engineering proceedings

MDPI

Proceeding Paper

Investigation into the End-Milling Parameters of Mg/B_4C Metal Matrix Composites †

K. S. Vijaysekar [1], K. Gobivel [2,*], Chithirai Pon Selvan [3], M. Krishnanand [1], E. Malarmathi [1], N. Mohamed Saajid [1] and A. Mohanraj [1]

1 Department of Mechanical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Kalavakkam, Chennai 603 110, India; vijaysekarks@ssn.edu.in (K.S.V.); krishnanand18074@mech.ssn.edu.in (M.K.); malarmathi18078@mech.ssn.edu.in (E.M.); mohamed18083@mech.ssn.edu.in (N.M.S.); mohanraj18086@mech.ssn.edu.in (A.M.)
2 Department of Mechanical Engineering, KCG College of Technology, Karapakkam, Chennai 600 097, India
3 School of Science and Engineering, Curtin University, Dubai International Academic City, Dubai 345 031, United Arab Emirates; pon.selvan@curtindubai.ac.ae
* Correspondence: gobivel@gmail.com
† Presented at the International Conference on Processing and Performance of Materials, Chennai, India, 2–3 March 2023.

Abstract: The automotive, biomedical, and aerospace industries are attracted towards magnesium-based alloys and composites because they are among the lightest structural materials available and have significantly enhanced mechanical and physical characteristics. When it comes to precision and functional requirements, such materials need to be machined. The aim of this study was to investigate the machinability behavior of Mg/B_4C metal matrix composite (MMC) through end-milling experiments. Different deformation behaviors of the composite were studied by varying the volume percentage of B_4C reinforcement between 5% and 10%. Using a milling tool dynamometer, the cutting forces on the tool were examined for various milling parameters. Moreover, Talysurf roughness was used to analyze the machined surface under each cutting parameter, and scanning electron microscopy was used to study the chips produced under different cutting conditions.

Keywords: Mg-B_4C composite; milling; cutting force; surface roughness; chip morphology

Citation: Vijaysekar, K.S.; Gobivel, K.; Selvan, C.P.; Krishnanand, M.; Malarmathi, E.; Mohamed Saajid, N.; Mohanraj, A. Investigation into the End-Milling Parameters of Mg/B_4C Metal Matrix Composites. *Eng. Proc.* **2024**, *61*, 33. https://doi.org/10.3390/engproc2024061033

Academic Editors: K. Babu, Anirudh Venkatraman Krishnan, K. Jayakumar and M. Dhananchezian

Published: 5 February 2024

1. Introduction

The search for new composite materials arises from the need to attain highly specific properties that are tailored to particular tasks. Magnesium and its alloys represent a topic of considerable interest for both scientific research and commercial applications. The utilization of magnesium alloys is constrained due to their inadequate creep resistance at high temperatures, low modulus and strength, and wear resistance. Therefore, reinforcements are required to enhance the properties of the base metal. These properties make magnesium-based composites important for aircraft frames, panels, suspension parts in automotives, lightweight armor, heat sinks in electronics, and golf club heads in sports.

Machinability is often unavoidable despite the near net shape of composite materials, due to their assembly requirements. However, a major challenge in machining is the presence of particulate inclusions in the material, leading to rapid tool wear and poor surface quality. Studies have shown that the cutting speed has a minimal effect on the 3D roughness, while the cutting depth and feed rate have the greatest impact. Therefore, to achieve a smoother machined surface, it is important to pay more attention to the feed rate and cutting depth. Input parameters that need to be considered include the micro hole diameter, pitch distance, and depth, while the outcomes to be measured include the power consumed, the wear rate of the tool, and the hole surface quality [1,2]. While studying the effects of an increasing SiC particle percentage on the cutting forces, it was found that there was a slight increase in cutting forces, but no significant impact from the increased SiC particle percentage [3].

Habrat et al. [4] investigated how laser heating affects the cutting forces and microstructure. They concluded that the process parameters have a significant impact on the machining forces and emphasized the importance of the work specimen diameter. A study on the surface roughness of the TiB2/7075 composite revealed that unstable cutting caused the roughness of the 7075 alloy to be the largest, while the roughness of the composite was minimal [5]. Furthermore, it was confirmed that speed is the most influential parameter for roughness, followed by depth, and feed has a lesser impact [6]. Analysis of the chip microstructure showed that gross fracture propagation occurred at the free surface, and variations in the shear bands occurred at different cutting speeds [7–9].

