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# EFFECT OF CUTTING PARAMETERS ON SURFACE INTEGRITY DURING NC TURNING OF Al 6061/SiC$_p$ METAL MATRIX COMPOSITE

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## ABSTRACT

*Metal matrix composite (MMC) has many advanced mechanical properties such as high wear resistance, less weight, high strength and stiffness, lower coefficient of thermal expansion and high thermal conductivity, which are widely used in the automotive, railway and aerospace industries. The main limitation in MMC application is difficult to machine, which leads to low production volumes and high machining costs. This study aims to investigate the surface integrity of metal matrix composites through the high-speed turning experiments. High cutting velocity with low feed rate were the dominant parameter associated with the surface roughness. Surface roughness as low as 0.20 micron was achieved at low feed rate of 0.10 mm/rev with high cutting velocity of 175 m/min on Al 6061/SiC$_p$ by solid coated (TiAlN) cemented carbide tool. Conversely, the lowest microhardness of 102 HV are obtained at high velocity of 200 m/min with feed rate of 0.10 mm/rev. The study concludes that high cutting velocity can effectively reduce surface roughness when machining difficult-to-cut materials. However, it is important to consider that reducing the feed rate can significantly increase the turning time. Additionally, flank wear and chip formation must be considered when selecting cutting parameters. Continuous and long chips that wrap around the machined surface can cause surface damage. This research demonstrates that hard turning is a viable alternative to grinding for achieving low surface roughness in MMCs, provided that the appropriate operating parameters are carefully selected.*

## 1. Introduction

In recent years, a new generation of materials known as metal matrix composites (MMCs) has emerged, owing to their significant scientific, technological, and commercial potential. MMCs have attracted considerable attention in the automotive and aerospace industries due to their outstanding properties, such as high strength, low weight, high modulus, low ductility, excellent wear resistance, high thermal conductivity, and low thermal expansion [1, 2]. These composites can be manufactured using a variety of cost-effective technologies. However, their poor machinability remains a major challenge, necessitating improvements in cutting tool materials and machining strategies [3].

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Among various MMCs, aluminium-based metal matrix composites (Al-MMCs) are being increasingly adopted as substitutes for conventional aluminium alloys in diverse engineering applications due to their enhanced mechanical and thermal performance [4].

From the perspective of metal cutting theory, analyzing surface integrity is one of the most effective approaches to understanding the machining behaviour of materials [5]. Surface integrity directly influences the functional performance of machined components, including their fatigue life, tribological characteristics, and mechanical compatibility [6]. It consists of two critical aspects: surface texture and microhardness.

Surface texture primarily refers to surface roughness, which represents the fine irregularities on a surface caused by machining. These are influenced by the tool geometry, cutting speed, feed rate, and cutting environment [7]. On the other hand, microhardness refers to the material's hardness on a microscopic scale, typically evaluated using indentation methods. The measured impression dimensions under a known load provide a quantitative hardness value, which reflects the surface's mechanical integrity and can be used to infer service performance [8].

To enhance tool life and performance during the machining of difficult-to-cut materials such as Al-MMCs, cemented carbide cutting tools are often used with coatings like titanium carbide (TiC), titanium nitride (TiN), and hafnium nitride (HfN). These coatings, generally 5–8 µm thick, are deposited over a tungsten carbide (WC) substrate and offer superior wear resistance and thermal stability, especially under high-speed machining conditions [9].

Although milling and turning are conceptually distinct operations, they share the fundamental principle of material removal through chip formation. Both aim to shape a workpiece to specified dimensions and tolerances [10].

The objective of the present study is to investigate the machinability of Al-MMCs using coated cermet carbide inserts, with a focus on evaluating the influence of various cutting conditions on surface quality and subsurface damage. The study aims to offer insights into the optimal machining parameters for improved surface integrity, which is critical for ensuring component performance in demanding applications.

