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The Investigation of Machinability and Surface Properties of Aluminium Alloy Matrix Composites

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Highlights:

- MMC specimens were prepared in the AA6061 matrix with ilmenite as reinforcement at different weight percentages, viz. 5%, 10%, and 15%.
- Metal matrix composite specimens were machined successfully.
- In the turning process, the cutting forces were observed to be minimum at higher speeds for MMCs with 10 and 15 wt.% reinforcement.
- Lower feed rates were applied for lower cutting forces during the turning to obtain a better surface finish.
- Higher levels of feed rates are not recommended for a better surface finish.

Abstract. Aluminum matrix composites (AMCs) are crucial to the progress of composite application areas due to their remarkable mechanical properties. Their usage has expanded into different fields such as the aerospace, automobile, and defense industries. The present study used wrought Al alloy AA6061 as the matrix, while ilmenite ($FeTiO_3$) particles were used as reinforcement at different weight percentages to prepare metal matrix composites. One of the most economical and simple casting routes among the several available fabrication techniques for the preparation of composites is the stir casting method, which was applied in the present investigation to prepare the AMCs. The machinability of the fabricated composites and the surface roughness property after machining were studied to understand the effect of speed and feed during machining. The results showed that an increase in speed decreased the cutting forces and the surface roughness. Meanwhile, an increase in surface roughness was observed with an increase in feed.

Keywords: *AA6061; ilmenite; machinability; metal matrix composites; surface roughness.*

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1 Introduction

Many researchers are currently interested in producing different combinations of materials due to the growing demand for products from composite materials with enhanced properties such as rigidity, high strength, fatigue, hardness and wear resistance. Several studies have, therefore, been conducted on aluminum alloy matrix composites (AMCs) in industrial laboratories and small-scale industries over the last two decades. AMCs are extensively used in the commercial sector and automobile and aerospace applications due to their high corrosion and wear resistance [1]. For example, the alloy AA2618 was combined with the reinforcement of silicon nitride (Si_3N_4), zirconium boride (ZrB_2), and aluminum nitride (AlN) in [2]. AMC was successfully synthesized with different weight percentages of the reinforcement, i.e. 0, 2, 4, 6, and 8 wt.%, using a stir casting process. The tribological behavior of the composites was studied at different temperatures while the effect of the process parameters and their percentage contribution was evaluated using the ANOVA and Taguchi methods. Moreover, genetic algorithm (GA) was used to optimize the greatest and average wear rate in order to investigate the effect of the process control parameters. In another study, Al6061-TiC MMCs were made by combining C and K_2TiF_6 with molten aluminum, after which the Vickers hardness tests conducted showed an increase in hardness [3]. The turning operation was also performed on 0, 2, and 4 wt.% composite specimens. The influence of process parameters such as cutting speed, feed rate, and depth of cut on the response of surface roughness and cutting force were studied during the process. It was observed that a higher cutting speed led to a lower surface roughness and cutting force, while a higher spindle speed produced more wear. Moreover, higher feed rates and depth of cut led to higher surface roughness and cutting force.

Satish & Karthick [4] investigated the dry sliding wear behavior of AMCs with SiC as reinforcement and found the sliding distance to be the most significant factor when compared with sliding velocity and the percentage of the composition. Another research observed the enhancement in hardness of AMCs with an increase in SiC wt.% [5]. MMCs of AA6061with silicon carbide were fabricated using the stir casting technique and the mechanical properties such as tensile strength and hardness were found to vary with the wt.% of the reinforcement [6]. It was also discovered that the wear and volume proportion of the reinforcement were inversely proportional to each other in the experiments conducted to study the effect of machining process parameters on the surface roughness of MMCs. The surface finish was observed to increase as the feed rate was increased, but it was not directly proportional to the spindle speed [7]. Moreover, Neeraj Pandey, *et al.* [8] fabricated aluminum matrix composites with aluminum borate whisker (ABOw) as reinforcement and evaluated the bending strength, compressive strength, hardness, and dry sliding wear behavior. The results showed a significant improvement in wear resistance for the 10% ABOw. Samal, *et al.* [9] prepared composites with Al5052 as matrix and TiC as reinforcement and observed an enhancement in wear properties with an increase in the proportion of the reinforcement.

