engineering proceedings

MDPI

Proceeding Paper

Effects of Tribology and Mechanical Properties on Silicon Carbide and Glass Fiber-Reinforced Hybrid Nanocomposites †

Maridurai Thirupathy and Muthuraman Vadivel *

Department of Mechanical Engineering, Vels Institute of Science, Technology and Advanced Studies (VISTAS), Chennai 600117, Tamil Nadu, India; maridurai.mechanical@gmail.com

* Correspondence: drvmuthuraman.se@velsuniv.ac.in

† Presented at the International Conference on Processing and Performance of Materials, Chennai, India, 2–3 March 2023.

Abstract: This study aims to enhance the mechanical and wear properties of hybrid nanocomposites by incorporating SiC nanoparticles and glass fibers into an epoxy resin matrix, utilizing a neural network for optimization. The mechanical properties were evaluated via flexural, impact, and wear tests. SiC nanoparticle concentrations were varied at three levels using the Taguchi technique. The results were optimized with the Taguchi signal-to-noise ratio approach. Regression analysis was used to determine the wear rate, flexural strength, and impact properties of the composites. SiC reinforcement significantly influenced the flexural and impact strength, along with wear resistance. The composition with 2% SiC showed a flexural strength of 95 MPa, while 4% and 6% SiC compositions exhibited strengths of 110.5 MPa and 125 MPa, respectively. The impact strength followed a similar trend. The wear test results demonstrated a decrease in the specific wear rate (Swr) and coefficient of friction (CoF) with an increasing SiC nanoparticle percentage. The optimal parameters were identified as 6% SiC nanoparticle loading, 15 N load, 160 RPM rotation speed, and a 40.2 mm sliding distance. The enhancement in impact strength is attributed to SiC nanoparticle reinforcement. The results were further refined using an artificial neural network for improved predictability. This research underscores the effectiveness of hybrid nanocomposites with SiC nanoparticles and glass fibers, as well as the potential of neural networks for process optimization, benefiting industries requiring high-performance materials.

Keywords: nanoparticle; neural network; ANN; glass fiber

Citation: Thirupathy, M.; Vadivel, M. Effects of Tribology and Mechanical Properties on Silicon Carbide and Glass Fiber-Reinforced Hybrid Nanocomposites. *Eng. Proc.* **2024**, *61*, 46. https://doi.org/10.3390/engproc2024061046

Academic Editors: K. Babu, Anirudh Venkatraman Krishnan, K. Jayakumar and M. Dhananchezian

Published: 17 February 2024

1. Introduction

In recent years, materials science has made substantial strides in advancing novel composites with improved mechanical properties. Hybrid nanocomposites, which combine the strengths of different materials, have garnered significant attention [1,2]. Notably, the combination of silicon carbide (SiC) and glass fiber (GF) reinforcements has demonstrated promising synergistic effects. The incorporation of SiC nanoparticles into composites has been found to enhance wear resistance, hardness, and strength. For instance, epoxy-based composites with varying SiC nanoparticle concentrations exhibit significant improvements in wear resistance and hardness. Hybrid composites, mixing SiC nanoparticles with carbon fibers, outperform pure epoxy resin. Glass fibers, known for their high strength, stiffness, and chemical resistance, are an ideal choice for reinforcing polymers. Their inclusion enhances material strength, and longer fibers with higher content significantly increase flexural strength [3–5].

This review explores the optimization of composite materials through statistical techniques, including the Taguchi method, regression analysis, and ANOVA. The Taguchi method, a widely used experimental design approach, identifies optimal combinations of parameters by varying input variables [6–8]. For example, it has been applied to optimize the wear resistance of carbon nanotube-reinforced epoxy composites. Regression analysis, which studies relationships among variables, has been employed to create mathematical models for predicting the mechanical properties of composites [9,10]. These models accurately forecast the strength of glass fiber-reinforced polyester, for instance. ANOVA, a statistical technique for analyzing data variance, is utilized to assess the impact of process parameters on output variables [11,12]. It has been used to investigate the effects of process parameters on the mechanical properties of composite materials, revealing, for example, that molding pressure significantly influences these properties.

