

Investigation on Mechanical and Machinability Properties of Aluminium Metal Matrix Composite Reinforced with Titanium Oxide (TiO₂) and Graphite (Gr) Particles

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Received: 20 August 2022, Revised: 23 November 2022, Accepted: 30 November 2022, Published: 25 August 2023

Abstract

This research paper deals with the preparation process and testing of metal matrix composites comprising Aluminium alloy (Al 6061) as the base metal and Titanium oxide (TiO₂) and Graphite (Gr) as reinforcements. Due to their high specific strength, superior malleability, lightweight, stiffness and excellent resistance to corrosion, oxidation and wear, the aluminium metal matrix composites are preferred in the automobile and industrial sectors for component manufacturing. No work reported on machinability properties of Titanium oxide (TiO₂) and Graphite (Gr) reinforced aluminium composites so far. This study prepared and studied samples composed of variable proportions of titanium oxide and graphite. The samples were prepared using the stir casting method. While stirring, the required additives were added to the molten aluminium mixture. To perform the tests, the samples were prepared according to standard dimensions after solidification. The mechanical properties of the prepared composite were examined using various test procedures, such as strength and hardness. Scanning electron microscopy was used to examine the microstructure of the test composite samples. The EDAX test confirmed the presence of graphite and Titanium oxide in the aluminium based composite specimens. Furthermore, machining was done to study the cutting forces on the tool. The test results showed a significant impact of the reinforced materials on the mechanical and machinability properties of aluminium metal matrix composites. Gr decreases hardness, while TiO₂ increases it. TiO₂ and Gr reinforcements increase the tensile strength of Al 6061 composites. The addition of TiO₂ decreased the composite's elongation. The proof strength of 2 % Al6061 was high, however it decreased with 3 % Gr and increased with TiO₂ reinforcement. Reinforcements increase cutting forces during machining; when comparing the machining of Al 6061 to that of 3 % Gr and 5 % TiO₂, a 50 % increase in cutting forces is noticed. However, excessive reinforcements may reduce cutting forces due to poor matrix-reinforcement adhesion.

Keywords: Metal matrix composites, Mechanical properties, Stir casting, Al 6061, TiO₂, Graphite

Introduction

Composite materials possess good mechanical properties compared to monolithic materials. They are among the most widely used materials due to their adaptability to different situations and relative ease of combining with other materials to serve specific purposes and exhibit desirable properties. They have fabulous high strength, lightweight, chemical and corrosion resistance, and have a low thermal expansion coefficient. They are formed by combining 2 or more materials with quite different properties and do not dissolve or blend. The different materials in the composite work together and exhibit unique properties. In the present world, most of the experimental work on composite materials is focused on their applications in the sectors of aerospace, automobiles, helicopters, spacecraft, etc. Aluminium matrix composites (AMCs) have strong physical and mechanical qualities, making them potential materials for a variety of applications. In comparison to traditional engineering materials, the metallic matrix's stiffness, specific strength, wear, creep and fatigue properties are improved with the addition of reinforcements. By adding desirable single and multiple reinforcement particulates like SiC, Al₂O₃, Gr, TiO₂, B₄C, AlN and fly ash as composites, the composite materials exhibit higher characteristics than the base alloy material.

Several authors have investigated microstructure/mechanical property links for aluminium with discontinuous reinforcement. The reinforcements have generally positive influence on the mechanical characteristics of aluminium alloys relative to the matrix properties. In the microstructure and wear characteristics of aluminium composites reinforced with varying percentages of graphite (2 % vol.) and Al_2O_3 (3 - 12 %) [1] were studied. Graphite and Al_2O_3 were mechanically alloyed after being introduced to an Al matrix. Tests for wear were performed using 3 different weights and four different sliding distances. As a result of the increased reinforcement in aluminium composites, it was found that the hardness and density of composites increased. The composite material with 12 % Al_2O_3 in it had the highest hardness and density values. In the wear testing, the composite containing 12 % Al_2O_3 likewise yielded the lowest weight loss. Powder metallurgy technique was used to create TiO_2 -coated Graphene nano platelets (GNPs) reinforced 7075 aluminium (Al) nanocomposites. Investigations have been done into how GNPs affect the mechanical characteristics and microstructure of aluminium matrix nanocomposites with and without TiO_2 coating layers. According to experimental findings, the addition of GNPs with TiO_2 coating layers increased the mechanical properties of the nano composites even more than the addition of pure GNPs. In compared to the matrix, the nanocomposites reinforced with TiO_2 -coated GNPs showed increases in yield strength, ultimate tensile strength, and microhardness of 22.9, 25.9 and 20.1 %, respectively [2]. Titanium and its alloys, on the other hand, stand out because to their exceptional strength and corrosion resistance. Titanium is increasingly used in architecture, chemical processing, medical, power generation, marine and offshore, sports and leisure and transportation [3,4].

