Faculty of Industrial and Manufacturing Technology and Engineering

OPTIMIZATION OF CUTTER GEOMETRICAL FEATURES AND MACHINING PARAMETERS FOR MACHINING ALUMINIUM SILICON CARBIDE (AlSiC) USING RSM

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**A thesis submitted
in fulfillment of the requirements for the degree of
Master of Manufacturing Engineering**

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2024

DECLARATION

I declare that this thesis entitled "Optimisation of Cutter Geometrical Features and Machining Parameters for Machining Aluminium Silicon Carbide (AlSiC) Using RSM" is the result of my research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ………………………………………..

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Date : 09/09/2024

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APPROVAL

I hereby declare that I have read this thesis and in my opinion, this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

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DEDICATION

I would like to dedicate this thesis to my parents, who have been my emotional anchors throughout my entire life. They gave the little they had to ensure I would have the opportunity of an education. Their efforts and struggles have allowed me to complete this research journey.

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ABSTRACT

Aluminium Silicon Carbide (AlSiC) metal matrix composites have gained significant attention due to their exceptional properties, combining the lightness of aluminum with the hardness and thermal conductivity of silicon carbide. However, machining AlSiC composites presents numerous challenges owing to their abrasive nature and the complexity of the machining process. Moreover, the lack of commercialization of a specific cutting tool for machining MMC materials is the source of several inherent problems such as rough machined surface and high cutting force. Addressing this matter, the development of a new cutter design specifically for machining MMC is necessitated. The objective of this study is to improve surface quality, machining force, and material removal rate. To achieve this, a comprehensive investigation was conducted involving the selection of appropriate cutting tools and the optimization of critical machining parameters, including cutting speed, feed rate, and depth of cut. Additionally, the effects of cutter geometrical features such as rake angle, clearance angle helix angle, and number of flutes were examined towards surface quality, machining force, and material removal rate. The experimental design was based on the Response Surface Methodology (RSM) design matrix, and machining tests were conducted using a CNC milling machine. Data obtained from these tests were analyzed using the Analysis of Variance (ANOVA), regression analysis, and desirability function approach. The results indicated significant interactions between machining parameters and tool geometries, highlighting the need for a systematic optimization approach. The optimized machining parameters and cutter geometrical features were validated through additional experiments, demonstrating remarkable improvements in improved surface finish, reduced cutting force, and higher material removal rate. Furthermore, the study provides valuable insights into the complex interplay between cutter geometrical features and machining parameters when dealing with AlSiC composites. In conclusion, this thesis offers a systematic approach to optimizing cutter geometrical features and machining parameters for AlSiC composite machining using RSM. The findings contribute to the advancement of machining processes for composite materials, particularly in industries where AlSiC composites find applications, such as aerospace and automotive. This research serves as a valuable resource for engineers and researchers seeking to enhance the efficiency and sustainability of AlSiC machining processes.

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ABSTRAK

PENGOPTIMUMAN CIRI-CIRI GEOMETRI PEMOTONG DAN PARAMETER PEMESINAN UNTUK PEMESINAN ALUMINIUM SILIKON KARBIDA (AlSiC) MENGGUNAKAN RSM