When milling the Mg AZ31 alloy, the main cutting forces fell as the machining speed rose but increased as the feed rose [10]. It was observed that increasing the depth resulted in a higher cutting force and the maximum profile peak–valley height for the roughness parameter [11]. While previous research has focused on the machinability of Al Mg-based metal matrix composites (MMCs) offer significant advantages for automobile and biomedical applications, and thus their machining behavior needs to be investigated. This current study aims to evaluate the milling of Mg-B_4C metal matrix composites with two different volume percentages (5% and 10%) and a varying milling speed (v) and feed (f) to understand the material's deformation behavior. To analyze the different conditions, the cutting force and surface roughness were measured using a dynamometer and profilometer, respectively. Additionally, scanning electron microscopy was used to study the chip morphology for selected conditions.

2. Materials and Methods

The workpiece was fabricated using a stir-casting process, followed by squeeze casting as a secondary process to enhance the distribution of reinforcements and reduce porosity. Firstly, the Mg ingot was melted in a crucible furnace. The furnace temperature was monitored and maintained closely around 700 °C. Then, B_4C particulates were preheated and stirred at a constant speed of 750 rpm using a stirrer. The resulting mixture was poured into a die and then squeezed with a load of 40 tonne. After fabrication, the workpieces Mg/B_4C (5% and 10% vol.) were rough-machined and loaded onto a milling machine, as shown in Figure 1. The final workpiece size was 100 × 100 × 10 mm. These volume levels of reinforcement enhance the mechanical properties for their applications, like a high hardness and modulus of elasticity, while also maintaining practical manufacturability [12]. The experimental work utilized an end mill cutter with an 8 mm diameter and 2 flutes. The cutting force was measured using a milling tool dynamometer with data acquisition software. The machined surface was measured for each cutting condition using a Talysurf Profilometer (Mitutoyo SJ210), and chips were collected and analyzed using a scanning electron microscope for selected conditions.

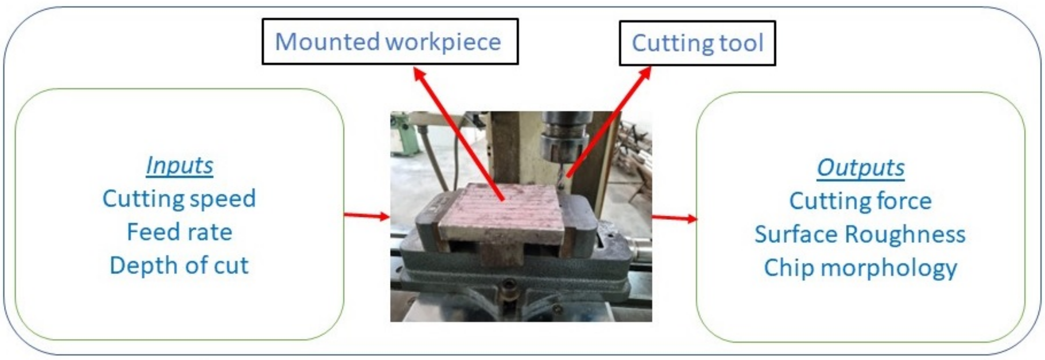

Figure 1. Milling machine and experimental method.

3. Results and Discussion

3.1. Analysis of Cutting Force versus Cutting Speed at Varying Feeds

The cutting forces for the 5% and 10% Mg/B_4C MMCs were obtained using a strain-gauge-based dynamometer for different combinations of 'v' at varying 'f', as depicted in Figure 2a–c. The cutting force was consistently higher for the vol. 10% MMC compared to the vol. 5% MMC across all cutting conditions due to the hardness of the composites [13]. This difference may be attributed to the higher agglomeration of B_4C precipitates on the cast workpiece in the vol. 10% material. An overall gradual increase in cutting force was observed with increasing 'v' across different 'f'. However, at a 'v' of 30.66 m/min and an 'f' of 176 mm/min, the cutting force for the vol. 5% material decreased marginally. In contrast, for the vol. 10% material, the cutting force increased gradually at an 'f' of 80 and 176 mm/min. However, the force decreased at an 'f' of 134 mm/min when the 'v' was increased.