Titanium and its alloys, however, stand out because to their extraordinary strength and corrosion resistance. Titanium is utilized increasingly in architectural, chemical processing, medical, power generation, maritime and offshore, sports and recreation and transportation [3,4]. Titanium alloys' strength is particularly attractive at higher temperatures. However, their maximum operating temperature is limited by their reaction with oxygen. TiO_2 has been regarded as one of the leading possibilities for a reinforcing material due to its low density, excellent mechanical capabilities, particularly at high temperatures and are resistant to wear [3-5].

The influence of surface roughness (SR) and material removal rate (MRR) on machining the TiB_2 reinforced Al-6063 composite materials was studied [6]. They adopted the Taguchi method for finding the optimal cutting factors for SR and MRR. It was noted that the speed and feed parameters are most significant, along with TiB_2 filler loading/depth of cut, which affect surface roughness. The influence of cutting speed, depth of cut and feed on SR in fabricated hybrid aluminium metal matrix composite (MMC) (Al/SiCp/ B_4Cp) by Taguchi experimental technique, and it was concluded that feed and cutting speed are the most influenced parameters [7]. The 2 types of composites, such as ZA43 silicon carbide and ZA43 silicon carbide and graphite, were fabricated with silicon carbide (5 %) and silicon carbide (5 %) and graphite as reinforcements, respectively. During machining, the composite containing silicon carbide and graphite as the cutting tool experienced more cutting force than the composite containing silicon carbide only [8]. The machinability properties of a Zinc-Aluminium alloy reinforced with SiC particulate metal matrix composite prepared by liquid metallurgy technique were studied. The MMC was fabricated with Zn (57 %), Al (43 %) and SiC (1 and 5 %) were added as reinforcement. Three different spindle speeds, feeds and depth of cuts were employed for the dry turning. The cutting force was significantly affected by speed, feed and depth of cut, whereas the surface finish was affected by speed and feed only [9]. The electro-discharge machine (EDM) is cost-effective for making dies and machining hard materials like ceramics. Using response surface methodology (RSM) and an appropriate Design of Experiments (DOE) technique, the effect of EDM process parameters on the MRR of Cu W MMC was investigated. The proposed mathematical model accurately described the performance within a set of parameters [10]. The metal matrix composites with Al 2024 as the base metal and Silicon Carbide (SiC) and Magnesium Oxide (MgO) as reinforcements in three different ratios (3, 6 and 12 %) were prepared using vertex method. In the machining experiments, 3 different cutting speeds (100, 150 and 200 $\text{m} \cdot \text{min}^{-1}$) and 3 different feed values (0.03, 0.06 and 0.12 mm/rev) were adopted, and the wear behaviour of cutting tools was examined using scanning electron microscopy (SEM). The selected cutting tool and cutting parameters were suitable for machining prepared composite materials [11]. The machinability of silicon carbide particulate aluminium metal matrix composite was investigated using a rhombic uncoated carbide tool. The influence of machining parameters, including cutting speed, feed and depth of cut on the tool wear and built-up was analysed. Based on test results and different SEM micrographs, the suitable range of cutting speed, feed and depth of cut were determined for proper machining of Al/SiC-MMC [12]. The impact of high-speed cutting parameters on the SR and cutting forces of machined Al/SiC composites were investigated using the experiment

method design and a 5-level central composite design. While the cutting speed was greater than $1,800 \text{ m} \cdot \text{min}^{-1}$, the feed rate was less than particle size/tooth, and the depth of cut was between 1 - 1.1 mm, the appropriate SR was achieved in the presence of coolant. Using CO_2 cryogenic coolant, the cutting forces increased by 3 - 8 % and SR improved by 19 - 23 % [13]. The influence of SiC particles (5, 15 and 20 %) on machining parameters such as cutting speed, feed rate and depth of cut on tool wear and cutting forces on tool wear in a turning process was studied. Utilizing titanium carbide inserts, continuous dry turning of Al/SiC particulate MMC by powder metallurgy was carried out.