## 2. Materials and Methods

The workpiece material used in this study is Al 6061 reinforced with SiC particles of metal matrix composite. As the matrix element, aluminium, titanium and magnesium alloy are used, while the popular reinforcements are silicon carbide (SiC) and alumina ($Al_2O_3$). Aluminium-based SiC particle reinforced MMC materials have become useful engineering materials due to their properties such as low weight, heat resistant, wear resistant and low cost.

Table 1. Chemical Composition of Al 6061/$SiC_p$

| Element | Wt. % |
|---|---|
| Silicon (Si) | 0.59 |
| Magnesium (Mg) | 1.04 |
| Carbon (C) | 0.001 |
| Chromium (Cr) | 0.09 |
| Copper (Cu) | 0.27 |
| Iron (Fe) | 0.15 |
| Manganese (Mn) | 0.004 |
| Zink (Zn) | 0.002 |
| Nickel (Ni) | 0.001 |
| Titanium (Ti) | 0.006 |
| Aluminum (Al) | 97.846 |

The requirements for any cutting tool material used for machining aluminium-based metal matrix composites should include wear resistance, high hot hardness, high strength and toughness, good thermal shock properties and adequate chemical stability at elevated temperature. Usually the cutting tool materials that used for machining are:

- Plain carbon and low alloy steels
- Cast cobalt alloy
- Carbon tool steel
- High speed steel (HSS)
- Cemented carbides
- Cermet
- Coated carbides
- Ceramics
- Synthetic diamond
- Cubic Boron Nitrides (CBN)

Cemented carbide tools are still largely used for machining the aluminium-based metal matrix composites. Over the years, the use of carbides for cutting tools has been established. However, with the increasing demand to achieve fast material removal and better surface quality, high speed machining was introduced and the use of the cemented carbide tools has become more problematic. For metal matrix composite, the concept of high-speed machining refers to speeds over 50 m/min approximately. In order to achieve higher cutting speeds, coated cemented carbides have been developed. The cutting tools used were solid coated (TiAlN) cemented carbide with two cutting edges. Ten different tools have been used in the experimentation. Each tool has been used for four experiments.

Figure 1. Solid Coated Cemented Carbide Cutting Tool

A numerical control (N.C.) lathe Alpha 400 series was used for all turning experiments. This is rigid, high precision and is used for all hard-turning process. The machine specifications of the lathe are given in Table 2. The spindle rotates from 15 rpm to 2500 rpm. The feed rate ranges from 0.03 mm/rev up to 0.40 mm/rev. The depth of cut can be controlled at minimum of 0.05 mm. A fixture was designed to mount the force dynamometer to the tool post of the lathe. Figure 2 shows the N.C. lathe fitted with Kistler force dynamometer.

Table 2. Numerical control lathe

| | |
|---|---|
| Type of machine | N.C. Alpha 400-Harrison |
| Spindle rotation | 15-300, 35-830,110-2500 RPM |
| Feed rates – mm/rev | 0.03 – 0.40 and<br>0.001 – 0.016 |
| Cross feeds | Half longitudinal values |
| Main motor | 7.5 K.W. |
| Constant power range | 5.5 K.W. |
| Electrical power supply | 21 K.V. |
| Overall length | 1960 mm |
| Overall width | 1445 mm |
| Overall height | 1572 mm |

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Figure 2. Numerical Control Lathe fitted with Kistler force dynamometer.

The surface roughness of the work materials was measured using Mitutoyo SJ 400 roughness tester. The stylus is of 0.80 mm radius with cut off length of 4.5 mm. Each cutting operation, the roughness was measured at 4 different places and the average are recorded.

Figure 3. Mitutoya Surface Roughness Measuring Set

An HMV Vickers hardness equipment was used to measure the microhardness. There were 15 types of chips for the desired cutting parameter was measured for the microhardness and average was used in the calculations. Images of the chip style were taken by a digital camera to compare the change in the chip as the volume of material removed increased.

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Figure 4. HMV Vickers Hardness Equipment

Turning is a very complicated cutting process which involves many parameters such as cutting speed, feed rate, depth of cut, tool geometry, etc. The most influential factors affecting the surface finish were studied by conducting a set of experiments. The factors considered for the experimentation were cutting speed, feed, and depth of cut. The experimental conditions are shown in Table 3. The experiments were conducted under dry condition.

