International Journal of Leading Research Publication (IJLRP)
E-ISSN: 2582-8010 ● Website: www.ijlrp.com ● Email: editor@ijlrp.com

Analysis of Characterization and Drilling Behaviour of Aluminium Based Hybrid Composites

Saurabh Singh[1], Dr. Sunil Kadiyan[2]

[1]M.Tech Scholar, Department of Mechanical Engineering, GITAM, Kablana, Jhajjar
[2]Associate Professor, Department of Mechanical Engineering, GITAM, Kablana, Jhajjar

Abstract
The growing demand for lightweight yet high-strength materials in sectors such as aerospace, automotive, and structural engineering has driven intensive research into metal matrix composites (MMCs). Aluminium, by virtue of its excellent strength-to-weight ratio, corrosion resistance, and workability, serves as a prime matrix candidate for such composites. However, to meet the escalating performance requirements, reinforcement with hard ceramic particles has emerged as an effective strategy. Hybrid composites comprising Al6061 alloy as the matrix, combined with varying proportions of SiC and fly ash, were synthesized using the stir casting technique. The process parameters were carefully optimized: reinforcements were preheated to 600°C to enhance wettability, stirring was carried out at 550 rpm for 10 minutes to ensure homogeneous dispersion, and the molten slurry was cast into preheated steel moulds. Four composite systems were developed—unreinforced Al6061, Al + 7% SiC, Al + 5% SiC + 5% fly ash, and Al + 7% SiC + 3% fly ash—chosen to systematically study the influence of reinforcement content and type. In essence, this study provides a balanced perspective on the dual impacts of hybrid reinforcement. It confirms that aluminium-based hybrid composites with SiC and fly ash are structurally superior and thus attractive for lightweight load-bearing applications.

Keywords: MRR, MMC, CGCG, Hardness, Flexibility

1. Introduction
In the rapidly advancing fields of aerospace, automotive, defense, and structural engineering, the demand for lightweight yet high-performance materials has grown exponentially. Traditional materials such as steel and pure aluminium, though extensively used, have limitations in terms of weight-to-strength ratio, corrosion resistance, and wear properties. To overcome these drawbacks, composite materials especially Metal Matrix Composites (MMCs) have emerged as a promising alternative[10]. Among MMCs, aluminium-based metal matrix composites (AMMCs) are the most widely used due to their excellent combination of light weight, mechanical strength, corrosion resistance, and thermal properties.

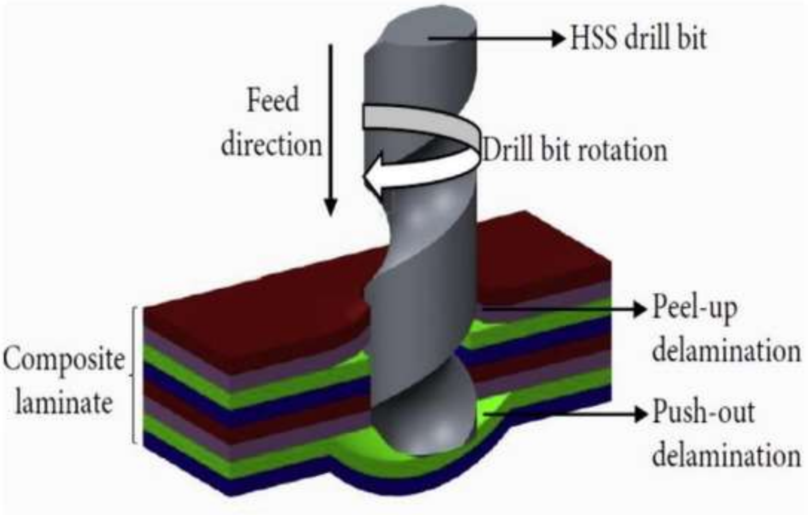

Fig 1 Drilling Process

The addition of reinforcement materials such as silicon carbide (SiC), aluminium oxide (Al_2O_3), boron carbide (B_4C), fly ash, graphite, or carbon nanotubes to the aluminium matrix has significantly improved its properties. These reinforcements help enhance mechanical performance, wear resistance, and thermal stability[14]. However, mono-reinforced composites often reach a saturation point where further enhancements are limited. This has led to the development of hybrid composites, wherein two or more reinforcement materials are used to optimize the physical and mechanical properties of the base matrix.
Hybrid composites are designed to capitalize on the individual advantages of each reinforcement. For instance, SiC offers excellent hardness and wear resistance, while graphite improves lubricity and reduces friction[16]. The synergistic effect of combining such reinforcements results in improved composite behaviour under both static and dynamic loading conditions. However, the inclusion of hard ceramic reinforcements introduces challenges in terms of machinability, particularly during drilling operations.