With an increase in cutting speed, depth of cut and feed rate, the tool wear increases [14]. The influence of EDM process parameters such as current, pulse on-time and pulse-off time on MRR and SR was studied in Al 7075 hybrid metal matrix composite reinforced with Silicon carbide (SiC) and Titanium carbide (TiC). The hybrid metal matrix composites were fabricated using the stir casting process, and machining was performed by EDM using a copper tool. With the help of design expert software, the optimum parameters were identified. The metal removal rate was decreased and SR was increased, when the weight fraction of reinforcement increased [15].

Recently, the TiO_2 is also used as reinforcement because of their high hardness, superior corrosion resistance and wear resistance [16]. This work is intend to put together the benefits of TiO_2 and Gr as reinforcements and aluminium as matrix to develop materials with improved properties. Most industries prefer metal-matrix composites with aluminium to take advantage of its ease of fabrication. Thus, the mechanical and machinability properties are important for metal matrix composites intended for different applications. The mechanical and machinability properties of aluminium metal matrix reinforced with titanium dioxide (TiO_2) and graphite (Gr) have not been reported so far in the literature. In this study, aluminium based composites reinforced with variable proportions of titanium oxide and graphite were prepared and studied. The fabrication process was done by stir casting by adding the required additives into the molten mixture of aluminium, followed by continuous stirring. The solidified samples were cut according to the standard dimensions and various test procedures were conducted to examine the mechanical and machinability properties of the prepared composites.

Materials and methods

Materials

Aluminium 6061 (Al 6061), Titanium dioxide (TiO_2) of size particulates $25 \mu\text{m}$ and Graphite (Gr) of particulates size $45 \mu\text{m}$ were used. Al 6061 alloy composed of Al (97.62 %), Mg (0.89 %), Si (0.72 %), Fe (0.23 %), Cr (0.22 %), Cu (0.21 %), Zn (0.1 %) and Ti (0.01 %).

Composite preparation

Al 6061 was used as the base material and graphite and TiO_2 particles were used as the reinforcement materials. The metal matrix composites were fabricated with graphite (3 %) by varying the TiO_2 particle weight fraction (0, 5 and 10 %). Al 6061 alloy was preheated at $450 \text{ }^\circ\text{C}$ for 2 h and TiO_2 and Gr particles were preheated at $1,000 \text{ }^\circ\text{C}$ for 1.5 h for improving the wetting properties by removing the absorbed hydroxide and other gases. The composite slurry was reheated to a molten state and mechanical mixing was carried out with mild steel impeller for 20 min at 200 rpm of stirring speed. The composite slurry was poured into permanent metallic mold and the castings were obtained in the form of round rods of $20 \text{ (diameter)} \times 150 \text{ (length)} \text{ mm}^2$.

Methods

Microstructure determination

The $10 \text{ (diameter)} \times 10 \text{ (thickness)} \text{ mm}^2$ specimen samples were cut, mounted in bakelite and polished with SiC abrasive papers up to 1,000 grit size on velvet cloth using copious amounts of water as lubricant and Al_2O_3 ($1 \mu\text{m}$) paste. Following that, the samples were polished with diamond paste ($0.5 \mu\text{m}$) and etched with Keller's etchant. A scanning electron microscope was used to examine the polished mounted samples (HITACHI S-3700N, Japan). EDX was used to perform the chemical analysis on the sample that had been prepared for SEM.

Hardness determination

The hardness of a material depends on the atomic structure and grain size near the tested surface. Brinell hardness test gives high exactness, repeatability and great portrayal readings. The Brinell hardness tests were performed with 10 mm diameter steel ball under 500 kg load.

Tension test

The tensile test was conducted as per ASTM E8M standard using computerized tensometer. For each composite, 3 test specimens were tested and average values of ultimate tensile strength and ductility (% elongation) were measured.

Cutting forces

The turning operations were performed on a Combination Turret Lathe at a cutting speed of 36 m/min and feed of 0.33 mm/rev with a depth of cut range of 0.25 - 1.0 mm. The cutting forces (feed, F_x and cutting forces, F_z) were measured using EMT CNC Lathe Tool Dynamometer with tangential, feed and radial ranges of 0 - 500 kg.

