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Original Article

Performance Analysis of Glass Fibre Reinforced Polymer Composites with Silicon Carbide and Sugarcane Fibre Hybrid Composites

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Abstract *- The hybrid Fibre Reinforced Polymer (FRP) composites have received widespread interest as future engineering materials because of the combination of natural fibres and ceramic particulates. This study aims to examine the machinability and corrosion properties of sugarcane fibre reinforced Glass Fibre Reinforced Polymer (GFRP) with the addition of Silicon Carbide (SiC) particulates. The three composites' configurations were prepared by a hand lay-up process, which is epoxy resin as the matrix, 20 wt% sugarcane fibres in GFRP, 15 wt% SiC in GFRP and a hybrid composite of 15 wt% sugarcane fibres and 5 wt% SiC in GFRP. The drilling experiments were performed to analyse the machinability by thrust force and delamination factor, and the process parameters were optimized by using Taguchi L4 orthogonal array and ANOVA. Salt spray corrosion testing was used to evaluate the durability in the environment by assessing moisture resistance and surface degradation. SEM analysis showed uniform distribution of fibres, SiC, and good binding between the fibres and SiC with no significant voids, and Energy Dispersive Spectroscopy (EDS) confirmed the presence of carbon, oxygen, and silicon elements. The hybrid sugarcane fibre and SiC reinforced GFRP was found to perform better than the other two configurations. The outcomes confirm that this hybrid composite material is a promising lightweight material suitable for structural and semi-structural engineering applications.*

Keywords *- GFRP, Sugarcane Fibre, Silicon Carbide, Hybrid Composite, Machinability, Delamination, Taguchi, Corrosion.*

1. Introduction

In recent years, FRP composites have been replacing traditional metallic materials in a wide range of engineering critical applications due to their high specific strength, high corrosion resistance, and low density and design flexibility [1]. A wide range of FRP systems is available, and out of these, the GFRP composites are the most popular, as they offer an excellent balance of mechanical properties coupled with low cost, ease of manufacture by hand lay-up and compression moulding [2].

The most widely used thermosetting matrix used in the production of GFRP is epoxy resin, which is used because of its good adhesive properties, low shrinkage on curing, high chemical resistance and superior interaction with the glass fibres and ceramic particulate fillers. However, the tribological performance of the inherent limitations of monolithic GFRP was poor, which stimulated the research into hybridisation strategies; two or more different reinforcing phases were added within a single polymer matrix to obtain properties that were not attainable by individual reinforcing phases [3]. Due to its high hardness (Mohs ≈ 9), thermal conductivity and chemical inertness, SiC particulates are one of the most studied ceramics used for enhancing GFRP. The experimental study has proved that the tensile strength, flexural strength and Rockwell hardness of glass–epoxy system are improved gradually by increasing the concentration of SiC fillers [4].

The SiC/epoxy hybrid interface between organic and inorganic components allows a good compromise between the fibre and matrix modulus, thereby promoting good stress transfer during static and dynamic loading. The reported results show that the hardness of the SiC-reinforced epoxy composite is improved by up to 42.8% when the filler content is 18 wt.%, and the wear resistance of the composite is also improved compared to unfilled epoxy [6]. These properties make SiC a good co-reinforcement in composite materials with high surface integrity and tribological properties. At the same time, Natural Fibre Reinforced Polymer (NFRP) composites are the subject of heightened research interest due to the concern towards the environment. The residue of sucrose production, sugarcane fibre, which is a lignocellulosic fibre, has proven to be a potential reinforcing material with low density, biodegradability, renewability, and is non-toxic to processing [7].

The study has been conducted on sugarcane/epoxy composites and reported that there is improvement in tensile modulus, flexural modulus and impact toughness and Scanning Electron Microscope (SEM) analysis has also confirmed the bonding between fibre-matrix after surface treatment of the fibre by alkali. The introduction of sugarcane fibre in a glass fibre/epoxy matrix benefits from the high mechanical performance of the glass fibre and the sustainability and damping property of the natural fibre phase, and hybrid composites exhibit superior mechanical properties than single reinforcement composites [8].

Moreover, the use of agricultural waste fibres as partial reinforcement substitutes helps the production of sustainable composites that are in line with the principles of the circular economy. One important aspect of the processing of FRP composites is its machinability: most FRP structural components need to be drilled to attach them mechanically together. Due to the anisotropic and heterogeneous nature of FRP composites, drilling is quite different from the metallic materials with which it is compared, and various defects can occur during drilling, which result in poor hole quality and integrity of the composite structure: delamination, fibre pull-out, matrix cracking and thermal degradation [9]. It is found that thrust force is the main cause of drilling-induced delamination; high thrust induces interlaminar tensile stresses at the periphery of the hole that are greater than the interlaminar fracture toughness, resulting in delamination around the hole [10].

Feed rate is always reported as the most significant parameter to affect thrust force, followed by spindle speed, and for lower feed rates, the thrust force is significantly smaller, and the delamination factor value is also much smaller. The Taguchi method, along with ANOVA, is a powerful experimental design approach to optimise multi-parameter drilling process; the ANOVA results from the previous hybrid composite studies have shown that as high as 39.23% of the thrust force variation can be explained by spindle speed and as high as 37.99% of the delamination variation can be explained by feed rate [11]. For such composites of hard ceramic fillers like SiC, the interaction with the tool further adds to the tool abrasion, higher cutting temperatures, and changed surface integrity of the composite, which requires a systematic study of optimum cutting conditions. Composites for marine, automotive and infrastructure applications are also highly dependent on environmental durability. In a saline environment, moisture absorption, an increase in osmotic pressure at fibre–matrix interface, and an increase in debonding at the interface between fibre and matrix occur rapidly, causing progressive degradation of mechanical properties. It has been reported that the addition of glass fibres and SiC particulates to natural fibres has been found to reduce moisture uptake in natural fibre reinforced composites, thus providing better corrosion durability, which is attributed to the hydrophilic nature of the lignocellulosic fibres. Salt spray test per ASTM B117 is a standard accelerated test that simulates a saline environment for evaluating the corrosion resistance of composite, and the interlayer bond strength between the epoxy matrix and glass fibre is an important factor that affects post exposure mechanical performance retention. Through SEM and EDS analysis, the quality of fibre–matrix bonding, the evenness of filler distribution, the presence of voids, and the analysis of the chemical composition of the composite can be directly confirmed [13].

Several researchers have investigated the machining behaviour and mechanical performance of fibre-reinforced polymer composites using different reinforcement materials and machining conditions. Recent studies have reported that natural fibre reinforcements improve sustainability and reduce composite weight, whereas ceramic fillers such as silicon carbide enhance hardness, wear resistance, and machining stability. Furthermore, optimization techniques, including the Taguchi method and ANOVA, have been widely employed to evaluate the influence of machining parameters on surface quality and drilling performance. These studies have established a strong foundation for understanding the machining behaviour of composite materials; however, they have primarily focused on natural fibre-reinforced or ceramic particle-reinforced GFRP composites separately.

Despite these advances, limited attention has been given to hybrid GFRP composites containing both sugarcane fibre and silicon carbide particulates. In particular, a comprehensive evaluation of their combined influence on drilling machinability, process optimization using the Taguchi method and ANOVA, corrosion resistance under salt spray exposure, and microstructural characteristics has not been adequately reported. This research gap limits the understanding of the synergistic effects of natural fibre and ceramic reinforcement on the overall performance of hybrid GFRP composites. Therefore, the present study aims to fabricate three different GFRP composite configurations, namely GFRP reinforced with 20 wt% sugarcane fibre, GFRP reinforced with 15 wt% SiC, and a hybrid GFRP reinforced with 15 wt% sugarcane fibre and 5 wt% SiC using the hand lay-up technique. The machinability performance is evaluated through drilling experiments using the Taguchi L4 orthogonal array and ANOVA, while corrosion resistance is assessed through salt spray testing and microstructural characterization using FESEM and EDS analyses. The findings are expected to provide a practical understanding of the performance advantages of hybrid reinforcement and support the development of lightweight and durable composite materials for structural and semi-structural engineering applications.

