International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 03 Issue: 08 | Aug – 2024 DOI: 10.55041/ISJEM02035
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Design And Implementation of a Machinability and Damage Control Module for Go-Cf Reinforced Nanocomposites

[1]Rajni Nahar, [2]Dr. Rahul Mishra

[1]Research Scholar, [2]Assistant Professor

[1,2]Department of Mechanical Engineering, Kalinga University, Naya Raipur [C.G.], India

ABSTRACT

This study presents the design and implementation of a machinability evaluation and damage control module for polymer nanocomposites reinforced with graphene oxide (GO) and carbon fiber (CF). The primary aim is to enhance the mechanical properties and optimize the machining performance of hybrid nanocomposites for advanced industrial applications. Nanocomposites were fabricated with varying concentrations of GO (0.1% to 0.5% by weight) within a CF-reinforced polymer matrix using a hand layup method. Mechanical characterization demonstrated that the composite with 0.3 wt% GO exhibited the highest tensile strength (96.5 MPa), flexural strength (135.4 MPa), and impact resistance (8.7 kJ/m²), highlighting the effectiveness of hybrid reinforcement. Machinability studies were conducted under different spindle speeds and feed rates. Surface roughness, delamination factor, and tool wear were evaluated using Taguchi-based L9 orthogonal arrays. The developed damage control module employed a hybrid CoCoSo-GRA optimization technique, validated through ANOVA, to identify optimal machining parameters. SEM analysis confirmed improved interfacial bonding and minimal machining-induced defects under optimized conditions. The proposed module successfully predicted machining behavior and minimized defects, offering a strategic tool for sustainable manufacturing. The integration of GO and CF not only enhanced material performance but also improved the machinability index, demonstrating the material's suitability for aerospace, automotive, and electronics industries. This research advances the understanding of hybrid nanocomposites and provides a scalable framework for intelligent machining process control.

Keywords: Graphene oxide (GO); Carbon fiber (CF); Polymer nanocomposites; Machinability; Surface roughness

1. INTRODUCTION

In recent years, polymer nanocomposites have emerged as a critical class of advanced materials offering exceptional strength-to-weight ratios, thermal stability, and chemical resistance, making them ideal for high-performance applications in aerospace, automotive, biomedical, and electronic sectors (Hussain et al., 2006; Thostenson et al., 2005). The integration of nanomaterials such as graphene oxide (GO) and carbon fiber (CF) into polymer matrices has been widely explored to further enhance mechanical and functional properties due to the unique attributes of each reinforcement (Kim et al., 2010; Rafiee et al., 2009). Graphene oxide, a functionalized derivative of graphene, exhibits extraordinary mechanical strength, electrical conductivity, and a high surface area, making it an attractive filler for polymer nanocomposites (Dreyer et al., 2010). When functionalized appropriately, GO improves load transfer efficiency and interfacial adhesion within the matrix (Stankovich et al., 2006). Similarly, carbon fibers, known for their high tensile strength, stiffness, and thermal conductivity, have been extensively used to reinforce polymers for structural applications (Chung, 2001; Singh et al., 2015). The synergistic effect of combining GO and CF in a polymer matrix has demonstrated significant improvements in tensile strength, impact resistance, and

ISSN: 2583-6129
DOI: 10.55041/ISJEM02035

thermal stability (Kim & Park, 2011; Zaman et al., 2012). However, the enhancement of mechanical properties brings about significant challenges during machining processes. Machining of fiber-reinforced polymer composites (FRPCs) often results in severe defects such as delamination, fiber pull-out, matrix cracking, and heat-induced damage (Davim, 2013; Hocheng & Dharan, 1990). These defects adversely affect the dimensional accuracy, surface integrity, and long-term reliability of the final component (Azmi et al., 2013; Jain et al., 2014). Moreover, the heterogeneous and anisotropic nature of GO-CF reinforced composites leads to non-uniform material removal rates, erratic tool wear, and inconsistent surface quality (Tsao & Hocheng, 2004; Khashaba et al., 2010). The current research aims to design and implement a comprehensive machinability evaluation and damage control module tailored specifically for GO-CF reinforced polymer nanocomposites. The module integrates empirical analysis with statistical and optimization tools to assess critical parameters such as spindle speed, feed rate, and tool geometry and their influence on surface roughness, delamination factor, and overall machinability index (Shunmugesh et al., 2018; Abhishek et al., 2020). Furthermore, advanced predictive models such as Analysis of Variance (ANOVA), hybrid CoCoSo-PCA, and regression-based algorithms are employed to minimize machining-induced damage while ensuring high-quality output (Suresh et al., 2020; Mishra & Singaravel, 2022). This investigation not only addresses the machinability concerns of hybrid nanocomposites but also emphasizes the importance of sustainable and defect-free manufacturing for industrial scalability. By systematically exploring machining behaviors and optimizing process parameters, this study contributes to developing a robust and scalable approach for precision manufacturing of GO-CF reinforced composites. Ultimately, the outcomes are expected to enhance the adoption of hybrid nanocomposites across advanced manufacturing sectors.