In conclusion, this review highlights previous research on hybrid nanocomposites that combine SiC nanoparticles and glass fibers, resulting in significant property enhancements. This research focuses on assessing the impact of varying SiC nanoparticle concentrations, alongside glass fibers, on the wear and mechanical properties of hybrid nanocomposites. It includes flexural and impact testing, wear rate analysis, optimization through the Taguchi method, and the use of artificial neural networks for prediction and process optimization.

2. Methodology

2.1. Material Preparation

This study involved creating a hybrid nanocomposite by adding SiC nanoparticles to epoxy resin, a process known to enhance mechanical properties. Preheating SiC nanoparticles at 200 °C for 60 min improved dispersion in the epoxy by breaking down agglomerates and increasing fluidity. This step also reduced epoxy viscosity at 50 °C, facilitating nanoparticle interaction. Three SiC nanoparticle concentrations, 2%, 4%, and 6%, were introduced into the epoxy using magnetic stirring for 30 min, ensuring even distribution. The hand lay-up technique added glass fibers, allowing precise control over the composite's properties. Afterward, composite specimens were air-dried for 24 h, which is essential for curing the resin and solidifying it around the fibers. The curing conditions were optimized to achieve the desired mechanical properties. The samples were then cut according to ASTM standards, with Table 1 showing the effect of composite percentage on physical and mechanical properties. The right balance of fiber and matrix content is essential for achieving the desired characteristics.

Table 1. Prepared hybrid composite percentages.

S. No.	Glass Fiber Material Composition in %	Epoxy Material Composition in %	Percentage of Nanoparticles of SiC
1	40	58	2
2	40	56	4
3	40	54	6

2.2. Experimental Procedure

In this research, the hybrid nanocomposite's characteristics were assessed using a 3-point flexural test, adhering to ASTM D790 standards for polymer and plastic materials. The objective was to measure the composite's flexural strength. Specimens, with dimensions of 120 × 15 × 5 mm, were placed on a 3-point bending device with a span-to-width ratio of 16 (see Figure 1). The Instron-3382 machine conducted the test at a speed of 3.6 mm/min. The load and corresponding displacement were recorded, and the load versus displacement plot was used to calculate the composite's strength using the formula:

$$\text{Flexural strength} = (3 \times \text{Load} \times \text{L})/(2 \times \text{b} \times \text{d}^2)$$

where L is the span, b is the sample's width, d is the thickness, and Load is the maximum load the specimen endured.

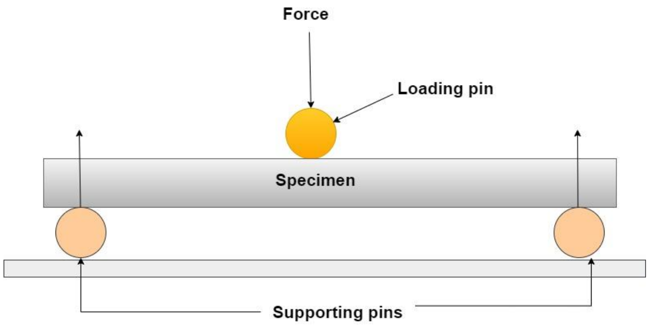

Figure 1. Illustration of flexural test setup.

This study also evaluated the impact resistance of the prepared nanocomposite materials using the Izod testing machine, following ASTM D256 standards. This test measures the energy required to break a sample with a swinging pendulum. Rectangular samples with dimensions of 63.5 mm × 13.5 mm × 4.5 mm were clamped vertically in the testing machine. An impact load was applied at the sample's center using a swinging pendulum with a known weight and velocity. The energy needed to break the specimen was measured, and the impact strength was calculated by dividing the energy by the specimen's cross-sectional area. This test assessed the composite materials' impact resistance, especially for applications where withstanding impact loading is critical.