Komposit matriks logam Aluminium Silicon Carbide (AlSiC) telah mendapat perhatian yang ketara kerana sifatnya yang luar biasa, menggabungkan keringanan aluminium dengan kekerasan dan kekonduksian terma silikon karbida. Walau bagaimanapun, pemesinan komposit AlSiC memberikan banyak cabaran kerana sifat kasarnya dan kerumitan proses pemesinan. Selain itu, kekurangan pengkomersilan alat pemotong khusus untuk pemesinan bahan MMC adalah punca beberapa masalah yang wujud seperti permukaan mesin yang kasar dan daya pemotongan yang tinggi. Untuk menangani perkara ini, pembangunan reka bentuk pemotong baru khusus untuk pemesinan MMC adalah perlu. Objektif kajian ini adalah untuk meningkatkan kualiti permukaan, daya pemesinan dan kadar penyingkiran bahan. Untuk mencapai matlamat ini, penyiasatan komprehensif telah dijalankan melibatkan pemilihan alat pemotong yang sesuai dan pengoptimuman parameter pemesinan kritikal, termasuk kelajuan pemotongan, kadar suapan dan kedalaman pemotongan. Selain itu, kesan ciri geometri pemotong seperti sudut garu, sudut heliks sudut kelegaan dan bilangan seruling telah dikaji terhadap kualiti permukaan, daya pemesinan dan kadar penyingkiran bahan. Reka bentuk eksperimen adalah berdasarkan matriks reka bentuk Response Surface Methodology (RSM), dan ujian pemesinan dijalankan menggunakan mesin pengilangan CNC. Data yang diperoleh daripada ujian ini dianalisis menggunakan Analisis Varians (ANOVA), analisis regresi dan pendekatan fungsi keinginan. Keputusan menunjukkan interaksi yang ketara antara parameter pemesinan dan geometri alat, menonjolkan keperluan untuk pendekatan pengoptimuman yang sistematik. Parameter pemesinan yang dioptimumkan dan ciri geometri pemotong telah disahkan melalui eksperimen tambahan, menunjukkan peningkatan yang luar biasa dalam kemasan permukaan yang lebih baik, mengurangkan daya pemotongan dan kadar penyingkiran bahan yang lebih tinggi. Tambahan pula, kajian ini memberikan pandangan yang berharga tentang interaksi kompleks antara ciri geometri pemotong dan parameter pemesinan apabila berurusan dengan komposit AlSiC. Kesimpulannya, tesis ini menawarkan pendekatan sistematik untuk mengoptimumkan ciri geometri pemotong dan parameter pemesinan untuk pemesinan komposit AlSiC menggunakan RSM. Penemuan ini menyumbang kepada kemajuan proses pemesinan untuk bahan komposit, terutamanya dalam industri di mana komposit AlSiC menemui aplikasi, seperti aeroangkasa dan automotif. Penyelidikan ini berfungsi sebagai sumber yang berharga untuk jurutera dan penyelidik yang ingin meningkatkan kecekapan dan kemampanan proses pemesinan AlSiC.

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

TABLE OF CONTENTS

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF TABLES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

اونيۈرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF FIGURES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF SYMBOLS

°	-	Angle
%	-	Percentage
cm	-	Centimeter
g	-	Gram
m	-	Meter
min	-	Minute
mm	-	Millimeter
N	-	Newton

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LIST OF ABBREVIATIONS

MMC	-	Metal Matrix Composites
MRR	-	Material Removal Rate
DOE	-	Design of Experiment
RSM	-	Response Surface Methodology
AlSiC	-	Aluminium Silicon Carbide

UTeM
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LIST OF PUBLICATIONS

JOURNAL:

1. R. Izamshah, M. Rafiq, A. Lamat, M.S. Kasim, M.S. Salleh, P.J. Liew, M.S.A. Aziz and R.S.A. Abdullah, Effect of Cutter Geometry and Cutting Parameters on Machining AlSC Material Matrix Composites, International Journal of Nanoelectronics and Materials, Volume 14 (Special Issue) August 2021 [343-352].
2. R. Izamshah, A. Lamat, M. Rafiq, M.Z. Kasman, M.S. Kasim, P.J. Liew, M.S.A. Aziz and R.S.A. Abdullah, Quality Evaluation on Rotary Ultrasonic Assisted Drilling for Chemically Strengthened Glass, International Journal of Nanoelectronics and Materials, Volume 14 (Special Issue) August 2021 [353-362].

