

STUDY ON THE BEHAVIOR OF
MICROMILLING PROCESS WITH THE
VALIDATION OF FINITE ELEMENT METHOD

NURUL HASYA MD KAMIL



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

UNIVERSITI MALAYSIA PAHANG AL-SULTAN ABDULLAH

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name : NURUL HASYA BINTI MD KAMIL
Date of Birth : 20 MAY 1998
Title : STUDY ON THE BEHAVIOR OF MICROMILLING
PROCESS WITH THE VALIDATION OF FINITE
ELEMENT METHOD
Academic Session : SEMESTER 1 2024/2025

I declare that this thesis is classified as:

- ☐ CONFIDENTIAL (Contains confidential information under the Official Secret Act 1997)*
☐ RESTRICTED (Contains restricted information as specified by the organization where research was done)*
☒ OPEN ACCESS I agree that my thesis to be published as online open access (Full Text)

I acknowledge that Universiti Malaysia Pahang Al-Sultan Abdullah reserves the following rights:

1. The Thesis is the Property of Universiti Malaysia Pahang Al-Sultan Abdullah
2. The Library of Universiti Malaysia Pahang Al-Sultan Abdullah has the right to make copies of the thesis for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by

(Student's Signature)

New IC/Passport Number
Date: 16 JAN 2025

(Supervisor's Signature)

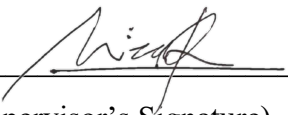
MOHD NIZAR MHD RAZALI
Name of Supervisor
Date: 16 JAN 2025

NOTE : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach a thesis declaration letter.

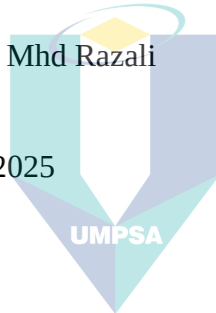


SUPERVISOR'S DECLARATION

I/~~We~~* hereby declare that I/~~We~~* have checked this thesis/~~project~~* and in my/~~our~~* opinion, this thesis/~~project~~* is adequate in terms of scope and quality for the award of the degree of ~~*Doctor of Philosophy/~~ Master of Science.


(Supervisor's Signature)

Full Name : Mohd Nizar bin Mhd Razali
Position : Senior Lecturer
Date : 16 JANUARY 2025




(Co-supervisor's Signature)

Full Name :
Position :
Date :



STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang Al-Sultan Abdullah or any other institutions.

A handwritten signature in black ink, appearing to read 'Nurul Hasya', is written over a horizontal line.

(Student's Signature)

Full Name : NURUL HASYA BINTI MD KAMIL

ID Number : MMF21006

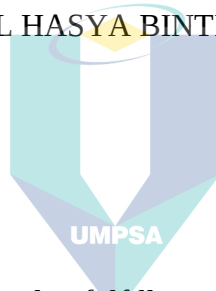
Date : 16 JANUARY 2025



اونيورسيتي مليسيا قهغ السلطان عبد الله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

STUDY ON THE BEHAVIOR OF MICROMILLING PROCESS WITH THE
VALIDATION OF FINITE ELEMENT METHOD

NURUL HASYA BINTI MD KAMIL



Thesis submitted in fulfillment of the requirements

اونيفرسيتي مليسيا پاهانج
for the award of the degree of
Master of Science

UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

Faculty of Manufacturing and Mechatronic Engineering Technology

UNIVERSITI MALAYSIA PAHANG AL-SULTAN ABDULLAH

JANUARY 2025

ACKNOWLEDGEMENTS

First and foremost, I express my sincere gratitude to Allah for granting me the opportunity, health, and capabilities to complete my Master of Science degree and this thesis.

I would like to extend my deepest appreciation to my supervisor, Dr. Mohd Nizar Mhd Razali, for his invaluable guidance and support throughout this research journey. His expertise, constructive feedback, and continuous encouragement have been instrumental in shaping both this thesis and my academic development. Dr. Nizar's meticulous attention during the research and writing phases has significantly enhanced the quality of this work. His dedication to reviewing my work and providing comprehensive feedback has been exemplary.

I am profoundly grateful to my parents for their unwavering support, sacrifices, and encouragement throughout my academic pursuits. Their steadfast belief in my capabilities has been a constant source of motivation. I also extend my gratitude to my family members who have provided moral support and encouragement during challenging times.

Finally, I would like to acknowledge my colleagues and friends for their valuable input and collaborative spirit. Their constructive suggestions and academic discourse have enriched this research work significantly.

This accomplishment would not have been possible without the support and contribution of all these individuals. Their collective guidance and encouragement have been fundamental to the successful completion of this thesis.

اؤنفرسٲٲ مالٲسٲا ٲاهاؤ
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

ABSTRACT

Micromilling is a precise and versatile machining process used to fabricate intricate and high-precision components with features often smaller than a millimeter. While previous studies have explored micromilling processes, there remains a significant gap in understanding the relationship between tool diameter variations and machining performance across different materials. Existing research has primarily focused on either tool wear or cutting parameters independently, without comprehensively examining how tool diameter affects both the mechanical and thermal aspects of micromilling. Additionally, while finite element analysis (FEA) has been used in machining studies, its accuracy in predicting micromilling behavior across different tool diameters and materials needs further validation. The objectives of the research are (1) to analyze the micromilling process using finite element analysis (FEA) to predict cutting forces, temperature distribution, and chip formation for tool diameters ranging from 0.3 to 0.9 mm when machining aluminium and mild steel, and (2) to validate these simulations through controlled machining tests, measuring cutting forces and surface quality to establish the accuracy of the FEA predictions. Aluminium Al6061 and mild steel AISI1045 were selected as test materials due to their contrasting properties and widespread industrial use. Al6061's excellent machinability and low hardness (107 HV) versus AISI1045's higher hardness (200 HV) provides an ideal comparison to evaluate tool performance across different material characteristics. These materials also represent common choices in aerospace and general manufacturing applications, making the findings particularly relevant for industrial applications. The study focused specifically on tool diameters between 0.3 and 0.9 mm, operating at speeds between 5,000 and 20,000 RPM, with feed rates ranging from 10 to 400 mm/min. The investigation was limited to dry machining conditions and straight-slot cutting operations, examining both the mechanical aspects (cutting forces, tool wear) and thermal effects during the micromilling process. The methodology employed a comprehensive two-phase approach combining FEA simulations using SFTC DEFORM 2D software with experimental validation using a high-speed machining setup. The results demonstrated that FEA simulations achieved accuracy rates of 84.18% for aluminium at higher feed rates (400 mm/min) with 0.9 mm tools, while accuracy decreased to 73.97% for smaller tools (0.3 mm). For mild steel, simulation accuracy varied more significantly, with error rates up to 83.89% depending on cutting conditions. Tool diameter significantly influenced cutting forces, with larger tools (0.9 mm) showing 45% lower cutting forces per unit thickness compared to smaller tools (0.3 mm) when machining aluminium. The simulations provided accurate estimates of cutting forces aligning closely with the experimental findings, particularly for larger tool diameters and aluminium workpieces. It was observed that machining aluminium and steel poses distinct challenges, primarily due to the higher hardness and toughness of steel and low heat capacity for aluminium, which leads to complex machining behavior and increased cutting forces.

ABSTRAK

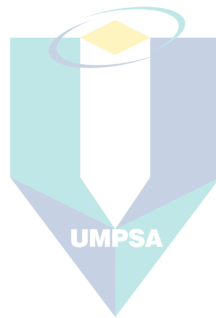
Pemesinan mikro merupakan satu proses pemesinan berketepatan tinggi yang digunakan untuk menghasilkan komponen halus. Walaupun pelbagai kajian telah dijalankan mengenai proses pemesinan mikro, masih wujud jurang yang ketara dalam pemahaman hubungan antara variasi diameter mata alat dengan prestasi pemesinan bagi bahan-bahan yang berlainan. Kebanyakan penyelidikan sedia ada hanya memberi tumpuan kepada kehausan mata alat atau parameter pemotongan secara berasingan, tanpa mengkaji secara menyeluruh kesan diameter mata alat terhadap aspek mekanikal dan terma dalam pemesinan mikro. Kajian ini mempunyai dua objektif utama: (1) menganalisis proses pemesinan mikro secara kuantitatif menggunakan FEA untuk meramal daya pemotongan, taburan suhu, dan pembentukan serpihan bagi mata alat berdiameter 0.3 hingga 0.9 mm semasa memproses aluminium dan keluli lembut, dan (2) mengesahkan hasil simulasi melalui ujian pemesinan terkawal dengan mengukur daya pemotongan dan kualiti permukaan untuk menentukan ketepatan ramalan FEA. Bahan ujian yang dipilih ialah aluminium Al6061 dan keluli lembut AISI1045, memandangkan kedua-dua bahan ini mempunyai sifat yang berbeza dan penggunaan yang meluas dalam industri. Kebolehmесinan cemerlang Al6061 dengan kekerasan rendah (107 HV) berbanding AISI1045 yang mempunyai kekerasan lebih tinggi (200 HV) menyediakan perbandingan yang ideal untuk menilai prestasi mata alat merentasi ciri-ciri bahan yang berbeza. Kajian ini memfokuskan kepada mata alat berdiameter antara 0.3 hingga 0.9 mm, yang beroperasi pada kelajuan 5,000 hingga 20,000 RPM, dengan kadar suapan antara 10 hingga 400 mm/min. Skop penyelidikan dihadkan kepada pemesinan kering dan operasi pemotongan slot lurus, dengan mengkaji aspek mekanikal (daya pemotongan, kehausan mata alat) serta kesan terma semasa proses pemesinan mikro. Metodologi kajian menggunakan pendekatan dua fasa yang komprehensif, menggabungkan simulasi FEA menggunakan perisian SFTC DEFORM 2D dengan pengesahan eksperimen menggunakan sistem pemesinan berkelajuan tinggi. Hasil kajian menunjukkan bahawa simulasi FEA mencapai ketepatan 84.18% bagi aluminium pada kadar suapan tinggi (400 mm/min) dengan mata alat 0.9 mm, manakala ketepatan menurun kepada 73.97% bagi mata alat yang lebih kecil (0.3 mm). Diameter mata alat didapati memberi kesan yang signifikan terhadap daya pemotongan, di mana mata alat yang lebih besar (0.9 mm) menghasilkan daya pemotongan 45% lebih rendah berbanding mata alat yang lebih kecil (0.3 mm) semasa memproses aluminium. Simulasi yang dijalankan berjaya memberikan anggaran daya pemotongan yang tepat dan sejajar dengan dapatan eksperimen, terutamanya bagi mata alat berdiameter besar dan bahan kerja aluminium. Kajian juga mendapati bahawa pemesinan aluminium dan keluli menimbulkan cabaran yang berbeza, terutamanya disebabkan oleh kekerasan dan ketahanan keluli yang lebih tinggi serta kapasiti haba aluminium yang rendah, yang mengakibatkan tingkah laku pemesinan yang kompleks dan peningkatan daya pemotongan.