Results and discussion

Figure 1 shows the SEM images of aluminium composite with TiO_2 and Gr and reinforcements, revealing the reinforcement morphology and its distribution in the MMC. The SEM images also clearly indicated the uniform distribution of the TiO_2 and Gr particles in the prepared composites. **Figure 2** shows the EDAX spectra of Al 6061 and AMC. The peak value shows the presence of Al and its compounds on the surface. The analysis revealed the presence of TiO_2 and Gr particles in Al alloy.

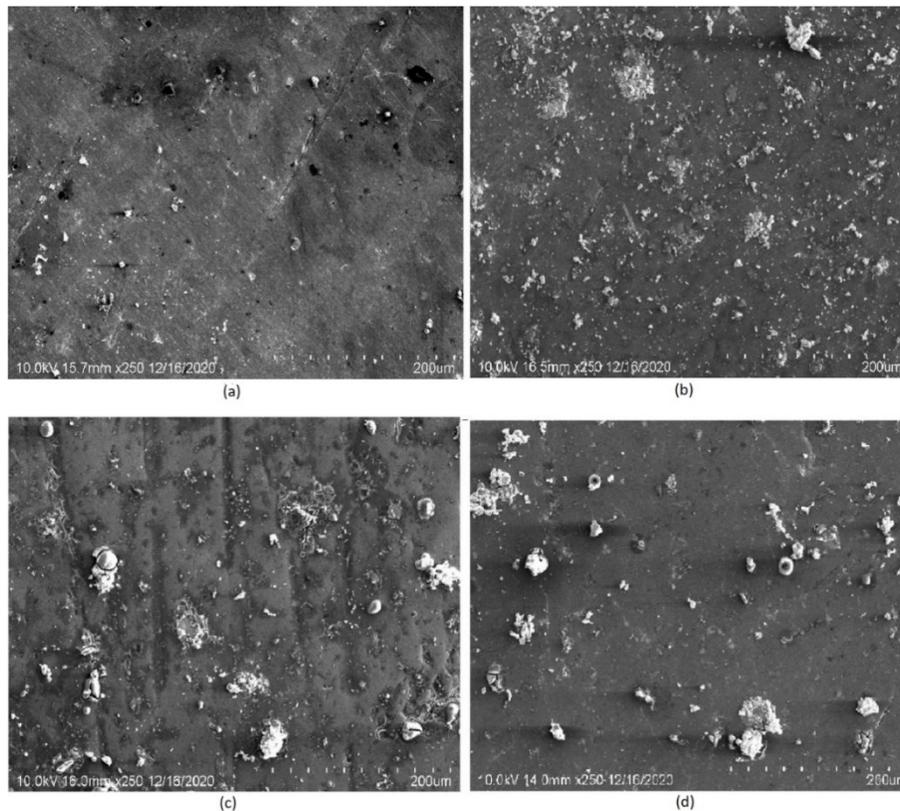


Figure 1 SEM micrographs of Al 6061 composite with different compositions, (a) Al 6061 matrix alloy, (b) Al 6061 + Gr (3%), (c) Al 6061 + Gr (3%) + TiO_2 (5%) and (d) Al 6061 + Gr (3%) + TiO_2 (10%).

