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Optimization of Machining and Wear Behavior of Al6061 Composites Reinforced with SiC Particles

[1]T Anil Kumar, [2*]S M Aradhya, [3]Eswaraiah K S, [4]Brijesh C

[1]*Associate Professor, Department of Mechanical Engineering, Ramaiah Institute of Technology, Bangalore*

[2 & 3] *Associate Professor, Department of Mechanical Engineering, Kalpataru Institute of Technology, Tiptur*

[4] *Assistant Professor, Department of Mechanical Engineering, Kalpataru Institute of Technology, Tiptur*

Abstract:

Metal Matrix Composites (MMCs) reinforced with SiCp having average particle size of 25μ and Graphite exhibits good wear resistance and machinability property. The present study attempts to investigate machining and wear properties of Al-SiC with the addition of 1% of graphite powder. These composites are fabricated through stir casting route with the addition of SiC particles from 3 to 9% in steps of 3% along with 1% of graphite powder by weight. Experiments were conducted by varying the cutting speeds and cutting parameters in turning, measuring the surface roughness, cutting force. The results confirms that machinability enhances with increased addition of reinforcement. The density and hardness tests are conducted and analysed for each composition. The worn surface examined through optical microscope and XRD analysis. X-ray diffraction (XRD) analysis confirms the presence SiC and Gr. It was also found that there exists good bonding between matrix and ceramic particles. The mechanical properties are evaluated through tensile test and compression test for prepared composites.

Keywords: XRD, Regression analysis, ANOVA

1. INTRODUCTION

The matrix for composite materials must be selected with careful consideration of its properties and its interaction with the reinforcement. As a crucial component in metal matrix composites (MMCs), the matrix should only be chosen after thoroughly assessing its chemical compatibility with the reinforcement. Various materials have been proposed by researchers based on their properties, with aluminum, titanium, and magnesium being widely used.

Beryllium, though the lightest structural material with a tensile modulus greater than steel, is brittle and not suitable for general applications. Magnesium, while lightweight, is highly reactive with oxygen. Among the available options, aluminum stands out due to its superior mechanical properties, high corrosion resistance, toughness, and low density. Of the aluminum alloys, Aluminum 6061 is one of the most commonly used due to its versatility as a heat-treatable alloy with medium to high strength capabilities. It offers excellent fatigue strength, with a density of 2.7 g/cm³ and a melting point of 580°C.

Currently, Al6061 is widely applied in various industries, including aircraft and aerospace parts, marine fittings, bicycle frames, camera lenses, drive shafts, electrical fittings, connectors, and brake components. It is especially favored in applications that require excellent castability, weldability, pressure tightness, and strong corrosion resistance. For these reasons, Al6061 alloy is selected for the present research work.

The reinforcement material enhances the stiffness and strength of the composite but can also reduce the density of metal matrix composites (MMCs). To achieve optimal properties, selecting the right reinforcement is crucial. This choice depends on factors such as the type and size of the reinforcement particles, the processing technique, and the chemical compatibility with the metal matrix. Research has demonstrated that ceramic particles are effective reinforcements for aluminum and aluminum alloys, as they significantly improve mechanical properties. Common ceramic reinforcements include carbides, oxides, and nitrides, with widely used materials being Silicon

Carbide (SiC), Aluminum Oxide (Al_2O_3), Titanium Diboride (TiB_2), Boron Carbide (B_4C), thorium, and graphite. To develop a material with enhanced mechanical properties and high thermal conductivity, graphite is often chosen as the reinforcement for MMCs. Among the most popular and commercially available aluminum-based MMCs are those reinforced with silicon carbide (SiC), due to their properties like low weight, thermal resistance, wear resistance, and cost-effectiveness. SiC has a high melting point (2730°C), an elastic modulus of 410 GPa, excellent resistance to chemical agents, and a low density (3.21 g/cm³), making it an ideal reinforcement for aluminum alloy matrices. Several processing methods, such as stir casting, spray deposition, squeeze casting, mechanical alloying, and powder metallurgy, have been developed to fabricate aluminum matrix composites (AMCs). Of these, the stir casting process is the most widely used due to its low capital cost, strong bonding between the matrix and particles, near-net shape production, and suitability for high-volume manufacturing.