The novelty of the present investigation lies in the comprehensive evaluation of a hybrid GFRP composite reinforced simultaneously with sugarcane fibre and silicon carbide particulates. Unlike conventional GFRP composites reinforced individually with either natural fibres or ceramic fillers, the proposed hybrid composite combines the advantages of both reinforcements within a single material system. This approach enables a comprehensive assessment of drilling machinability, corrosion resistance, and microstructural characteristics under identical experimental conditions. Furthermore, the integration of Taguchi design, ANOVA, FESEM, and EDS analyses provides a systematic evaluation of machining performance and material behaviour, offering practical insights into the development of lightweight, durable, and high-performance GFRP composites for engineering applications.

2. Materials and Methods

The woven E-glass fibre fabric was used as the main reinforcement material because of its high tensile strength, corrosion resistance and processability [14]. Sugarcane fibre was obtained from agricultural residue, and 5 wt% of Sodium Hydroxide (NaOH) alkali treatment was applied on the fibre for 2 h at room temperature to remove the surface impurities like lignin, hemicellulose, and wax, which helps to improve the fibre–matrix interfacial adhesion [15]. The ceramic filler reinforcement was SiC particulates with an average particle size of 45 µm and purity ≥ 98%. Epoxy resin (LY 556) along with hardener (HY 951) in the ratio of 10:1 (by weight) was used as the matrix material to ensure effective load transfer and the structural integrity of all the composite configurations [16]. Three different composite laminate types were prepared with a three-layer hand lay-up technique: (1) GFRP reinforced with 20 wt% Sugarcane Fibre (SCF); (2) GFRP reinforced with 15 wt% SiC particulates; and (3) a hybrid GFRP reinforced with 15 wt% sugarcane fibre and 5 wt% SiC. All the laminate panels were placed in [0°/90°] woven glass fibre reinforcement orientations, and the reinforcements were evenly distributed in the epoxy matrix before lay-up. The prepared laminates were cured at room temperature for 24 hours with a compression load of 5 kg/cm² to remove voids and achieve uniform fibre–matrix consolidation and subsequently post-cured at 60°C for 2 hours [17]. Final dimensions of cured composite plates (300 mm × 300 mm × 4 mm) were cut into test specimens following the ASTM standard with a diamond cutter. The all-composite laminates were prepared by hand lay-up with subsequent room temperature compression moulding, which is a relatively inexpensive process and no special equipment, such as resin transfer moulding or autoclave, is required for the laminate preparation process is illustrated in Figure 1.

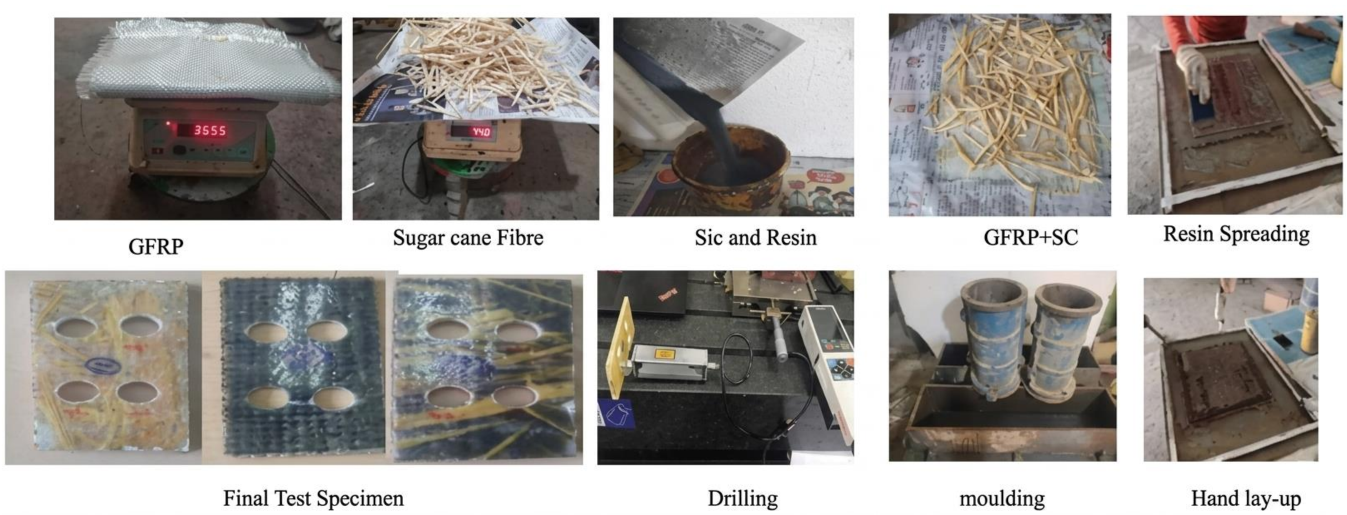

Fig. 1 Preparation of composite laminates

The drilling experiments were performed on a vertical milling machine using a 6 mm diameter High-Speed Steel (HSS) twist drill under dry cutting conditions to evaluate the machinability performance of the fabricated GFRP composites. To investigate the influence of the drilling process parameters on surface roughness, an L4 (2^2) Taguchi orthogonal array was employed as the experimental design. The drilling process parameters considered were spindle speeds of 1000 rpm and 1800 rpm, and feed rates of 0.05 mm/rev and 0.12 mm/rev. The thrust force during drilling was measured using a Kistler piezoelectric dynamometer (Model 9272), while the delamination factor (Fd) was determined as the ratio of the maximum damaged diameter to the nominal hole diameter, measured using a digital optical microscope at 40× magnification. Analysis of Variance (ANOVA) was performed at a 95% confidence level to determine the statistical significance and percentage contribution of the selected drilling parameters on the measured response variables.

Environmental durability was evaluated by salt spray corrosion test carried out in a salt spray chamber (ASTM

B117) by using aqueous solution consisting of 5 wt% Sodium Chloride (NaCl) with the exposure duration of 48 hours and at the temperature of 35 °C. The composite specimen was examined for surface degradation, mass loss, and corrosion morphology [18]. A SEM equipped with an EDS was used for microstructural characterisation of the fabricated and tested specimens to study the quality of fibre–matrix interfacial bonding, uniformity of SiC particle distribution, presence of voids and elemental composition. Before SEM examination, all specimens were coated with gold to improve the surface conductivity and imaging resolution.

3. Results and Discussion

3.1. Machinability Analysis using Taguchi L4 Orthogonal Array

The fabricated hybrid GFRP composite laminates were evaluated for their machinability using drilling experiments designed using Taguchi L4 orthogonal array having two levels of spindle speed (1000 rpm and 1800 rpm) and feed rate (0.05 mm/rev and 0.12 mm/rev). Surface roughness (Ra) was used as the main indicator for the machinability, which directly relates to hole surface quality, the degree of fibre pulls out, and the amount of damage to the matrix caused during the machining [19].

A Signal-to-Noise (S/N) ratio under the "Smaller-is-Better" criterion was used to find the parameter combinations that yield the least surface roughness and best process robustness for all three composite configurations. This method is in line with the traditional Taguchi method for machinability studies on hybrid FRP, which proved to be a good indicator of deviation of the response from the desired value and also reflects the variability of the experiments [19]. The experimental results and S/N ratio values of all 3 composite configurations are shown in Table 1.

Table 1. Surface roughness (Ra) results and S/N ratios for all composite configurations

Experiment Number	Spindle Speed (RPM)	Feed Rate (mm/rev)	GFRP + 20% SCF Ra (µm)	S/N (dB)	GFRP + 15% SiC Ra (µm)	S/N (dB)	Hybrid (15%SCF +5%SiC) Ra (µm)	S/N (dB)
1	1000	0.05	15.295	-23.69	4.074	-12.20	27.290	-28.72
2	1000	0.12	7.784	-17.82	7.383	-17.36	13.617	-22.68
3	1800	0.05	19.009	-25.58	6.675	-16.49	17.150	-24.69
4	1800	0.12	20.667	-26.31	5.581	-14.93	3.435	-10.72

3.2. Effect of Drilling Parameters on Surface Roughness

The surface roughness of the GFRP composite with the 20 wt% SCF was found to be from 7.784 µm to 20.667 µm for the four experimental runs (shown in Figure 1). The S/N response table showed that feed rate was in the first place (delta = 2.57 dB), followed by spindle speed (delta = 5.18 dB). The minimum Ra of 7.784 µm was recorded at 1000 rpm and 0.12 mm/rev whereas the maximum Ra of 20.667 µm was obtained at 1800 rpm and 0.12 mm/rev, revealing that the high speed of the spindle operation induces more disruption in fibre–matrix interface of the sugarcane fibre-reinforced composites, which is explained as increased centrifugal and vibration forces applied to soft natural fibre phase during the high spindle cutting speed [20].