Table 3. Process parameters and their levels

| Levels | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) |
|---|---|---|---|
| 1 | 100 | 0.10 | 0.2 |
| 2 | 100 | 0.20 | 0.2 |
| 3 | 100 | 0.30 | 0.2 |
| 4 | 125 | 0.10 | 0.2 |
| 5 | 125 | 0.20 | 0.2 |
| 6 | 125 | 0.30 | 0.2 |
| 7 | 150 | 0.10 | 0.2 |
| 8 | 150 | 0.20 | 0.2 |
| 9 | 150 | 0.30 | 0.2 |
| 10 | 175 | 0.10 | 0.2 |
| 11 | 175 | 0.20 | 0.2 |
| 12 | 175 | 0.30 | 0.2 |
| 13 | 200 | 0.10 | 0.2 |
| 14 | 200 | 0.20 | 0.2 |
| 15 | 200 | 0.30 | 0.2 |

## 3. Results & Discussions

### 3.1 Surface Roughness

Surface roughness (Ra) is a widely used colloquial term to describe the general quality of a machined surface [3]. While “surface finish” is a broader term not necessarily tied to surface texture or pattern, a lower surface roughness value typically implies a better surface finish [5]. Surface roughness is of particular interest in manufacturing because it directly affects the friction between contacting surfaces. It influences not only how a surface feels and appears but also its behavior during contact, coating, or sealing operations.

Surface roughness is a key performance measure in machining processes, especially in finish turning. Figure 5 illustrates the measured surface roughness values at cutting speeds of 100, 125, 150, 175, and 200 m/min with a feed rate of 0.10 mm/rev for a 100 mm length of cut (referred to as Trial 1). At a cutting speed of 100 m/min, the surface roughness was initially 0.43 µm. This low value can be attributed to the sharp, unworn cutting edge. As the cutting speed increased to 125 m/min and 150 m/min, the roughness values were 0.52 µm and 0.34 µm, respectively. These differences though relatively small (0.18 µm) show a general trend of decreasing roughness. At 175 m/min and 200 m/min, the surface roughness further decreased to 0.20 µm and then increased slightly to 0.29 µm.

Previous studies have shown that surface roughness tends to improve (i.e., decrease) with increasing cutting speed, up to a certain point [5,6]. Beyond this optimal range, further increases in cutting speed can cause deterioration in surface finish due to tool wear and thermal effects [8]. Surface roughness is affected by several factors, including machining parameters, tool geometry, workpiece material, and tool wear [9]. Manufacturing engineers must also consider cutting time when selecting parameters. While a lower feed rate generally produces a smoother surface, it also results in significantly longer machining times.

The experiment continued at a higher feed rate of 0.20 mm/rev with the same cutting speeds. The surface roughness values for this trial were 1.06, 1.08, 1.02, 0.90, and 0.81 µm at 100, 125, 150, 175, and 200 m/min respectively. At a feed rate of 0.30 mm/rev, the roughness values increased further to 2.50, 2.42, 2.33, 2.23, and 2.03 µm, respectively, at the same cutting speeds.

Researchers who studied machining of Aluminum Metal Matrix Composites (MMCs) using different cutting tool materials observed that rough surfaces were often caused by flank and crater wear [4,6,7]. Low feed rates at high cutting speeds tend to result in lower surface roughness. However, high cutting speeds also generate elevated temperatures at the tool-workpiece interface, which can soften the tool material and worsen the surface finish. This behavior explains the slightly increased values of surface roughness in trial 2.

As both feed rate and cutting speed increased, surface roughness tended to increase. Built-up edge (BUE) formation also significantly influenced surface finish [10]. At higher cutting speeds, the increased temperature can reduce material adhesion, potentially eliminating the BUE. However, when BUE detaches, it can remove parts of the tool material, leading to cutting edge chipping and deteriorated surface quality.