2. RELATED WORK

Based on prior experience, the available resource, and the machining data handbook by Alok Nayar, (2015) a range of independent variables, including speed, feed, and point angle, was chosen. Ranganathan (2014) and Senthilvelan used grey analysis to multi-response optimise hot-turning machining. In order to determine the ideal major intervening parameters in the micro-EDM of stainless steel (SS) 316L, Suresh et al. conducted experiments.
Srinivasan (2015) investigated the impact of drilling settings on roundness inaccuracy when drilling Glass Fiber Reinforced Polypropylene (GFR/PP) matrix composites with a "Brad and Spur" drill bit. The experiment makes use of solid carbide drill bits, and the effects of spindle speed, feed rate, and drill diameter are studied using the L27 orthogonal array. The cutting parameter is thoroughly and in-depth assessed and optimised using the Box-Behnken Design (BBD) method. Drilling parameter analysis and productivity, as well as quality, are influenced by design. The roundness error is calculated using the output results' analysis of variance (ANOVA) and response surface methodology (RSM), which are also used to analyse the output results. One of the most major ovalty issues that must be handled on a cylindrically drilled item is the roundness error. The standard metrological tool for roundness error inspection, which is commonly done in a quality room, is the coordinate measuring machine (CMM). The results

demonstrated that it is possible to forecast the response variable using the model while minimising roundness error.

Tan (2015) found that dimensional tolerance is frequently influenced by the work part's surface integrity or surface roughness. In this article, the Taguchi and response surface techniques will be used to reduce the surface roughness of drilled carbon-glass hybrid fibre reinforced polymer (CGCG) utilising tungsten carbide, and K20 drill bits. The effects of spindle speed, feed rate, and tool shape on surface roughness were examined in order to determine the optimal cutting settings for lowering the aforementioned response.

Localized convection is caused by the millions of interactions between the base fluid molecules and the nanoparticles, Subhedar et al (2016). In comparison to microparticles, nanoparticles have a million times more surface area per unit volume. As a result, the NCF's heat conductivity increases with surface area and the quantity of contacts. the volume percentage of nanoparticles used in NCF. It has been found that the thermal conductivity of NCF would increase as the volume fraction of nanoparticles increased because solid particles have a high thermal conductivity.

Mohammed Razzaq Alaa (2017) uses the Al7075 alloy in a variety of applications because of how it responds to heat treatment and the age-hardening process.

Using the FSP method, Periasamy et al. (2019) investigated the mechanical characteristics of an Al7075 hybrid composite with SiC and Gr as reinforcements. Gr particles were observed to form a thin, self-lubricating layer over the base metal, and SiC reinforcement was found to increase the base metal's hardness.

Zhong (2021) discovered that composites are frequently employed in the industry due to their distinctive features. AMCs are used in a wide range of industries, including vehicles, buildings, factories, and sports, thanks to their less expensive existence. The physical properties of the metal or composite are the factor that has the biggest impact on how they behave. In order to assess performance under predetermined conditions, Kamble (2019) used microstructural analysis.

Hernadewit (2019) conducted research to outline the steps and processes involved in DOE in order to identify the best quality parameter for each quality characterization. When milling pulp using a hydra pulper, nominal works best when the pulp freeness is 650 Canadian Standard Freeness. Signal-to-Noise (S/N) Ratio, orthogonal array, and analysis of variances are used to display the outcome. Conclusion: The pulp composition at level 1 (100%), the pulp consistency at level 2, and the milling time factor at level 2 all contributed to the optimum freeness obtained.

Using the FSP method, Periasamy et al. (2019) investigated the mechanical characteristics of an Al7075 hybrid composite with SiC and Gr as reinforcements. Gr particles were observed to form a thin, self-lubricating layer over the base metal, and SiC reinforcement was found to increase the base metal's hardness.