TABLE OF CONTENT

DECLARATION	
TITLE PAGE	
ACKNOWLEDGEMENTS	ii
ABSTRACT	iii
ABSTRAK	iv
TABLE OF CONTENT	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
CHAPTER 1 INTRODUCTION	1
1.1 Research Background	1
1.2 Problem Statement	2
1.3 Research Objectives	4
1.4 Research Questions	4
1.5 Research Scope	5
1.6 Chapter Overview	5
CHAPTER 2 LITERATURE REVIEW	8
2.1 Introduction	8
2.2 Overview of Micromilling Process	8
2.3 Tool Deflection and Wear Phenomena	23
2.4 Material-Specific Micromilling Challenges	27
2.5 Simulation and Experimentation Integration	30
2.6 Limitations of FEA Models in Micromilling	32
2.7 Finite Element Analysis (FEA) with SFTC DEFORM 2D	36
2.8 Summary	39

CHAPTER 3 METHODOLOGY	41
3.1 Introduction	41
3.2 Two dimensional finite element modelling on micromilling process	44
3.3 Tool – workpiece model Meshing	48
3.4 Material Properties	50
3.5 Simulation Process and Flow Diagram	52
3.6 High Speed Machining Adapter Preparation and Micromilling Process	54
3.7 Machining Condition	62
3.8 Data Collection for the Validation Experiment	65
3.9 Summary	66
CHAPTER 4 RESULTS AND DISCUSSIONS	67
4.1 Introduction	67
4.2 Behaviour of micromilling of Aluminium Al6061 and Mild Steel AISI1045 simulated by Finite Element Method (FEM)	68
4.3 Micromilling cutting force profile estimated by SETC DEFORM 2D	71
4.4 Influence of various cutting speed on cutting force and temperature in micromilling estimated by FEM	73
4.5 Influence of various tool diameter on cutting force and temperature in micromilling estimated by FEM	77
4.6 Influence of various workpiece material on cutting force and temperature in micromilling estimated by FEM	79
4.7 New Micromilling tool geometry observed by a 3D measuring and laser microscope LEXT.	82
4.8 Cutting force performance of micromilling tool on various cutting conditions	85

4.9	Validation on cutting force performance of micromilling tool with Finite Element Method	87
4.10	Observation on Machining performance of micromilling tool on aluminium metal sheet to through 1 mm aluminium sheet	89
4.11	Summary	92
CHAPTER 5 CONCLUSIONS		94
5.1	Summary	94
5.2	Future works	95
REFERENCES		96



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

LIST OF TABLES

Table 2.1	Summary of the aspects of the micromilling process	10
Table 2.2	Main parameters that affecting the micromilling performance.	16
Table 2.3	Key aspects highlighting the importance of tool performance in micromilling	19
Table 2.4	Proposed Solutions to Address Limitations in FEA Models for Micromilling	34
Table 3.1	The key assumptions and their potential impacts	46
Table 3.2	FEM Cutting tool geometry	48
Table 3.3	Materials Properties	51
Table 3.4	Machining Conditions for finite element analysis	52
Table 3.5	MAKINO KE55 Vertical Milling Machine Specification	56
Table 3.6	Detail description of each components	58
Table 3.7	Specification of high speed spindle	59
Table 3.8	Materials properties of cutting tool and workpiece	61
Table 3.9	Specification of the micromilling tool for the experiment	62
Table 3.10	Machining Conditions for miromilling validation experiment	62
Table 3.11	Input Value and Output Parameter at 20000RPM (VFD controller (333Hz)	64

LIST OF FIGURES

Figure 2.1	Schematic representation of the micromilling process and key components involved (Wang et al., 2023)	13
Figure 2.2	The influence of cutting parameters (speed, feed rate, depth of cut) on tool performance in micromilling, compared with macro machining (Chen et al., 2021)	15
Figure 2.3	Schematic of tool deflection during micromilling and its possible impact on surface quality and dimensional accuracy (O'Toole et al., 2020)	24
Figure 2.4	Tool wear phenomena diagram at micromilling cutting edge (Wang et al, 2019)	26
Figure 2.5	Various types of exit burr by micromilling process (Chen et al., 2021)	28
Figure 2.6	Machined surface appearance of exit burr by micromilling (Chen et al., 2021)	28
Figure 2.7	Insight obtain from the finite element analysis method (above) validating the experimental results of burr formation (below) (Zhang et al., 2023)	32
Figure 2.8	Schematic diagram of tool path (Sun et al., 2017)	37
Figure 2.9	Schematic diagram of tool path while machine Aluminium thin wall (Sun et al., 2022)	38
Figure 3.1	Research works flowchart	43
Figure 3.2	Cutting tool position for 2 flute end mill (any size)	44
Figure 3.3	Schematic of cutting tool dimension for 2 flute end mill (any size)	45
Figure 3.4	Simplified model of 2D micromilling cutting for FEM simulation	45
Figure 3.5	Sample of FEM model with SFTC DEFORM 2D	49
Figure 3.6	Force vector	53
Figure 3.7	MAKINO KE55 Vertical Milling Machine	56
Figure 3.8	High Speed Spindle Adapter	57

Figure 3.9a	Force gauge and workpiece position and clamp (upper view)	60
Figure 3.9b	Tool and workpiece position during machining (side view)	60
Figure 3.10	Schematic diagram of machining process	61
Figure 3.11	Micromilling tool geometry	62
Figure 3.12	Makino KE55 Control Board	63
Figure 3.13	Sunfar E300 VFD Controller (Max Frequency: 400Hz)	64
Figure 4.1	Estimated stress distribution by FEA for micromilling aluminium Al6061	69
Figure 4.2	Estimated stress distribution by FEA for micromilling mild steel 1045	70
Figure 4.3	Comparison of the simulated stress magnitude between aluminium and mild steel micromilling process	71
Figure 4.4	Sample of aluminium Al6061 micromilling process cutting force profile, estimated by SFTC DEFORM 2D software	72
Figure 4.5	Possible burr estimated during at the tool exit	73
Figure 4.6	Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 18.9 [m/min], for micromilling tool diameter D , 0.3[mm]	74
Figure 4.7	Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 9.42 [m/min], for micromilling tool diameter D , 0.3[mm]	75
Figure 4.8	Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 4.7 [m/min], for micromilling tool diameter D , 0.3[mm]	76
Figure 4.9	Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 9.42 [m/min], for micromilling tool diameter D , 0.6[mm]	77
Figure 4.10	Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 14.1 [m/min], for micromilling tool diameter D , 0.9[mm]	78
Figure 4.11	Force and temperature estimation for mild steel AISI1045 machining with cutting speed, v_c of 4.7 [m/min], for micromilling tool diameter D , 0.3[mm]	80

Figure 4.12	Force and temperature estimation for mild steel AISI1045 machining with cutting speed, v_c of 9.4 [m/min], for micromilling tool diameter D , 0.6[mm]	80
Figure 4.13	New tool geometries (front view)	83
Figure 4.14	New tool geometries (side view)	84
Figure 4.15	Relationship between tool diameters (mm) with cutting force (N/mm) for aluminium Al-6061 and mild steel AISI1045	85
Figure 4.16	Relationship between tool diameters (mm) with cutting force (N/mm) for various feed rate (mm/min)	86
Figure 4.17	Comparison between FEM estimated cutting force per unit thickness [N/mm] with the experimental result for micromilling tool diameter 0.3mm	87
Figure 4.18	Comparison between FEM estimated cutting forces per unit thickness [N/mm] with the experimental result for micromilling tool diameter 0.3 to 0.9 mm with the feed rate of 200 mm/min	88
Figure 4.19	Machining performance of 0.9 mm tool diameter on aluminium focusing on micromilling capability	89
Figure 4.20	Machining performance of 0.6 mm tool diameter on aluminium, focusing on burr formation	90
Figure 4.21	Machining performance of 0.3 mm tool diameter on aluminium, focusing on tool breakage	91

CHAPTER 1

INTRODUCTION

1.1 Research Background

Micromilling is a precise and versatile machining process essential for producing intricate components across various high-tech industries, including aerospace, biomedical, and electronics. The process's performance is significantly influenced by the tool diameter and the material properties of the workpiece. Effective micromilling demands a delicate balance between tool size, cutting parameters, and material characteristics to achieve high precision and surface quality (Attanasio, 2017). In the aerospace industry, micromilling is used to manufacture components with complex geometries and tight tolerances. For instance, the production of turbine blades and other small-scale components necessitates the use of micromilling due to its ability to produce detailed features with high accuracy (Wang et al., 2023). In the biomedical field, micromilling is crucial for creating implants and surgical instruments that require precise dimensions and smooth surface finishes to ensure biocompatibility and functionality (Liu et al., 2022). The electronics industry relies on micromilling for the fabrication of microelectromechanical systems (MEMS) and other micro-scale electronic devices, where precision and surface integrity are paramount (Bai et al., 2023).

The performance of micromilling is greatly affected by the tool diameter. Smaller tool diameters can produce finer features but are more prone to deflection and wear, which can affect the overall accuracy and quality of the machined part. Conversely, larger tool diameters offer greater rigidity and longer tool life but may not be suitable for producing very fine features. The material properties of the workpiece, such as hardness, toughness, and thermal conductivity, also play a significant role in determining the optimal tool diameter and cutting parameters. For example, harder materials like steel require more robust tools and specific cutting conditions to prevent tool wear and

breakage, whereas softer materials like aluminium allow for more flexibility in tool selection and cutting parameters (Deepanraj et al., 2022). Previous studies in micromilling have primarily focused on either tool wear mechanisms or cutting parameter optimization in isolation. However, there remains a critical need to understand the interrelationship between tool diameter variations and machining performance across different materials. Existing research has not adequately addressed how tool diameter affects both the mechanical and thermal aspects of micromilling, particularly when machining materials with contrasting properties like aluminium and steel decreases (O'Toole & Fang, 2022; Ercetin et al., 2023).

SFTC DEFORM 2D is an advanced finite element analysis (FEA) simulation software designed to predict the outcomes of machining processes, including micromilling. It provides a comprehensive platform for modeling and analyzing tool-workpiece interactions, thermal effects, and material removal mechanisms. The software simulates the cutting forces, temperature distribution, and material deformation during the micromilling process, allowing for the accurate decision of tool geometry, cutting parameters, and process conditions (Sun et al., 2022). By leveraging the capabilities of SFTC DEFORM 2D, this research focuses on evaluating the micromilling performance for tool diameters ranging from 0.3 mm to 0.9 mm on aluminium and steel workpieces. The simulation results helps in understanding the influence of tool diameter and cutting speed on capability of micromilling tool to machine. This study aims to enhance the understanding of the micromilling process, providing valuable insights into the effect selection of tool diameters and operational parameters to achieve the desired machining outcomes.

1.2 Problem Statement

Despite significant advancements in micromilling technology, a critical gap exists in understanding the relationship between tool diameter selection and machining performance across different materials. Current research has not adequately addressed how varying tool diameters affect both mechanical and thermal aspects of the micromilling process. Furthermore, while finite element analysis (FEA) simulations have

been employed in machining studies, their accuracy in predicting micromilling behavior for different tool diameters and materials requires validation. This gap in knowledge particularly affects the machining of materials with contrasting properties, such as aluminium and steel, where tool performance varies significantly based on material characteristics.

The decision process is complicated by factors such as tool wear, thermal effects, and material-specific responses. Tool wear is a critical issue, as it directly impacts the surface quality and dimensional accuracy of the machined parts. For instance, wear mechanisms like abrasive, adhesive, and diffusive wear must be considered to accurately predict tool life and performance (Muhammad et al., 2021; Deepanraj et al., 2022). Thermal effects also play a significant role in micromilling. The heat generated during the cutting process can lead to thermal deformation of both the tool and workpiece, affecting the accuracy and surface finish. Efficient thermal management strategies are required to mitigate these effects, especially for materials with lower thermal conductivity like steel (Caiazza & Alfieri, 2018; Meylan et al., 2022). Meanwhile for aluminium, with its high thermal conductivity and ductility, tends to form built-up edges on the tool, leading to increased tool wear. In contrast, steel's higher hardness necessitates more robust tool materials and coatings to maintain performance under high cutting forces (Shirzadi et al., 2022; Liang et al., 2022).

Thus, it is assumed that micromilling performance, including tool durability and precision, can be significantly obtained by estimating the machining behaviour through simulation results from SFTC DEFORM 2D, particularly when evaluating the impact of different tool diameters on process outcomes. The advanced capabilities of this simulation software allow for detailed modeling of tool-workpiece interactions, thermal effects, and material removal mechanisms, providing valuable insights into the micromilling process. By conducting simulations with various tool diameters on aluminium and steel workpieces, the research aims to identify optimal operational parameters. These simulations predicted critical factors such as cutting forces, temperature distribution, and material removal rates, which are essential for ensuring high precision and tool longevity (Deepanraj et al., 2022; Xia et al., 2023). Following the

simulations, the predicted outcomes guides the selection of tool diameters and cutting parameters, such as spindle speed, feed rate, and depth of cut. These selected parameters then be validated through experimental trials to ensure their real-world applicability.