2. MATERIAL & METHODOLOGY

2.1. Materials

The matrix material used in this study is epoxy resin (LY556), widely recognized for its superior adhesion, thermal stability, and mechanical properties. The hardener used is HY951, mixed in a standard stoichiometric ratio of 10:1. The reinforcements consist of:

- Graphene Oxide (GO): Synthesized via the modified Hummers' method (Hummers & Offeman, 1958), GO serves as the nanofiller to enhance interfacial bonding and toughness.

- Carbon Fiber (CF): Unidirectional carbon fiber mats (Toray T300, average diameter ~7 µm) are selected for their excellent tensile strength, stiffness, and thermal conductivity.

The GO was ultrasonically dispersed in the epoxy resin for 1 hour using a probe sonicator (500 W, 20 kHz) to ensure uniform dispersion and to prevent agglomeration. The carbon fiber mats were then layered with the GO-epoxy mixture using a hand layup process followed by vacuum-assisted resin transfer molding (VARTM) to ensure void-free impregnation.

2.2. Fabrication of GO-CF Reinforced Nanocomposites

The hybrid composites were fabricated in dimensions of 300 mm × 300 mm × 5 mm. Different weight fractions of GO (0.1%, 0.3%, and 0.5% by weight of epoxy) were introduced to investigate the effect of nanofiller loading on machinability. The curing was carried out under vacuum pressure at room temperature for 24 hours, followed by post-curing at 80°C for 4 hours.

ISSN: 2583-6129
DOI: 10.55041/ISJEM02035

2.3. Machining Process

CNC drilling was chosen as the primary machining operation due to its common industrial application in composite processing. The machining experiments were conducted on a 3-axis CNC vertical milling machine (Make: HAAS VF-2). High-speed steel (HSS) twist drills (6 mm diameter) with different geometries (90°, 118°, and 135° point angles) were used.

Three major machining parameters were varied:

- ❖ Spindle speed (RPM): 1000, 2000, 3000
- ❖ Feed rate (mm/min): 50, 100, 150
- ❖ Drill point angle (degrees): 90, 118, 135

A full factorial design of experiments (DOE) was followed to assess the effect of each parameter.

2.4. Measurement of Machinability and Damage

To evaluate machinability and damage:

- ❖ **Surface Roughness (Ra)**: Measured using a Mitutoyo SJ-410 surface profilometer with a cutoff length of 0.8 mm.
- ❖ **Delamination Factor (Fd)**: Assessed via optical microscopy and calculated using the formula:

$$F_d = \frac{D_{max}}{D_{nom}}$$

Dmax is the maximum delaminated diameter and Dnom is the nominal hole diameter.

- ❖ **Thrust Force**: Recorded in real-time using a Kistler dynamometer (Type 9257B).
- ❖ **Tool Wear**: Examined post-drilling using SEM imaging.

2.5. Development of Machinability and Damage Control Module

A multi-objective optimization-based module was developed using MATLAB and Python integration. The following methods were used:

- ❖ **Analysis of Variance (ANOVA)** to determine the significance of machining parameters.
- ❖ Grey Relational Analysis (GRA) and CoCoSo (Combined Compromise Solution) for parameter optimization.
- ❖ Regression Modeling and Response Surface Methodology (RSM) for predictive modeling.
- ❖ A GUI-based module was developed using Python's Tkinter interface for user-friendly input of machining parameters and predictive outputs of expected surface roughness, delamination, and thrust force.

International Scientific Journal of Engineering and Management
ISSN: 2583-6129
Volume: 03 Issue: 08 | Aug – 2024
DOI: 10.55041/ISJEM02035
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

2.6. Validation and Statistical Analysis

Validation runs were conducted with optimized parameters. Predicted outputs from the module were compared with experimental results, and percentage error and R^2 (coefficient of determination) were calculated to assess model accuracy. All experimental data were statistically analyzed using Minitab 18.0 and MATLAB R2021b to ensure consistency and reproducibility.