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Ultimately, high cutting speed combined with low feed rate emerged as the most effective combination for achieving superior surface finish. An average surface roughness as low as 0.20 µm was achieved at 175 m/min and 0.10 mm/rev feed rate. However, it's important to balance this with machining efficiency, as lower feed rates significantly increase cycle time. Additionally, flank wear and chip formation patterns (especially continuous chips that may wrap around the tool or workpiece) must also be considered when selecting parameters. Improper chip control can damage the machined surface.

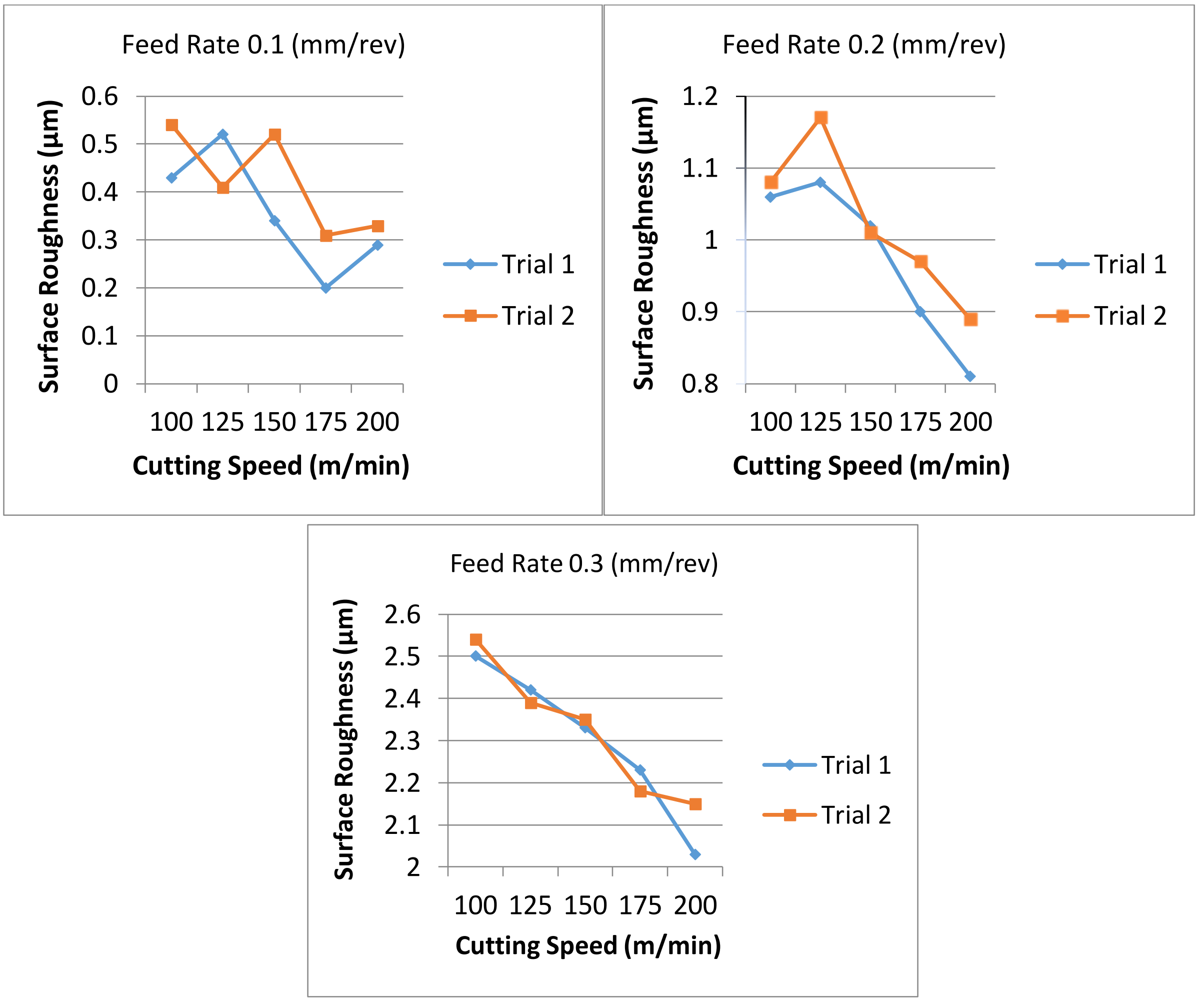


Fig 5. Effect of cutting speed at feed rate of 0.1mm/rev;0.2mm/rev and 0.3mm/rev on surface roughness.