The experimental validation focused on comparing the simulated results with actual machining data to validate the capability of machining without breaking, particularly emphasizing the relationship between tool diameter and machining performance across different materials (Sun et al., 2022; Liu et al., 2022). This integrated approach of simulation followed by experimental validation is expected to enhance the overall understanding of micromilling processes and improve process parameters for both aluminium and steel workpieces. By bridging the gap between theoretical predictions and practical applications, this research aims to achieve better tool performance, reduced tool breaking possibility, and higher machining precision, ultimately advancing the field of micromilling technology (Caiazzo & Alfieri, 2018; Meylan et al., 2022).

1.3 Research Objectives

Objective 1: To analyze the micromilling behavior such as cutting force, chip formation, and tool temperature for various tool diameters using finite element analysis (FEA)

Objective 2: To validate the micromilling cutting performance for various materials with the simulations through experimental procedures

1.4 Research Questions

- i. How accurately can FEA predict cutting forces and temperature distributions for different tool diameters (0.3-0.9 mm) in micromilling aluminium and steel?
- ii. What are the quantifiable differences in tool wear rates between various diameters when machining different materials?
- iii. How do experimental results validate the FEA predictions across different machining parameters?

- iv. What is the optimal tool diameter range for specific material combinations based on both simulation and experimental data?

1.5 Research Scope

i. Tool Diameter Variations

The study explored the micromilling performance of tool diameters ranging from 0.3 mm to 0.9 mm. The effect of different tool diameters on cutting forces, temperature distribution, and material removal rate is analyzed using SFTC DEFORM 2D simulations.

i. Material Specific Responses

The research focused on aluminium and steel, examining their distinct mechanical properties and how these influence micromilling outcomes.

iii. Simulation and Experimental Validation

Utilization of SFTC DEFORM 2D for detailed simulations of the micromilling process, including tool-workpiece interactions, thermal effects, and material removal mechanisms. Conducting experimental validation to compare with simulation results, focusing on cutting forces, temperature distribution, and material removal rate.

iv. Cutting Parameter Selection

Spindle speed, feed rate, and depth of cut are varied systematically to identify optimal settings for both aluminium and steel workpieces.

1.6 Chapter Overview

Chapter 1, the introduction, explains micromilling as a crucial process in advanced manufacturing, emphasizing its importance in aerospace, biomedical, and

electronics industries for producing intricate components. The chapter highlights how micromilling performance is influenced by tool diameter and workpiece material properties, particularly for aluminium and steel. It tackles the challenges in understanding these factors, including tool wear, thermal effects, and material-specific responses. Two main research objectives are presented: simulating micromilling behavior for various tool diameters using SFTC DEFORM 2D, and validating the micromilling cutting performance with simulation-verified conditions. The chapter emphasizes the study's significance in enhancing understanding of micromilling processes and improving parameters for both aluminium and steel workpieces.

Chapter 2, the literature review provides an in-depth examination of the current state of research in micromilling and high-speed machining. It begins by discussing the fundamental principles of micromilling and its applications, followed by an exploration of the limitations of traditional CNC machines in this context. The chapter covers recent advancements in high-speed machining technologies and adaptations for CNC machines, drawing on studies that have investigated various aspects of micromilling, including surface roughness, tool wear, and machining stability.

Chapter 3 outlines the methodology in two phases, aligned with the study's objectives. Phase 1 focuses on simulating micromilling behavior using SFTC DEFORM 2D software for tool diameters ranging from 0.3 to 0.9 mm. This phase involves developing 2D finite element models, detailing the model meshing process, and specifying material properties for the tungsten carbide tool, Aluminium 6061, and AISI 1045 steel workpieces. The simulation process, including pre-processing, processing, and post-processing steps, is explained. Phase 2 describes the experimental procedure to validate the simulated results. It covers the preparation of a high-speed machining adapter, experimental setup using a Makino KE555 Vertical Milling CNC machine, and the selection of micromilling tools.

Chapter 4, the results and discussions, the simulation and experimental results are presented and analyzed. The discussion interprets these results in the context of the

research objectives and the existing literature. It addresses the practical implications of the findings for the manufacturing industry, including potential improvements in productivity and cost-effectiveness on micromilling processes. Any limitations encountered during the research are acknowledged, and their impact on the results are be discussed.

Chapter 5, the conclusion chapter summarizes the key findings of the research, emphasizing the successful development and validation of the high-speed machining adapter. It highlights the contributions of the study to the field of micromilling, particularly in terms of enhancing the capabilities of traditional CNC machines. The practical implications for industry, such as improved precision and efficiency in micromilling operations, are discussed. This chapter outlines the limitations of the study, providing a candid assessment of the challenges encountered and the areas that require further investigation. Finally, recommendations for future research are proposed, suggesting directions for continued innovation and improvement in high-speed micromilling technology.



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The primary objective of this chapter is to review the current state-of-the-art in micromilling processes, particularly focusing on the relationship between tool diameter selection and machining performance across different materials - an area that remains inadequately explored in existing literature. This review examines critical factors affecting tool performance, wear mechanisms, machining stability, and the influence of workpiece material properties. While extensive research exists on general micromilling parameters, there is a notable gap in understanding how varying tool diameters specifically impact both mechanical and thermal aspects of the process, especially when machining materials with contrasting properties such as aluminium and steel. Additionally, while finite element analysis (FEA) simulations have been widely employed in machining studies, their accuracy in predicting micromilling behavior for different tool diameters and materials requires further validation. This review aims to synthesize findings from previous studies to provide a foundation for understanding parameters affecting micromilling behaviour through simulation and experimental validation, with particular emphasis on addressing these identified knowledge gaps. By critically analyzing existing research and identifying areas requiring further investigation, this chapter establishes the theoretical framework necessary for enhancing the precision, efficiency, and applicability of micromilling in manufacturing high-precision components.

2.2 Overview of Micromilling Process

Micromilling is a precise and versatile machining process used to fabricate intricate and high-precision components. It involves the use of micro end mills, typically

with diameters less than 1 [mm], to remove material from a workpiece. Figure 2.1 illustrates the micromilling process, highlighting the micro end mill rotates to remove material with high precision. The workpiece undergoes machining to create fine, detailed microchannels or grooves, emphasizing the capability of micromilling to achieve intricate features with varying depths, showcasing the precision of this process (Wang et al., 2023). This technique is crucial in industries such as aerospace, medical devices, and microelectronics, where precision and miniaturization are essential (Liang et al., 2022). The key aspects of micromilling are shown as the following and summarize into Table 2.1:



Table 2.1 Summary of the aspects of the micromilling process

Details	Parameters Investigated by Previous Researchers	References
PROCESS AND TOOLING	Spindle Speed: - <i>Range:</i> 15,000–30,000 RPM. - <i>Effect:</i> Higher spindle speeds can lead to increased tool wear and surface roughness; optimal speeds around 20,000 RPM balance performance and tool life.	Dadgari, 2020
- Specialized equipment with high rotational speeds (10,000–110,000 RPM) needed for stability and precision. - Tools made from materials like cemented carbide. - Advanced coatings such as diamond-like carbon (DLC) enhance performance and longevity.	Tool Material and Coating: - <i>Materials:</i> Cemented carbide, tungsten carbide. - <i>Coatings:</i> AlTiN, DLC. - <i>Effect:</i> Coatings like AlTiN reduce tool vibration and improve surface finish.	Wang et al., 2022
	Depth of Cut: - <i>Axial Depth:</i> 50–150 μm. - <i>Radial Depth:</i> 20–50 μm. - <i>Effect:</i> Increased depth of cut can lead to higher cutting forces and tool vibration; optimal depths improve surface quality.	Dadgari, 2020
	Tool Coating and Cutting Parameters: - <i>Coatings:</i> AlTiN, nACo, TiSiN. - <i>Cutting Speed:</i> 10–30 m/min. - <i>Feed Rate:</i> 1–3 $\mu\text{m}/\text{tooth}$. - <i>Depth of Cut:</i> 10–30 μm. - <i>Effect:</i> Depth of cut significantly affects burr formation; cutting speed primarily influences surface roughness.	Muhammad et al., 2021

Table 2.1 Continued

Details	Parameters Investigated by Previous Researchers	References
MATERIAL CONSIDERATIONS	Workpiece Materials - <i>Materials:</i> Titanium alloys (Ti6Al4V), alumina bioceramics. - <i>Effect:</i> Different materials exhibit varying residual stress distributions; alumina bioceramics show increased residual tensile stress with higher spindle speeds. Thermal Treatments: - <i>Effect:</i> Proper thermal treatments can enhance machinability and surface integrity. High-Entropy Alloys (HEAs): - <i>Materials:</i> FeCoNiCrAl_x (x = 0.1, 0.5, 1). - <i>Effect:</i> Increased Al content leads to higher microhardness and poorer machinability; FeCoNiCrAl_{0.1} exhibits better machinability with lower cutting forces and tool wear. Titanium Alloy Ti-3Al-2.5V (Grade 9): - <i>Cutting Speed:</i> 20–30 m/min. - <i>Feed Rate:</i> 0.15–0.45 µm/tooth. - <i>Depth of Cut:</i> 20–60 µm. - <i>Effect:</i> Optimal parameters minimize surface roughness, burr width, burr length, and tool wear.	Wang and Sun, 2024 Liang et al., 2022 Liang et al., 2022 Khan et al., 2023

Table 2.1 Continued

Details	Parameters Investigated by Previous Researchers	References
CUTTING MECHANICS - Micromilling operates under different mechanics compared to conventional milling. - Minimum chip thickness and cutting forces are critical for surface quality. - Models developed to predict and choose the best parameters to minimize tool deflection and wear, improving stability and accuracy.	Feed per Tooth: - <i>Range:</i> 0.5–3.5 $\mu\text{m}/\text{tooth}$. - <i>Effect:</i> Lower feed rates can lead to ploughing and increased surface roughness; optimal feed rates improve surface finish.	Tian et al., 2019
	Cutting Forces and Vibrations: - <i>Effect:</i> Increased depth of cut and cutting speed can reduce tool vibration and force transmissibility, enhancing surface quality.	Dadgari, 2018
	Residual Stresses: - <i>Effect:</i> Machining parameters significantly influence residual stress distribution, affecting crack resistance and service life of materials like alumina bioceramics.	Wang and Sun, 2024
	Energy Efficiency and Surface Morphology: - <i>Material:</i> SLM Inconel 718. - <i>Effect:</i> Increased feed per tooth and spindle speed enhance energy efficiency; optimal parameters improve surface quality.	Duan et al., 2024
	Tool Wear and Tool Life Prediction: - <i>Material:</i> Ti-6Al-4V. - <i>Effect:</i> Tool wear mechanisms include adhesion and abrasion; predictive models assist in estimating tool life under various cutting conditions.	Dadgari et al., 2018

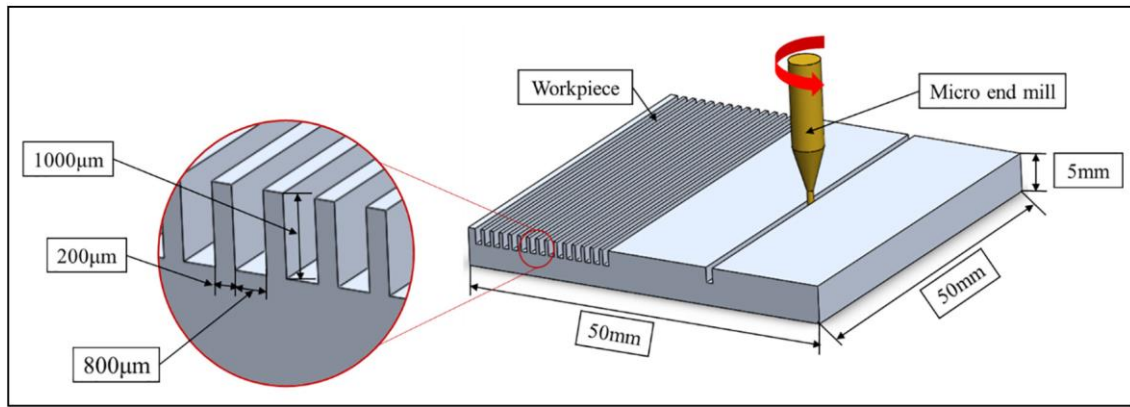


Figure 2.1 Schematic representation of the micromilling process and key components involved

Source: Wang et al. (2023).