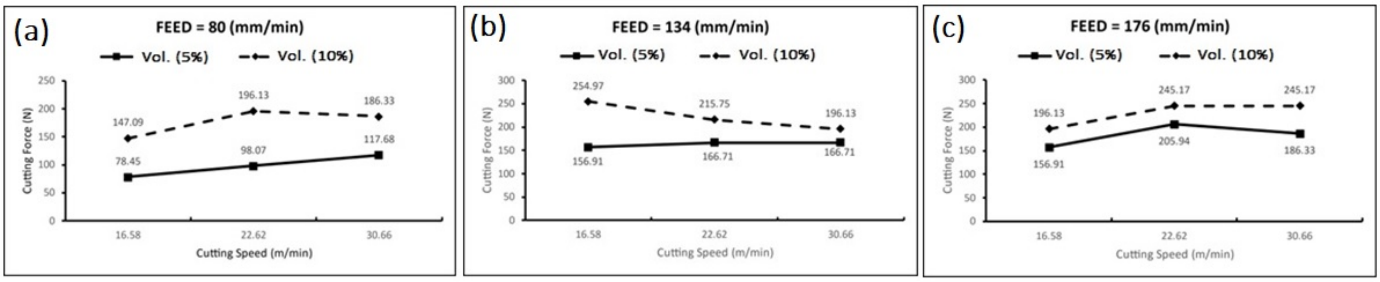

Figure 2. Cutting force vs. cutting speed at varying feeds (**a**) 80 mm/min (**b**) 134 mm/min and (**c**) 176 mm/min.

3.2. Analysis of Cutting Force versus Feed at Varying Cutting Speeds

The cutting force for different 'f' values at varying 'v' values for vol. 5% and 10% materials are shown in Figure 3a–c. The cutting force gradually rose with an increase in 'f' for vol. 10% material across all 'v' values. For vol. 5%, the force increased with an increase in 'f' at 'v' values of 22.62 and 30.66 m/min. However, at a 'v' value of 16.58 m/min, the force was higher at an 'f' value of 134 mm/min, whereas it decreased at an 'f' value of 176 mm/min. Overall, the composition percentage had a greater tendency to affect the cutting forces and, at a higher volume, the consistent behavior observed, attributed to the tool wear, was more pronounced.

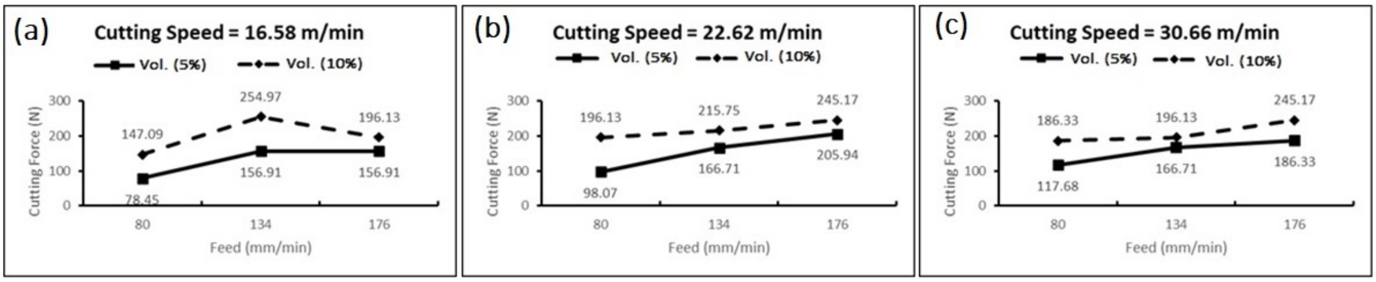

Figure 3. Cutting force vs. feed at varying cutting speeds (**a**) 16.58 m/min (**b**) 22.62 m/min and (**c**) 30.66 m/min.

3.3. Chip Morphology

The chip was formed at a cutting parameter of 'v' 16.58 m/min and 'f' 176 mm/min, as shown in Figure 4A–D for vol. 5% and 10%. Figure 4A shows that the tear propagated more from the free end, whereas a limited tear was obtained at vol. 10%, as shown in Figure 4B. The observations of closure in Figure 4C show that a regular pattern comprising a sawtooth profile was obtained at the free surface [14]. However, vol. 10% showed an irregular sawtooth pattern due to a higher volume of particulates.