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 1

INTRODUCTION

1.1 Research Background

Aluminum Silicon Carbide (AlSiC) is a composite material known for its unique properties, making it valuable for various high-performance applications. This metal matrix composite poses exceptional thermal conductivity, low coefficient of thermal expansion, lightweight nature, high stiffness, wear resistance, and thermal stability, which are valuable for applications in electronic packaging, aerospace, and automotive industries (Karvanis et al., 2016). In addition, its corrosion resistance and thermal shock resistance, coupled with electrical insulation properties when tailored, enhance its suitability for harsh environments (Malik Abdul Karim, 2023). Furthermore, AlSiC's high specific heat capacity and low density contribute to its proficiency in efficiently managing heat and reducing overall weight in various high-performance applications (Rajeswari and Amirthagadeswaran, 2017). Figure 1.1 and 1.2 show examples of AlSiC applications in the automotive and aerospace areas.

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Figure 1.1: Automotive brake disc made from AlSiC metal matrix composite (Rajeswari and Amirthagadeswaran, 2017)

Figure 1.2: AlSiC metal matrix composite liquid-cooled aircraft power module base (Malik Abdul Karim, 2023)

However, achieving precise machining of AlSiC material is a challenging task (Mao Wang, 2023). Owing to its composite nature where silicon carbide particles are embedded in an aluminum matrix. Furthermore, the lack of commercialization of a specific cutter for the machining of MMC materials indirectly affects cutting performance such as surface roughness, cutting force, cutting temperature, and tool life.

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The existing body of literature on machining AlSiC highlights the importance of cutter geometrical features and machining parameters in achieving efficient and cost-effective machining. Several studies have explored the influence of factors such as cutting tool materials, tool geometries, and cutting parameters on machining performance. However, a comprehensive and systematic approach that combines these factors, especially utilizing statistical techniques remains relatively unexplored.

Despite previous efforts to optimize AlSiC machining, there is a pressing need to develop a holistic and statistically driven approach. The research problem at hand centers on the lack of a systematic methodology that considers the interactions between cutter geometrical features and machining parameters for AlSiC machining. This knowledge gap necessitates the development of a robust optimization framework that can enhance the efficiency and precision of AlSiC machining processes.

Therefore, the primary objective of this research project is to optimize cutter geometrical features and machining parameters for AlSiC machining using Response Surface Methodology (RSM). Given the increasing demand for AlSiC components, both in traditional and emerging industries, optimizing the machining process for this material is of paramount importance. This research is timely and relevant, addressing a critical gap in knowledge and offering practical solutions for improving AlSiC machining efficiency and precision thus contributing to the advancement of manufacturing processes for advanced materials.

1.2 Problem Statements / Challenges in Machining AlSiC MMC Material

The AlSiC Metal Matrix Composite (MMC) is typically manufactured to near-net-shape using either casting or infiltration processes. Consequently, secondary processes, such as deburring and machining become imperative to achieve the final component dimensions. The extant body of literature focusing on the machining of AlSiC underscores the prevalent challenges encountered by researchers. These challenges predominantly arise from the non-homogeneous and anisotropic nature of the material, necessitating a profound comprehension of the mechanics of the cutting process (Hazari Naresh, 2023). Furthermore, the presence of the abrasive characteristics of the reinforcement, coupled with the metal matrix, introduces a heightened level of intricacy during machining (Tomadi et al., 2017; Li and Laghari, 2019). Notable issues reported in dealing with this material encompass rough machined surfaces, excessive cutting forces, elevated cutting

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temperatures, and shortened tool life (Yakup et al., 2011; Kumar and Chhabra, 2014). For reference, Figure 1.3 illustrates the microstructure of the AlSiC material.