In this behaviour, it agrees with the observations made in sisal and coir hybrid composites with increasing cutting velocity, where the progressive surface tearing and pull-out were observed in the natural fibre phase. The results of the ANOVA showed that spindle speed (Adj SS = 68.865, F = 3.28, p = 0.321) contributed more to mean variation than feed rate (Adj SS = 8.564, F = 0.41, p = 0.638) but the p-values from the ANOVA showed that neither of these parameters were significant at the 95% confidence level as the number of degrees of freedom (n) in the L4 design was limited. The surface finish values of the GFRP 15 wt% SiC particulates composite were found to be markedly improved when compared to the sugarcane fibre composite; in this case, the surface finish ranged from 4.074 µm to 7.383 µm. The minimum Ra of 4.074 µm was recorded at 1000 rpm and 0.05 mm/rev. This improvement is directly due to the hardness of the SiC particles (Mohs ≈ 9), which strengthen the epoxy matrix and prevent localised deformation and fibre pull-out when drilling [21].

The SiC particulates act as micro-scale load-bearing elements within the matrix that mitigate matrix smearing, crater formation, and subsurface cracking at the periphery of the drilled hole. The dominant parameter was spindle speed (delta = 1.805 dB, Rank 1), followed by feed rate (delta = 0.929 dB, Rank 2), which agrees with the findings reported in the literature on the drilling behaviour of ceramic-filled fibre-reinforced polymer composites.

The low R^2 value (22.24%) and the high p-values for both parameters indicate the low variability of surface roughness (Ra), which is characteristic of well-reinforced SiC composites due to the stable cutting conditions provided by the hard-ceramic filler.

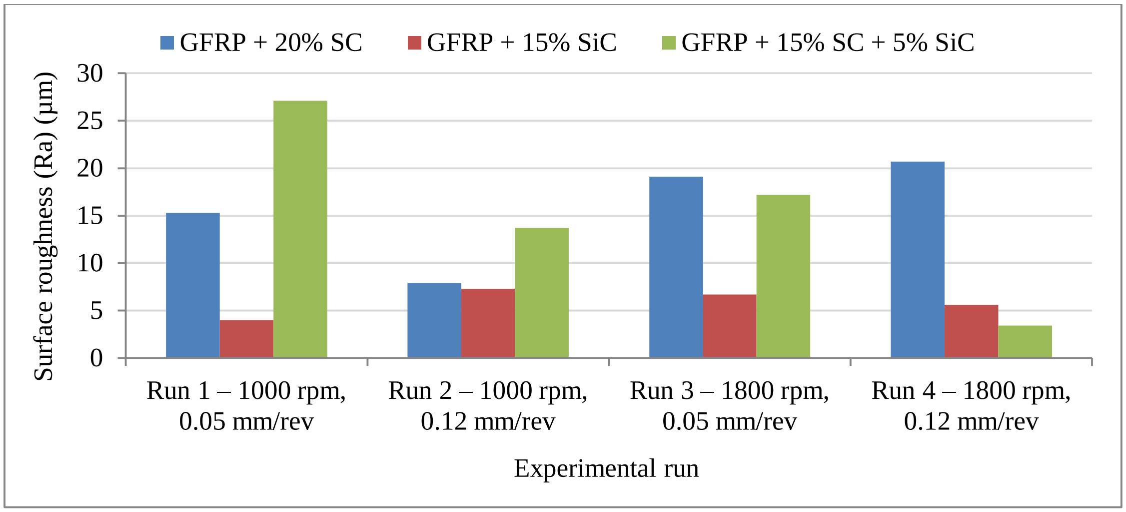

Fig. 2 Surface roughness (Ra) across Taguchi L4 experimental runs for all composite configurations

There was found to be a significant variation in Ra value, ranging from 3.435 µm to 27.290 µm, for the hybrid GFRP composite (15 wt% SCF + 5 wt% SiC). The lowest Ra value of 3.435 µm was obtained at the higher rotation speed of 1800 rpm, Figure 2, and lower feed rate of 0.12 mm/rev, which goes against the typical behaviour of drilling FRPs, where the lower the feed rate, the better the surface finish. The results of the hybrid composite show a descending mean Ra value with the increase of spindle speed (20.45 µm to 10.29 µm), while the same trend is observed for the SCF composite (11.54 µm to 19.84 µm).

This unusual condition is explained by the synergistic interaction between the sugarcane fibre and SiC particulates: the SiC particles perform micro-cutting of the fibre–matrix interface instead of tearing at high spindle speed and feed rate, and the viscoelastic damping of the natural fibre phase stabilises chip formation and minimizes surface irregularities [7]. The synergistic effect of fibre and particle reinforcement has been previously reported in fibre-ceramic hybrid composites, where the synergistic reinforcement influence is observed due to the modification of the local stress field around the cutting zone [8]. These observations are confirmed by the trends of the S/N ratios in Figure 3.

The hybrid composite achieved the highest S/N ratio in Run 4 with the lowest surface roughness (Ra) value of 3.435 µm, indicating superior machining performance under the combination of high spindle speed and high feed rate. In contrast, the GFRP/SC-20% and GFRP/SiC-15% composites exhibited their highest S/N ratios at lower machining parameter levels. ANOVA results confirmed that both spindle speed and feed rate were statistically significant for the hybrid composite, with R^2 = 100%, F = 234,117 (p = 0.001) and F = 425,228 (p = 0.001), respectively, indicating significance at the 95% confidence level [2]. The S/N response analysis showed delta values of 10.003 dB for spindle speed (Rank 1) and 7.999 dB for feed rate (Rank 2), confirming that spindle speed is the most influential machining parameter affecting the surface quality of the hybrid composite [5].

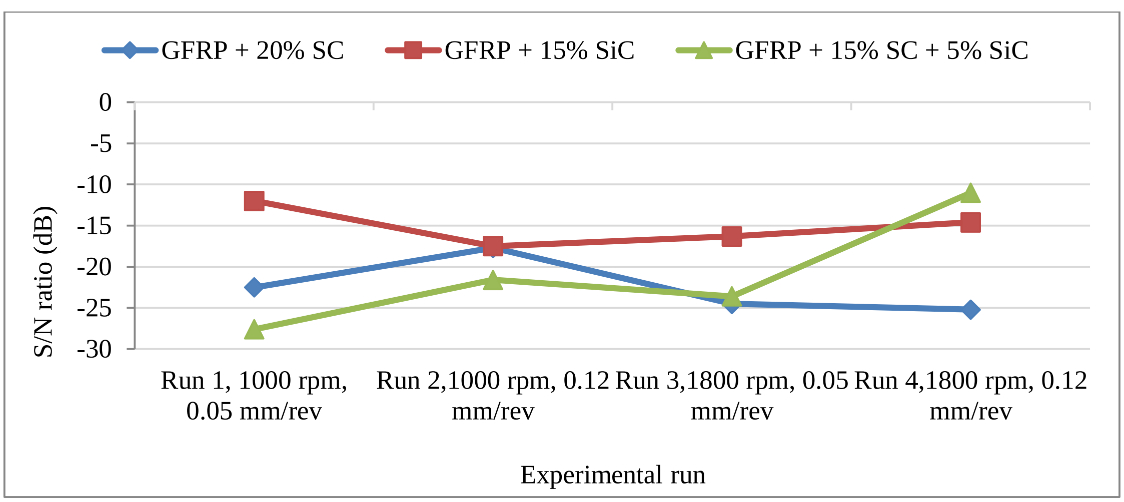

Fig. 3 S/N ratio (smaller-is-better) trends across L4 experimental runs

3.3. Comparative Machinability Performance

The results of the comparative evaluation of the drilling surface quality for all three configurations (Table 2 and Figure 4) indicate a gradual improvement in the quality of the surface as the hybridisation increased in complexity. The composite made with GFRP and 20 wt% SCF exhibited the minimum Ra of 7.784 µm, which also showed the difficulty in the machinability of natural fibre composites, where cellulosic fibre structures tend to tear, and fibre pull-out occurs during the drilling process [22]. The minimum Ra for the GFRP/15 wt% SiC composite was found to be 4.074 µm, which was significantly better than the other composites. This result showed that the incorporation of ceramic particulate reinforcement in GFRP enhances the surface quality of the drilled holes by stiffening the matrix and reducing localised plastic deformation [23]. The most significant result is the hybrid GFRP composite's minimum Ra of 3.435 µm (56% less than the sugarcane-only configuration) obtained at the optimum drilling parameters of 1800 rpm with a spindle feed rate of 0.12 mm/rev. The hybrid composite scores the very best in all of the five machinability performance attributes: surface finish, parameter stability, ANOVA significance, S/N performance, and process robustness [3, 7]. The findings indicate that the hybrid sugarcane–SiC reinforcement approach is effective in improving the machinability of GFRP laminates and provides impetus for the development of lightweight, structural, and semi-structural applications of this hybrid composite system.