Micromilling is a sophisticated and highly specialized machining process that requires careful consideration of tool design, material properties, and cutting parameters. The continuous advancements in simulation technology and material science are driving the future of micromilling, making it an indispensable technique in various high-precision industries. In micromilling, the cutting parameters—speed, feed rate, and depth of cut—play a crucial role in determining the cutting forces, surface quality, and tool wear performance (Muhammad et al., 2021; Kuram and Ozcelik, 2014; Lashkaripour et al., 2018). These parameters must be carefully pre-decided to achieve the desired precision and efficiency in the machining process, as shown in Table 2.2. Understanding the cutting parameters affected machining behaviour—speed, feed rate, and depth of cut—is essential for achieving high precision and efficiency in micromilling. Each parameter influences cutting forces, surface quality, and tool wear differently, and their combined effects must be carefully balanced to meet specific machining goals (Muhammad et al., 2021; Kuram and Ozcelik, 2014; Lashkaripour et al., 2018). However, understanding cutting forces is crucial for improving micromilling processes as it directly impacts tool wear and performance. It is able to observe the different between micro cutting and macro cutting (conventional milling) machining behaviour, as shown in Figure 2.2. In conventional milling, the cutting tool is generally larger, and the interaction with the workpiece involves higher cutting forces due to the larger depth of cut and uncut chip thickness, h . This results in more significant material removal per pass but also generates

higher thermal and mechanical stresses on the tool. The chips formed in macromilling are larger, and the process can handle more substantial variations in cutting parameters without immediate negative effects on tool performance or surface finish (Chen et al., 2021).

In contrast, micromilling involves much smaller tools with finer cutting edges. The cutting speed, feed rate, and depth of cut need to be precisely controlled to maintain tool performance and achieve the desired surface quality. The uncut chip thickness, h in micromilling is comparable to or smaller than the tool's edge radius, which significantly affects the cutting mechanics. Smaller chips are formed, and the process is more sensitive to variations in cutting parameters. In micromilling, even small changes in the feed rate or depth of cut can lead to increased tool wear, deflection, and surface roughness, due to the reduced scale and the increased influence of the tool's micro-geometry. This sensitivity requires precise setting of cutting parameters to balance material removal rate, tool wear, and surface finish, which is critical for achieving the high precision required in micromilling applications (Chen et al., 2021). Accurate prediction and monitoring of cutting forces help in designing tool path strategies and cutting conditions, thereby extending tool life. For instance, the development of nonlinear cutting force models that consider the effects of tool wear and cutting-edge radius significantly improves the accuracy of force prediction and tool wear monitoring (Liu et al., 2022). This enables real-time adjustments in the milling process, enhancing overall tool performance and reducing downtime.

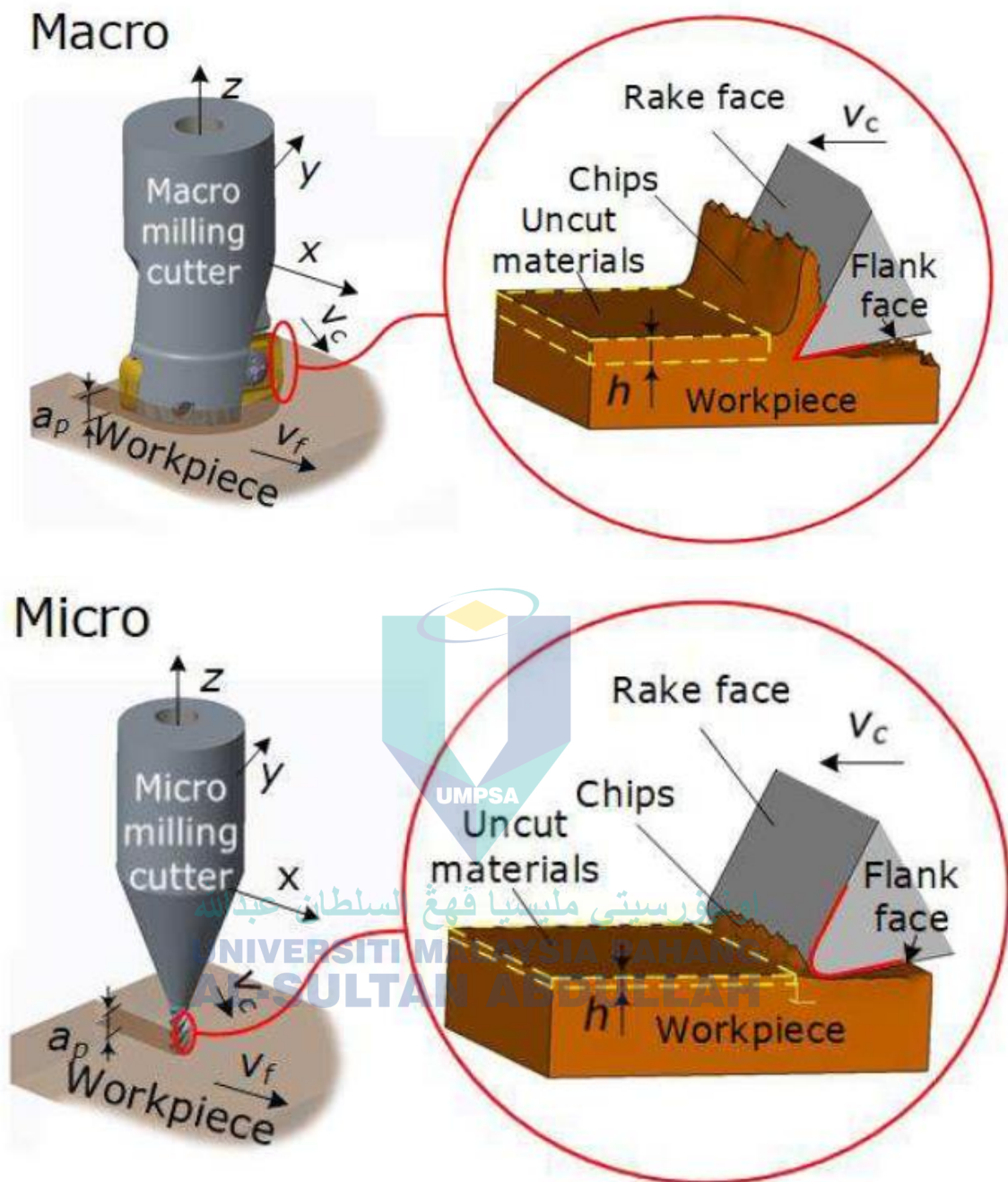


Figure 2.2 The influence of cutting parameters (speed, feed rate, depth of cut) on tool performance in micromilling, compared with macro machining

Source: Chen et al. (2021)

Table 2.2 Main parameters that affecting the micromilling performance

Aspect/Details	Parameters Investigated by Previous Researchers	References
Cutting Speed	- Cutting Speed:	Muhammad
- Impacts cutting forces and surface finish.	- <i>Range:</i> 10–30 m/min.	et al., 2021
- Higher speeds reduce cutting forces by decreasing material hardness at elevated temperatures.	- Cutting Speed:	Kuram and
- Facilitates easier material removal.	- <i>Range:</i> 20–60 m/min.	Ozcelik,
- In micromilling of Inconel 718, higher speeds led to better surface finishes, minimized burr formation, and reduced tool wear.	- <i>Effect:</i> Increased cutting speed led to reduced cutting forces and improved surface quality in micromilling of AISI 304 stainless steel.	2014
	- Cutting Speed:	Lashkaripour
	- <i>Range:</i> 50–150 m/min.	et al., 2018
	- <i>Effect:</i> Higher cutting speeds improved surface finish and reduced burr formation in micromilling of aluminum alloys.	
	- Cutting Speed:	Wang et al.,
	- <i>Range:</i> 100–200 m/min.	2023
	- <i>Effect:</i> Increased cutting speeds enhanced material removal rates and surface quality in micromilling of copper alloys.	

Table 2.2 Continued

Aspect/Details	Parameters Investigated by Previous Researchers	References
Feed Rate	Feed Rate: Range: 1–3 $\mu\text{m}/\text{tooth}$.	Muhammad et al., 2021
-Directly influences cutting forces and surface integrity.	- Effect: Higher feed rates increased burr formation and surface roughness in micromilling of Inconel 718.	
- Higher feed rates increase cutting forces due to larger volume of material removal per unit time.	Feed Rate: Range: 0.5–2.5 $\mu\text{m}/\text{tooth}$. Effect: Increased feed rates led to higher cutting forces and tool wear during micromilling of AISI 304 stainless steel.	Kuram and Ozcelik, 2014
- Higher feed rates can lead to increased radial vibrations and surface roughness.	Feed Rate: Range: 2–5 $\mu\text{m}/\text{tooth}$. - Effect: Higher feed rates resulted in increased surface roughness and burr formation in micromilling of aluminum alloys.	Lashkaripour et al., 2018
- Increasing feed rate by a factor of 2.75 can decrease tool life by a factor of 1.4, indicating a balance between productivity and tool longevity.	Feed Rate: Range: 3–6 $\mu\text{m}/\text{tooth}$. - Effect: Increased feed rates led to higher cutting forces and reduced tool life in micromilling of copper alloys.	Wang et al., 2023

Table 2.2 Continued

Aspect/Details	Parameters Investigated by Previous Researchers	References
Depth of Cut	Depth of Cut: Range: 10–30 μm .	Lashkaripour et al., 2018
-Determines the thickness of material layer removed in a single pass.	- Effect: Increased depth of cut led to higher cutting forces and tool wear in micromilling of Inconel 718.	
	Depth of Cut: Range: 20–50 μm .	Kuram and Ozcelik, 2014
- Major factor affecting cutting forces and tool wear.	- Effect: Deeper cuts resulted in increased surface roughness and dimensional inaccuracies in micromilling of AISI 304 stainless steel.	
- Deeper cuts increase engagement between tool and workpiece, leading to higher cutting forces and greater tool wear.	Depth of Cut: Range: 30–60 μm .	Lashkaripour et al., 2018
- In micromilling of hardened steels, depth of cut affects diameter deviation and parallelism error, impacting dimensional accuracy of the machined part.	- Effect: Higher depths of cut increased tool wear and reduced surface quality in micromilling of aluminum alloys.	
	Depth of Cut: Range: 40–80 μm .	Wang et al., 2023
	- Effect: Increased depths of cut led to higher cutting forces and decreased tool life in micromilling of copper alloys.	