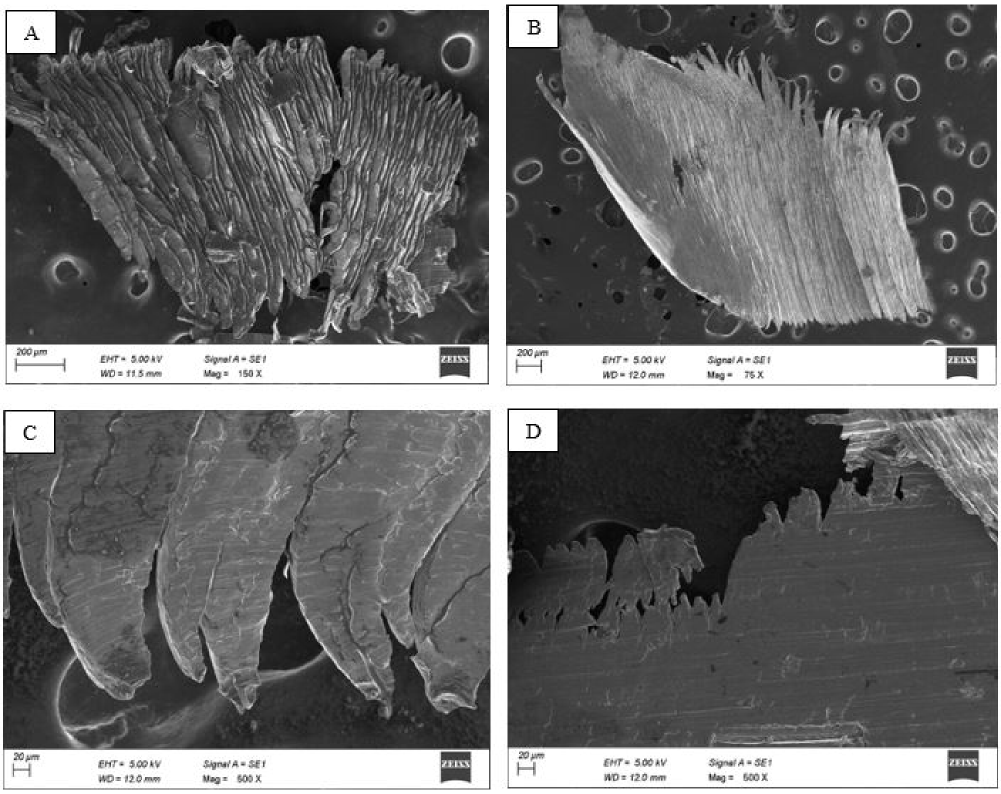

Figure 4. Chip morphology at 'v' 16.58 m/min and 'f' 176 mm/min (**A**–**D**) captured at various locations.

The chip morphology obtained for the cutting parameter 'v' 30.66 m/min and 'f' 80 mm/min is shown in Figure 5A–E for vol. 5% and 10%. In Figure 5A, a straight and regular chip pattern formed at vol. 5%, whereas, for the same condition, irregular and curl-shaped chip formed for vol. 10%, as shown in Figure 5B. Figure 5C,D show the free-end views of chips under their respective conditions. As we can observe, the chip with 5% reinforcement has a larger number of segments (i.e., a narrower lamella width), whereas the chip with 10% reinforcement has fewer segments (i.e., a wider lamella width). This is because the cutting force has a direct relationship with chip formation. As the vol. % of reinforcement rose, the force obtained during machining also increased significantly, and the roughness measured after machining also increased. Therefore, as the reinforcement percentage increases, the cutting force rises, leading to a rise in the segmentation ratio. Hence, the number of segments is more in the 5% chip and less in the 10% chip. Figure 5 E,F provide clear evidence of this. The increase in cutting force and segmentation ratio also affects the free side and rake side of the chip. Linear stacks of striations are observed on the free end of the 5% chip (Figure 5C), whereas curved striations are observed on the 10% reinforcement chip (Figure 5D). A visible tear is observed on the rake side of the 10% chip, whereas no visible tear is observed on the 5% chip. In all comparisons of the free side between the 5% and 10% chips (Figure 5C,D), it is observed that the fracture on the free side is limited for the 5% chip, whereas it is more pronounced for the 10% chip.