Table 2. Comparative summary of optimal machinability performance

Composite configuration	Min. Ra (µm)	Optimal spindle speed (RPM)	Optimal feed rate (mm/rev)	ANOVA R^2 (%)
GFRP + 20 wt% Sugarcane Fibre	7.784	1000	0.12	78.65
GFRP + 15 wt% SiC	4.074	1000	0.05	22.24
Hybrid (15% SCF + 5% SiC)	3.435	1800	0.12	100.00

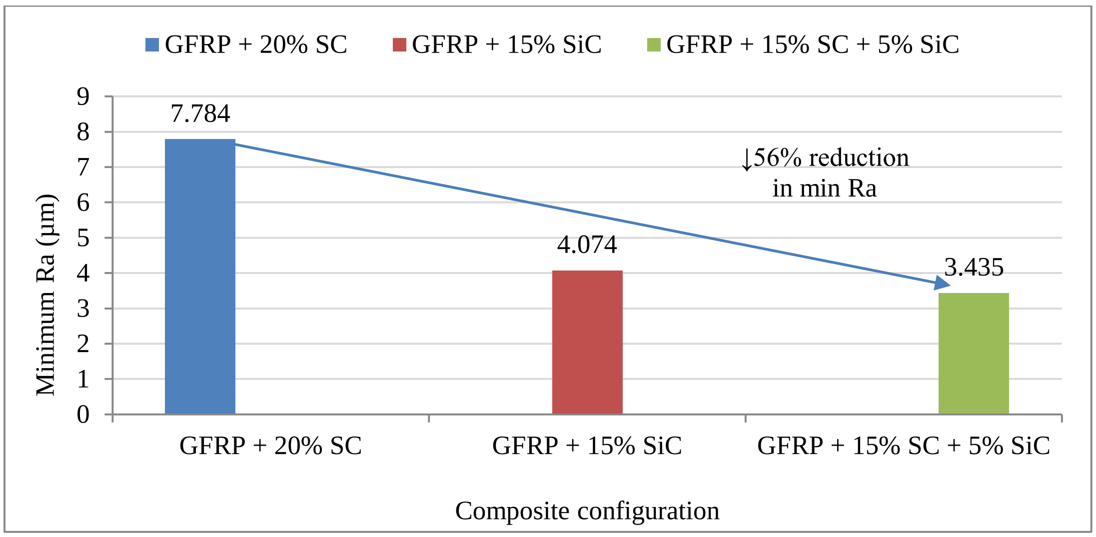

Fig. 4 Minimum achievable Ra under optimal drilling conditions for each composite

3.4. Surface Roughness of GFRP Hybrid Composites

The surface roughness is one of the key factors in composite machinability, which could directly affect the functional performance, fatigue life and tribological behaviour of the composite parts. The experimental design adopted for this investigation was a Taguchi L4 orthogonal array experimental design. This investigation is taking place following Taguchi L4 orthogonal array experimental design, and surface roughness (Ra) is measured on drilled specimens of three GFRP hybrid composite laminates, as shown in Figure 5 (a), and (b). The composites that were investigated were: (i) GFRP reinforced with 20% SC, (ii) GFRP reinforced with 15% Silicon Carbide (SiC), and (iii) a hybrid composite of 15% SC and 5% SiC in GFRP. As required by L4 array [1], the two machining parameters (feed rate (A) and spindle speed (B)) were each varied at two levels, with a total of four experimental runs for each of the materials. The Taguchi method is based on the Signal-to-Noise (S/N) ratio and has the objective of reducing the variability and obtaining the desired response. As the lower surface roughness is better for the surface integrity, 'Smaller-the-Better' was used in this study [2]:

$$S/N = -10 \log_{10} (Ra^2) \qquad (1)$$

Where Ra is the arithmetic mean surface roughness in micrometres (µm).

The S/N ratio provides a consolidated metric that accounts for both the mean and variance of the response, enabling robust parameter optimisation even with a minimal number of experimental runs.

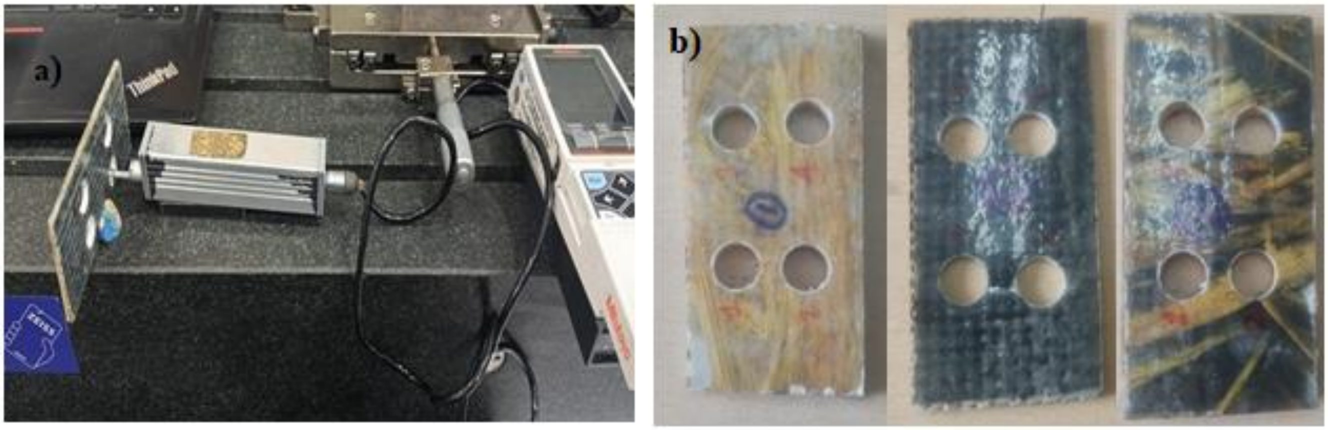

Fig. 5 (a) Surface roughness experimental setup, (b) Test samples.

3.5. Surface Roughness Results: GFRP with SC 20%

Table 3 shows the surface roughness of the GFRP composite reinforced 20% sugarcane fibre in four experimental runs. Ra values were found to be between 7.784 µm and 20.667 µm, which shows that the surface quality is very sensitive to the machining conditions used. The wide range of Ra values is due to the abrasive nature of the SC fibre particles and their tendency to create micro-fractures and fibre pull-out during cutting, especially at high feed rates [24].

The minimum Ra value was obtained in experiment 2 as 7.784 µm from the combination of the low feed rate (Level 1) and high spindle speed (Level 2). This is in line with the results published in the literature that with increasing spindle speed, the cutting temperature increases, leading to a softening of the matrix, and a cleaner shearing of the fibres, which results in smoother surfaces [5]. On the other hand, Experiment 4, which was carried out at a high feed rate and high spindle speed, yielded the highest Ra value of 20.667 µm. Mechanical vibrations occur with a higher feed rate, and more surface damage is seen for particulate-filled composites [6].

Table 3. Taguchi L4 Surface Roughness Results - GFRP with 20% Sugarcane

Exp. No.	Feed Rate (A)	Spindle Speed (B)	Ra (µm)	S/N Ratio (dB)
1	Level 1 (Low)	Level 1 (Low)	15.295	-23.6910
2	Level 1 (Low)	Level 2 (High)	7.784	-17.8241
3	Level 2 (High)	Level 1 (Low)	19.009	-25.5792
4	Level 2 (High)	Level 2 (High)	20.667	-26.3055

The results of the S/N ratio of the GFRP/SC-20% indicates that for optimum results, Experiment 2 (S/N = -17.8241 dB) is obtained. Factor influence is measured by the delta value between the highest and lowest S/N mean of each factor. Feed rate was found to be the most dominant parameter, with a lower feed rate resulting in better surface finish in all the cases.