The attention of researchers is currently turning to hybrid metal matrix composites, which are expected to produce improved properties compared to traditional materials and single reinforced composites [10]. Aluminum MMCs are preferred to conventional materials in automotive, marine, and aerospace applications due to their improved wear resistance and high strength-to-weight ratio [11]. Moreover, the addition of B_4C particulates to the A16061 matrix produces enhanced mechanical properties of the base alloy [12]. Some researchers have observed that the addition of magnesium into the melt was able to improve the fly ash and SiC particles wettability in the matrix [13]. The presence of Mg_2Si particles in aluminum alloys, especially the 6000 series, also gives them the unique property of undergoing aging or precipitation hardening. It was also reported that mechanical properties such as hardness, load-bearing, and strength effectiveness are enhanced when the matrix is reinforced with Si_3N_4 [14]. Meanwhile, the macro and micro hardness have been observed to decrease by 10.43% and 11.12% with the addition of graphite particles as reinforcement [15]. Furthermore, dry sliding wear tests were conducted on MMCs reinforced with graphite and FA particles [16]. The results showed that the composites were influenced by the sliding distance and wt.% of the reinforcement. Therefore, the present study attempted to determine the machinability and surface finish properties of AA6061and ilmenite MMCs in a turning operation considering the importance of MMCs in industrial applications and the problems associated with their machining.

2 Experimental Details

This study used AA6061 as the matrix while the particles of ilmenite ($FeTiO_3$) were reinforced at different weight percentages of 5, 10, and 15 wt.% using the stir casting method in order to prepare the metal matrix composites (MMCs). The aluminum alloy (AA6061) was hardened by precipitation, with its main alloying elements being magnesium and silicon and the chemical composition as shown in Table 1. The alloy has good mechanical properties, including moderate to high strength and being heat-treatable. It is commonly used in aerospace applications like motorboats truck frames, helicopter rotor skins, rivets, tubes, transportation, pylons, shipbuilding, rail coaches, and heavy-duty frameworks. Meanwhile, ilmenite is a lean magnetic titanium-iron magnetic oxide mineral that is iron-black or steel-gray. It is an oxide of titanium made of crystalline iron ($FeTiO_3$) and has a trigonal structure. The ilmenite crystal structure is a sequence version of corundum such that all the cations are similar but possess alternating layers perpendicular to the trigonal c-axis in the ilmenite ions Fe^{2+} and Ti^{4+}, as shown in Figure 1. The properties of the ilmenite include being light-weight, corrosion-resistant, weakly magnetic, and reacting poorly to hand magnets. Its powder was acquired in this research from Trimex sands Pvt. Ltd. Srikakulam, while the metal matrix composites were made with AA6061 as matrix and the ilmenite powder as reinforcement.

Table 1 AA6061 alloy chemical formulation.

Material	Mg	Fe	Cu	Mn	Si	Al
AA6061	0.69	0.23	0.31	0.33	0.52	Balance

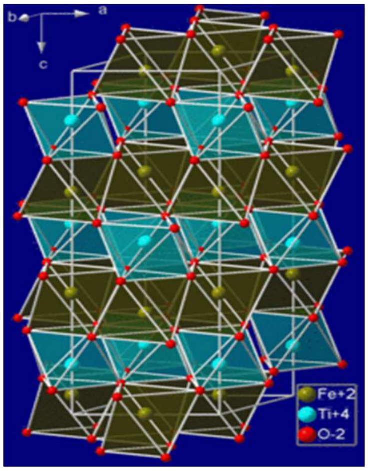


Figure 1 Crystal structure of ilmenite.