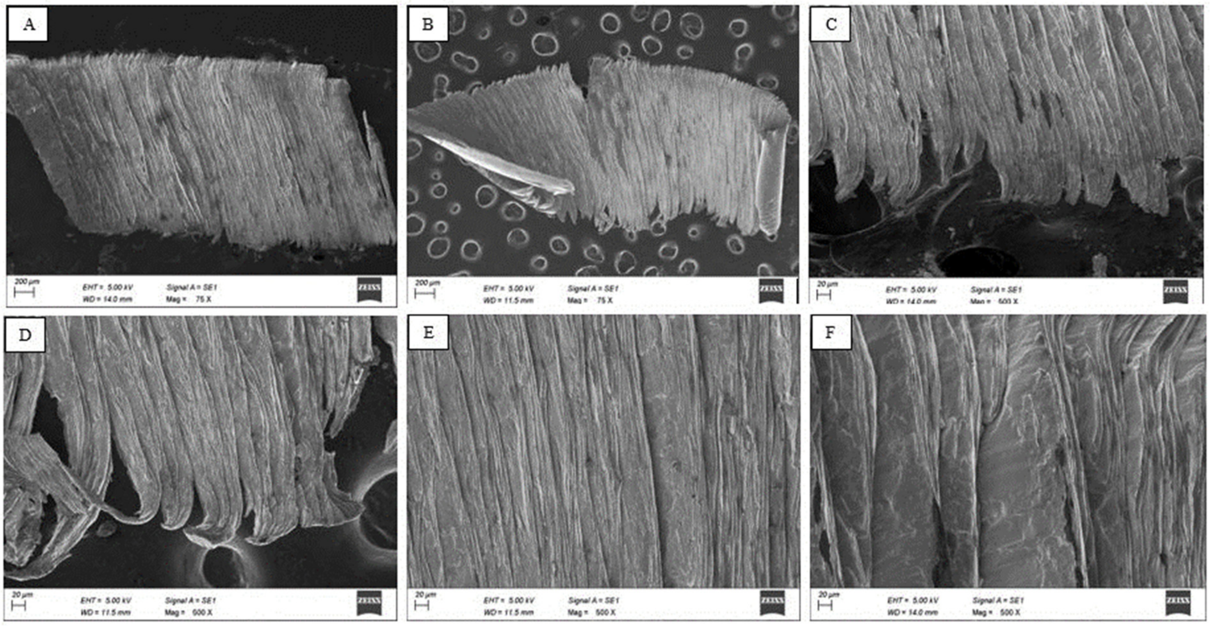

Figure 5. Chip morphology at 'v' 30.66 m/min and 'f' 80 mm/min (**A**–**F**) captured at various locations.

3.4. Analysis of Surface Roughness versus Feed at Varying Cutting Speeds

The surface roughness of the vol. 5% and 10% materials at varying 'v' and 'f' values are shown in Figure 6a–c, as measured by the Talysurf profilometer. The roughness values for vol. 10% were generally higher than for vol. 5% across all conditions, although at 'f' values of 134 mm/min and 'v' values of 22.62 m/min, as well as at 'f' values of 176 mm/min and 'v' values of 16.58 m/min, the roughness value was marginally reduced compared to vol. 5%. The roughness value decreased as 'v' increased at 'f' values of 134 and 176 mm/min for vol. 5% material, but increased at the high 'v' value of 30.66 m/min. For the vol. 10% material, the roughness value increased as 'v' increased at an 'f' value of 80 mm/min. However, a marginal decrease in roughness was observed when 'v' increased at an 'f' value of 134 mm/min. The roughness value gradually increased at intermediate 'v' values and further decreased at the high 'v' value of 30.66 m/min at an 'f' value of 176 mm/min.

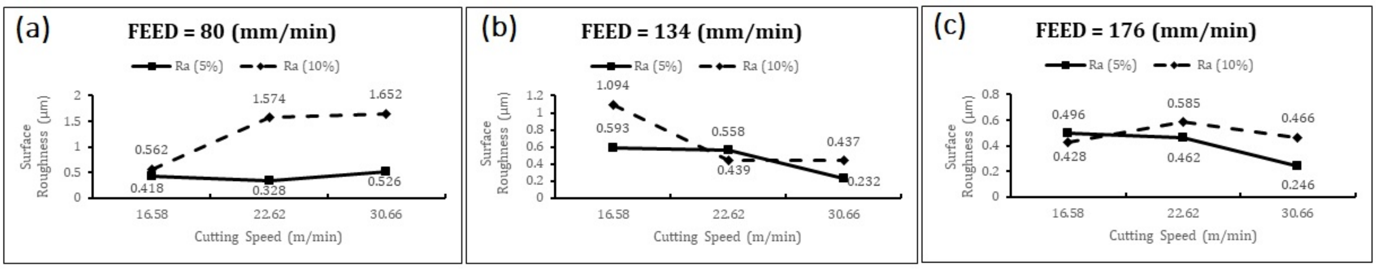

Figure 6. Roughness (Ra) vs. cutting speed at varying feeds (**a**) 80 mm/min (**b**) 34 mm/min and (**c**) 176 mm/min.