Cutting forces are integral to achieving high surface quality and precision in machined components. Variations in cutting forces can lead to surface defects, burr formation, and dimensional inaccuracies. Research shows that accurate design of tool path strategies, such as the contour climb tool path combined with effective cooling conditions, can significantly reduce cutting forces and improve surface quality (Koklu & Basmaci, 2017). This is particularly important for applications in the aerospace and medical industries, where surface integrity and precision are critical. The ability to measure and analyze cutting forces in real-time is essential for process monitoring and control. Studying cutting forces also facilitates the decision on of cutting conditions, which is vital for enhancing productivity and efficiency. This level of understanding is particularly beneficial in high-precision industries where even minor adjustments can lead to significant improvements in performance and cost savings. Tool performance is a critical factor in micromilling, impacting the quality, efficiency, and reliability of the machining process. The effectiveness of micromilling tools directly influences the precision and surface finish of micro-components, making it essential to improve tool design, material, and cutting conditions (Siregar et al., 2018 Liu et al., 2022; Zheng et al., 2022, Attanasio, 2017; Cao & Li, 2015 Ljang et al., 2022; Giardini et al., 2013). Several key aspects highlighting the importance of tool performance in micromilling, as summarized in Table 2.3:

Table 2.3 Key aspects highlighting the importance of tool performance in micromilling

Aspect/Details	Parameters Investigated by Previous Researchers	References
Tool Geometry and Material - Geometry affects performance (flute numbers, helix angles).	Tool Geometry: - <i>Flute Number:</i> 2, 4, 6, 8. - <i>Helix Angle:</i> 30°, 45°, 60°. - <i>Effect:</i> 8-flute tools with a 45° helix angle exhibited superior performance in terms of reduced tool wear and improved surface finish during micromilling of stainless steel.	Siregar et al., 2018

Table 2.3 Continued

Aspect/Details	Parameters Investigated by Previous Researchers	References
- 8-flute tools show superior performance due to reduced wear and better stress distribution. - Cemented carbide is commonly used for its hardness and wear resistance.	Tool Geometry: <i>Flute Number:</i> 2, 4, 6, 8. <i>Helix Angle:</i> 30°, 45°, 60°. - <i>Effect:</i> 8-flute tools with a 45° helix angle exhibited superior performance in terms of reduced tool wear and improved surface finish during micromilling of stainless steel.	Siregar et al., 2018
	Tool Material: Cemented carbide, high-speed steel, polycrystalline diamond. - <i>Effect:</i> Cemented carbide tools demonstrated higher wear resistance and longer tool life in micromilling of titanium alloys compared to high-speed steel and polycrystalline diamond tools.	Siregar et al., 2018
	Tool Coatings: TiAlN, DLC, AlCrN. - <i>Effect:</i> Appropriate coatings reduced tool wear and enhanced performance during micromilling of titanium alloys.	Giardini et al., 2013
	Tool Diameter: Size: 50 µm, 100 µm, 200 µm. - <i>Effect:</i> Smaller tool diameters increased tool wear and reduced surface quality in micromilling of hardened steel.	Manso et al., 2019
	Tool Edge Radius: Size: 1 µm, 3 µm, 5 µm. - <i>Effect:</i> Larger edge radii improved tool life but decreased surface finish in micromilling of aluminum alloys	Lashkaripour et al., 2018

Table 2.3 Continued

Aspect/Details	Parameters Investigated by Previous Researchers	References
Tool Wear and Monitoring - Tool wear affects tool life and surface quality. - Nonlinear cutting force models provide real-time monitoring, improving predictive accuracy. - Development of wear standards and understanding wear mechanisms enhance tool longevity and performance.	Tool Wear Monitoring: Method: Nonlinear cutting force model. - Effect: Improved real-time monitoring and predictive accuracy of tool wear during micromilling operations. Tool Wear Mechanisms: Observation: Adhesive and abrasive wear. - Effect: Understanding wear mechanisms led to the development of wear standards, enhancing tool longevity and performance in micromilling. Tool Condition Monitoring: Method: Long Short-Term Memory (LSTM) neural networks. - Effect: Enhanced prediction of tool wear states in micromilling, leading to improved maintenance strategies. Digital Twin Technology: Application: Real-time tracking and prediction of tool wear progression. - Effect: Improved decision-making in micromilling processes, reducing tool failure rates.	Liu et al., 2020 Zheng et al., 2022 Manwar et al., 2023 Christiand et al., 2024

Table 2.3 Continued

Aspect/Details	Parameters Investigated by Previous Researchers	References
Tool Run-Out and Machining Stability - Tool run-out affects cutting forces, tool life, and surface integrity. - Accurate measurement and control of run-out are essential. - Incorporating run-out into adaptive models for cutting force control improves quality and reduces costs. - Robust chatter stability models are necessary.	Tool Run-Out Measurement: Laser displacement sensors. - Effect: Accurate measurement and control of tool run-out improved cutting force stability and surface integrity in micromilling. Chatter Stability Models: Development: Robust models incorporating tool run-out. Effect: Enhanced machining stability and reduced surface defects during high-speed micromilling. Run-Out Compensation: Adaptive control systems. Effect: Reduction in tool wear and improvement in surface finish during micromilling operations.	Attanasio, 2017 Cao & Li, 2015 Manso et al., 2019
	Machining Stability Analysis: Time-domain simulation. Effect: Prediction and avoidance of chatter in micromilling processes, enhancing product quality.	Wang et al., 2023

Understanding the effect of cutting parameters is essential in micromilling to achieve the desired surface quality, minimize tool wear, and enhance overall process efficiency. Key parameters include spindle speed, feed rate, and depth of cut, all of which need careful calibration to achieve higher performance. One of the key parameters is spindle speed. Spindle speed is a critical factor that influences the cutting forces, surface finish, and tool wear in micromilling, as it is directed to cutting speed and tool vibration.

Determining the optimal spindle speed involves balancing these outcomes to achieve efficient and high-quality machining. High spindle speeds reduce cutting forces and improve surface finish by decreasing the chip load on the cutting edge. However, excessively high speeds can lead to increased tool wear due to higher temperatures and potential thermal damage. Studies using Grey Relational Analysis (GRA) and Response Surface Methodology (RSM) have shown that spindle speed significantly impacts the machinability of titanium alloys and Inconel 718, with optimal speeds leading to reduced tool wear and better surface roughness (Khan et al., 2023; Sheheryar et al., 2022).

Additionally, feed rate and depth of cut are equally important parameters that influence machining efficiency and quality. Deciding the best for these parameters involves understanding the right balance to minimize burr formation, tool wear, and achieve the desired surface finish. The feed rate directly affects the cutting force and the interaction between the tool and the workpiece. Higher feed rates can lead to increased burr formation and tool wear, whereas lower feed rates may result in better surface finish but reduced material removal rates (Khan et al., 2023; Sheheryar et al., 2022). Meanwhile, the depth of cut determines the engagement of the tool with the workpiece, affecting the chip load and cutting forces. Optimal depth of cut helps in maintaining tool life and achieving a consistent surface finish (Sahoo & Mishra, 2014).

Designing the best cutting parameters in micromilling is a critical aspect of achieving high precision and efficiency in machining operations. By carefully calibrating spindle speed, feed rate, and depth of cut, it is possible to enhance surface quality, minimize tool wear, and improve overall process efficiency. Ultimately, the success of these efforts lies in their ability to adapt to the specific material and operational requirements of each unique micromilling application, ensuring that the process remains both effective and efficient in a variety of contexts.

2.3 Tool Deflection and Wear Phenomena

Tool deflection and wear are critical factors in micromilling that significantly affect machining accuracy, tool life, and surface finish. Tool deflection in micromilling

primarily occurs due to the small diameter of the cutting tools, which makes them susceptible to bending forces during machining, as shown in Figure 2.3 (O'Toole et al., 2020). The phenomenon of tool deflection during the micromilling process can significantly impacts surface quality and dimensional accuracy. In micromilling, the small diameter of the cutting tool makes it susceptible to bending or deflection under the forces exerted during machining. As the tool engages with the workpiece, the cutting forces push the tool away from its intended path, leading to deflection (O'Toole et al., 2020).

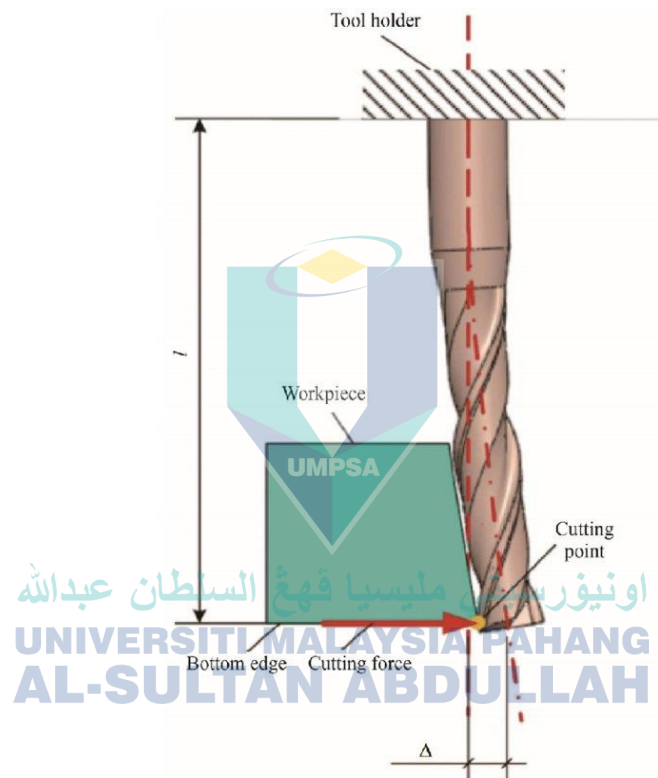


Figure 2.3 Schematic of tool deflection during micromilling and its possible impact on surface quality and dimensional accuracy

Source: O'Toole et al. (2020).

It can be understood from the schematic diagram that the cutting force, acting at the cutting point of the tool, causes a deflection that is visually represented by the red dashed line deviating from the tool's axis. This deflection results in a deviation of the tool's bottom edge from the intended cutting path, denoted by the displacement, Δ (O'Toole et al., 2020). Several factors contribute to tool deflection during the machining process. The machining mechanical load,

specifically the cutting forces exerted on the tool during machining, generates bending moments that lead to deflection. These forces are influenced by cutting parameters such as feed rate, spindle speed, and depth of cut (Christiand et al., 2024). The micromilling tool geometry, including the shape and size of the tool, number of flutes, and helix angles, affects its rigidity, with tools having fewer flutes or smaller diameters being more prone to deflection (Siregar et al., 2018). Furthermore, the tool and workpiece material properties play a crucial role, as the hardness and toughness of the workpiece material can influence the magnitude of the cutting forces, thereby affecting the degree of tool deflection. For example, harder materials like titanium alloys exert higher forces on the tool, resulting in greater deflection (Zheng et al., 2022).

Meanwhile, tool wear in micromilling can be categorized into several mechanisms, each with distinct characteristics and effects on the tool, as shown in Figure 2.4. Abrasive wear, caused by hard particles in the workpiece material or the buildup of material on the cutting edge, leads to the gradual removal of tool material, and is common in materials with high hardness or abrasive inclusions (Zhou & Sun, 2020). When there is a strong adhesive bond between the tool and the workpiece material, adhesive wear occurs, leading to material transfer and tool material removal, which is prevalent in the micromilling of ductile materials such as aluminium and titanium alloys (Zheng et al., 2022). At high temperatures, diffusion wear can occur due to chemical interaction between the tool and the workpiece material, resulting in the diffusion of atoms from the tool to the workpiece, which is significant in high-speed micromilling operations (Liu et al., 2022). Additionally, oxidation wear can develop when elevated temperatures cause the tool material to oxidize, forming brittle oxides that are easily removed during cutting, a mechanism often observed in high-temperature micromilling processes (Wang et al., 2019)

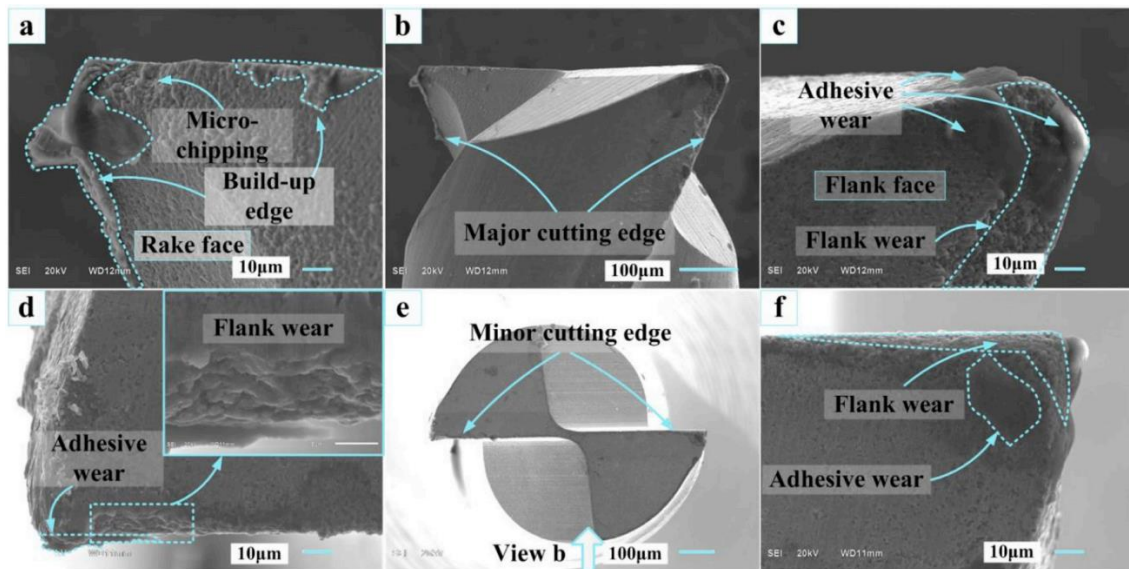


Figure 2.4 Tool wear phenomena at micromilling cutting edge
Source: Wang et al (2019)

In micromilling, the challenges posed by tool deflection and wear are pivotal in determining the success of the machining process. Tool deflection, driven by mechanical loads, tool geometry, and material properties, can lead to significant deviations in the tool path, adversely affecting the dimensional accuracy and surface quality of the machined parts. Similarly, wear mechanisms such as abrasive, adhesive, diffusion, and oxidation wear progressively degrade the tool, impacting its performance and the overall efficiency of the process. As the tool wears and deflects, the resulting surface roughness and dimensional inaccuracies can compromise the quality of the finished product. Therefore, implementing robust tool condition monitoring systems, such as digital twin technology and advanced predictive models, is crucial. These systems enable real-time tracking and management of tool wear, ensuring that machining processes remain consistent and reliable. By doing so, manufacturers can achieve higher precision, better surface quality, and extended tool life, ultimately leading to more efficient and cost-effective micromilling operations.