According to Sivashankar (2020), the more uniformly distributed reinforcement materials are, the better MMCs perform in terms of Ra and VB. In comparison to other fabrication methods, Sooryaprakash's (2020) stir-casting process has provided better distribution of reinforcement particles in MMCs. The melting point of the material and the duration of the stirring were found to affect the production of goods free from defects. In the Al 2024 alloy, Kurt et al. looked into the size, surface roughness, roundness, and radial deviation of drilled holes. The majority of study has been done using traditional particle reinforcement. Today, emphasis is being placed on readily available and affordable reinforcement. One of the least expensive materials utilised as reinforcement in composites made of the aluminium matrix is fly ash. Only a small percentage of the millions of tonnes of fly ash powder produced by thermal power plants using coal gets used. Al-Si alloy – fly ash composites have been used to make a variety of parts, including pistons, engine covers, connecting rods, and other castings. The production of Al-Si alloy-fly ash composites used powder metallurgy.

3. Research Methodology

The research methodology outlines the systematic process followed to accomplish the objectives of the study .This section details the material selection, fabrication process, experimental design, characterization techniques, and machining tests undertaken to evaluate both the mechanical and drilling behaviour of aluminium-based hybrid composites reinforced with silicon carbide (SiC) and fly ash. The methodology is designed to ensure reliability, repeatability, and the applicability of results across similar materials and industrial contexts. The research employs both experimental and statistical analysis tools to evaluate the microstructural, mechanical, and machining responses of the fabricated composites.
The study follows an experimental research approach, involving:

1. Fabrication of hybrid composites using stir casting
2. Material characterization using mechanical testing and microstructure analysis
3. Drilling performance evaluation using controlled machining trials
4. Design of Experiments (DOE) and Analysis of Variance (ANOVA) to analyze parameter effects and interactions

The research combines qualitative analysis (microstructural studies) with quantitative analysis (mechanical/machining metrics and statistical modeling) to form comprehensive conclusions.

Material Selection and Justification

- **Matrix Material**: Aluminium 6061 alloy was selected due to its favorable properties such as lightweight, good corrosion resistance, excellent formability, and moderate strength.
- **Reinforcements**:
  - **Silicon Carbide (SiC)** was chosen for its high hardness, wear resistance, and thermal stability.
  - **Fly Ash** was selected as a low-cost, eco-friendly reinforcement with good strength-to-weight contribution and availability.

The hybrid approach aims to synergize the hardness and thermal resistance of SiC with the weight-saving and cost-reduction benefits of fly ash.

Fabrication Method: Stir Casting

The hybrid composites were synthesized using stir casting, which allows for effective reinforcement incorporation and is industrially scalable.

A. Preprocessing

- Aluminium ingots were cleaned and cut into small chunks.
- SiC and fly ash particles were dried at 600°C for 1 hour to remove moisture.
- Surface treatments (e.g., with magnesium) were optionally applied to improve wettability.

B. Melting and Stirring

- Al6061 was melted in an electric furnace at 750°C.
- A mechanical stirrer created a vortex to ensure uniform mixing.
- Preheated reinforcements were added incrementally.
- Stirring continued at 550 rpm for 10 minutes.

C. Casting and Cooling

- The composite slurry was poured into preheated steel molds.
- Castings were allowed to solidify under ambient air.
- Samples were machined to standard dimensions for testing.

4. SIMULATION RESULT AND DISCUSSION

This section presents the experimental findings from the mechanical characterization, microstructural analysis, and drilling performance assessment of aluminium-based hybrid composites reinforced with silicon carbide (SiC) and fly ash. Data were collected through systematic tests on various composite formulations and benchmarked against unreinforced Al6061.

4.1 Hardness

The Brinell hardness tests showed a substantial improvement with the addition of reinforcements.

Composition	Hardness (BHN)
Al6061 (unreinforced)	68.5
Al + 7% SiC	89.2
Al + 5% SiC + 5% fly ash	93.8
Al + 7% SiC + 3% fly ash	96.4

The hybrid composites demonstrated an average 35–40% increase in hardness over plain aluminium. This enhancement is attributed to the inherent hardness of SiC and the particulate strengthening effect of fly ash, which also acted as micro-barriers to dislocation motion.

4.2 Tensile and Flexural Strength

Tensile testing according to ASTM E8 standards revealed:

Composition	Ultimate Tensile Strength (MPa)
Al6061	160.2
Al + 7% SiC	195.7
Al + 5% SiC + 5% fly ash	202.4
Al + 7% SiC + 3% fly ash	209.8

Similarly, three-point bending tests showed:

Composition	Flexural Strength (MPa)
Al6061	210.4
Al + 7% SiC	265.1
Al + 5% SiC + 5% fly ash	273.6
Al + 7% SiC + 3% fly ash	278.9

These increases validate the reinforcing effect, with hybrid formulations providing up to 31% enhancement in tensile strength and 32% in flexural strength, likely due to synergistic load transfer from the aluminium matrix to the hard reinforcements.