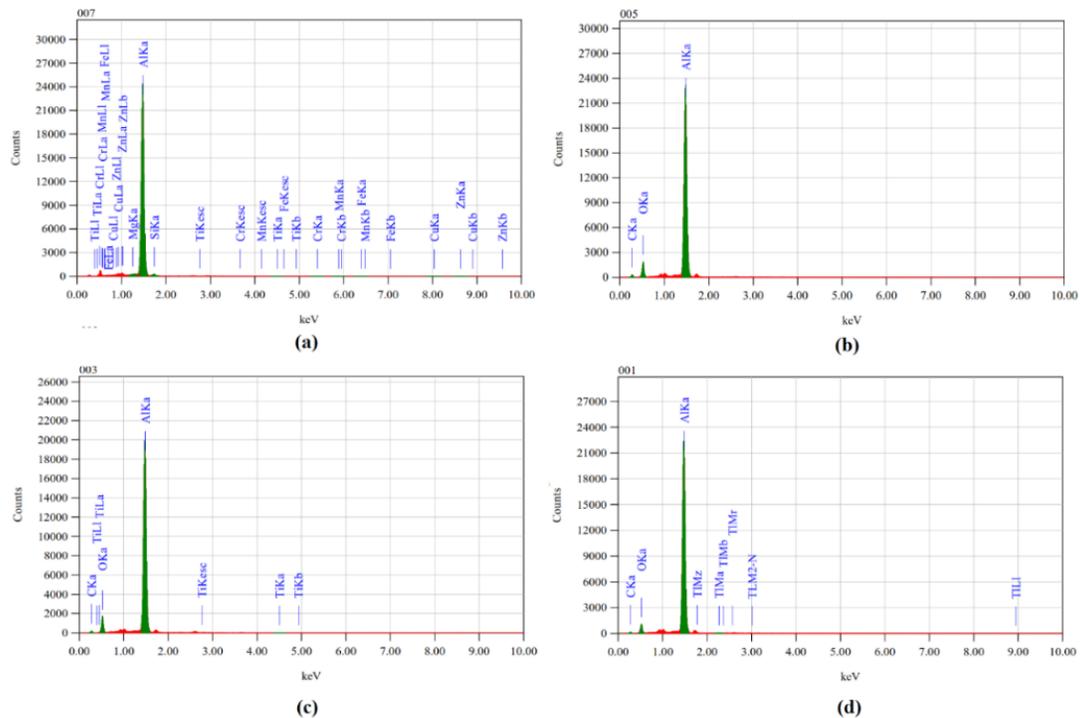


Figure 2 EDAX spectra of Al 6061 composite with different compositions, (a) Al 6061 matrix alloy, (b) Al 6061 + Gr (3%), (c) Al 6061 + Gr (3%) + TiO₂ (5%) and (d) Al 6061 + Gr (3%) + TiO₂ (10%).

Mechanical and machinability properties

The effect of TiO₂ and Gr content on the hardness of Al 6061AMCs is presented in **Figure 3**.

The hardness of the composite depends on the type of reinforcements added to the Al 6061. The hardness has been noticed to be decreased with the addition of Gr particles and it is significantly lower than the hardness value of the base Al 6061 matrix alloy. This decrease in hardness may be owing to the occurrence due the brittle and soft graphite particles. Further, the addition of TiO₂ hard particulates to the base metal matrix increases the hardness of the composite. Similar increase in hardness has been seen by other researchers with higher TiO₂ concentration compared to the base material [17].

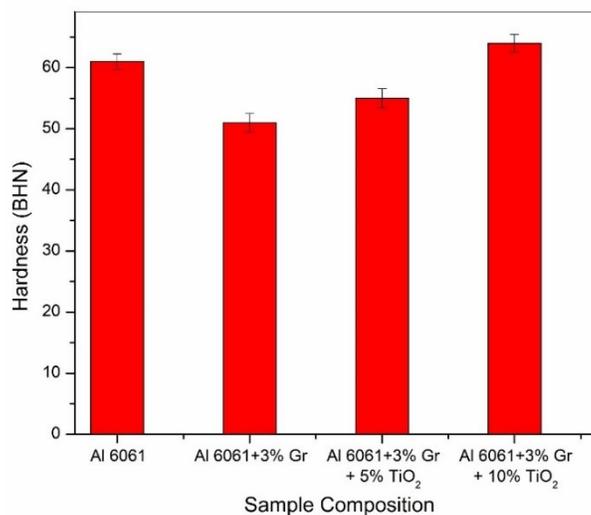


Figure 3 Influence of reinforcements on hardness of the Al6061 alloy reinforced with Gr and TiO₂.

Figure 4 shows the ultimate tensile strength of the aluminium metal matrix composites. The addition of graphite to the base metal decreased the strength, as graphite is brittle in nature. The strength of Al 6061 matrix was increased by adding 5 % of TiO_2 . The addition of particle reinforcement composite increases tensile strength because the load is passed to the reinforcing components, hence enhancing the load bearing capabilities of the composites. Other researchers [18] have similarly seen a rise in UTS with increasing concentrations of reinforcement. Further, an increase in TiO_2 reinforcement (10 %) caused a decrease in strength, possibly due to poor interfacial bonding between the matrix and reinforcement. The percentage of elongation increased with the addition of Gr to the matrix and decreased with TiO_2 (5 %) to the base material. The decrease in elongation was predominant with the increase of TiO_2 (10 %) composition (**Figure 5**). The % elongation falls as the vol % of reinforcement increases [19] as the elongation is negatively impacted by the increased number of nucleation sites present for cracks to form [5,20,21]. Moreover, the % elongation compared to Al 6061, increases with addition of Gr and decreases as the TiO_2 addition to the matrix. The variation in proof stress for the composite material is depicted in **Figure 6**. The addition of Gr to base material results in a drop in proof stress and the addition of TiO_2 (5 %) enhances the proof stress. It has also been observed that Proof stress of the composite increases with the increase in weight % of TiO_2 .