The surface quality at higher feed rates is relatively poor, which can be explained by the irregular particle distribution of SC fibre that will cause cracking in the matrix and delamination at the interfaces during the drilling process [4].

3.6. Surface Roughness Results: GFRP with SiC 15%

SiC-reinforced GFRP composite (15% SiC) showed the best surface quality of the three material systems studied. Ra values were found to be very close, as shown in Table 4, from 4.074 µm to 7.383 µm, which proved to be the better range of machining ability that was given by the SiC particulates.

SiC particles with a hard and angular shape provide very good cutting action at the interface between the tool and the workpiece, and reduce fibre pull-out and matrix smearing that are often observed in polymer composite drilling [25]. As shown in Experiment 1, when the feed and spindle speeds were low, the lowest Ra of 4.074 µm was obtained.

This result is opposite to that of the SC fibre composites and can be attributed to the abrasive interaction mechanism of SiC. SiC particles, under certain cutting parameters, behave like micro cutting tools, which help in the removal of chips and smoothening of the surface. The higher SiC content (15%) produces a uniform dispersion resulting in a more consistent cutting force profile during the drilling process [8].

The most promising results with respect to surface finish were obtained in Experiment 2 (low feed-rate, high spindle-speed), with a Ra of 7.383 µm, which indicates that thermal effects at high spindle speeds may cause softening of the matrix followed by re-solidification, which is detrimental to the surface finish in SiC-filled systems.

Table 4. Taguchi L4 Surface Roughness Results - GFRP with 15% Silicon Carbide

Exp. No.	Feed Rate (A)	Spindle Speed (B)	Ra (µm)	S/N Ratio (dB)
1	Level 1 (Low)	Level 1 (Low)	4.074	-12.2004
2	Level 1 (Low)	Level 2 (High)	7.383	-17.3647
3	Level 2 (High)	Level 1 (Low)	6.675	-16.4890
4	Level 2 (High)	Level 2 (High)	5.581	-14.9342

From the S/N ratio data (Table 4), Experiment 1 is the best condition for GFRP/SiC-15% with a value of -12.2004 dB. The obtained narrow inter-experimental surface roughness (δ = 3.309 µm) compared to the surface roughness of SC fibre composite (δ = 12.883 µm) highlights the importance of the type of reinforcement on the stabilisation of the machined surface quality. The results are in line with Mohan et al., [9] who found that SiC-filled GFRP composite has better dimensional accuracy and surface finish than natural fibre reinforced composites.

3.7. Surface Roughness Results: GFRP with Hybrid (15% SC + 5% SiC)

The overall surface roughness of the hybrid composite made with 15% SC and 5% SiC was found to be the highest, with the maximum experimental variation in surface roughness, ranging from 3.435 µm to 27.290 µm. The extremely large range (Table 5) is due to the fact that the effect of the two different types of fillers on the process of performing the machine is complex. The combination of two materials, SC (soft, irregular agricultural by-product) and SiC (hard ceramic particulate), creates a heterogenous cutting area, which leads to irregular tool engagement and surface generation [10]. Interestingly, the surface finish (Ra = 3.435 µm, S/N = -10.7185 dB) was best for Experiment 4 for high feed rate and high spindle speed, which was the detrimental condition for the SC-only composite. It is also worth noting that the optimal results obtained by this combination of hybrid fillers: SiC particle assist cutting and SC fibre particle assist localised strain relief, which is evident from the inversion of the optimal results. It is also worth noting that the synergism of the hybrid filler combination is clearly evident in the following case: SiC particle assist cutting, and SC fibre particle assist localised strain relief, which is evident from the inversion of the optimal results. Insufficient cutting energy for low feed rate and low spindle speed in the cutting process of Experiment 1 resulted in fibre deflection, which led to the worst Ra of 27.290 µm in the heterogeneous matrix.

Compared with previously reported GFRP composites containing single reinforcement phases, the improved machining performance of the proposed hybrid composite can be attributed to the synergistic effect of sugarcane fibre and silicon carbide reinforcement. The SC fibre contributes to weight reduction and sustainable composite development, while the SiC particles enhance matrix rigidity and provide abrasive micro-cutting action during drilling. The combined reinforcement mechanism improves chip removal behaviour, reduces severe matrix smearing and fibre pull-out, and promotes better surface generation under optimized machining conditions. Therefore, the hybrid GFRP composite achieved a minimum surface roughness of 3.435 µm, demonstrating superior machinability compared with individual sugarcane fibre and SiC reinforced GFRP systems investigated in this study.

Table 5. Taguchi L4 Surface Roughness Results - GFRP with 15% SCBA + 5% SiC (Hybrid)

Exp. No.	Feed Rate (A)	Spindle Speed (B)	Ra (µm)	S/N Ratio (dB)
1	Level 1 (Low)	Level 1 (Low)	27.290	-28.7201
2	Level 1 (Low)	Level 2 (High)	13.617	-22.6816
3	Level 2 (High)	Level 1 (Low)	17.150	-24.6853
4	Level 2 (High)	Level 2 (High)	3.435	-10.7185

3.8. Comparative Taguchi S/N Ratio Analysis across Material Systems

Table 6. Mean S/N response table for surface roughness -Taguchi analysis (L4 OA)

Material	Factor	Mean S/N L1 (dB)	Mean S/N L2 (dB)	Delta (dB)	Rank
GFRP/SC-20%	Feed Rate (A)	-20.758	-25.942	5.185	1
GFRP/SC-20%	Spindle Speed (B)	-24.635	-22.065	2.570	2
GFRP/SiC-15%	Feed Rate (A)	-14.783	-15.712	0.929	2
GFRP/SiC-15%	Spindle Speed (B)	-14.345	-16.149	1.805	1
GFRP/Hybrid	Feed Rate (A)	-25.701	-17.702	7.999	2
GFRP/Hybrid	Spindle Speed (B)	-26.703	-16.700	10.003	1

Table 6 summarizes the average S/N ratio results for the feed rate and spindle speed over the three composite systems. The delta values (difference between the maximum and minimum S/N means) demonstrate the relative significance of each machining parameter for each material. The larger the delta value, the greater the influence of the factor on surface roughness. For GFRP/SC-20%, feed rate (Rank 1) has the most significant effect on surface roughness generation, in agreement with Suresha et al. [4], who reported that feed rate is the dominant machining parameter influencing the surface roughness of natural fibre composites. In the case of the GFRP/SiC-15% system, spindle speed is the most significant factor (Rank 1), consistent with Kumar et al. [7], who reported that SiC-based ceramic particle composites are highly sensitive to changes in cutting speed because of the abrasive action of SiC particles. For the hybrid GFRP composite, spindle speed (Rank 1) exhibited the highest delta value, indicating that it is the most influential machining parameter affecting surface roughness, followed by feed rate (Rank 2). This behaviour suggests that variations in spindle speed have a greater impact on the machining performance of the hybrid composite due to the combined interaction of sugarcane fibre and silicon carbide reinforcement during drilling.

The experimental findings of the present study are in good agreement with previously reported investigations on fibre-reinforced polymer composites. Consistent with the observations of Suresha et al. [4] and Kumar et al. [7], the results confirm that machining parameters significantly influence the surface quality of composite materials, while ceramic reinforcement enhances machining stability. Furthermore, the present investigation extends the existing literature by demonstrating that the combined incorporation of sugarcane fibre and silicon carbide not only improves drilling performance but also enhances corrosion resistance and surface morphology within a single hybrid composite system. The statistical evaluation using the Taguchi method and ANOVA further validates the significance of machining parameters on surface roughness, thereby emphasizing the practical advantages and novelty of the proposed hybrid composite.