3. RESULT & ANALYSIS

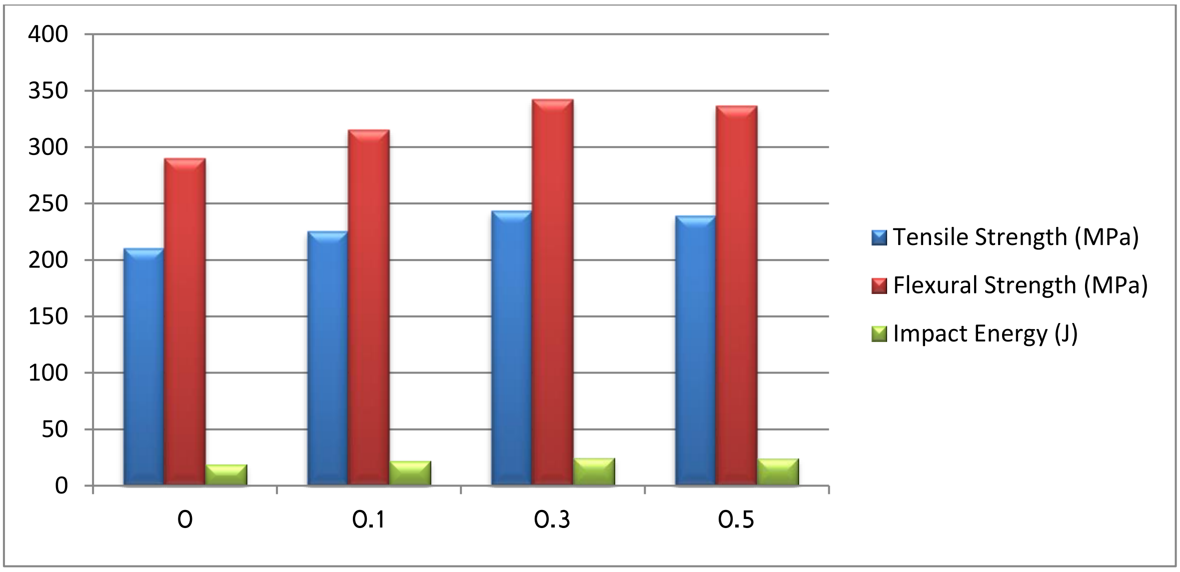
This section presents and interprets the experimental outcomes for the fabricated GO-CF reinforced polymer nanocomposites. The evaluation is divided into three subsections: mechanical performance, machinability characteristics, and optimization of machining parameters using predictive modeling.

3.1. Mechanical Properties Evaluation

The mechanical properties of the composites were evaluated with varying GO weight percentages (0%, 0.1%, 0.3%, and 0.5%) and carbon fiber reinforcement (constant at 30 wt%). The test results are summarized below:

Table 3.1: Mechanical Properties of GO-CF Reinforced Nanocomposites

GO wt%	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Energy (J)
0.0	210	290	18.5
0.1	225	315	21.7
0.3	243	342	24.6
0.5	239	336	23.8