A two-step mixing stir casting method was adopted to produce the AA6061 matrix composites reinforced with ilmenite particles. This involved melting the AA6061 aluminum alloy in an electric furnace while the ilmenite powder was preheated to 600 °C for 30 minutes in a muffle furnace to remove the moisture content. The powder was added to the molten material at 800 °C to 850 °C during the formation of a vortex in the melt due to stirring, after which the molten composite was poured into a metal die. The aluminum metal matrix composite specimens shown in Figure 2 were prepared at 5, 10, and 15 wt.% of ilmenite powder. Meanwhile, a section was cut from the cast specimen for the metallography. Initially, the specimen was ground using a belt grinder, followed by rough polishing with different grades of emery papers at 300, 400, 600, 1/0, 2/0, and 3/0.

Figure 2 Metal matrix composite specimen after stir casting.

The specimen was later placed on a disc polisher with velvet cloth for final polishing, washed, dried, and etched with Keller's solution, and dried again. The microstructure was later observed under an Olympus optical microscope and a JEOL 6510 LV scanning electron microscope (SEM) and the cast specimens were machined using a CNC lathe machine (Figure 3) with cemented carbide inserted as a cutting tool at two different speeds, 360 rpm and 560 rpm, with 0.16, 0.14, and 0.20 mm/rev feed rates and a constant cutting depth of 0.25 mm. The forces obtained during the machining were measured using a dynamometer and the surface roughness with a Mitutoyo profilometer.

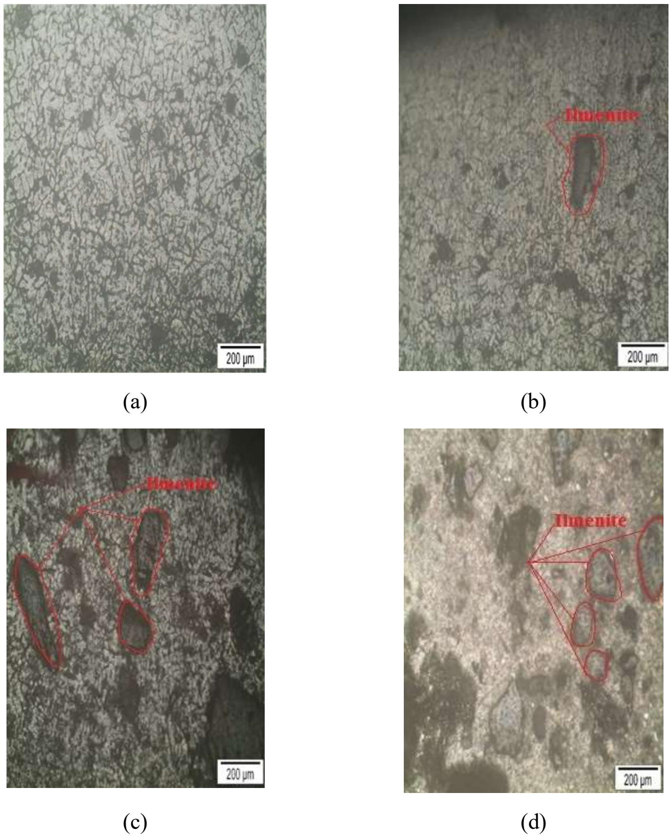
Figure 3 CNC machine used in the experiment and the experimental setup.

3 Results and Discussion

In this study, aluminum metal matrix composites were fabricated and machined at different proportions of reinforcement and later tested for surface roughness. The results obtained in the tests are presented and discussed in this section.

3.1 Microstructural Characterization

The microstructure evaluation was conducted using an optical microscope and SEM after polishing and etching the samples with the results presented in Figures 4 and 5. The SEM and optical micrographs showed that the deposition of ilmenite powder in the matrix was relatively consistent and the porosity in all MMCs was low. It was also observed that there was a strong bond between the particulates of the reinforcement due to the use of the stir casting method matrix.



(a) (b)

(c) (d)

Figure 4 Optical microscope images: a) base metal, b) 5% ilmenite composite, c) 10% ilmenite composite, d) 15% ilmenite composite.