In this study, the wear behavior of the hybrid nanocomposites, reinforced with SiC nanoparticles and glass fibers, was assessed using a wear apparatus. The evaluation followed ASTM G99 standards. A cylindrical pin, measuring 10 mm in diameter and 50 mm in length, was crafted from the hybrid nanocomposite material. The base disc was composed of En 31 material. Experimentation was carried out using a Taguchi L27 array design.

In this study, two key output responses were Swr (specific wear rate) and CoF (coefficient of friction). Swr quantifies the material loss per unit sliding distance and is calculated as:

$$\text{Swr} = (\Delta\text{w}/\text{L}) \times (1/\text{Ds})$$

Here, Δw is the mass loss after testing, L is the applied load, and Ds is the sliding distance. CoF measures the ratio of tangent force (Ft) to normal force (Fn) on the specimen:

$$\text{Cf} = \text{Ft}/\text{Fn}$$

The experiments involved varying the input responses—load (L), rotation speed (Sr), sliding distance (Ds), and composition (C)—across three levels.

3. Results and Discussion

3.1. Flexural Strength

This study assessed the flexural strength of the alloy by employing the three-point bend test, according to ASTM D790 standards, using a continuous crosshead speed of 3.6 mm/min. The corresponding displacement data were recorded to determine flexural strength. Table 2 summarizes the test outcomes, demonstrating an increase in flexural strength as the SiC nanoparticle content rises. The composition with 2% SiC exhibits a flexural strength of 95 MPa, while the 4% and 6% SiC compositions reach strengths of 110.5 MPa and 125 MPa, respectively. This strength enhancement is attributed to SiC nanoparticles reinforcing the epoxy matrix, thereby increasing stiffness and durability. The inclusion of glass fibers further contributes to improved flexural strength, acting as load-bearing elements.

Table 2. Flexural property of the alloy.

S. No.	Composite	Flexural Strength (Mpa)
1	Glass fiber epoxy with 2% SiC	95
2	Glass fiber epoxy with 4% SiC	110.5
3	Glass fiber epoxy with 6% SiC	125

3.2. Impact Test

In this study, we assessed impact resistance by conducting Izod impact tests, according to ASTM D256 standards. Test specimens were prepared with notches to create stress concentration points and then subjected to pendulum impacts. Impact strength was quantified as energy absorption per unit specimen width. The results indicated that the inclusion of SiC nanoparticles in the glass epoxy composite enhanced impact strength. Specifically, composites with 2%, 4%, and 6% SiC additives exhibited impact strengths of 524.23 J/m, 531.1 J/m, and 543.3 J/m, respectively (Figure 2). The SiC nanoparticles acted as reinforcing agents, improving strength and stiffness. Additionally, the introduction of stiff glass fibers further bolstered impact resistance, showcasing a synergistic strengthening effect.

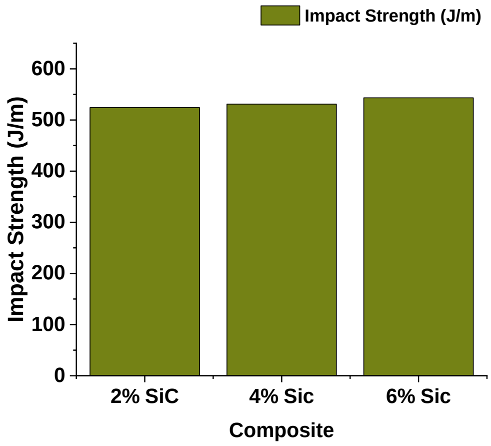

Figure 2. Impact result obtained from the experiment.

3.3. Wear Test

In the wear test, we utilized an L27 Taguchi design to investigate the impact of input parameters on the Swr and CoF in the composite. Table 3 displays these input parameters and the wear test results. The base disc material employed in this research is En 31, with a fixed 10 mm diameter and a 50 mm length pin attached to the testing machine.