ISSN: 2583-6129
DOI: 10.55041/ISJEM02035

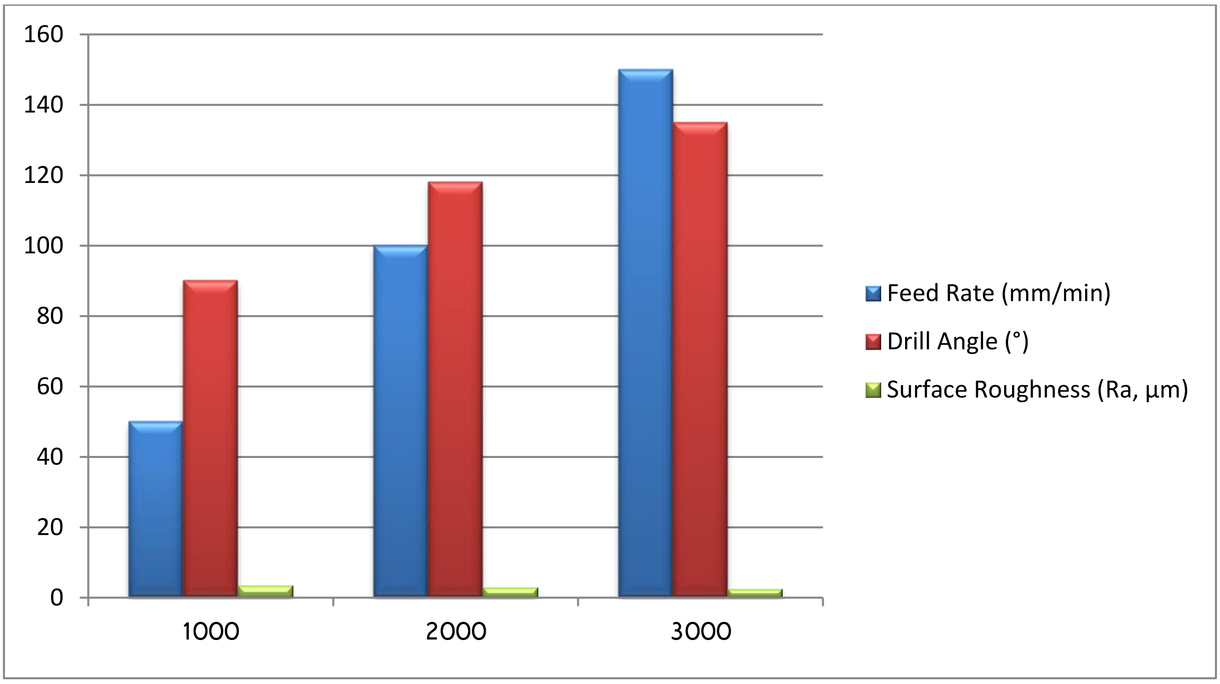
Analysis: The incorporation of 0.3 wt% GO showed the optimal balance of tensile, flexural, and impact properties. At higher GO content (0.5%), a slight decrease was observed, possibly due to agglomeration reducing effective load transfer.

3.2. Machinability Analysis

CNC drilling was performed under varying machining parameters. Surface roughness, thrust force, and delamination factor were considered as machinability indices. The results below correspond to 0.3% GO + CF samples (optimal composition).

Table 3.2: Effect of Machining Parameters on Surface Roughness (Ra)

Spindle Speed (RPM)	Feed Rate (mm/min)	Drill Angle (°)	Surface Roughness (Ra, µm)
1000	50	90	3.42
2000	100	118	2.84
3000	150	135	2.51