4.3 Thrust Force

Drilling experiments used a Taguchi L9 orthogonal array with three factors: spindle speed, feed rate, and tool material. Results showed clear increases in thrust force with reinforcement addition.

Sample data at 1200 RPM and 0.10 mm/rev:

Composition	Thrust Force (N)
Al6061	102
Al + 7% SiC	137
Al + 5% SiC + 5% fly ash	142
Al + 7% SiC + 3% fly ash	148

Thus, hybrid composites needed up to 45% higher thrust force than pure Al. The presence of hard particles created resistance to cutting edge penetration, with tool impacts on SiC/fly ash clusters spiking forces further.

4.4 Surface Roughness

Surface finish (Ra) measured via profilometer indicated deterioration with reinforcement.

Composition	Surface Roughness Ra (µm)
Al6061	1.12
Al + 7% SiC	1.81
Al + 5% SiC + 5% fly ash	1.94
Al + 7% SiC + 3% fly ash	2.03

The rougher surfaces are explained by micro-ploughing, particle pull-out, and abrasive scoring during chip evacuation.

4.5 Burr Formation

Interestingly, burr height decreased with reinforcement, showing how harder phases limit plastic deformation.

Composition	Burr Height (µm)
Al6061	345
Al + 7% SiC	292
Al + 5% SiC + 5% fly ash	281
Al + 7% SiC + 3% fly ash	276

However, some SEM edge views displayed small micro-cracks at high reinforcement contents, due to localized brittle fracture.

4.6 Chip Morphology

Chip analysis showed:

- Al6061: long, continuous, curled chips, indicative of ductile flow.
- Hybrid composites: short, segmented, irregular chips, with signs of brittle fracture near reinforcement-rich zones.

This reflects how hybrid microstructures shift chip formation from purely ductile to partially brittle mechanisms, consistent with observations by Singh & Bansal (2020).

4.7 Statistical Analysis (DOE/ANOVA)

Taguchi S/N ratios confirmed that:

- Feed rate had the strongest impact on thrust force and surface roughness.
- Spindle speed inversely affected surface roughness (higher speed → better finish due to thermal softening).
- Tool material (carbide vs HSS) showed significant effects, with carbide reducing forces by ~10%.

ANOVA results showed:

- Feed rate contributed 58.3% to thrust force variation.
- Reinforcement type/percentage embedded in the matrix indirectly explained over 25% variation in combined responses.

5. Conclusion

This paper undertook an analytical and experimental exploration into the characterization and drilling behaviour of aluminium-based hybrid composites reinforced with SiC and fly ash. The aim was to understand how these reinforcements influence mechanical properties, microstructure, and crucial machining outcomes. The conclusions drawn here are based on rigorous experimentation, microstructural analysis, and statistical interpretations. Incorporating SiC and fly ash into Al6061 significantly enhanced hardness by up to 40%, and improved tensile and flexural strength by approximately 30%, compared to unreinforced aluminium. Microstructural analysis confirmed good dispersion of reinforcements, aided by preheating and controlled stirring. Optical and SEM images validated grain refinement and strong interfacial bonding, critical for effective load transfer. This underlines that even with a relatively simple process like stir casting, carefully tuned parameters can yield composites with superior static mechanical performance.

