of epoxy composites. J Appl Polym Sci 139(2):51470
12. Ching YC, Azmi A (2014) Preparation and characterization of copper/copper coated silicon carbide composites. Int J Precis Eng Manuf 15(6):1215–1221
13. Barmouz M, Besharati Givi MA, Seyfi J (2011) On the role of processing parameters in producing Cu/SiC metal matrix composites via friction stir processing: investigating microstructure, micro hardness, wear and tensile behavior. Mater Charact 62(1):108–117
14. Lin WH, Chang HF (1998) Effect of chelating agents on the structure of electroless copper coating on alumina powder. Surf Coat Technol 107:48–54
15. Purohit A, Gupta G, Pradhan P, Agrawal A (2023) Development and erosion wear analysis of polypropylene/Linz-Donawitz sludge composites. Polym Compos 44(10):6556–6565
16. Prajapati PK, Kumar S, Singh KK (2023) Taguchi approach for comparative optimization of tribological behavior of glass fabric reinforced epoxy composite with and without graphene-nano platelets filler. Mater Today Proc 72(3):1605–1612
17. Singh M, Antil P, Singh S, Katal N, Bakshi DK, Alkesh (2023) RA-ECDM of silicon wafers using Taguchi's methodology and machine learning algorithms. Silicon 15: 1511–1526.

18. Liu R, Zong W, Gao C, Chi Z, Zhang L (2007) New and clean strategy for the determination of Cu2+ in electroless copper plating baths. Spectrochim Acta A Mol Biomol Spectrosc 68:150–155
19. Gan X, Wu Y, Liu L, Shen B, Hu W (2007) Electroless copper plating on PET fabric using hypophosphite as reducing agent. Surf Coat Technol 201:7018–7023
20. Lancaster JK (1990) Material-specific wear mechanisms: relevance to wear modelling. Wear 141:159–183
21. Ibrahim AT (1990) A mechanisms for solid particle erosion in ductile and brittle Materials. MS Thesis, Wichita State University
22. Antil P, Singh S, Manna A (2018) Electrochemical discharge drilling of SiC reinforced polymer matrix composite using Taguchi's grey relational analysis. Arab J Sci Eng 43(3):1257–1266
23. Antil P, Singh S, Kumar S, Manna A, Puruncu CI (2019) Erosion analysis of fiber reinforced epoxy composites. Mater Res Express 6:106520
24. Antil P, Singh S, Kumar S, Manna A, Katal N (2019) Taguchi and multi-objective genetic algorithm based optimization during ECDM of SiCp/Glass fibers reinforced PMCs. Indian J Eng Mater Sci 26(3):211–219
25. Bagci M (2016) Determination of solid particle erosion with Taguchi optimization approach of hybrid composite systems. Tribol Int 94:336–345
26. Bagci M, Imrek H (2013) Application of Taguchi method on optimization of testing parameters for erosion of glass fiber reinforced epoxy composite materials. Mater Design (1980–2015) 46:706–712
27. Jakhar C, Saroha A, Antil P, Ahlawat V, Rani A, Buddhi D, Kumar V (2022) Deep cryogenic treated high carbon steel blades: tribological, morphological and economic analysis. Surf Rev Lett 30(1):2241002
28. Antil P, Singh S, Manna A (2018) Analysis on effect of electroless coated SiCp on mechanical properties of polymer matrix composites. Part Sci Technol 37(7):791–798