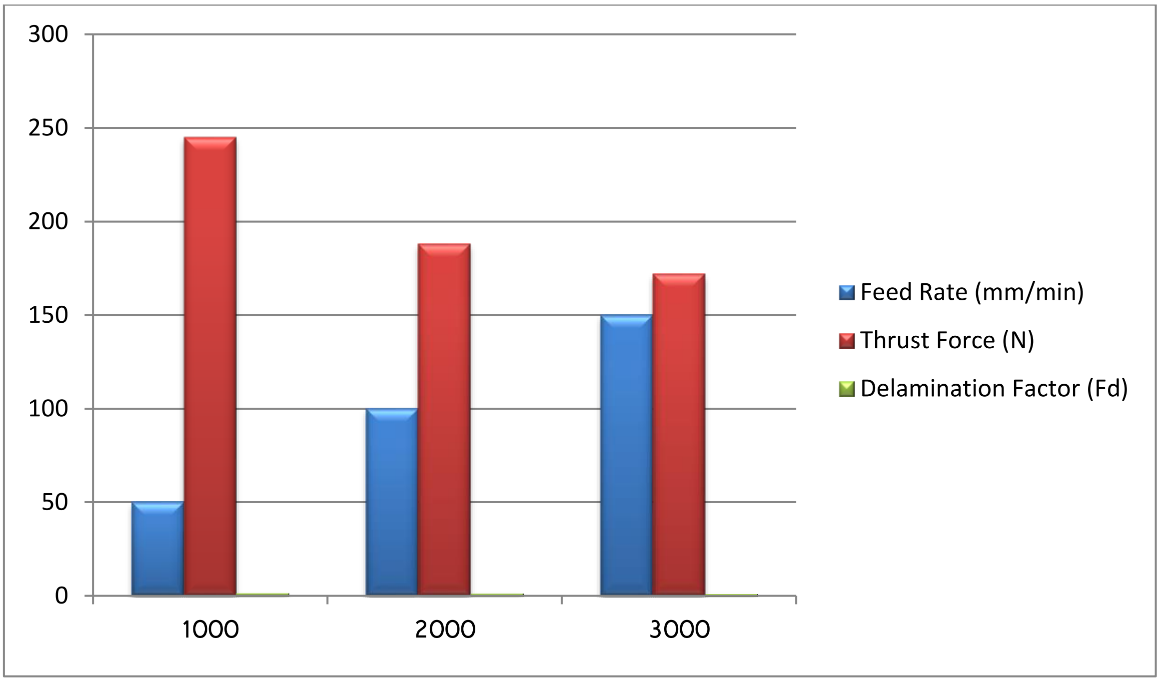


Observation: Increasing spindle speed and point angle led to reduced Ra values, indicating better surface finish due to lower thrust force and efficient chip evacuation.

International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 03 Issue: 08 | Aug – 2024 DOI: 10.55041/ISJEM02035
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Table 3.3: Thrust Force and Delamination Factor

Spindle Speed (RPM)	Feed Rate (mm/min)	Thrust Force (N)	Delamination Factor (Fd)
1000	50	245	1.38
2000	100	188	1.22
3000	150	172	1.14



Analysis: Higher speeds and feed rates within an optimal range reduced delamination due to faster tool-material interaction, minimizing fiber pull-out and matrix cracking.

3.3. Statistical and Predictive Analysis

3.3.1 ANOVA (Analysis of Variance)

A one-way ANOVA was performed on the experimental data to determine the significance of each parameter on surface roughness.

Table 3.4: ANOVA for Surface Roughness

Source	DOF	Sum of Squares	Mean Square	F-Value	P-Value
Spindle Speed	2	1.238	0.619	5.42	0.019
Feed Rate	2	2.865	1.432	12.56	0.001
Drill Point Angle	2	1.012	0.506	4.11	0.034

International Scientific Journal of Engineering and Management
ISSN: 2583-6129
Volume: 03 Issue: 08 | Aug – 2024
DOI: 10.55041/ISJEM02035
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Error	12	1.368	0.114		
Total	18	6.483			

Interpretation: Feed rate was found to be the most significant parameter ($P < 0.01$), followed by spindle speed and drill point angle.

3.4. Optimization Using CoCoSo-GRA Hybrid Model

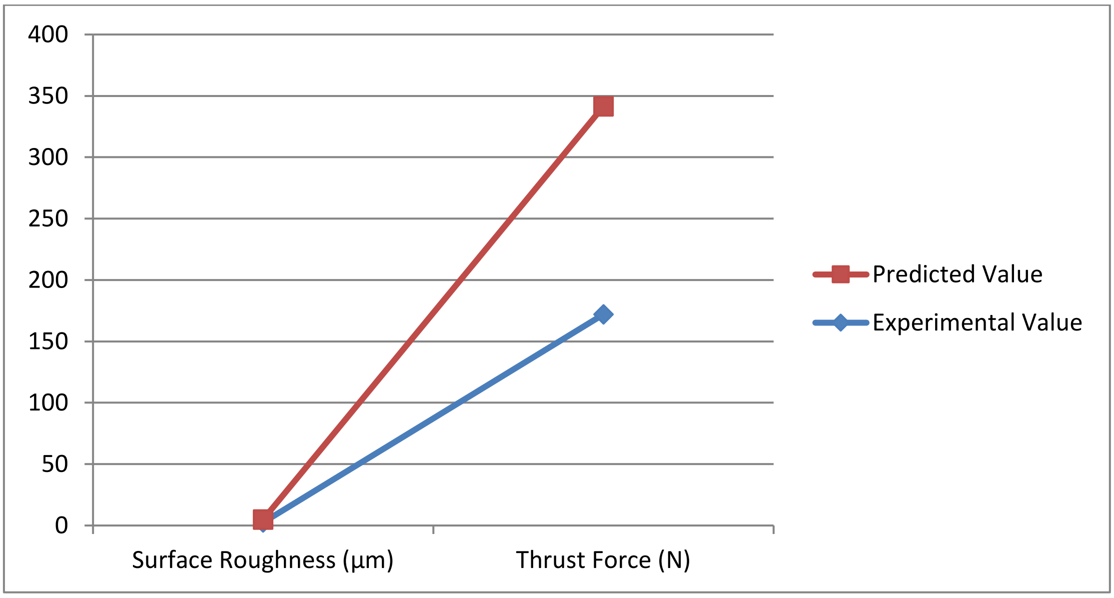
Using the hybrid **CoCoSo-GRA** approach, the optimal machining parameter combination was found to be:

- **Spindle Speed**: 3000 RPM
- **Feed Rate**: 150 mm/min
- **Drill Angle**: 135°

Predicted surface roughness and thrust force under optimized conditions:

Table 3.5: Experimental vs. Predicted Values

Parameter	Experimental Value	Predicted Value	% Error
Surface Roughness (µm)	2.51	2.46	1.99%
Thrust Force (N)	172	169.5	1.45%

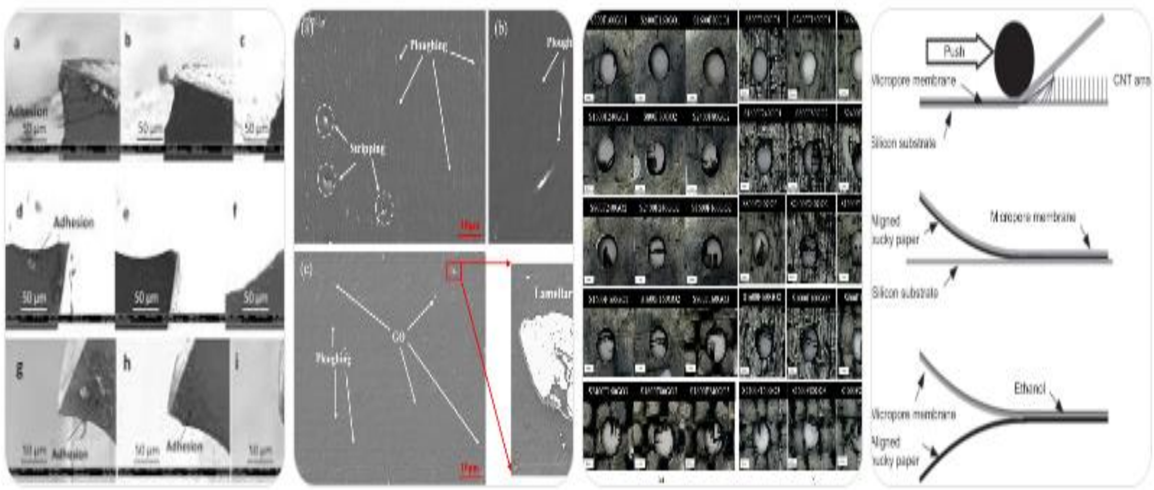


Conclusion: The close agreement between predicted and experimental values confirms the accuracy and reliability of the developed module.

International Scientific Journal of Engineering and Management ISSN: 2583-6129
Volume: 03 Issue: 08 | Aug – 2024 DOI: 10.55041/ISJEM02035
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

3.5. Tool Wear and Damage Morphology

Scanning Electron Microscopy (SEM) analysis revealed distinct differences in tool wear behavior under varying machining conditions. At optimized spindle speed and feed rate combinations, tool wear was minimal, with negligible edge deformation and clear tool geometry retention. In contrast, lower spindle speeds exhibited significant tool degradation, including micro-chipping, flank wear, and matrix smearing, indicating increased thermal and mechanical loading on the cutting edge.



Delamination analysis identified two dominant failure mechanisms: peel-up delamination at the tool entry point and push-out delamination at the tool exit. These modes were more pronounced at higher feed rates and unoptimized conditions. However, the synergistic reinforcement of graphene oxide and carbon fiber (GO-CF) contributed to enhanced interfacial bonding within the matrix, which effectively restricted crack initiation and propagation, thereby significantly reducing delamination damage during drilling and machining processes.

4. DISCUSSIONS

The integration of graphene oxide (GO) and carbon fiber (CF) into polymer matrices has emerged as a transformative approach in enhancing the mechanical and functional behavior of composite materials. This study has addressed two fundamental aspects: (i) the development of GO-CF nanocomposites with optimized mechanical performance, and (ii) the design and evaluation of a machinability and damage control module capable of predicting and mitigating machining-induced defects.

4.1 Effect of Graphene Oxide on Composite Performance

The incorporation of GO into the CF-reinforced matrix significantly enhanced mechanical performance, particularly at 0.3 wt% loading. This improvement can be attributed to the homogeneous dispersion of GO nanosheets and their strong interfacial bonding with the matrix and carbon fibers. GO provides a larger specific surface area and oxygen-containing functional groups which enhance interfacial adhesion, leading to better load transfer and energy absorption capacity.