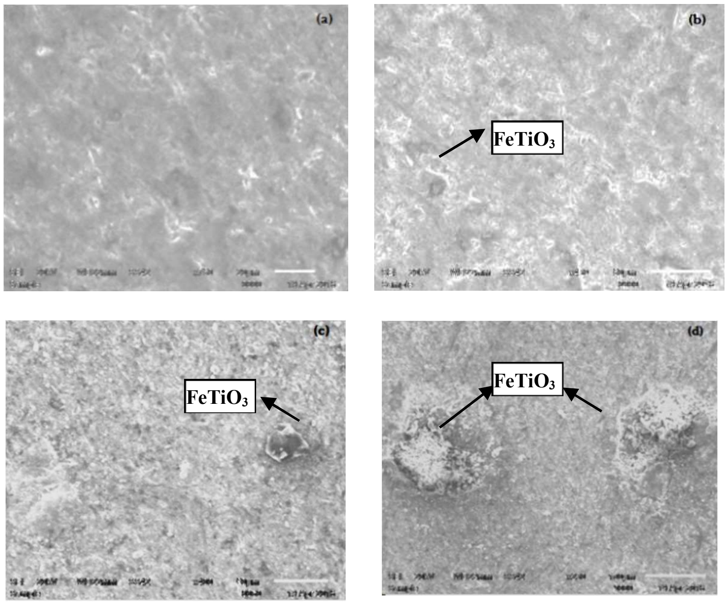


Figure 5 SEM images: a) base metal, b) 5% ilmenite composite, c) 10% ilmenite composite, d) 15% ilmenite composite.

3.2 Machining Studies

The cast base metal and metal matrix composites were machined and the influence of the wt.% of the reinforcement particles on the cutting forces was recorded. The result is presented as part of the experimental results in Table 2.

Table 2 Cutting force values after turning of base metal and MMCs.

Specimen No.	Depth of cut (mm)	Speed (rpm)	Feed rate (mm/rev)	Cutting forces(N)			
				(Base metal AA6061)	wt.% of ilmenite in MMC		
					5%	10%	15%
1	0.25	560	0.14	21.57	81.25	8.43	46.48
2	0.25	560	0.16	14.94	25.77	12.66	16.75
3	0.25	560	0.20	22.65	70.49	7.249	18.58
4	0.25	360	0.14	14.78	19.21	54.95	73.40
5	0.25	360	0.16	5.417	15.64	21.07	24.3
6	0.25	360	0.20	12.32	19.16	64.07	95.97

Figure 6 shows the impact of speed on the mean cutting force when turning the composites of base metal and the metal matrix. The tables and graphs show that the MMCs with 10% and 15% reinforcement reduced the cutting force as the speed increased while the base metal AA6061 and MMC with 5% reinforcement increased the cutting force. A similar trend was also observed by Xu, *et al.* [17]. Figure 7 shows that the cutting force at two speeds decreased at a particular feed rate of 0.16 mm/rev and increased again when the feed rate value increased beyond 0.16mm/rev. This gives an idea of the rate of feed to be applied for lower cutting forces.

The surface roughness values of the MMC specimens after machining are presented in Table 3 and displayed as a graph in Figure 8. The results show that the values after machining decreased with an increase in speed. This was observed in the machining of the composite specimens irrespective of the feed rate applied. This is associated with the fact that an increase in speed reduces build-up edge creation and also contributes to the reduction in surface roughness at higher cutting speeds.

The influence of different feed levels on the surface roughness is shown in Figure 9. The surface roughness values were observed to increase as the feed was increased. A similar trend was reported by Abdullah, *et al.* [18] these results indicate that higher feed levels are not recommended for better surface finishing.