After conducting the wear test and analyzing the results, the optimal combination of input parameters for minimizing the responses was determined using the S/N analysis method. The S/N ratio was computed by taking the logarithm of the reciprocal of the squared deviations from the target values, with the lowest value serving as the target for the Swr and the highest value serving as the target for the CoF. Figure 3 illustrates the optimal combination of input parameters, including 6% SiC nanoparticle loading, 15 N of load, 160 RPM of rotation speed, and 40.2 mm of sliding distance, selected based on the desirability function, which measures the proximity of the response to the target value. The wear test outcomes indicated that both the Swr and CoF decreased as the percentage of SiC nanoparticle loading increased. The optimal combination of input parameters was found to be 6% SiC nanoparticle loading, 15 N of load, 160 RPM of rotation speed, and 40.2 mm of sliding distance, resulting in the lowest Swr and CoF. This S/N ratio analysis approach effectively determined the optimal combination of input parameters to minimize wear in the composite material.

Table 3. Results from the wear test.

C (%)	Load (N)	Sr	Ds	Swr (mm^3/Nm)	CoF
2	15	120	35.4	1.85	0.29
2	15	120	35.4	1.85	0.29
2	15	120	35.4	1.85	0.29
2	20	140	37.8	0.61	0.34
2	20	140	37.8	0.61	0.34
2	20	140	37.8	0.61	0.34
2	25	160	40.2	0.1	0.36
2	25	160	40.2	0.1	0.36
2	25	160	40.2	0.1	0.36
4	15	140	40.2	0.33	0.3
4	15	140	40.2	0.31	0.29
4	15	140	40.2	0.32	0.29
4	20	160	35.4	0.98	0.14
4	20	160	35.4	0.98	0.34
4	20	160	35.4	0.97	0.34
4	25	120	37.8	1.72	0.09
4	25	120	37.8	1.74	0.71
4	25	120	37.8	1.73	0.23
6	15	160	37.8	0.11	0.09
6	15	160	37.8	0.15	0.11
6	15	160	37.8	0.13	0.09
6	20	120	40.2	0.12	0.14
6	20	120	40.2	0.14	0.14
6	20	120	40.2	0.15	0.13
6	25	140	35.4	0.32	0.15
6	25	140	35.4	0.33	0.19
6	25	140	35.4	0.35	0.21

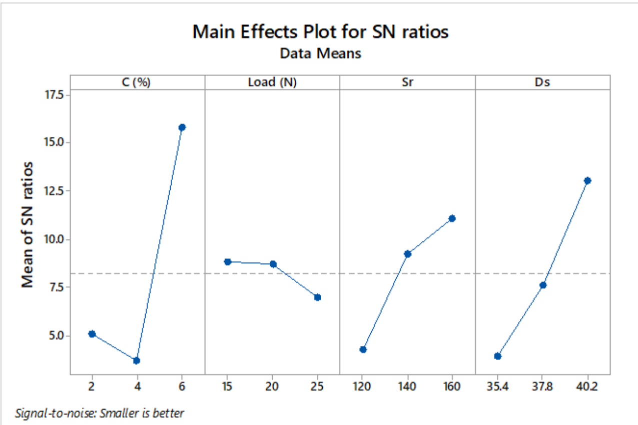

Figure 3. Optimal combination for minimizing the responses.

Linear regression analysis was conducted with MINITAB software to create predictive mathematical equations for both the CoF and Swr. Equation (1) represents the CoF equation, and Equation (2) represents the Swr equation. These equations serve as valuable tools for accurate response prediction, reducing the need for additional experiments and saving both time and costs. Furthermore, these equations establish a quantitative relationship between input parameters and responses, facilitating the optimization of composite material properties.

$$\text{Cof} = 0.244 - 0.0478\ \text{C} + 0.00689\ \text{L} - 0.00033\ \text{Sr} + 0.0030\ \text{Ds} \quad (1)$$

$$\text{Swr}\ (\text{mm}^3/\text{Nm}) = 11.19 - 0.1633\ \text{C} - 0.0046\ \text{L} - 0.02092\ \text{Sr} - 0.1808\ \text{Ds} \quad (2)$$

Table 4 summarizes the experimental results obtained from the optimal input parameter combination for the wear test and includes the predicted equations for the Swr and CoF. It allows for a comparison between the actual experimental values and those predicted through the developed equations.