References

1. Babu, S. S., Dhanasekaran, C., Anbuchezhiyan, G., & Palani, K. (2022). Parametric analysis on drilling of aluminium alloy hybrid composites reinforced with SIC/WC. Engineering Research Express, 4(2), 025036.
2. Okay, F., Islak, S., & Turgut, Y. (2021). Investigation of machinability properties of aluminium matrix hybrid composites. Journal of Manufacturing Processes, 68, 85-94.
3. Senthil, V., Balasubramanian, E., Raju, G. S., & Senthilkumar, N. (2024). Drilling studies on MWCNT- and zirconia-reinforced aluminium alloy 8011 hybrid composite: a machine learning approach. Arabian Journal for Science and Engineering, 49(11), 14741-14762.
4. Selvan, C. P., Girisha, L., Koti, V., Madgule, M., Davanageri, M. B., Lakshmikanthan, A., & Chandrashekarappa, M. P. G. (2023). Optimization of stir casting and drilling process parameters of hybrid composites. Journal of Alloys and Metallurgical Systems, 3, 100023.
5. Rajaravi, C., Elaiyarasan, U., Gobalakrishnan, B., & Srinivasan, R. G. (2022). Surface roughness and microstructure analysis on drilling of titanium diboride in-situ aluminium metal matrix composite. Surface Topography: Metrology and Properties, 10(2), 025034.
6. Jagadeesh, P., Rangappa, S. M., Suyambulingam, I., Siengchin, S., Puttegowda, M., Binoj, J. S., ... & Cuadrado, M. M. M. (2023). Drilling characteristics and properties analysis of fiber reinforced polymer composites: a comprehensive review. Heliyon, 9(3).
7. Kayaroganam, P., Krishnan, V., Natarajan, E., Natarajan, S., & Muthusamy, K. (2021). Drilling parameters analysis on in-situ Al/B4C/mica hybrid composite and an integrated optimization approach using fuzzy model and non-dominated sorting genetic algorithm. Metals, 11(12), 2060.
8. Raj, M. K. A., Rathanasamy, R., Rathinasamy, P., Kumar, P. M., Periyasamy, S., Alahmadi, A. A., ... & Lee, I. E. (2025). Analysis of thrust force generation during the drilling of natural fiber based hybrid composite. Scientific Reports, 15(1), 15382.
9. Sapkota, G., Ghadai, R. K., Das, S., Das, P. P., & Chakraborty, S. (2023). A comparative study on multi-objective optimization of drilling of hybrid aluminium metal matrix composite. International Journal on Interactive Design and Manufacturing (IJIDeM), 17(6), 3177-3187.
10. Kishore, G., Parthiban, A., Krishnan, A. M., & Krishnan, B. R. (2021). Investigation of the surface roughness of aluminium composite in the drilling process. Mater. Phys. Mech., 47(5), 739-746.
11. Rajasekaran, S., & Mohanavel, V. (2024). Sustainable Optimization of Drilling Parameters for AA2017/AlN Composite Materials: A Grey Relational Analysis Approach. In E3S Web of Conferences (Vol. 552, p. 01033). EDP Sciences.
12. Karakoç, H., Bilgin, M., & Karabulut, Ş. (2024). Study on the friction drilling behaviors and tribological properties of aluminum matrix composites. Materials Today Communications, 38, 108086.
13. Senthil Babu, S., Dhanasekaran, C., Parthiban, A., Vasudevan, N., & Mekonnen, A. (2023). Analysis of MRR, Thrust Force, and Torque in Drilling Al/BN/Al2O3 Composites using Hybrid Grey–Taguchi Technique. Journal of Nanomaterials, 2023(1), 8175140.
14. Kumar, R. S., & Anbuchezhiyan, G. (2023, November). Comparative investigation of drilling characteristics (material removal rate) of coir powder blended GFRP and aluminium oxide powder

blended GFRP against GFRP-A novel approach. In AIP Conference Proceedings (Vol. 2822, No. 1). AIP Publishing.

15. Sridhar, A. K., Bolar, G., & Padmaraj, N. H. (2022). Comprehensive experimental investigation on drilling multi-material carbon fiber reinforced aluminium laminates. Journal of King Saud University-Engineering Sciences, 34(7), 391-401.
16. Elhadi, A., Amroune, S., Slamani, M., Arslane, M., & Jawaid, M. (2025). Assessment and analysis of drilling-induced damage in jute/palm date fiber-reinforced polyester hybrid composite. Biomass Conversion and Biorefinery, 15(3), 4243-4258.
17. Dhanasekaran, C. (2022). Drilling parameter analysis of hybrid composites (Al/B4C/graphite) using grey relational and Taguchi techniques. Materials Today: Proceedings, 68, 1280-1287.
18. Motorcu, A. R., Ekici, E., Kesarwani, S., & Verma, R. K. (2024). Evaluation of Machining Characteristics and Tool Wear During Drilling of Carbon/Aluminium Laminated. FME Transactions, 52(3).
19. Jebaratnam, J. M., Hassan, M. H., Mahmud, A. S., & Gérald, F. (2023). Characterization of nanocomposite tetrahedral amorphous carbon coated drill bits for improved drilled-hole quality in carbon fiber-reinforced polymer/Al7075-T6 stacks. Journal of Composite Materials, 57(27), 4255-4274.
20. Hariharasakthisudhan, P., Logesh, K., Sivakumar, R., & Sathickbasha, K. (2024). Optimizing the drilling process parameters of AZ91 based hybrid composites using TOPSIS and grey relational analysis. Engineering Research Express, 6(3), 035559.