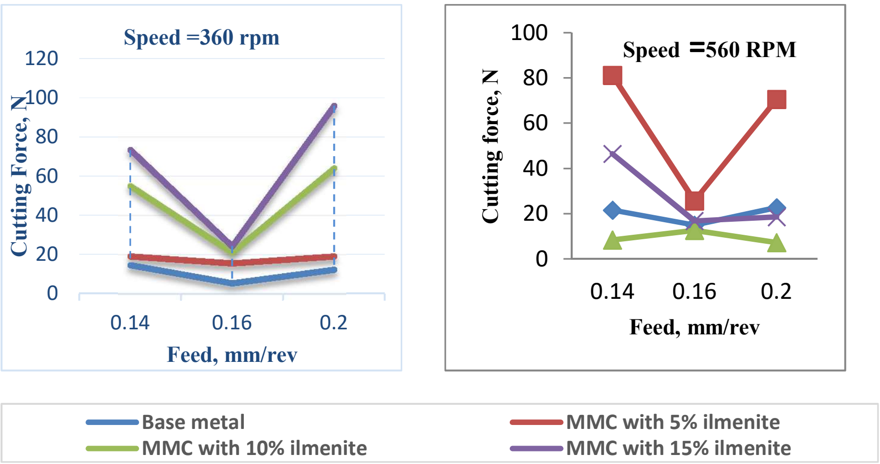


Figure 6 Effect of feed on cutting force at different speeds.

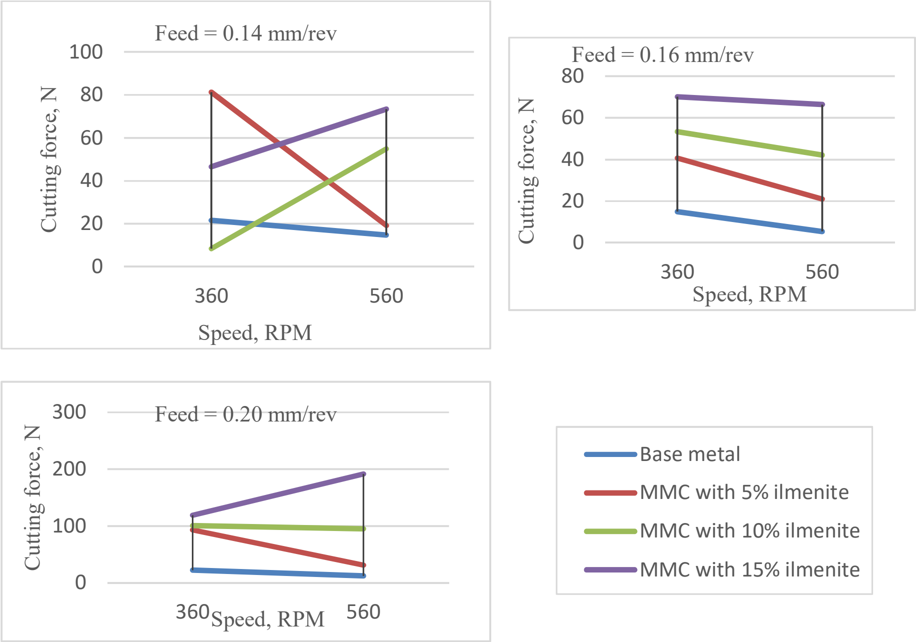


Figure 7 Influence of speed on cutting force at different feeds.

Table 3 Surface roughness values after turning of base metal and MMCs.

Specimen No.	Speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	Surface roughness (R_a) (µm)			
				(Base metal AA6061)	wt.% of ilmenite in MMC		
					5%	10%	15%
1	560	0.25	0.14	2.5	3.17	4.52	3.82
2	560	0.25	0.16	3.45	4.0	4.97	4.5
3	560	0.25	0.20	4.25	4.5	5.77	5.0
4	360	0.25	0.14	4.2	4.20	5.2	4.69
5	360	0.25	0.16	4.5	4.50	5.5	4.9
6	360	0.25	0.20	5.36	5.36	6.41	5.7