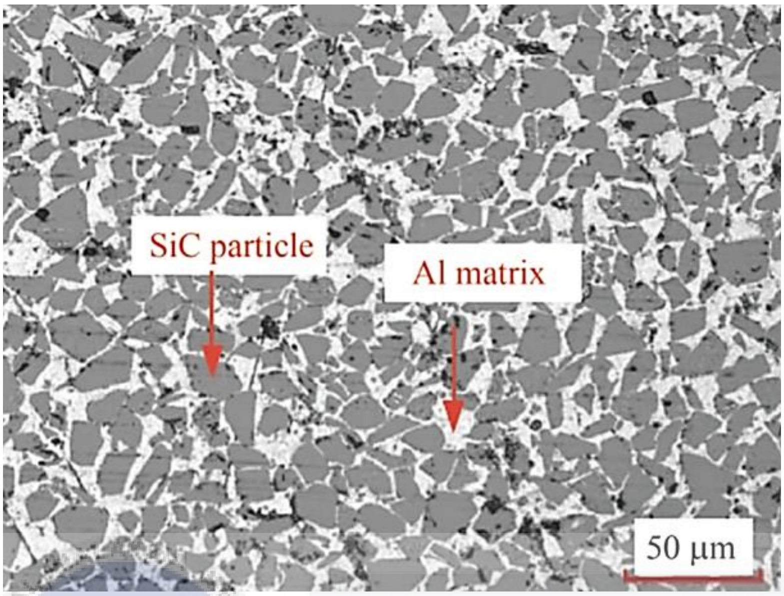

Figure 1.3: Microstructure of AL/SiC particle (Yakup et al., 2011)

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The mechanics of the shearing process for Metal Matrix Composite (MMC) materials deviate from those of homogeneous materials, giving rise to the potential deterioration of material properties, particularly at the sub-surface level (Omkar Mypati, 2024). The machined surface conditions for MMCs can be classified into three distinct categories, illustrated in Figure 1.4. The first category pertains to uncut particles, a consequence of the cutter tip's incapacity to effectively shear and fracture the resilient particles. This outcome results in the formation of a rough machined surface due to the protrusion of particles onto the outer surface. The second category involves particle dislocation, resulting from an insufficient cutting depth between the tooltip and the particles, causing them to shift deeper into the material. As a byproduct of particle dislocation, the surface hardness of the workpiece may be elevated. The final category encompasses particle cutting and breaking, achieved with an optimal cutting depth between the tooltip and the particle, facilitating efficient shearing to fracture the particle. During this phase, the magnitudes of the cutting force, known as particle fracture force, can escalate rapidly, potentially causing chipping at the tool's rake face. Furthermore, the configuration of the machined surface is influenced by the ratio between the matrix and the particles as illustrated in Figure 1.5, offering a comparative view of rough and smooth machined surfaces, respectively.

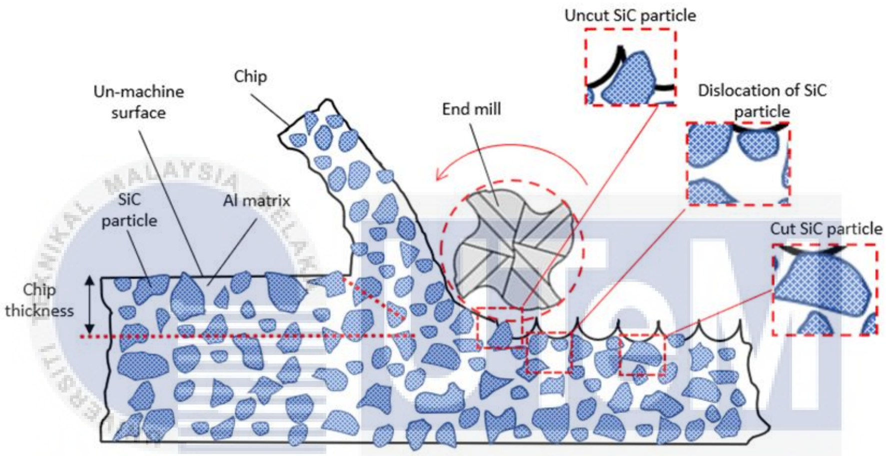

Figure 1.4: Mechanic of material removal for Al/SiC MMC material (Omkar Mypati, 2024)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