Table 4. Predicted and experimental results of the optimal combination.

Optimal Combination	Experimented		Predicted	
	Swr (mm^3/Nm)	CoF	Swr (mm^3/Nm)	CoF
6% of C 15 N of L, 160 RPM of Sr, and 40.2 mm of Ds	0.1	0.12	0.13	0.14

The outcomes of the wear test are further analyzed in Design Expert to investigate the effects of the composition of SiC, load, speed of rotation, and sliding distance on both the Swr and CoF. Figure 4a shows the contour plot of the Swr, indicating that an increase in the percentage of SiC nanoparticles, coupled with a decrease in the load, speed of rotation, and sliding distance, results in a decrease in the Swr. Similarly, Figure 4b shows the contour plot of the CoF, indicating that an increase in the composition of SiC nanoparticles, coupled with a decrease in the load, speed of rotation, and sliding distance, results in a decrease in the CoF. The results suggest that increasing the composition of SiC nanoparticles and reducing the load, speed of rotation, and sliding distance can significantly reduce the Swr and CoF of the composite material. This can be advantageous in applications where the material is subjected to wear and friction, such as in bearings, gears, and other mechanical components. The insights gained from this analysis can be used to optimize the manufacturing process and improve the performance of the material in real-world applications.

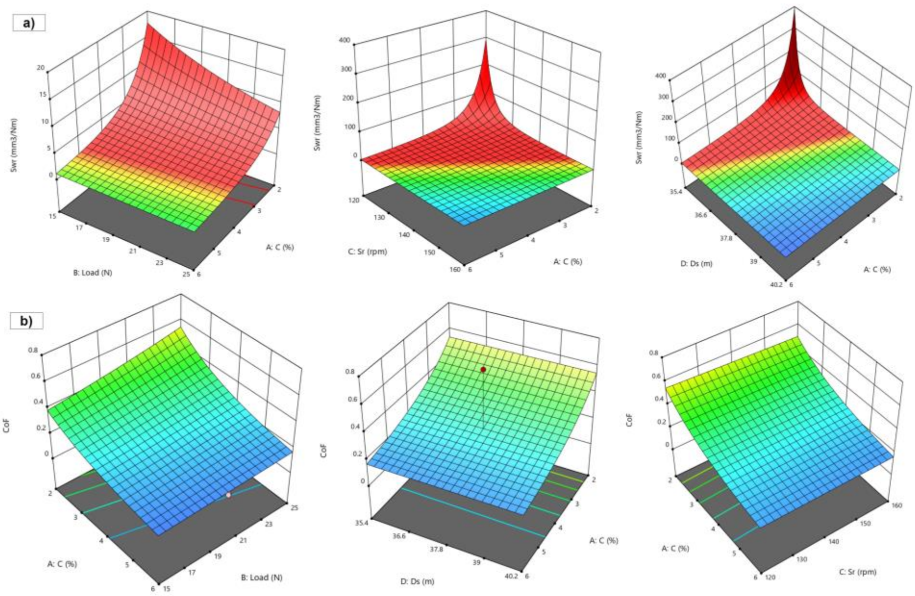

Figure 4. Surface plot of the responses (**a**) specific wear rate, (**b**) Coefficient of friction.

The SEM analysis in Figure 5 illustrates the wear mechanism on the sample surfaces under optimal conditions. SiC nanoparticles and glass fibers are embedded within the composite material matrix. SEM images show that the wear rate is lowest at a 6% SiC composition compared to 2% and 4%, indicating SiC's reinforcing effect. SiC nanoparticle size and distribution vary with the composition percentage. A better bond between fiber and resin is observed in SEM analysis, correlating with reduced wear as SiC composition increases.