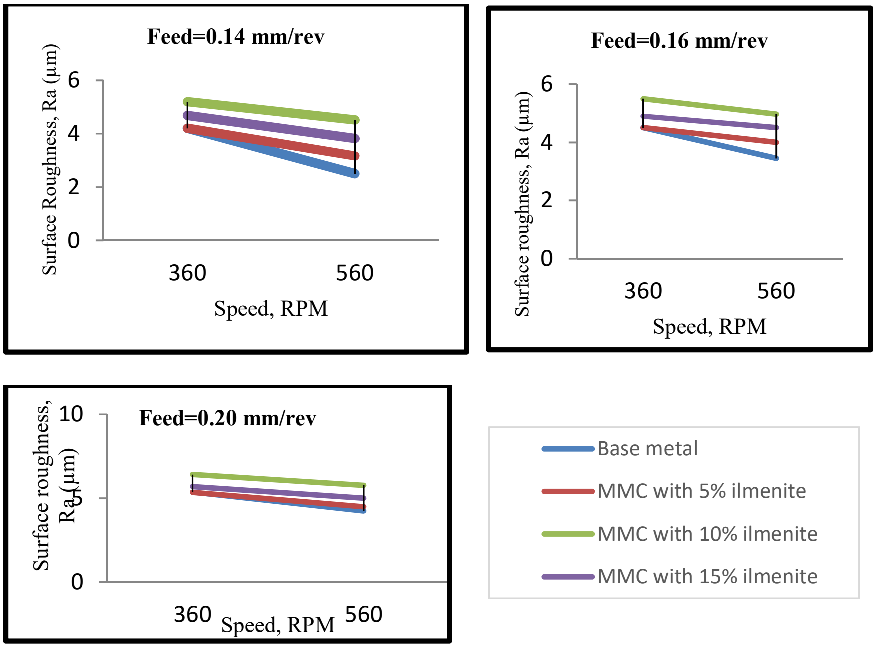


Figure 8 Surface roughness graphs for a depth of cut = 25 mm at different cutting speeds.

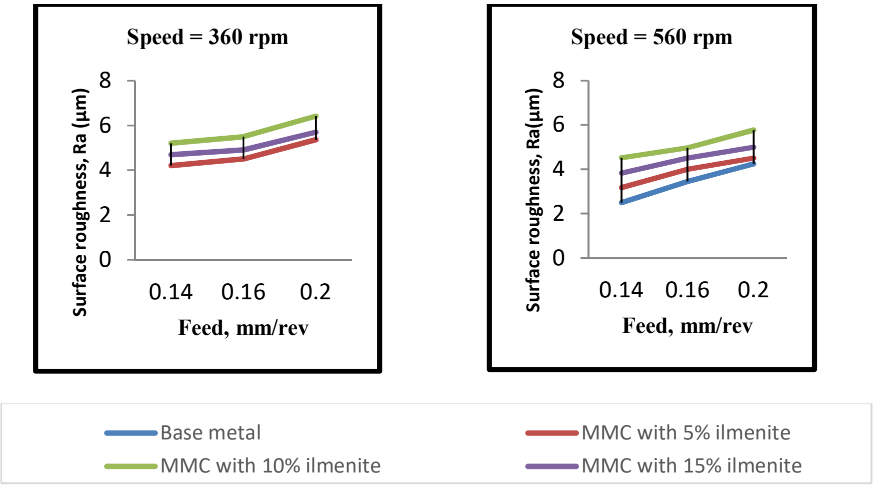


Figure 9 Effect of feed rate on the surface roughness at 0.25 mm depth of cut.

4 Conclusions

AA6061MMC composite specimens were prepared using stir casting, after which the effects of the addition of ilmenite reinforcement particles on their machinability and surface roughness was evaluated. The conclusions drawn from the experiment are stated as follows:

1. AA6061 metal matrix composite specimens were successfully fabricated at 5, 10, and 15 wt.% of ilmenite powder using the stir casting process.
2. Optical micrography and SEM images showed that the ilmenite particles were evenly distributed in the aluminum alloy matrix.
3. The machinability investigations showed that an increase in cutting speed led to a low cutting force for the 10% reinforcement composite.
4. The cutting force was found to be minimum at a feed rate of 0.16 mm/rev and increased again as the feed rate increased.
5. At different feed rates, the surface roughness on the specimens decreased as the cutting speed was increased.
6. At different speeds, the surface roughness value increased as the feed rate was increased.

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