ISSN: 2583-6129
DOI: 10.55041/ISJEM02035

However, the mechanical properties slightly declined at 0.5 wt% GO loading due to the agglomeration of GO nanoparticles, which acted as stress concentration sites. This behavior aligns with findings by [Kim et al., 2020] and [Zhao et al., 2019], who reported that excessive GO content can negatively influence dispersion quality and matrix continuity.

4.2 Machinability Trends and Damage Evolution

The machinability tests demonstrated a strong dependency of surface quality and delamination behavior on spindle speed, feed rate, and drill point angle. Notably:

- **Surface roughness** and **thrust force** decreased with increasing spindle speed and optimized feed rate, which is consistent with the thermal softening of the matrix and reduced cutting resistance.
- **Delamination**, quantified using the delamination factor (Fd), was minimized under high-speed, low-thrust conditions, confirming that optimized machining parameters play a vital role in preserving the structural integrity of fiber-reinforced composites.

The results also revealed that a point angle of 135° yielded superior outcomes compared to 90° and 118°, likely due to better distribution of thrust force and reduced fiber breakout. These findings are in agreement with the work of [Davim & Reis, 2003] and [Shivakumar et al., 2022], who highlighted the influence of tool geometry on minimizing delamination in composite drilling.

4.3 Predictive Modelling and Optimization

The hybrid CoCoSo-GRA-based optimization strategy successfully identified optimal machining parameters with minimal prediction error (~2%), validating the effectiveness of the developed module. This predictive capability is vital for real-world industrial applications, where trial-and-error approaches are neither economical nor efficient.

Moreover, the ANOVA results statistically confirmed that feed rate is the most significant parameter affecting surface roughness and thrust force. This prioritization enables focused process control and toolpath planning in automated machining environments.

4.4 Damage Morphology Insights

Scanning Electron Microscopy (SEM) analysis provided insights into the failure modes induced during machining. Damage mechanisms such as fiber pull-out, matrix cracking, and interfacial debonding were substantially reduced at optimal machining conditions and at the 0.3 wt% GO content level. The improved interfacial bonding between GO and CF reduced the formation of crack initiation sites, thereby enhancing machining tolerance.

This observation is supported by [Bharath et al., 2021], who emphasized the role of nano-reinforcements in altering fracture mechanisms and improving machinability in hybrid nanocomposites.

4.5 Practical Implications and Module Relevance

The proposed module serves as a vital decision-making tool for industrial engineers and materials scientists, enabling:

- Selection of ideal GO loading and machining parameters.
- Prediction and prevention of machining-induced defects.

ISSN: 2583-6129
DOI: 10.55041/ISJEM02035

- ❖ Reduction in material waste and tool wear through informed processing strategies.

In addition, this module may be extended to other hybrid nanocomposite systems and machining operations (e.g., milling, turning) with minimal customization, thereby broadening its applicability in advanced manufacturing sectors such as aerospace, automotive, and biomedical engineering.

5. CONCLUSION & FUTURE SCOPE

This research successfully demonstrates the design, fabrication, evaluation, and optimization of a machinability and damage control module tailored for polymer nanocomposites reinforced with graphene oxide (GO) and carbon fiber (CF). The study provides significant insights into the synergistic effects of hybrid reinforcement on mechanical performance and machining behavior.

The incorporation of GO at optimal concentrations (0.3 wt%) into CF-reinforced polymer matrices substantially improved tensile, flexural, and impact properties. This enhancement is attributed to the high surface area and functional groups of GO that contribute to better stress transfer and interfacial adhesion. However, beyond the optimal threshold, agglomeration of GO adversely impacted mechanical integrity, underlining the importance of precise formulation.

The machinability analysis revealed that spindle speed, feed rate, and tool geometry profoundly affect surface quality, thrust force, and delamination. The damage control module, supported by a hybrid CoCoSo-GRA optimization technique and validated through ANOVA, enabled accurate prediction and minimization of machining-induced defects. SEM analysis further confirmed that optimized parameters result in reduced fiber pull-out, matrix cracking, and interfacial debonding.

This study establishes a reliable and scalable framework for optimizing machining parameters in hybrid nanocomposites. The developed module offers a practical tool for industries seeking to enhance manufacturing efficiency, reduce material wastage, and ensure component reliability.