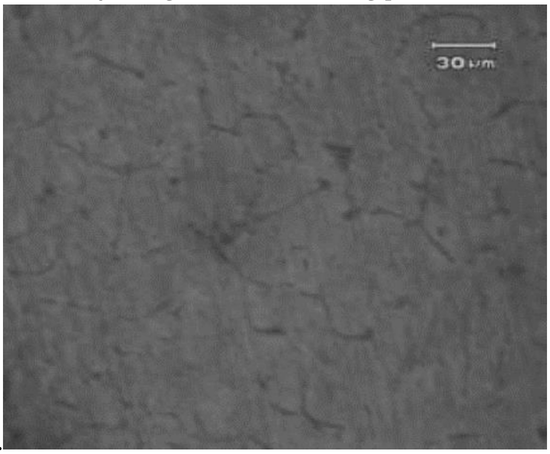
2. FABRICATION OF COMPOSITE

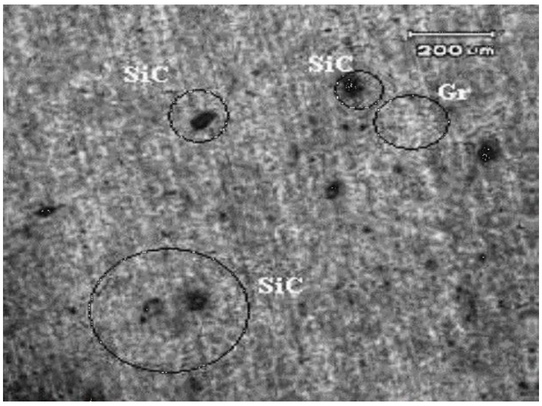
The metal matrix composites of Al6061 alloy reinforced with SiC and graphite were prepared in a resistance furnace. The stir casting process set up is shown in Figure 3.1. Initially the base metal Al 6061 castings were made. Easily and abundantly available SiC in particulate form has been used as reinforcement which acts as main load bearing member. They were pre oxidized at

650º C for two hours and transferred into the molten matrix along with graphite particles of 50 µm size. It was stirred at a constant rate.

3. MICROSTRUCTURE ANALYSIS

The optical micrograph of the aluminum metal matrix and the one reinforced with 9 wt. % of SiCp and Graphite shown in Fig. 1(a) and 1(b). It demonstrate that no evidence of the proximity of despondencies neither at interfaces nor in the system was found with optical microscopy, which shows that a decent holding between the grid and earth particulate was obtained by using the molten mixing procedure. The SiC particles are seen to be angular in shape.





1(a) Optical micrograph of alloy (Al6061) 1(b) Al6061+9%SiC+1%Gr

4. XRD ANALYSIS

Aluminium with 3, 6, 9% SiC additions were subjected to X-Ray Beam diffraction examination to confirm the presence of constituents. Fig. shows the four highest intensity peaks, which are distinctly visible for aluminium while other peaks in Fig. 2(a) and 2(b) represents the presence of SiC. Similarly for other graphs indicating low peaks for Graphite. Different matching percentages obtained for other combinations. X-Ray diffraction reveals the presence of SiC and Graphite.