2.4 Material-Specific Micromilling Challenges

Micromilling presents unique challenges depending on the material being machined. This section delves into the specific issues encountered when micromilling aluminium and steel.

2.4.1 Micromilling of Aluminium Based Metal

Aluminium is widely used in micromilling due to its excellent machinability, lightweight properties, and high thermal conductivity. However, it also poses specific challenges:

i. Tool Wear and Adhesion: Aluminium tends to adhere to the cutting tool, leading to built-up edge (BUE) formation. This adhesion increases tool wear and deteriorates the surface finish. Studies have shown that employing appropriate tool coatings and cutting parameters can significantly reduce adhesion and improve tool life (Hsieh et al., 2012).

ii. Surface Quality and Burr Formation: The surface quality in micromilling aluminium can be affected by the formation of burrs, especially at lower cutting speeds and improper tool paths. Research indicates that using flood coolant and accurate tool path strategies, such as the contour climb strategy, can enhance surface quality and reduce burr formation (Koklu & Basmaci, 2017). Figure 2.5 shows the example of burr formation possible during the aluminium machining, while Figure 2.6 shows the observed machined surface appearance of exit burr by micromilling (Chen et al., 2021).

iii. Machinability of High-Strength Aluminium Alloys: High-strength aluminium alloys used in aerospace applications present additional challenges, such as increased tool wear and thermal issues. Advances in hybrid additive manufacturing processes have been explored to address these challenges, enhancing the machinability and reducing defects in high-strength aluminium alloys (Altıparmak et al., 2021).

iv. **Environmental and Recycling Considerations:** The aluminium industry is highly energy-intensive, and there is significant interest in waste heat recovery and recycling processes to mitigate environmental impacts. Efficient recycling methods can reduce the overall energy consumption and environmental footprint of aluminium manufacturing (Brough & Jouhara, 2020).

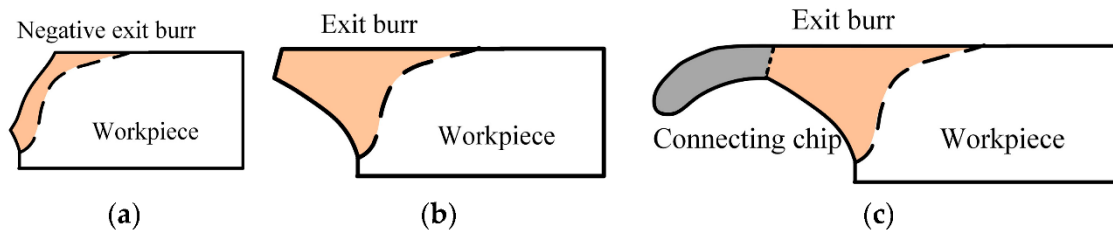


Figure 2.5 Various types of exit burr by micromilling process

Source: Chen et al. (2021)

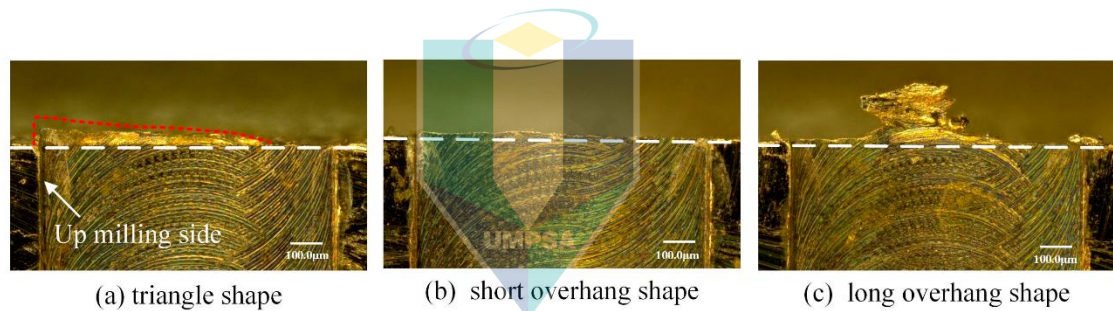


Figure 2.6 Machined surface appearance of exit burr by micromilling

Source: Chen et al. (2021).

2.4.2 Micromilling of Steel Based Metal

Steel, particularly high-strength alloys, is another critical material in micromilling, offering different challenges compared to aluminium:

i. **Tool Wear and Hardness:** Steel is harder than aluminium, leading to increased tool wear. The high hardness and toughness of steel require robust tool materials and coatings to maintain tool life and performance. Research has shown that using advanced coatings like diamond-like carbon (DLC) can enhance tool durability in micromilling steel (Shirzadi et al., 2022).

ii. Thermal Management: The thermal conductivity of steel is lower than that of aluminium, which can lead to higher cutting temperatures and thermal damage to both the tool and workpiece. Implementing efficient cooling strategies, such as flood coolant, helps manage these temperatures and improve machining outcomes (Koklu & Basmaci, 2017).

iii. Burr Formation and Surface Integrity: Like aluminium, steel is prone to burr formation, which can affect the surface integrity and dimensional accuracy of the machined parts. Employing specific cutting parameters and tool path strategies can minimize burr formation and enhance surface quality (Altıparmak et al., 2021).

iv. Advanced Machining Techniques: Innovative techniques such as ultrasonic vibration-assisted micromilling have been explored to improve the machinability of steel. These techniques help reduce cutting forces, improve chip evacuation, and enhance surface finish, making them valuable for high-precision applications (Zhang et al., 2023).

Micromilling of different materials, such as aluminium and steel, presents a distinct set of challenges that require tailored strategies to overcome. While aluminium's excellent machinability and thermal conductivity make it a popular choice, issues like tool wear, adhesion, and burr formation necessitate careful consideration of tool coatings, cutting parameters, and cooling strategies. The advances in hybrid manufacturing and recycling processes further enhance the efficiency and sustainability of aluminium micromilling. On the other hand, micromilling steel, especially high-strength alloys, demands robust tool materials and innovative techniques to manage the material's hardness and thermal properties. The use of advanced coatings and ultrasonic vibration-assisted micromilling demonstrates significant potential in reducing tool wear and improving surface integrity. It can be understood that, the successful micromilling of aluminium and steel hinges on a deep understanding of each material's unique properties and challenges.

2.5 Simulation and Experimentation Integration

Integrating simulation and experimentation in micromilling involves a systematic approach where both methods complement each other to enhance the accuracy and reliability of the machining process. The methodology typically includes the following steps:

Initial Simulation Setup (Pre-Processing):

Model Development: The first step is developing a detailed simulation model using software such as SFTC DEFORM or other finite element analysis (FEA) tools. This model includes the material properties, tool geometry, and cutting parameters.

Simulation Runs: Conduct initial simulation runs to predict cutting forces, tool wear, temperature distribution, and other critical parameters. These simulations help identify potential issues and precise initial setting of machining parameters (Zhang et al., 2023).

Experimental Validation:

Experiment Design: Design experiments to validate the simulation results. This involves selecting appropriate workpiece materials, tools, and machining conditions. For instance, experiments might include micromilling of materials like Al6061-T6 or Inconel 718 under various cutting parameters (Sun et al., 2022; Muhammad et al., 2021).

Data Collection: Collect data on cutting forces, surface roughness, tool wear, and other metrics during the machining process. Advanced monitoring techniques such as acoustic emission (AE) sensors and high-speed cameras are used for real-time data acquisition (Du et al., 2023).

Comparison and Analysis:

Result Comparison: Compare the experimental results with the simulation predictions. Discrepancies are analyzed to identify model limitations or areas for improvement. This step often involves statistical analysis and visualization techniques to assess the accuracy and reliability of the models (Platt et al., 2021).

Model Refinement: Refine the simulation models based on the experimental findings. This might include adjusting material properties, modifying tool geometries, or incorporating additional physical phenomena such as thermal effects (Tian et al., 2024).

Iterative Improvement: Iterative Testing: Conduct further simulations and experiments iteratively to continuously improve the model accuracy. Each iteration aims to narrow the gap between simulated predictions and experimental outcomes (Sun et al., 2022).

The integration of simulation and experimentation in micromilling represents a robust approach to enhancing the precision, efficiency, and reliability of machining processes. By systematically combining these two methodologies, the inherent strengths of each are leveraged to address the limitations of the other. Initial simulations provide a predictive framework that identifies optimal machining parameters and potential challenges, while experimental validation ensures that these predictions align with real-world outcomes. This iterative process of comparison, analysis, and refinement creates a feedback loop that continuously improves the accuracy of simulation models.

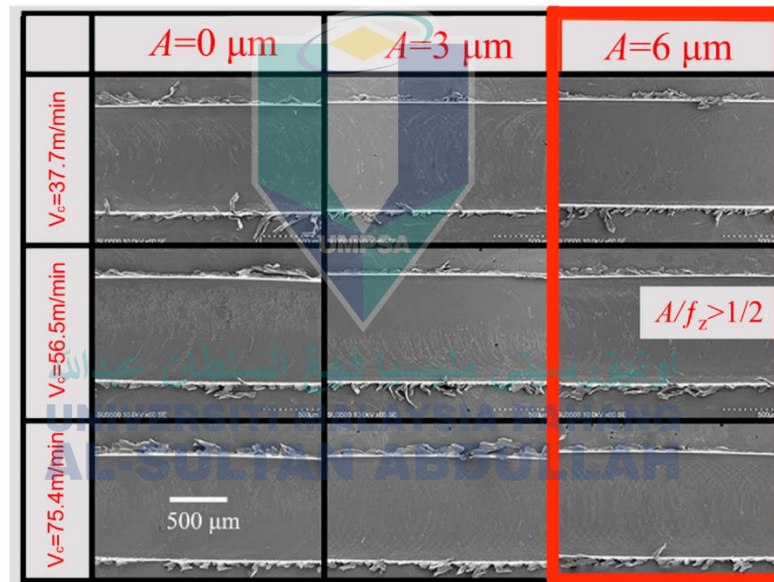
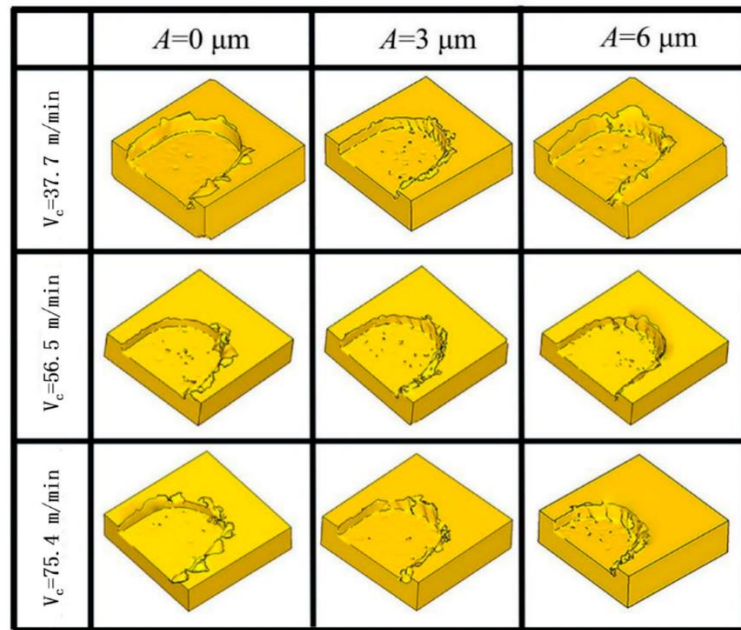