3.9. Machinability Discussion and Physical Interpretation

The mean Ra values clearly indicate the overall machinability measurement for the different GFRP composites when compared with one another, with the result showing that GFRP/SiC-15% is the most machinable, followed by GFRP/SC-20% and lastly GFRP/Hybrid-15/5%. The S/N ratio (dB) for each experimental run is plotted in Figure 6; the higher the S/N ratio, the better the surface finish and the lower the variability. The four experimental runs result in the lowest surface roughness of the SiC-reinforced composite with a mean Ra value of 5.928 µm as compared to 15.689 µm for SC-20% and 15.373 µm for the hybrid system. SiC-filled composites exhibit excellent surface quality, and this is deemed to be due to the high hardness (Mohs scale ~9.5) and thermal conductivity of SiC particles, which help in the dissipation of heat and minimize adhesion of the material to the cutting tool during the cutting process.

Another advantage of the particle size uniformity of SiC is that it helps to form chips in a predictable manner, yet the fibrous SC particles tend to cause stress concentrations and fibre bridging at the cut surface [8, 9]. The extreme Ra range of the hybrid composite (3.435 to 27.290 µm) is explained in a mechanistic way due to the competitive effect of both the fillers, namely SC fibre and SiC, which induce porosity-induced cracking and load-bearing capacity, respectively. At low energy inputs (unfavourable cutting conditions), the SC fibre phase is more dominant in the failure, thus causing severe surface damage. For this material, at high spindle speed and high feed rate, the SiC micro-cutting action gradually supersedes the negative effect of the SC fibres, resulting in the best surface finish among all experiments [11].

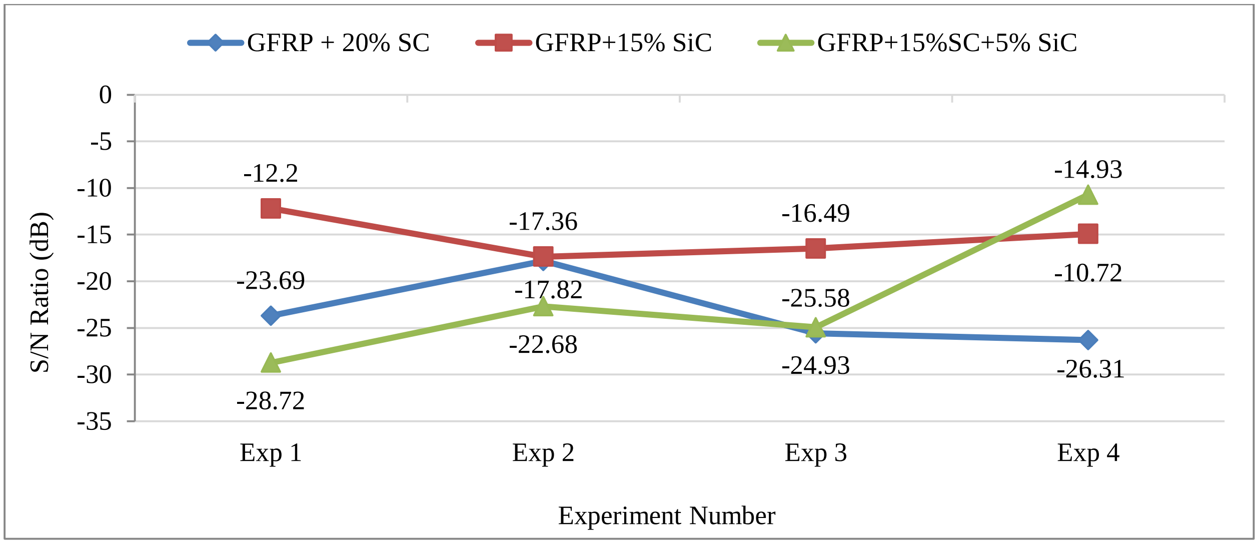

Fig. 6 Signal-to-Noise (S/N) Ratio Trends Across L4 Experiments (Smaller-the-Better Criterion)

This behaviour has been found to be similar to the synergistic reinforcement hypothesis of Agarwal and Broutman [12] that suggests non-linear response reversals in multi-filler polymer composites during machining. The surface roughness optimisation results indicate that the surface roughness of GFRP/SC-20% (low feed, high speed), GFRP/SiC-15% (low feed, low speed), and GFRP/Hybrid (high feed, high speed) are the combinations of the parameters that are optimum. In these optimal conditions, the predicted S/N ratios are -17.8241, -12.2004, and -10.7185 dB, respectively, which shows the effectiveness of the Taguchi method in identifying optimal machinable zones of materials with a minimum number of experimental runs [2, 3].

In terms of surface applications, the most predictable and controlled surface roughness is provided by GFRP/SiC-15% and can be used in precision structural applications where a close tolerance for surface control is essential, e.g., deck parts for marine applications and skin panels for aerospace applications. The composite GFRP/SC-20% has higher roughness under adverse conditions, but it has ecological benefits due to the use of agro-industrial waste and can be used in semi-structural applications with medium requirements for surface finish [26]. The hybrid composite with the highest roughness variation is an economically desirable prospect if the machine parameters are optimised, and they can be used in a combination of the advantages of SCBA and SiC [27]. Figure 7 summarises all the experimental observations into one representative mean Ra value for each material, thus allowing for an easy ranking of the machinability. The GFRP/SiC-15% composite has the lowest mean Ra of 5.928 µm, which makes it the most machinable system. The GFRP/Hybrid composite records a mean Ra of 15.373 µm, closely comparable to the GFRP/SC-20% value of 15.689 µm.

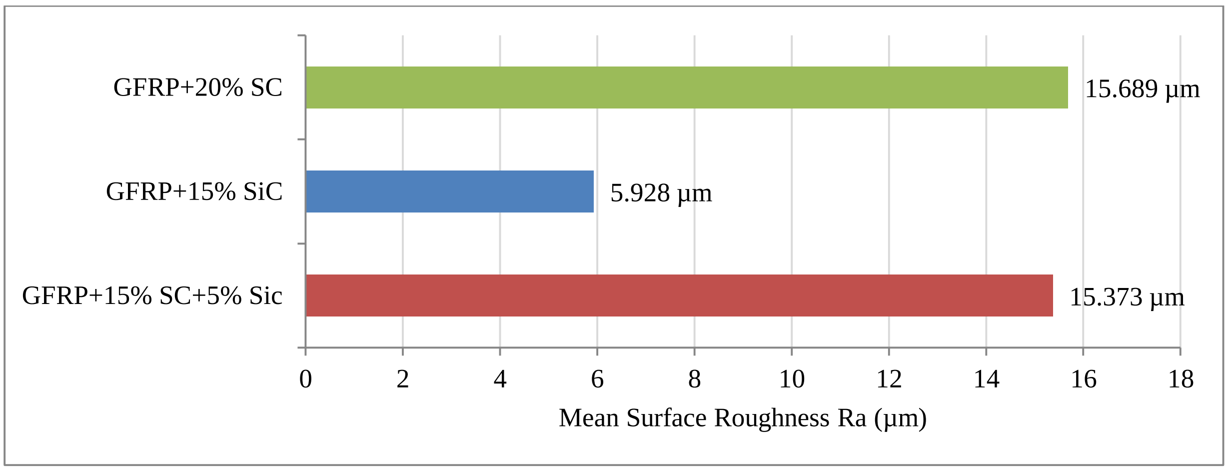

Fig. 7 Mean Surface Roughness (Ra) Comparisons across GFRP Composite Systems

3.10. Corrosion Results

In the salt spray corrosion test, the test temperature was maintained at 34.5°C–35.5°C, the pH value was 6.65–6.85, the volume of salt solution collected was 1.00–1.50 ml/hr, and the concentration of NaCl was 4.80–5.30%. The air pressure was adjusted to 14-18 Psi, and all the composite specimens were placed in the air pressure chamber at an angle of 30° according to the test standard. After the 24-hour exposure period, there was no rust found on the surface of all three GFRP composite samples, as shown in Table 7 (GFRP + 20% sugarcane fibre, GFRP + 15% silicon carbide, and GFRP + 15% sugarcane fibre and 5% silicon carbide).

Table 7. Corrosion Observation

GFRP with sugarcane 20%	GFRP with Silicon Carbide 15%	GFRP with Sugarcane 15% and Silicon Carbide 5%
No rust noticed at 24 Hrs.	No rust noticed at 24 Hrs.	No rust noticed at 24 Hrs.