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### 3.2 Microhardness

Microhardness, as a key physical parameter of surface integrity, is influenced by a variety of factors, including technological parameters, the stereometrics and micro-geometry of the cutting edge, and others [4]. Among these, the cutting speed plays a particularly significant role during the surface layer formation process [1]. It directly affects the amount and rate of heat generated in the machining zone. This heat, in turn, penetrates the subsurface layers of the workpiece material, potentially altering its microstructural and mechanical properties, including microhardness. Given this, the functionality of the machined surface which is closely tied to microhardness can be substantially affected by thermal and mechanical loads induced during turning [7].

From Figure 6 it can be seen that as cutting speed is increased the chip microhardness is decreased. It is found that the lowest values of chip micro-hardness were at the highest values of cutting speed mean at level 200 m/min. This was because, as cutting speed is increased the cutting forces are decreased thus lowering the amount of heat generation and as a result the rate of strain hardening is decreased. Also, at high cutting speed and the time allowed to machine the surface is shorter meaning that the time during which the tool is in contact with the work piece is short, so heat generation due to the mechanism of cutting and friction which is a function of rubbing between tool and work piece as of a small amount [2,5]. A small quantity of heat which is transferred to the chip does not result microstructure change of the chip and strain hardening is of negligible effect compared with lower cutting speed [10]. In Figure 6, feed rate is shown to have its effect on chip microhardness. However, as feed rate is increased the chip microhardness is increased relatively up to the highest feed rate at level 0.3mm/rev. Thus, as feed rate is increased, a large amount of metal removed is subjected to higher temperature and plastic deformation because of an increase in cutting force and normal force which result in temperature increase of the chip and plastic deformation which results hardening of the chip especially at the interface between the chip and tool [10]. At the slow cutting speed, the heat input to the material was high and it resulted in wider HAZ, whereas, at a faster cutting speed, the heat input was lower and a correspondingly narrower HAZ was obtained [9].

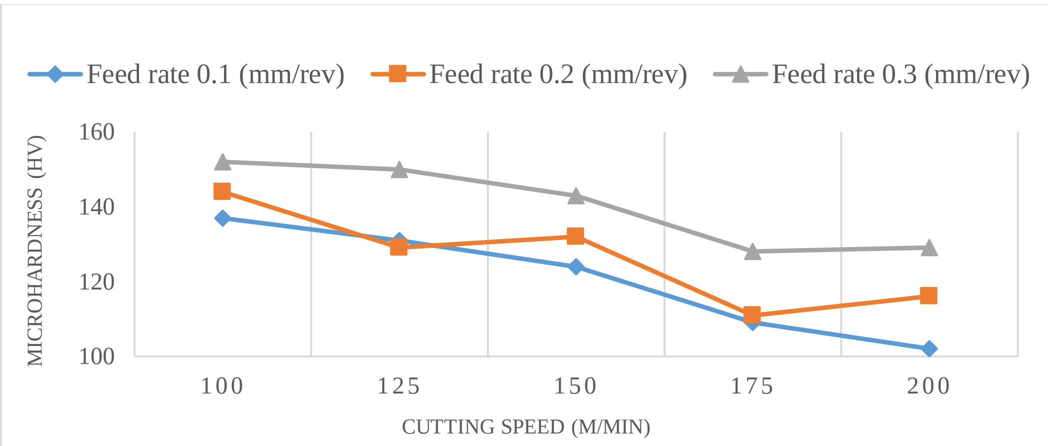


Fig 6. Effect of cutting speed at feed rate of 0.1mm/rev;0.2mm/rev and 0.3mm/rev on microhardness.