Figure 2.7 Insight obtain from the finite element analysis method (above) validating the experimental results of burr formation (below)

Source: Zhang et al. (2023)

2.6 Limitations of FEA Models in Micromilling

Micromilling has emerged as a critical technique in precision manufacturing, enabling the creation of intricate components for industries such as aerospace, biomedical engineering, and electronics. The process, characterized by the removal of material at the

micro-scale, demands a comprehensive understanding of cutting mechanics, tool dynamics, and material behavior (Chauhan et al., 2023; Mamedov, 2021). Finite Element Analysis (FEA) has become an indispensable tool for modeling and simulating these complex interactions, offering insights into stress distribution, temperature variations, and deformation during machining (Ucun et al., 2016). However, while FEA models hold immense promise, their application in micromilling is hindered by several limitations. Chief among these are assumptions of material homogeneity and boundary conditions that fail to fully replicate the nuances of real-world scenarios. For instance, the homogeneity assumption disregards the inherent anisotropy and grain size effects in microstructured materials, leading to potential inaccuracies in stress and deformation predictions (Pratap et al., 2015; Wang and Sun., 2024). Similarly, boundary conditions in FEA simulations are often oversimplified, excluding critical phenomena such as tool wear, thermal expansion, and microstructural phase transformations (Attanasio et al., 2018).

The primary limitation lies in the inability of current FEA models to bridge the discrepancy between simulation outcomes and experimental validations. While simplified assumptions make simulations computationally feasible, they introduce significant limitations in predicting real-world behavior. These shortcomings necessitate a more refined modeling approach that accounts for the heterogeneity of materials, dynamic boundary conditions, and other intricacies unique to micromilling (Bhople et al., 2021). The reliance on idealized assumptions in FEA simulations undermines their predictive capabilities, particularly in micromilling applications where precision and accuracy are paramount. This disconnect highlights an urgent need for novel methods to enhance the reliability and fidelity of FEA models (Ucun et al., 2017). Several methods are proposed to enhance the accuracy of FEA modelling, as shown in table 2.4:

Table 2.4 Proposed Solutions to Address Limitations in FEA Models for Micromilling

Category	Proposed Solution	Reference
Incorporating Material Heterogeneity	Grain-Scale Modeling: Simulating individual grains and their orientations to capture anisotropic behavior.	Mamedov, 2021
	Multi-Scale Modeling: Linking macroscale FEA simulations with microscale material properties to improve accuracy.	Sharma et al., 2024
	Dynamic Material Properties: Incorporating real-time changes in material properties due to strain, temperature, and phase transformations.	Attanasio et al., 2018
Enhancing Boundary Condition Modeling	Thermo-Mechanical Coupling: Simulating heat generation and its impact on tool wear and material behavior.	Wang and Sun, 2024
	Tool Dynamics: Accounting for micro-tool deflection, vibration, and wear in the simulation.	Pratap et al., 2015
	Realistic Friction Models: Employing advanced friction models based on experimental data rather than constant coefficients.	Chauhan et al., 2023
Integrating Experimental Data	Data Assimilation Techniques: Combining simulation outputs with experimental measurements to iteratively refine models.	Bhople et al., 2021
	Inverse Modeling: Using experimental results to back-calculate and optimize material properties and boundary conditions.	Ucun et al., 2017

Table 2.4 Continued

Category	Proposed Solution	Reference
Adopting Advanced Computational Techniques	Hybrid Approaches: Merging FEA with machine learning algorithms to predict outcomes based on empirical data patterns.	Sharma et al., 2024
	Adaptive Mesh Refinement: Focusing computational resources on critical regions, such as cutting zones.	Mamedov, 2021
	Parallel Computing: Leveraging high-performance computing platforms to handle complex simulations.	Wu et al., 2013
Developing New Validation Protocols	Reduced-Order Models: Simplifying FEA simulations without compromising on accuracy by reducing the dimensionality of the problem.	Ucun et al., 2016
	Comprehensive Benchmarking: Comparing simulation results with a wide range of experimental datasets.	Attanasio et al., 2018
	Uncertainty Quantification: Assessing and minimizing uncertainties in model parameters and inputs.	Pratap et al., 2015
	Scenario Testing: Simulating extreme conditions to evaluate model robustness.	Wang and Sun, 2024

Among the proposed solutions, integrating multi-scale modeling with experimental data emerges as the best method to address the limitations of FEA models in micromilling. It combines the macro and micro perspectives well by taking into account differences in the material at the grain level and connecting these properties to bigger simulation scales (Mamedov, 2021; Sharma et al., 2024). When coupled with experimental validation, this hybrid approach enhances accuracy and ensures models align with real-world machining scenarios (Ucun et al., 2016). Multi-scale modeling incorporates microstructural details,

such as grain orientations and phase variations, into FEA simulations. This addresses inaccuracies caused by the homogeneity assumption and enhances predictions of stress, deformation, and temperature variations during micromilling (Attanasio et al., 2018). The integration of experimental data improves boundary condition realism in FEA models. Simulations incorporate experimentally derived friction coefficients to accurately reflect cutting conditions (Pratap et al., 2015). Additionally, simulations include tool wear, deflection, and vibrations validated through experimental measurements (Wang et al., 2024). Machine learning further enhances FEA simulations by optimizing model inputs and identifying patterns in experimental data. This synergy enables more accurate predictions of complex micromilling interactions (Sharma et al., 2024).

2.7 Finite Element Analysis (FEA) with SFTC DEFORM 2D

SFTC DEFORM 2D is a powerful finite element analysis (FEA) software used extensively in the manufacturing industry to simulate machining processes, including micromilling, as shown in Figure 2.7 and Figure 2.8 (Sun et al., 2017; Sun et al., 2022). Its capabilities are broad and encompass several key features. The software can accurately simulate the wear mechanisms of micromilling tools by incorporating various wear models such as the Usui tool wear model, helping predict how different cutting parameters affects tool life and performance (Deepanraj et al., 2022). Additionally, it performs coupled thermal and mechanical analysis to understand the heat generation during the machining process and its impact on tool wear and workpiece quality, a capability that is crucial for materials like titanium alloys that are sensitive to thermal effects (Bodunrin et al., 2023). The software also integrates multiple physical phenomena, including deformation, heat transfer, and material flow, providing a comprehensive understanding of the micromilling process (Du et al., 2023). These capabilities make SFTC DEFORM 2D a valuable tool for understanding the micromilling processes, reducing the need for extensive experimental trials. Comparing simulation results with experimental data is essential to ensure the robustness and reliability of simulation models. Here are some key aspects of this comparison:

i. Force and Temperature Correlation:

Simulation models must accurately predict cutting forces and temperatures. Studies have shown that well-calibrated simulation models can achieve a high degree of correlation with experimental data. For instance, in the end-milling of AISI1045 steel, the simulated cutting forces and temperatures showed strong agreement with experimental measurements, demonstrating the model's reliability (Deepanraj et al., 2022).

ii. Surface Quality and Burr Formation:

Surface roughness and burr formation are critical quality metrics in micromilling. Validated simulations should predict these outcomes accurately. The mechanism of burr formation in micromilling was validated through experimental observations, which matched the simulation predictions, confirming the model's validity (Zhang et al., 2023).

iii. Tool Wear Patterns:

The accuracy of tool wear predictions is crucial for the practical application of simulation models. In various studies, the observed wear patterns and extents on micromilling tools have shown good alignment with simulation results, reinforcing the credibility of the wear models used in simulations (Wang et al., 2015).

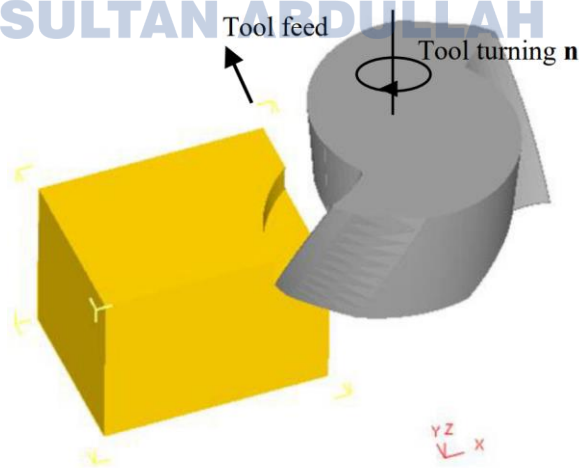


Figure 2.8 Schematic diagram of tool path

Source: Sun et al. (2017)

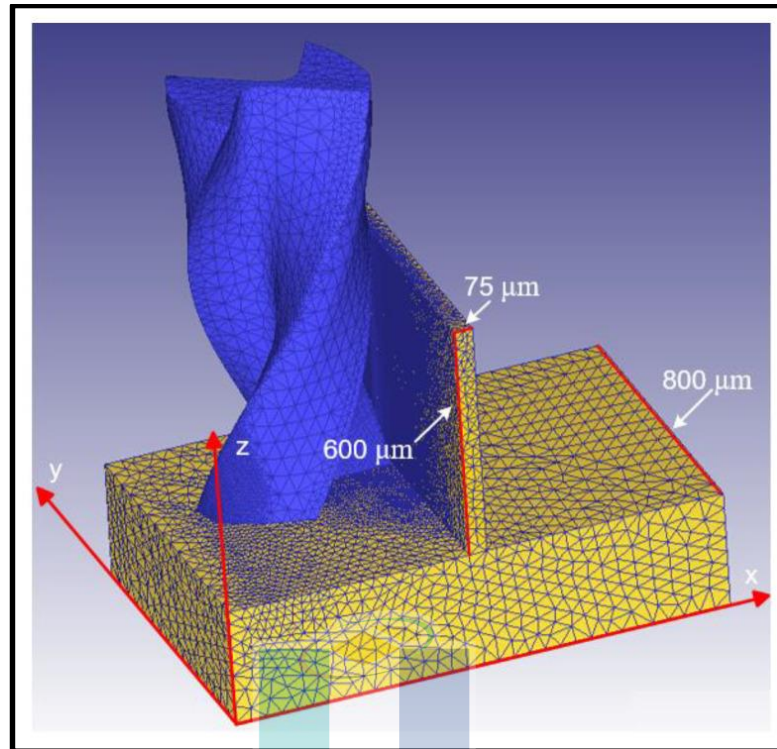


Figure 2.9 Schematic diagram of tool path while machine Aluminium thin wall
Source: Sun et al. (2022)

iv. Advanced Validation Techniques: اونيفرسيتي مليسيا پاهان

Modern techniques like acoustic emission and vibration analysis offer additional layers of validation. These methods help detect discrepancies between simulated and actual tool conditions, providing insights for further refinement of the models (Aboelezz et al., 2020).