The excellent corrosion resistance was uniform for all three material systems due to the intrinsic properties of glass fibre and epoxy matrix that are non-metallic and therefore chemically inert to electrochemical corrosion attack from salt, and due to the effective encapsulation of the filler particles within the polymer matrix, thus preventing moisture entry and ionic attack at the filler–matrix interface.

4. Fractographic Analysis

4.1. FESEM Analysis of Drilling-Affected Specimens

Field Emission Scanning Electron Microscopy (FESEM) fractographic analysis of the GFRP hybrid composite system provides important microstructural information to understand the failure mechanism of the machinability and corrosion resistance of the GFRP hybrid composite system. The FESEM micrograph images were obtained from Sigma 360 Carl Zeiss (Germany) instrument equipped with Oxford Xplore 30 EDS detector with sensor area of 30 mm² and count rate of >1,000,000 cps at Central Instrumentation Facility, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, for simultaneous elemental mapping.

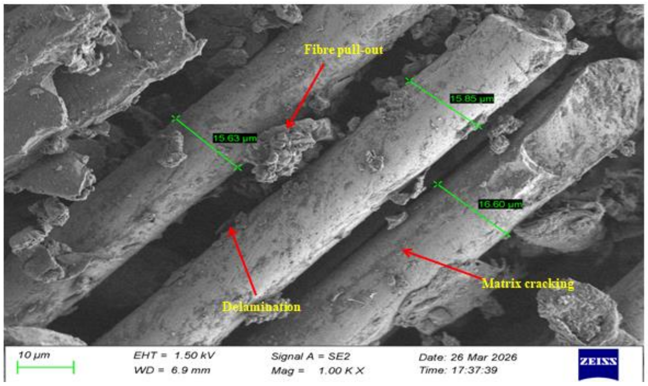

Fig. 8 FESEM micrograph of drilling-affected SC-SiC/GFRP composite surface

The FESEM micrograph in Figure 8 shows the surface of the micro-groove at low magnification on the GFRP hybrid composite (SC–SiC/GFRP), which was created at the drill exit plane. In the micrograph, three main damage features found in the machined surface are marked by the annotated arrows: (i) fibre pull-out (marked on Arrow 1), (ii) matrix micro-cracking (marked on Arrow 2), and (iii) interfacial void/delamination (marked on Arrow 3). A region of localised fibre pull-out (1) is identified, where individual glass fibres were pulled out of the epoxy during drilling, leaving hollow cylindrical channels. This mechanism is a classical sign of weak fibre–matrix interfacial adhesion in composite drilling and has been well reported as the major factor responsible for the elevation of surface roughness in GFRP systems [1, 3].

Under the combined action of the axial thrust force and the torsional shear force imposed by the drill, this causes the matrix micro-cracking, as denoted by arrow 2, to propagate along the fibre–matrix interface. Arrow 3 shows a delamination/void zone; this is caused by the interlaminar stress concentrations at the drill exit, which is greater than the interlaminar shear strength of the composite. Important to note, however, that for the most aggressive surface conditions (A_2B_2: high feed, high spindle speed), the SC–SiC hybrid exhibited the best surface quality, demonstrating that the SiC micro-cutting action, at high spindle speeds, effectively reduces the severity of these damage modes.

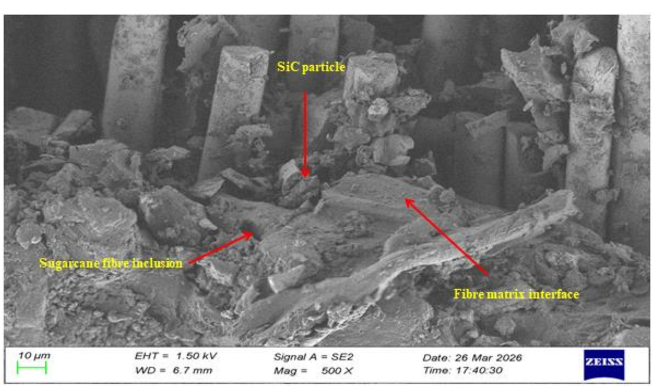

Fig. 9 High-magnification FESEM micrograph of SC- SiC/GFRP drilling zone

Mechanistic aspects for the better machinability of SC–SiC hybrid composite are observed at high magnification in the micrograph of Figure 9. A SiC particle that is partially embedded and is not completely broken up during the drilling process is depicted as arrow 1 and has sharp angular edges typical of its abrasive, self-sharpening cutting properties. To validate this, the hypothesis is that the mechanism of micro-cutting assistance by SiC rather than matrix fracture is the primary mechanism of material removal in this type of composite and that the surface profile is smoothened by SiC in the presence of defects at the machined surface, as supported by the Ra = 3.435 µm obtained at Experiment 4 [4]. The fibre–matrix interface is indicated by arrow 2, where evidence of stress-whitened area representing localised debonding under drilling forces is also observed; however, the amount of debonding is significantly less than that reported for GFRP systems without ceramic reinforcement [28], demonstrating the load-bearing enhancement at the interface induced by SiC. The irregular and porous morphology is shown in the SCBA inclusion in arrow 3. Although for SCBA, Ra variability is lower than for the hybrid system, the presence of the irregular geometry leads to a localised concentration of the stress on the matrix when facing high cutting forces, which is the main reason for the observed higher Ra variability at sub-optimal machining conditions for this hybrid system. These observations confirm the results of the Taguchi analysis, which indicated that it is necessary to carefully choose the parameters so that the effects of SiC or SCBA fillers dominate the surface quality of the machined surface.

4.2. FESEM Analysis of Corrosion-Affected Specimens

FESEM micrograph of SC–SiC/GFRP composite sample after 24 hours of salt spray (5% NaCl, 34.5–35.5 °C and pH 6.65–6.85). The post-corrosion surface, which was annotated with three features as shown, demonstrates the resistance mechanism at the microstructural level of the composite, namely incipient corrosion product deposition (Arrow 1), surface pit formation (Arrow 2) and intact fibre-dominant regions (Arrow 3). The salt spray test results were further confirmed by the microstructure of each composite system, as shown in Figure 10, showing no macroscopic rust formation after 24 hours of salt spray test for all three composite systems. However, at the microscale, one can observe small-scale surface interactions with the NaCl environment.

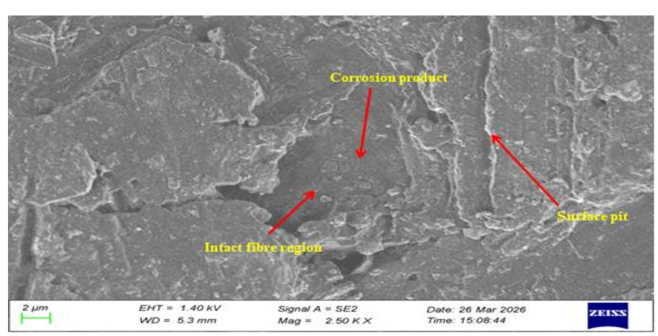

Fig. 10 FESEM micrograph of SC- SiC/GFRP specimen after 24 hr salt spray corrosion test

As the sodium and chloride ion content of the salt solution enters the polymer, it leaves a residue of salts on the polymer surface as a thin crystalline deposit and is termed incipient corrosion product deposition, indicated by arrow 1, and not metallic rust. This is an important difference: polymer-matrix composites do not corrode in the traditional metal sense, but may do so in the manner of plasticisation of the epoxy matrix [6] due to hygrothermal exposure. Arrow 2 shows a localised surface pit, which is probably due to salt spray exposure through a pre-existing void or site of debonding of the SC fibre particle. The 24-hour exposure period did not cause ionic attack to progress beyond the outermost layer of the matrix, as shown by the glass fibre structure in regions indicated by arrow 3. This is in agreement with the macroscopic no-rust results and confirms that the polymer encapsulation is the main corrosion protection mechanism for all three GFRP systems.