## 4. Conclusion

Building on the foundation of earlier studies conducted primarily in industrialized nations, this research aims to enhance the understanding and performance of turning processes applied to metal matrix composites (MMCs). By identifying and optimizing machining parameters, the productivity and cost-effectiveness of machining MMCs can be significantly improved. Prior research has already established the viability of machining MMCs using appropriate tool materials and cutting conditions [1,3]. This study further emphasizes that proper selection of parameters such as cutting speed, feed rate, and tool material can make the machining process more efficient and economically viable across various industrial applications.

The surface roughness of MMCs during turning operations is predominantly affected by cutting speed. Higher cutting speeds generally lead to better surface finishes. However, increasing the cutting speed also raises the temperature in the cutting zone, potentially causing softening of the tool material [3]. Feed rate also plays a critical role where bigger feed rates tend to degrade surface quality by producing rougher surfaces [4]. At constant depth of cut, higher cutting speed with lower feed rate initially improves surface finish for hard to machine MMCs, but this improvement plateaus or reverses at very high speeds due to thermal effects and tool wear.

Among the examined parameters, cutting speed and feed rate were the most influential in determining surface finish. Additionally, tool wear directly impacts surface roughness and often serves as the trigger for tool replacement in finish turning applications [5].The machinability tests indicated that tool wear is a critical factor in the turning of Al/SiC MMCs. Two common wear types were identified: flank wear and crater wear, with flank wear being dominant. Abrasive wear was the primary mechanism, with no significant evidence of chemical wear. Cutting speed emerged as the most influential parameter, with increased speeds accelerating wear rates. Feed rate was the second most significant factor where higher feeds produced increased tool wear [2,5].

Interestingly, flank wear was more sensitive to cutting speed than to feed rate. At lower cutting speeds, increased cutting forces and the formation of built-up edge (BUE) accelerated wear. Based on these findings, for rough or medium turning, it is recommended to use low cutting speeds with high feed rates and depths of cut in combination with coated carbide tools to maximize tool life. For finish machining, high cutting speeds with low feed rates yield superior surface finishes when using coated cutting tools [7].

Another observed phenomenon was the variation in chip microhardness. The lowest chip microhardness values were found at the highest cutting speeds, while the highest micro-hardness was recorded at elevated feed rates. Increased cutting speeds reduce cutting forces and heat generation, thereby lowering strain hardening effects due to shorter contact time between the tool and workpiece [10].

Conversely, higher feed rates produce more significant deformation and heat at the tool chip interface, resulting in increased chip hardness. At low cutting speeds, the heat input is greater, leading to a wider heat-affected zone (HAZ). In contrast, higher cutting speeds result in lower heat input and narrower HAZ, minimizing thermal damage to the workpiece surface [9].

The machinability of MMCs in turning operations is strongly dependent on cutting parameters. Surface roughness is best minimized through high cutting speeds and low feed rates, while tool life is extended under lower speeds and higher feeds. Tool wear, particularly flank wear due to abrasion, is a critical limitation in MMC machining and must be factored into process planning. Optimizing these parameters not only improves surface finish and productivity but also enhances the economic feasibility of hard turning as an alternative to grinding for difficult to machine materials.

While reaching all the initially proposed goals, this dissertation is still far from answering all the questions raised by the complex phenomenon occurring in hard turning. Several future directions of investigations are proposed in relation with completed work.

(i) Surface roughness -Turning the material using different nose radius tool with fine feed rate and high speed turning.

(ii) Chip formation -The generated chips should be investigated through SEM as a function of cutting conditions and tool wear, the physical cause for chip segmentation should be determined. Measurement of temperatures at various operating parameters can be studied.

(iii) Tool wear -Tool life may be investigated based on operating parameters of the cutting regime as variation factors. The effect of chemical reactions between the tool and work material should be investigated from the view point of chemical wear and white layer formation on chips.

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