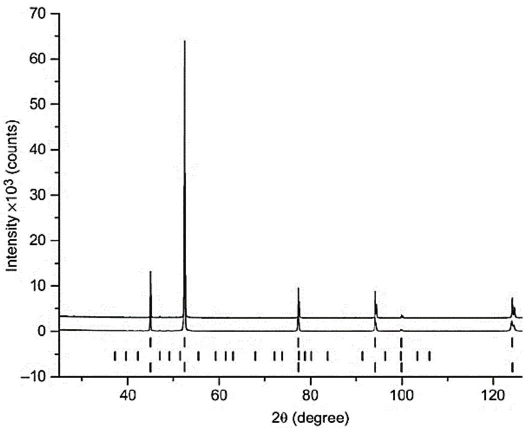


Fig 2(a) XRD of Al6061

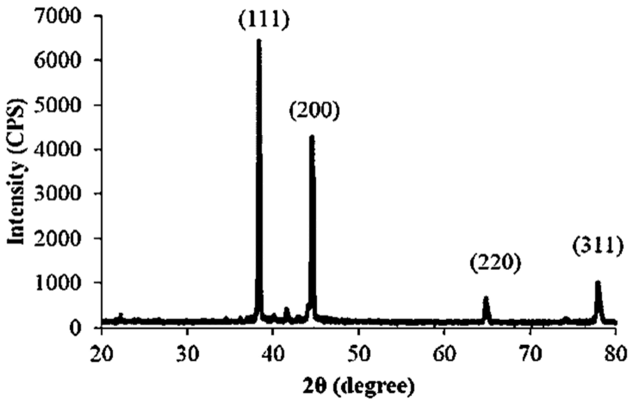


Fig 2(b) XRD of Al6061+9%SiC+1%Gr

5. MACHINING STUDIES

Machining is done by considering the machining parameters. Three process parameters are changed in three separate levels. The below table gives the experimental result for base alloy and alloy with SiC 9% and 1% Graphite additions. The below Table 1 gives the information of surface roughness and cutting force values for different cutting parameters for Al6061/9%SiC /1%Gr

Table 1: Cutting force and surface roughness values for various cutting parameters

Sl. No	Cutting parameters			Cutting force,	Surface Roughness
	Feed	Speed	Depth of Cut	N	R_a (μm)
	0.3	120	0.3	100	28
	0.3	250	0.3	85	26
	0.3	400	0.3	70	24
	0.3	600	0.3	60	23
	0.3	900	0.3	50	21
	0.2	400	0.3	50	19
	0.25	400	0.3	60	21
	0.3	400	0.3	80	26
	0.4	400	0.3	100	32
	0.5	400	0.3	110	37
	0.3	400	0.1	50	27
	0.3	400	0.2	60	28
	0.3	400	0.3	80	27

Sl. No	Cutting parameters			Cutting force, N	Surface Roughness R_a (µm)
	Feed	Speed	Depth of Cut		
	0.3	400	0.4	100	24
	0.3	400	0.5	135	23

6. OPTIMIZATION USING S/N RATIOS AND ANOVA

Analysis of Variance (ANOVA) was employed to determine the statistically significant parameters that influence the performance criteria during the wear testing of the composite samples, as well as to evaluate the percentage contribution of each control factor to the wear rate. The analysis was performed at a confidence level of 95%. The experiment was carried out for 16 trials, as outlined below. The wear rates obtained from the L16 trials are presented in Table 2.

Table 2: Wear rate for different testing conditions

Sl. No	Applied Load, N	Sliding speed, rpm	Sliding distance, m	Composition	Wear rate, mm^3/m
1	10	100	500	Al6061	0.0584
2	10	200	1000	Al6061+3%SiC+1%Gr	0.006178
3	10	300	1500	Al6061+6%SiC+1%Gr	0.006517
4	10	400	2000	Al6061+9%SiC+1%Gr	0.007545
5	20	100	1000	Al6061+6%SiC+1%Gr	0.005217
6	20	200	500	Al6061+9%SiC+1%Gr	0.00578
7	20	300	2000	Al6061	0.009787
8	20	400	1500	Al6061+3%SiC+1%Gr	0.008686
9	30	100	1500	Al6061+9%SiC+1%Gr	0.007068
10	30	200	2000	Al6061+6%SiC+1%Gr	0.00855
11	30	300	500	Al6061+3%SiC+1%Gr	0.006609
12	30	400	1000	Al6061	0.00836
13	40	100	2000	Al6061+3%SiC+1%Gr	0.009703
14	40	200	1500	Al6061	0.008177
15	40	300	1000	Al6061+9%SiC+1%Gr	0.007791
16	40	400	500	Al6061+6%SiC+1%Gr	0.00874

Table 3: Regression analysis table

Sources	DF	Adj SS	Adj MS	F Value	P Value
Regression	6	0.000026	0.000004	8.94	0.002
Applied Load(N)	1	0.000009	0.000009	17.79	0.002
Sliding speed (rpm)	1	0.000004	0.000004	8.96	0.015

Sources	DF	Adj SS	Adj MS	F Value	P Value
Sliding distance(m)	1	0.00001	0.00001	21.57	0.001
Composition	3	0.000003	0.000001	1.78	0.021
Error	9	0.000004	0.0		
Total	15	0.00003			