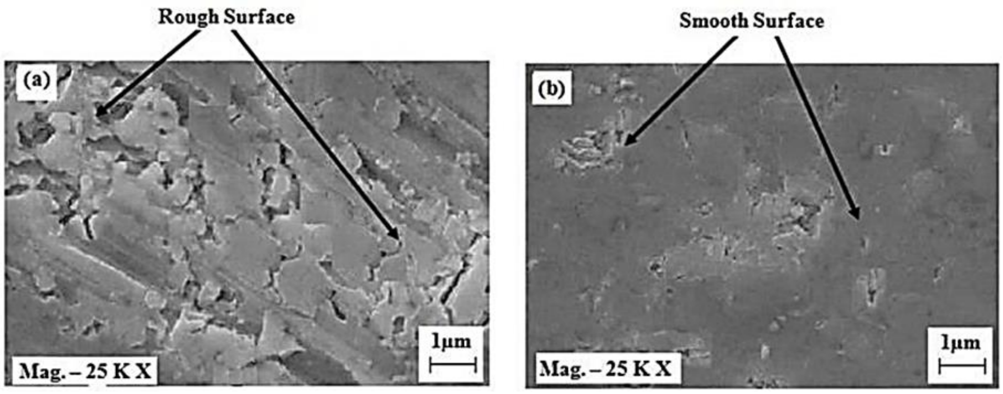

Figure 1.5: Comparison of the smooth and rough surfaces of MMC materials (Kumar and Chhabra, 2014)

Surface finish assumes a pivotal role in a broad spectrum of engineering applications, encompassing aspects such as part lubrication, wear resistance, and surface friction. Particularly within the realm of machining, the surface finish value stands as a primary performance indicator, offering an evaluative gauge for both part precision and ultimate dimensions. Surveying the corpus of literature on the machining of MMC materials, it emerges that machining parameters including speed, feed rate, depth of cut, and cutting tool geometry exert a pronounced influence over the surface roughness value. It is noteworthy, however, that these machining parameters significantly impact the magnitude of cutting forces, which bear considerable relevance to tool wear rates. Thus, the judicious selection of appropriate machining parameters and cutting tool geometry is pivotal to optimizing machining performance comprising surface roughness, cutting forces, and material removal rates. These optimizations assume critical importance in the successful machining of MMC materials, thereby constituting the central objective of this thesis.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.3 Research Objectives

The primary objective of this research is to enhance the precision for machining AlSiC MMC materials. The overarching goal encompasses several key sub-objectives:

1. Investigate the impact of cutter geometrical features, including helix angle, rake angle, clearance angle, and the number of flutes, alongside machining parameters such as spindle speed, feed rate, and depth of cut on machining performance metrics, namely surface roughness, cutting force, and Material Removal Rate (MRR).

2. Optimize the cutter geometrical features (helix angle, rake angle, clearance angle, and number of flutes) and machining parameters (spindle speed, feed rate, and depth of cut) to achieve superior machining performances characterized by high-quality surface roughness, reduced cutting force and elevated MRR.
3. Validate the efficacy of the newly proposed endmill based on the identified optimum cutter geometrical features and machining parameters, ensuring its effectiveness in achieving the desired machining outcomes.

1.4 Research Scopes

To achieve the research objectives and establish a framework for the research procedure, it is essential to define the scope of this study. This research specifically focuses on aluminum metal matrix composites (MMC), where the metal matrix is aluminum (Al) and the reinforcement is silicon carbide (SiC). The geometric parameters mentioned in the objectives will be gathered from both the literature review and the recommended data from the manufacturer. For the experimental design, the Taguchi statistical technique will be employed for screening purposes and Response Surface Methodology (RSM) will be used with the Box-Behnken approach as the Design of the Experiment (DoE). During the statistical analysis and optimization stages, Analysis of Variance (ANOVA) will be implemented in this study. This phase will specifically concentrate on evaluating the cutting performances namely surface roughness, cutting force, and material removal rate.