3.5. Analysis of Surface Roughness versus Cutting Speed at Varying Feeds

The roughness values with respect to 'f' at varying 'v' are depicted in Figure 7a–c. The roughness increases with a rise in 'f' at the 'v' values of 22.62 and 30.66 m/min. However, it was observed that the roughness value increased at an 'f' value of 134 mm/min and then decreased to 176 mm/min for a 'v' value of 16.58 m/min for the vol. 5% material. Conversely, for vol. 10%, the roughness value increased at an intermediate 'f' value of 134 mm/min and decreased at the high 'f' value of 176 mm/min at 'v' 16.58 m/min. Additionally, the roughness value marginally decreased when 'f' increased at 'v' 22.62 m/min. Furthermore, at 'v' 30.66 m/min, the roughness value marginally reduced at an intermediate 'f' value of 134 mm/min and gradually increased at the 'f' value of 176 mm/min. Towards the cutting direction, the material deformed plastically, and ploughing took place, which leads to cracks and other surface defects [15].

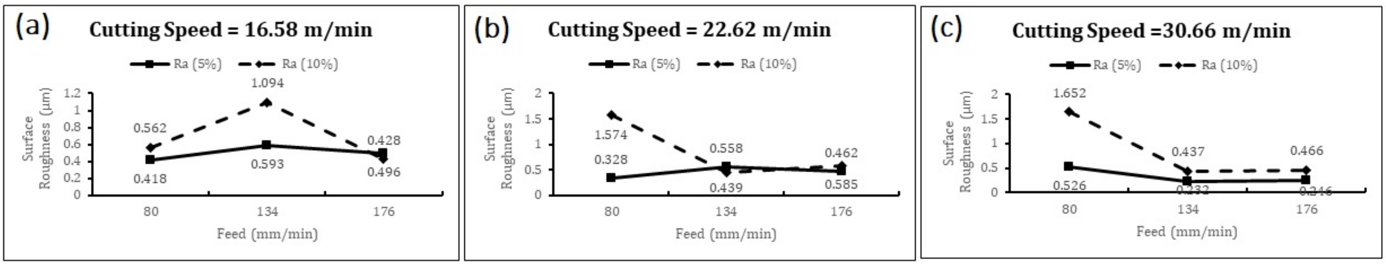

Figure 7. Roughness (Ra) vs. feed at varying cutting speeds (**a**) 16.58 m/min (**b**) 22.62 m/min and (**c**) 30.66 m/min.

4. Conclusions

The present work on the milling of boron-carbide-reinforced magnesium metal matrix composite prepared via the stir casting route followed by squeeze casting yields the following conclusions:

- When comparing the cutting speeds for 5% and 10% boron-carbide-reinforced MMC, it was found that the probability of interaction of the ceramic particles greatly influences the cutting force;
- Irregular trends in the cutting forces were observed due to the agglomeration and uneven distribution of particles at different locations in the lattice of the metal matrix composite;
- In most cases, a decreasing trend for surface roughness with a rise in cutting speed and feed was observed. The abrupt fluctuations in surface roughness can be attributed to the uneven distribution of B_4C particles;
- SEM analysis revealed that the 5% B_4C-reinforced MMC chips have a greater number of lamella structures and segmentations compared to the 10% B_4C-reinforced MMC chips. Visible tears can be observed on the rake sides of the 10% B_4C-reinforced MMC chips.

Author Contributions: Supervision, K.S.V.; writing—review and editing, K.G.; project Administration, C.P.S.; experimental investigation, M.K.; data collection, E.M.; original draft and validation, N.M.S.; analysis, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Sri Sivasubramaniya Nadar College of Engineering with grant number SSN/IFFP/NOVEMBER 2019/1-29/11.