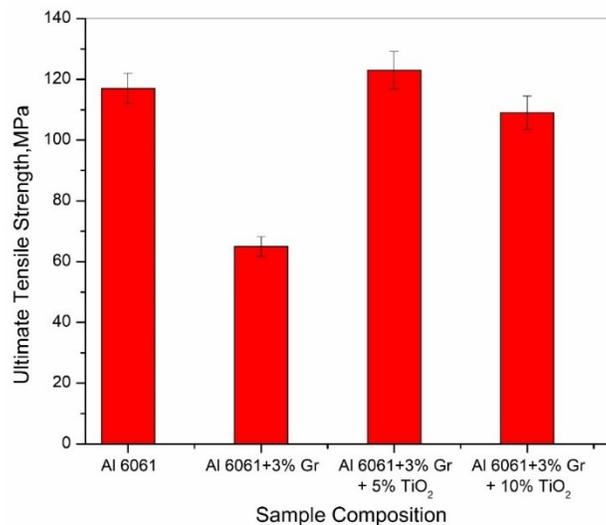


Figure 4 Ultimate tensile strength of the samples.

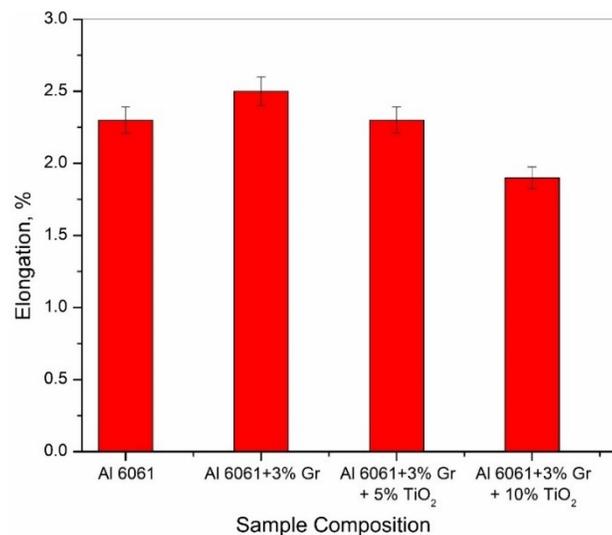


Figure 5 Percentage elongation of the samples.

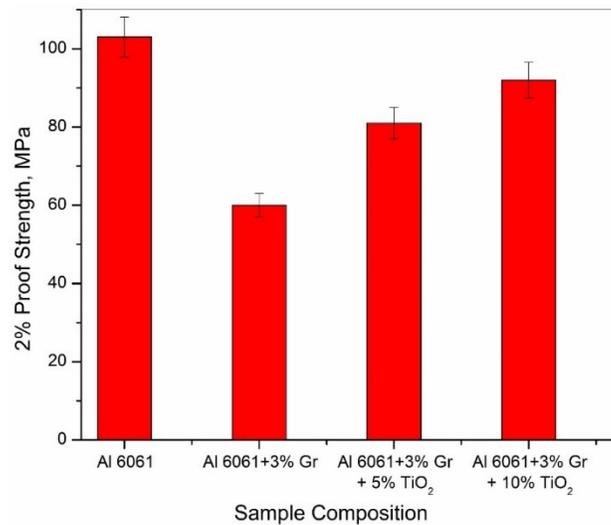


Figure 6 Two % proof strength of the samples.

To analyze the machinability factors, the measurement of cutting force components is essential [22,23]. Turning operations were performed on the composite samples of 20 mm in diameter at 570 rpm for different depths of cuts varying from 0.25 to 1 mm, with 0.25 mm incremental values to evaluate the cutting forces. The feed force on the carbide-tipped tool in the direction of tool travel (F_x) and the main cutting force in the cutting velocity vector (F_z) direction during machining Al 6061/TiO₂/Gr-MMC were measured and presented in **Figures 7 and 8**.