Artificial neural network (ANN) is a machine-learning technique inspired by brain function, used to predict complex non-linear functions in diverse fields. In this study, an ANN model was developed to predict the Swr and CoF based on inputs: load (L), rotation speed (Sr), sliding distance (Ds), and SiC composition. The process included network architecture selection, training using the back-propagation algorithm, testing with separate data, and validation with new data. The ANN model proved highly accurate in predicting responses of 99.12%, as depicted in Figure 6. This model eliminates the need for experimental predictions, allowing for optimized wear characteristics by selecting optimal input parameters.

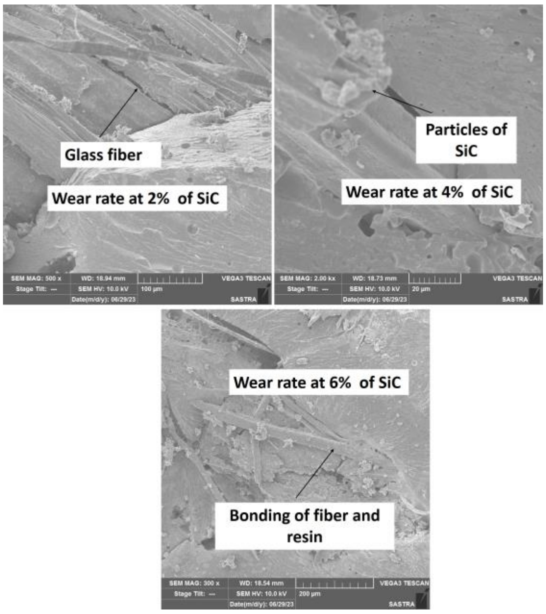

Figure 5. SEM analysis of the composite.

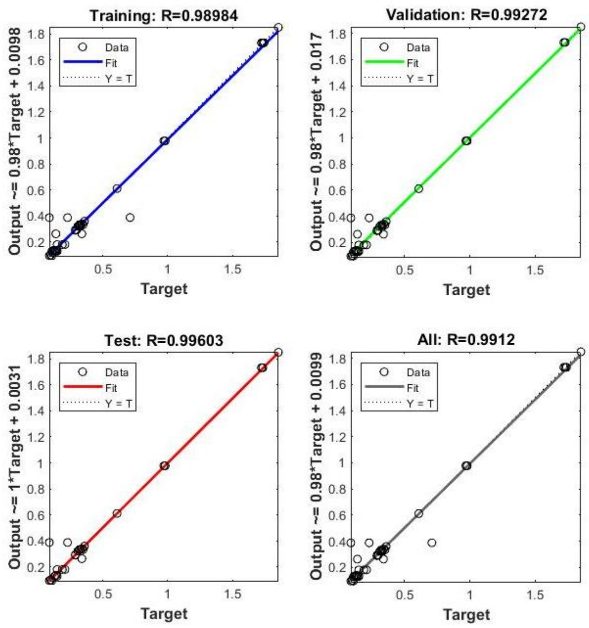

Figure 6. Accuracy of the model developed in this research.

4. Conclusions

- This study yielded significant findings on the mechanical and wear properties of hybrid nanocomposites.
- The flexural strength improved as SiC loading increased, with a 6% SiC composition showing the highest strength.

- The impact strength increased with increasing SiC concentration, reaching its highest point at 6% SiC, attributed to the reinforcement effect of SiC nanoparticles.
- The wear test revealed reduced wear rates with higher SiC loading, enhancing wear resistance.
- The optimal parameters for minimal wear rate and friction were found to be 6% SiC loading, 15 N load, 160 RPM rotation speed, and 40.2 mm sliding distance.
- Artificial neural networks enhanced response prediction accuracy at a percentage of 99.12%. This study highlights the effectiveness of SiC and glass fiber hybrid nanocomposites in enhancing properties and optimizing manufacturing processes, with broad applicability in high-performance materials.