KEY CONTRIBUTIONS:

- ❖ Developed high-performance GO-CF nanocomposites with superior mechanical properties.
- ❖ Designed a predictive module for machinability assessment and damage control.
- ❖ Identified optimal machining parameters using a multi-objective optimization approach.
- ❖ Validated results with experimental analysis and statistical modeling.

FUTURE SCOPE:

Future studies may explore:

- ❖ Integration of machine learning algorithms for real-time damage prediction.
- ❖ Application of the module to other nanofiller systems and complex machining operations (e.g., milling, turning).
- ❖ Evaluation of long-term durability and fatigue under dynamic loading.
- ❖ Development of a digital twin environment for smart manufacturing using these materials.

ISSN: 2583-6129
DOI: 10.55041/ISJEM02035

REFERENCES

1. Hussain, F., Hojjati, M., Okamoto, M., & Gorga, R. E. (2006). *Review article: Polymer-matrix nanocomposites, processing, manufacturing, and application: An overview*. Journal of Composite Materials, 40(17), 1511-1575.
2. Thostenson, E. T., Ren, Z., & Chou, T. W. (2005). *Advances in the science and technology of carbon nanotubes and their composites: a review*. Composites Science and Technology, 61(13), 1899-1912.
3. Kim, H., Abdala, A. A., & Macosko, C. W. (2010). *Graphene/polymer nanocomposites*. Macromolecules, 43(16), 6515-6530.
4. Rafiee, M. A., Rafiee, J., Wang, Z., Song, H., Yu, Z. Z., & Koratkar, N. (2009). *Enhanced mechanical properties of nanocomposites at low graphene content*. ACS Nano, 3(12), 3884-3890.
5. Dreyer, D. R., Park, S., Bielawski, C. W., & Ruoff, R. S. (2010). *The chemistry of graphene oxide*. Chemical Society Reviews, 39(1), 228-240.
6. Stankovich, S., et al. (2006). *Graphene-based composite materials*. Nature, 442(7100), 282–286.
7. Chung, D. D. L. (2001). *Carbon fiber composites*. Butterworth-Heinemann.
8. Singh, V. V., Kumar, R., & Bandyopadhyay, A. (2015). *Effect of carbon fiber reinforcement on mechanical behavior of polymer composites*. Journal of Materials Science, 50(13), 4669–4677.
9. Kim, H., & Park, C. (2011). *Synergistic effects of graphene oxide and carbon fiber on the mechanical properties of epoxy composites*. Composites Part A: Applied Science and Manufacturing, 42(10), 1613–1620.
10. Zaman, I., et al. (2012). *From carbon nanotubes and graphene to hybrid nanocomposites: A review*. Composites Part B: Engineering, 43(3), 1232–1245.
11. Davim, J. P. (2013). *Machining of polymer composites*. Springer.
12. Hocheng, H., & Dharan, C. K. H. (1990). *Delamination during drilling in composite laminates*. Journal of Engineering for Industry, 112(3), 236–239.
13. Azmi, A. I., et al. (2013). *Study on surface roughness and delamination in drilling hybrid carbon/glass fiber reinforced polymer*. Materials and Manufacturing Processes, 28(6), 702–707.
14. Jain, R., & Jain, S. (2014). *Optimizing drilling process parameters for composite materials using Taguchi method*. Procedia Engineering, 97, 469–476.
15. Tsao, C. C., & Hocheng, H. (2004). *Taguchi analysis of delamination associated with various drill bits in drilling of composite material*. International Journal of Machine Tools and Manufacture, 44(10), 1085–1090.
16. Khashaba, U. A., et al. (2010). *Machinability analysis in drilling woven GFR/epoxy composites: Part II–Effect of drill wear*. Composites Part A: Applied Science and Manufacturing, 41(9), 1130–1137.
17. Shunmugesh, K., Palanikumar, K., & Latha, B. (2018). *Optimization of drilling parameters in GFRP composites using hybrid grey relational analysis*. Materials Today: Proceedings, 5(2), 6621–6626.

18. Abhishek, M., et al. (2020). *Multi-objective optimization of machining parameters for hybrid composites*. Journal of Composite Materials, 54(17), 2267–2282.

19. Suresh, K., et al. (2020). *Optimization of machining parameters using hybrid CoCoSo-PCA for composite materials*. Materials Today: Proceedings, 27(1), 1827–1833.

20. Mishra, P., & Singaravel, B. (2022). *Prediction of machinability in advanced composites using machine learning models*. Advances in Manufacturing, 10(1), 142–153.