Institutional Review Board Statement: Internal funded faculty project for work on magnesium alloys.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Xiong, Y.; Wang, W.; Shi, Y.; Jiang, R.; Shan, C.; Liu, X.; Lin, K. Investigation on surface roughness, residual stress and fatigue property of milling in-situ TiB2/7050Al metal matrix composites. *Chin. J. Aeronaut.* **2021**, *34*, 451–464. [CrossRef]
2. Devaraj, S.; Malkapuram, R.; Singaravel, B. Performance analysis of micro textured cutting insert design parameters on machining of Al-MMC in turning process. *Int. J. Light. Mater. Manuf.* **2021**, *4*, 210–217. [CrossRef]
3. Laghari, R.A.; Li, J. Modeling and optimization of cutting forces and effect of turning parameters on SiCp/Al 45% vs. SiCp/Al 50% metal matrix composites: A comparative study. *SN Appl. Sci.* **2021**, *3*, 706. [CrossRef]

4. Habrat, W.; Krupa, K.; Markopoulos, A.P.; Karkalos, N.E. Thermo-mechanical aspects of cutting forces and tool wear in the laser-assisted turning of Ti-6Al-4V titanium alloy using AlTiN coated cutting tools. *Int. J. Adv. Manuf. Technol.* **2021**, *115*, 759–775. [CrossRef]
5. Chen, J.; Yu, W.; Zuo, Z.; Li, Y.; Chen, D.; An, Q.; Geng, J.; Chen, M.; Wang, H. Effects of in-situ TiB2 particles on machinability and surface integrity in milling of TiB2/2024 and TiB2/7075 Al composites. *Chin. J. Aeronaut.* **2021**, *34*, 110–124. [CrossRef]
6. Senthil, P.; Selvaraj, T.; Sivaprasad, K. Influence of turning parameters on the machinability of homogenized Al-Cu/TiB2 in situ metal matrix composites. *Int. J. Adv. Manuf. Technol.* **2013**, *67*, 1589–1596. [CrossRef]
7. Gobivel, K.; Vijay Sekar, K.S. Machinability Studies on the Turning of Magnesium Metal Matrix Composites. *Arch. Metall. Mater.* **2022**, *67*, 939–948. [CrossRef]
8. Davis, B.; Dabrow, D.; Ju, L.; Li, A.; Xu, C.; Huang, Y. Study of chip morphology and chip formation mechanism during machining of magnesium-based metal matrix composites. *J. Manuf. Sci. Engg.* **2017**, *139*, 091008. [CrossRef]
9. Dabade, U.A.; Joshi, S.S. Analysis of chip formation mechanism in machining of Al/SiCp metal matrix composites. *J. Mater. Proc. Technol.* **2009**, *209*, 4704–4710. [CrossRef]
10. Gobivel, K.; Vijay Sekar, K.S. Influence of cutting parameters on end milling of magnesium alloy AZ31B, Mater. *Today Proc.* **2022**, *62*, 933–937.
11. Yu, W.; Chen, J.; Ming, W.; An, Q.; Chen, M. Experimental and FEM study of cutting mechanism and damage behavior of ceramic particles in orthogonal cutting SiCp/Al composites. *Ceram. Int.* **2021**, *47*, 7183–7194. [CrossRef]
12. Patel, M.; Singh, M.K.; Sahu, S.K. Abrasive Wear Behaviour of Sand Cast B 4 C Particulate Reinforced AA5052 Metal Matrix Composite. In *Innovative Product Design and Intelligent Manufacturing Systems: Select Proceedings of ICIPDIMS*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 359–369.
13. Gopal, P.M.; Prakash, K.S. Minimization of cutting force, temperature and surface roughness through GRA, TOPSIS and Taguchi techniques in end milling of Mg hybrid MMC. *Measurement* **2018**, *116*, 178–192. [CrossRef]
14. Sahoo, S.K.; Sahoo, B.N.; Panigrahi, S.K. Investigation into machining performance of microstructurally engineered in-situ particle reinforced magnesium matrix composite. *J. Mag. Alloys* **2023**, *11*, 916–935. [CrossRef]
15. Teng, X.; Huo, D.; Wong, E.; Meenashisundaram, G.; Gupta, M. Micro-machinability of nanoparticle-reinforced Mg-based MMCs: An experimental investigation. *Int. J. Adv. Manuf. Technol.* **2016**, *87*, 2165–2178. [CrossRef]