The main effects plot for means, as presented in Table 3, explains the variation in wear rate under the effect of each process parameter. It was observed that the wear rate increases as load, sliding distance, and speed increase. The hybrid composite (Al6061 + 9% SiC + 1% Gr powder) exhibited higher wear resistance compared to both the mono composite and the hybrid composite containing only graphite powder. With increase in load, the delamination wear mechanism becomes more predominant, accelerating the wear rate. Higher loads result in increased localized stress on the composite at points of asperity contact, which promotes abrasive wear by creating deeper grooves. The wear rate of the alloy also rises with increasing sliding speed. As the speed increases, the friction-induced temperature at the interface escalates, leading to the softening of surface and subsurface layers of the wear area. The lack of matrix-strengthening particles in the aluminum alloy exacerbates this issue. The absence of solid lubricants prevents the formation of a friction-reducing tribofilm on the alloy surface, intensifying the softening effect as sliding speed increases. In comparison to the aluminum alloy, the composite materials exhibit improved wear resistance. The incorporation of SiC strengthens the matrix and reduces the likelihood of adhesive wear by minimizing direct contact between the matrix and the counter surface. Consequently, the effects of delamination and adhesive wear are mitigated. When comparing the mono composite with the hybrid composite, the hybrid composite demonstrates superior wear resistance. This is primarily due to the formation of a friction-controlling tribofilm, which is enriched with a significant amount of graphite lubricant. This tribofilm acts as a protective barrier, reducing oxidation on the composite surface and contributing to the composite's improved wear performance.

7. REGRESSION ANALYSIS

The mathematical models for response criteria were developed using regression models using

Minitab 17. For the most part a second-order polynomial reaction surface scientific model was utilized to break analysis of the different parameters on every response criteria. The regression equations obtained is highlighted in Table 4

Table 4: Regression equations

Material Composition	Equation
Al6061	0.003454 + 0.000065 Load + 0.000005 Sliding speed + 0.000001 Sliding Distance
Al6061+3%SiC+1%Gr	0.003207 + 0.000065 Load + 0.000005 Sliding speed + 0.000001 Sliding Distance
Al6061+6%SiC+1%Gr	0.002669 + 0.000065 Load + 0.000005 Sliding speed + 0.000001 Sliding Distance
Al6061+9%SiC+1%Gr	0.002459 + 0.000065 Load + 0.000005 Sliding speed + 0.000001 Sliding Distance

The predicted values for wear rate for each composition were calculated using applied load of 25 N, Slidings distance of 750 m and sliding speed of 250 rpm with the help of above equations obtained from uncoded surface regression equations. Comparison of predicted and experimental values for regression equations as represented in Table 5

Table 5: Error table

Sl No	Predicted (mm^3/m)	Experimental (mm^3/m)	% Error
01	0.007329	0.006112	17.31
02	0.007082	0.007821	10.43
03	0.006544	0.005664	13.42
04	0.006334	0.005256	17.02

8. CONCLUSIONS

Mono and hybrid composites were fabricated using SiC and Gr powder as reinforcements, respectively. Microstructural analysis through optical imaging showed a uniform distribution of reinforcements within the matrix material, further confirmed by XRD analysis. Mechanical properties such as tensile strength, density, hardness, and compressive strength were evaluated, with hybrid composites exhibiting superior values compared to the base material and the mono composite. Surface roughness increased with a higher feed rate, and the inclusion of SiC/Gr particle reinforcements contributed to this increase. However, surface roughness decreased as cutting speed increased. The tribo-performance of all compositions was investigated across varying levels of selected process parameters. Wear performance experiments were planned using the Taguchi's DoE with orthogonal array L16 was employed. The optimised combination for minimal wear rate was identified through the main effects plot for the SN ratio, and ANOVA was used to determine the contribution of each input parameter to the output variables. ANOVA results indicated that sliding distance had the most significant impact on wear rate, while the type of composite was the least significant factor. A predictive mathematical model through regression analysis was performed to examine wear rate, which was subsequently validated through practical testing. The experimental results aligned well with the predicted values.

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