Author Contributions: M.T. was involved in data collection, data analysis, and manuscript writing. M.V. was involved in conceptualization, data validation, and the critical review of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: All the data are available from the corresponding author and can be made available on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Stalin, B.; Ravichandran, M.; Karthick, A.; Meignanamoorthy, M.; Sudha, G.T.; Karunakaran, S.; Bharani, M. Investigations on Microstructure, Mechanical, Thermal, and Tribological Behavior of Cu-MWCNT Composites Processed by Powder Metallurgy. *J. Nanomater.* **2021**, *2021*, 3913601. [CrossRef]
2. Varol, T.; Canakci, A.; Ozsahin, S. Modeling of the prediction of densification behavior of powder metallurgy Al-Cu-Mg/B4C composites using artificial neural networks. *Acta Metall. Sin. (Engl. Lett.)* **2015**, *28*, 182–195. [CrossRef]
3. Shoba, C.; Ramanaiah, N.; Rao, D.N. Optimizing The Machining Parameters For Minimum Surface Roughness In Turning Al/6% SiC/6%RHA Hybrid Composites. *Procedia Mater. Sci.* **2015**, *10*, 220–229. [CrossRef]
4. Banerjee, T.; Dey, S.; Sekhar, A.P.; Datta, S.; Das, D. Design of Alumina Reinforced Aluminium Alloy Composites with Improved Tribo-Mechanical Properties: A Machine Learning Approach. *Trans. Indian Inst. Met.* **2020**, *73*, 3059–3069. [CrossRef]
5. Zhao, L.; Yu, X.; Jiao, J.; Song, X.; Cheng, X.; Liu, M.; Wang L liang Zheng, J.; Lv, W.; Zhong, G.; He, Y.B.; et al. Building cross-phase ion transport channels between ceramic and polymer for highly conductive composite solid-state electrolyte. *Cell Rep. Phys. Sci.* **2023**, *4*, 101382. [CrossRef]
6. Manroo, S.A.; Khan, N.Z.; Ahmad, B. Study on surface modification and fabrication of surface composites of magnesium alloys by friction stir processing: A review. *J. Eng. Appl. Sci.* **2022**, *69*, 25. [CrossRef]
7. Xu, M.; Qing, Y.; Yin, Y.; Ai, S.; Duan, J.; Li, H.; Li, Y. 3D network conductive polymer/Pt composites as elcetrocatalyst for methanol oxidation. *Int. J. Electrochem. Sci.* **2020**, *15*, 929–946. [CrossRef]
8. Kumar, K.; Sharma, A.; Bharti, A.; Bansal, A.; Kumar, A.; Kandpal, B.C.; Ramdas, N. Machining response in turning stir cast alumininum alloy based metal matrix composite. *Mater. Today Proc.* **2019**, *18*, 2619–2624. [CrossRef]
9. Sunitha, N.; Manjunatha, K.G. Evaluation of Corrosion Studies of as Casted and Heat Treated Aluminum 6065 Metal Matrix Composite by Weight Loss Method. *Mater. Today Proc.* **2018**, *5*, 22727–22733. [CrossRef]
10. Laghari, R.A.; Li, J.; Laghari, A.A.; Wang, S.Q. A Review on Application of Soft Computing Techniques in Machining of Particle Reinforcement Metal Matrix Composites. *Arch. Comput. Methods Eng.* **2020**, *27*, 1363–1377. [CrossRef]
11. Virkunwar, A.K.; Ghosh, S.; Basak, R. Tribological performance optimization of Al6061-fly ash composites using the taguchi method and grey relational analysis. *Mater. Today Proc.* **2021**, *46*, 603–608. [CrossRef]
12. Saravanan, G.; Bhaskar, G.B. Influence of Silicon Carbide Reinforcements on Mechanical and Wear Behaviour AA7075/15% wt. Glass fiber Hybrid Composites. *Silicon* **2022**, *15*, 1451–1464. [CrossRef]