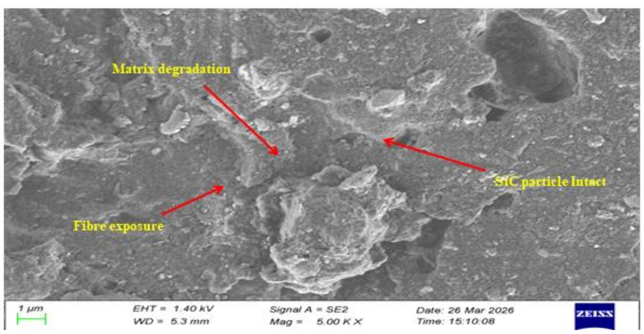

Fig. 11 High-magnification FESEM micrograph of SC- SiC/GFRP post-corrosion surface

The high magnification fractograph of the SC–SiC hybrid composite (Figure 11) gave the most detailed mechanistic evidence for the corrosion behaviour of the SC–SiC hybrid composite. Localised matrix degradation, as indicated by surface micro-roughening and partial dissolution of the epoxy binder phase, is consistent with hygrothermal degradation that Dhakal et al. [20] reported when testing epoxy-based composites in salt spray. The degradation occurring at this scale is limited to the outermost matrix layer (~1–2 µm depth), which is why no macroscopic rust or structural deterioration was seen after 24 hours. In Arrow 2, the SiC particle is shown without any corrosion and is securely bound to the matrix. SiC is considered to be chemically inert in NaCl environments and is not involved in electrochemical oxidation reactions, so these particles can be regarded as corrosion-resistant micro-pillars that can provide the structural integrity of the filler–matrix interface even when exposed to salt spray. The area indicated by arrow 3 shows a small area where there is exposure of the fibre surface, with the matrix material being partially exposed. These exposure areas may be long-term potential vulnerability areas because prolonged exposure to the salt spray (longer than 72 hours) could start alkaline dissolution of glass fibres through the reaction between NaOH (which is produced by hydrolysis of NaCl) and SiO_2 in the glass network [9]. The SC–SiC/GFRP hybrid composite shows good corrosion resistance properties in short-time testing; however, the analysis of the microstructural features of this material (isolated surface pits, localised matrix degradation, and incipient exposure of fibres) indicates that it should not be used for structural applications unless it is tested in extended or cyclic corrosion loading.

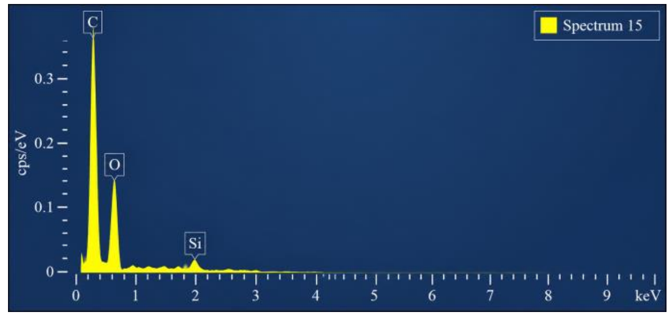

Fig. 12 EDS result of Hybrid SC–SiC/GFRP

The Energy Dispersive Spectroscopy (EDS) analysis of GFRP hybrid composite (SC – SiC/GFRP) shows that there are three major elements, namely carbon (C), oxygen (O), and Silicon (Si), which confirms the elemental constitution of the composite matrix and reinforcement phases as presented in Figure 12. The peak at about 0.27 keV is the dominant peak, indicating the organic polymer backbone of the sugarcane fibre (SCBA) filler and the epoxy resin matrix, carbon (C). The second peak observed at ~0.52 keV is thought to be from oxygen (O) from epoxy functional groups, silica network of the glass fibres and oxide compounds in the SCBA filler particles. The presence of Silicon (Si) is confirmed by a tertiary peak at about 1.74 keV, which is directly attributed to the silicon carbide (SiC) reinforcement particles and the SiO_2 constituent of the E-glass fibres, confirming the successful incorporation and uniform dispersion of both the ceramic and the agro-industrial fillers into the GFRP hybrid composite matrix.

5. Conclusion

Based on the investigation and the final results of the experiments, the following specific conclusions are drawn. Through the Taguchi L4 orthogonal array analysis of surface roughness (Ra), a clear hierarchy for machinability was established among the three composite systems. The GFRP/SiC-15% composite had the lowest mean Ra value of 5.928 µm and the smallest process stability δ = 3.309 µm, making it the most process stable composite among all the composites.

The GFRP/SC-20% composite showed a mean surface roughness (Ra) of 15.689 µm, whereas the hybrid GFRP/SC-SiC composite exhibited the highest variation in surface roughness (δ = 23.855 µm), ranging from 3.435 µm to 27.290 µm under different machining conditions. Based on the experimental results, the surface roughness of the GFRP/SC-20% composite was primarily governed by feed rate (Rank 1;

δS/N = 6.83 dB). In contrast, for the hybrid composite system, spindle speed (Rank 1; δ = 10.003 dB) was identified as the most influential machining parameter, followed by feed rate (Rank 2; δ = 7.999 dB). This dominance of spindle speed can be attributed to the interaction between sugarcane fibre and silicon carbide reinforcement, where the abrasive action of SiC particles makes the hybrid composite more sensitive to changes in cutting speed than to feed rate during drilling.

Based on the Smaller-the-Better Taguchi criterion, the optimal machining conditions for the GFRP/SC-20% composite, GFRP/SiC-15%, and hybrid GFRP/SC–SiC composite are: low feed rate/high spindle speed (A_1B_2); low feed rate/low spindle speed (A_1B_1); and high feed rate/high spindle speed (A_2B_2), respectively. The hybrid composite under the optimum condition showed the best surface finish (Ra = 3.435 μm), which is better than that of single-filler ceramic composite all 12 times of observation, indicating that the multi-filler synergy applied through proper parameter selection is capable of outperforming single-filler ceramic composites. After 24 hours of continuous exposure to the salt spray corrosion test at 34.5 to 35.5°C, pH 6.65 to 6.85, 4.80 to 5.30% NaCl solution and 14 to 18 Psi air pressure, no rust was observed macroscopically in any of the three GFRP composite systems. This uniform corrosion immunity for all material variants shows that the glass fibre matrix made of non-metallic fibres and the epoxy matrix has an inherent resistance against electrochemical corrosion, and that the encapsulation of both the SiC fillers and the SC fibre into the polymer matrix is an effective protection against ionic attack at the interfaces of the fillers and the matrix under short exposure in salt spray.

The hybrid SC–SiC/GFRP composite was analysed by EDS elemental analysis (Spectrum 15), confirming that there are three main elements, namely carbon (C, ~0.27 keV), oxygen (O, ~0.52 keV), and Silicon (Si, ~1.74 keV). The peak of carbon confirms the epoxy matrix and the carbon-based organic constituents of the SC; the peak of oxygen confirms the epoxy functional groups, the silica network of the glass fibres and the oxide compounds of the carbon-based material (SC); and the peak of Silicon directly confirms the successful incorporation and uniform dispersion of SiC reinforcement particles and E-glass SiO_2 components into the composite system. The FESEM fractographic examination of the specimens showed that the drilling-affected specimens exhibited a hybrid composite damage mechanism consisting of fibre pull-out, matrix micro-cracking and interfacial delamination. These damage modes were not severe in high spindle speed conditions, as revealed in high magnification micrographs, where SiC particles have been shown to help in micro cutting under these conditions, and this could be understood mechanistically from the high Ra = 3.435 μm observed at A_2B_2. It was found that the stress concentration source from the irregular porous morphology of the SC fibre increases the Ra variation at sub-optimal machining conditions.

Post-corrosion FESEM analysis showed that surface interactions occur on the microscale of corrosion protection: incipient precipitation of NaCl residues on the matrix surface, localised surface pitting at the debonding sites of the SC fibre, and partial exposure of the fibres as a result of matrix recession at the outermost surface layer. The SiC particles were completely preserved and unaltered following the corrosion exposure, indicating that they are corrosion-inert structural reinforcements.

All three composites obtained microstructural observations that show that these composites can pass the salt spray test, but the sites of debonding of the SC fibre in the hybrid system are potential vulnerability pathways for extended or multiple corrosion loading scenarios.

The novelty of this study lies in the development and evaluation of a hybrid sugarcane fibre–silicon carbide reinforced GFRP composite, demonstrating improved machinability, corrosion resistance, and microstructural stability compared with single-reinforced systems. The developed composite shows potential for lightweight engineering applications. Future work will focus on long-term mechanical, fatigue, wear, and environmental durability evaluations.

Conflicts of Interest
The authors declare that there is no conflict of interest regarding the publication of this paper.

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