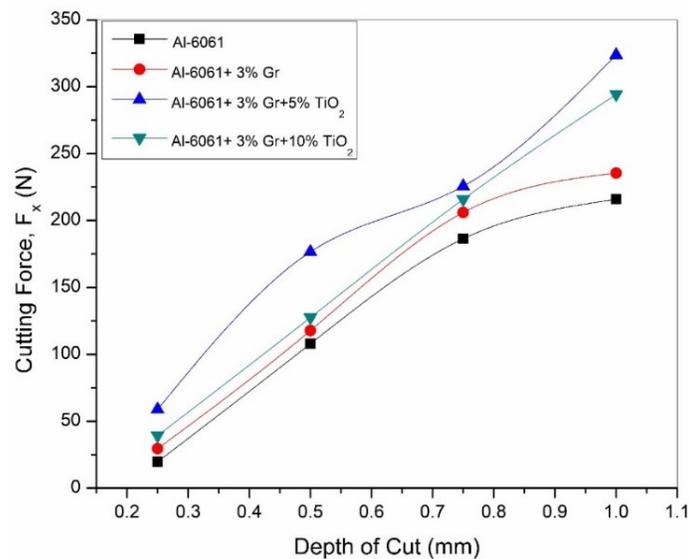


Figure 7 Influence the depth of cut on feed force, F_x at constant Cutting speed: 36 m/min and Feed: 0.33 mm/rev.

Plots 7 and 8 show the influence of TiO₂ and Gr reinforced Aluminium metal matrix composites on the depth of cut and cutting forces in the direction of tool travel and tangential direction, respectively. The cutting force in the direction of tool travel is low for all the depth of cuts for Al6061 composite, and this force on the cutting tool increases while cutting the reinforced composite for all depth of cuts. Higher values of forces have been reported on the cutting tool while performing a turning operation on Al 6061 with 3 % Gr and 5 % TiO₂. The same trend has been observed for tangential cutting force also.

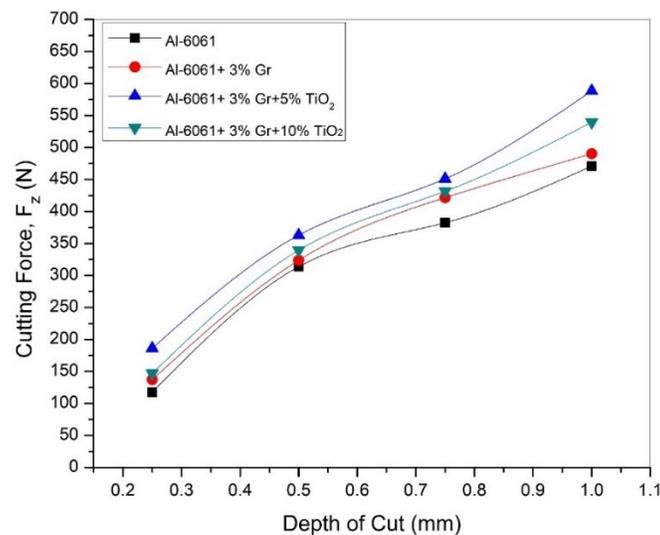


Figure 8 Influence the depth of cut on cutting force, F_z , at constant Cutting speed: 36 m/min and Feed: 0.33 mm/rev.

Conclusions

In this investigation, aluminium-based composites reinforced with varying quantities of titanium oxide and graphite were fabricated and examined. Stir casting method was used to prepare Al 6061 hybrid metal matrix composites reinforced with Gr and TiO₂. Samples of the composites were cut to standard dimensions and then various techniques were used to examine the mechanical properties and machinability characteristics of the composites were also examined. The following conclusions are drawn from the test findings. The addition of Gr to the base metal decreases hardness, whereas the addition of TiO₂ improves hardness. The tensile strength of Al 6061 alloy composites was increased by 5 % TiO₂ and 3 % Gr reinforcements. The percentage elongation of metal matrix composites decreased as the TiO₂ reinforcement increased. The 2 % proof strength of Al6061 alloy was strong, but it dropped with adding 3 % Gr and increased with TiO₂ reinforcement. Reinforcements have a more significant influence on cutting tool forces. The addition of reinforcements, to some extent, increases the cutting forces. Comparing the machining of Al 6061 to the machining of 3 % Gr and 5 % TiO₂, the increase in these cutting forces is observed about 50 %. Significant additional reinforcement results in a lower cutting force, probably due to poor interfacial bonding between the matrix and reinforcement.

Acknowledgments

The authors would like express their gratitude to Jawaharlal Nehru Technological University Hyderabad, Hyderabad, India for providing collaborative research grant under TEQIP-III scheme.

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