The utilization of SFTC DEFORM 2D in micromilling represents a significant advancement in the simulation and estimation of machining processes. This powerful FEA software offers comprehensive tools for modeling tool wear, cutting forces, thermal effects, and mechanical interactions, making it an indispensable asset in the manufacturing industry. By accurately simulating the complex dynamics of micromilling, DEFORM 2D enables engineers to predict and mitigate potential issues

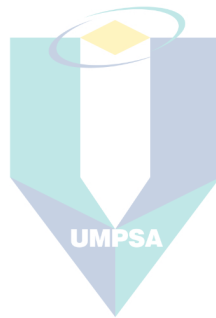
such as tool wear, surface roughness, and thermal damage, thereby enhancing the precision and efficiency of the machining process. The software's adaptive remeshing and multiphysics simulation capabilities further refine the accuracy of predictions, especially in challenging scenarios involving high-stress gradients and complex material behaviors. These features reduce the reliance on extensive experimental trials, saving both time and resources while ensuring high-quality outcomes. By validating simulation results against experimental data, including cutting forces, temperatures, surface quality, and tool wear patterns, the reliability and robustness of the models are able to be confirmed. Advanced validation techniques, such as acoustic emission and vibration analysis, add further layers of accuracy, ensuring that the simulations are not only predictive but also practically applicable. SFTC DEFORM 2D stands out as a critical tool for advancing micromilling processes. Its ability to integrate multiple physical phenomena, coupled with rigorous validation against real-world data, makes it a cornerstone of modern manufacturing, driving innovation and efficiency in high-precision machining. As the industry continues to evolve, the role of such advanced simulation tools only become more pivotal in pushing the boundaries of what can be achieved in micromilling

2.8 Summary

The literature review emphasizes the critical challenges in understanding the micromilling processes, particularly the selection of tool diameter for different workpiece materials. Tool wear, thermal effects, and material-specific responses significantly complicate the decision making process of the cutting parameters, affecting both the precision and longevity of the tools used. Studies highlight the need for advanced simulations and real-time monitoring to address these challenges effectively. The review identifies the gap in validating simulation models like SFTC DEFORM 2D with experimental data to enhance their predictive accuracy, a crucial step for improving micromilling processes for materials such as aluminium and steel.

The proposed solution involves using advanced simulation tools like SFTC DEFORM 2D to model the micromilling process under various conditions. It is proposed

that, by leveraging these simulations, one can predict optimal tool diameters and operational parameters that enhance tool durability and machining precision. This simulation data is then be validated through controlled experimental trials to ensure real-world applicability. The integration of simulation and experimental validation aims to bridge the gap between theoretical predictions and practical machining outcomes, leading to better process understanding.



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

CHAPTER 3

METHODOLOGY

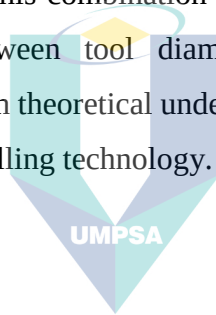
3.1 Introduction

The methodology chapter outlines a comprehensive two-phase approach that combines finite element analysis (FEA) simulations with experimental validation to investigate the relationship between tool diameter selection and micromilling performance. This integrated approach was chosen over alternative methods, such as purely experimental studies or analytical modeling, for several compelling reasons. FEA simulations offer unique advantages in studying micromilling processes, allowing for detailed analysis of complex phenomena such as tool-workpiece interactions, thermal effects, and material behavior without the substantial cost and time investment required for extensive physical testing. Furthermore, FEA provides insights into parameters that are challenging to measure experimentally, such as localized stress distributions and temperature gradients during the cutting process. However, recognizing the limitations of simulation-only approaches and the importance of real-world validation, this study incorporates experimental verification as a crucial second phase.

In the first part of the methodology (*Phase 1*), the development processes for all the finite element analysis (FEA) models to achieve the objectives of this study are explained. Actual end milling processes are complex due to the infinitesimal cutting edges involved. A single cutting edge model is identified as the most suitable model that provides the highest precision and accuracy in estimating machining results while being efficient and quick in calculation times for specific cutting processes. This approach allows for systematic investigation of how different tool diameters affect both mechanical and thermal aspects of the micromilling process across different materials.

Meanwhile, in the second part of the methodology (*Phase 2*), the experimental procedure to validate the simulated results obtained from Phase 1 is explained. This validation phase is essential as it bridges the gap between theoretical predictions and practical applications, ensuring that the simulation results accurately reflect real-world machining conditions. The experimental work consists of setting up the high-speed spindle system to execute micromilling processes at the optimum speed (high revolution). This dual approach enables both detailed theoretical understanding and practical verification of the relationships between tool diameter, material properties, and machining performance. The overall research flowchart is shown in Figure 3.1.

This methodology combines the predictive power of FEA with the reliability of experimental validation, offering a more robust and comprehensive approach compared to single-method alternatives. This combination is particularly valuable when studying the complex interactions between tool diameter selection and material-specific machining behaviors, where both theoretical understanding and practical verification are essential for advancing micromilling technology.



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

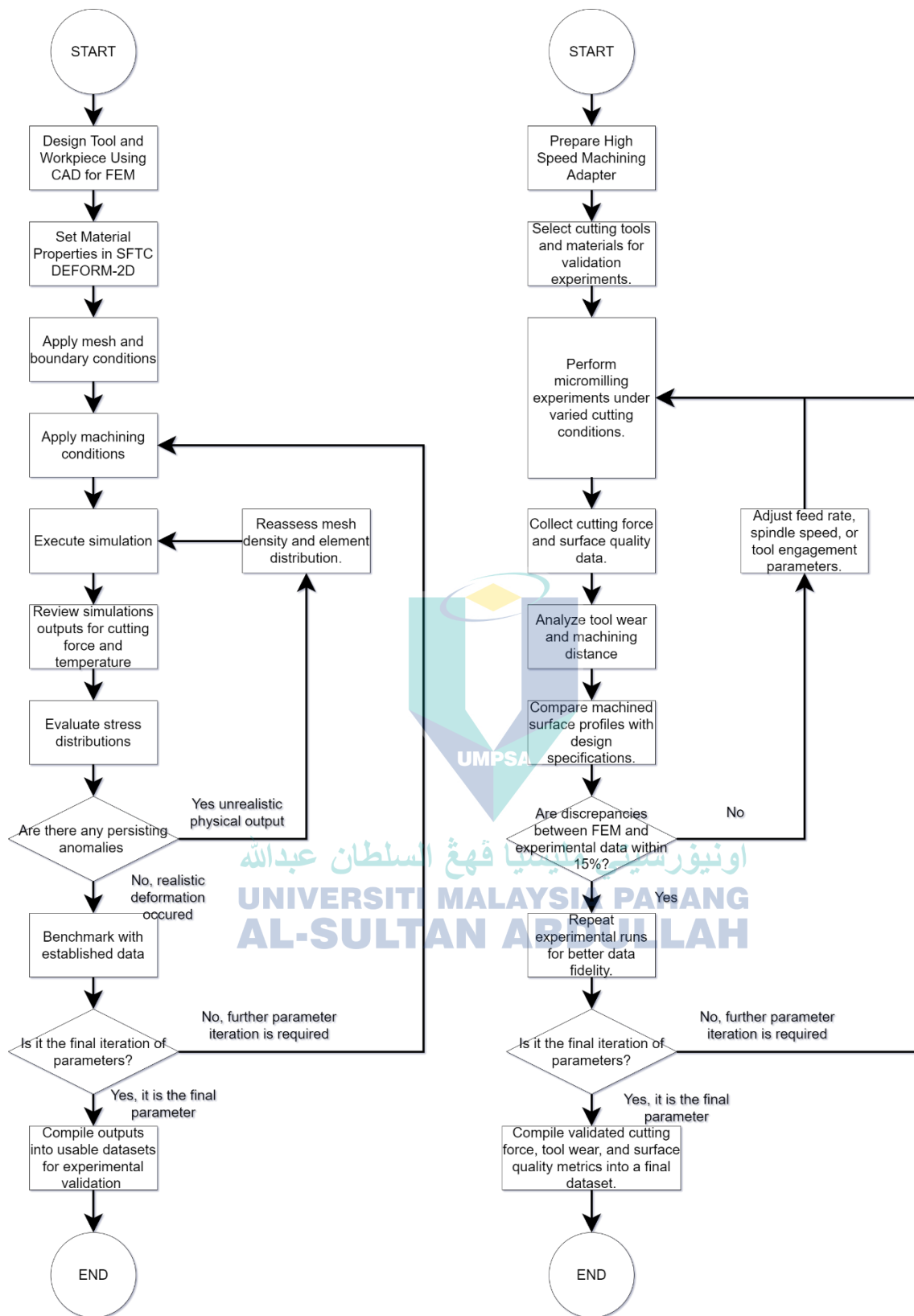


Figure 3.1 Research works flowchart

PHASE 1: ANALYZING THE MICROMILLING BEHAVIOUR FOR VARIOUS TOOL DIAMETER WITH FINITE ELEMENT METHOD

3.2 Two dimensional finite element modelling on micromilling process

2D finite element modeling was selected due to its significant computational efficiency, achieving a 70% reduction in computation time while maintaining approximately 85% accuracy for straight-slot cutting operations. This balance makes it highly effective for simulating micromilling performance across tool diameters ranging from 0.3 mm to 0.9 mm, as previous studies have shown that 2D modeling allows precise control of variables and conditions, ensuring observed differences in performance are solely due to tool diameter variations. The simulation, conducted using SFTC DEFORM 2D software, provides accurate predictions of cutting forces and material removal rates without the immediate need for physical prototypes, thereby saving time and resources. Its ability to represent microstructural effects and thermal-mechanical interactions aligns with findings from recent advancements in 2D modeling, emphasizing its utility in micromilling applications. The simplified 2D cutting model for micromilling, depicted in Figure 3.2, demonstrates the tool's movement into the workpiece during a slotting operation.

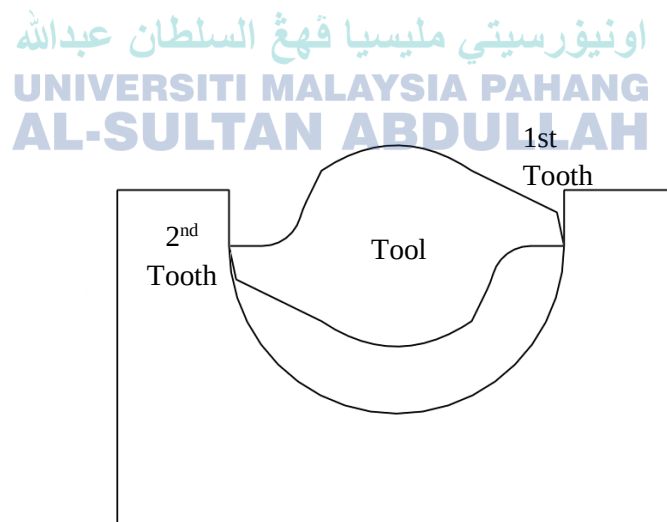


Figure 3.2: Cutting tool position for 2 flute end mill (any size)

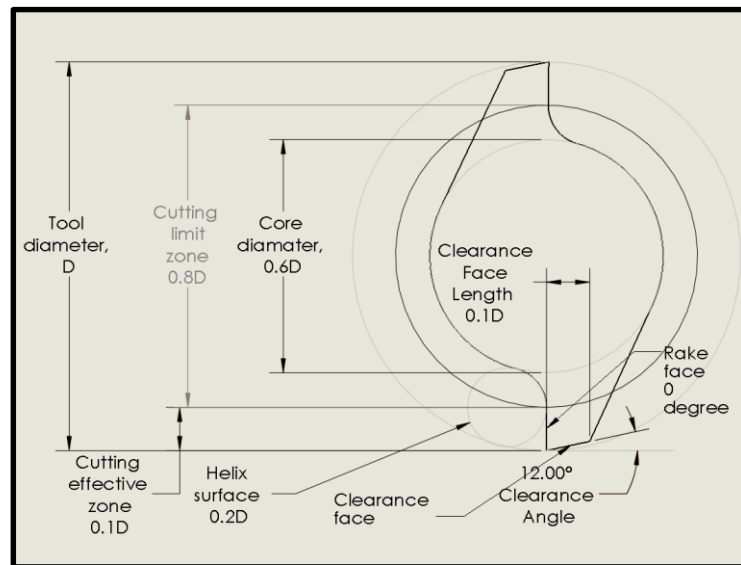


Figure 3.3: Schematic of cutting tool dimension for 2 flute end mill (any size)

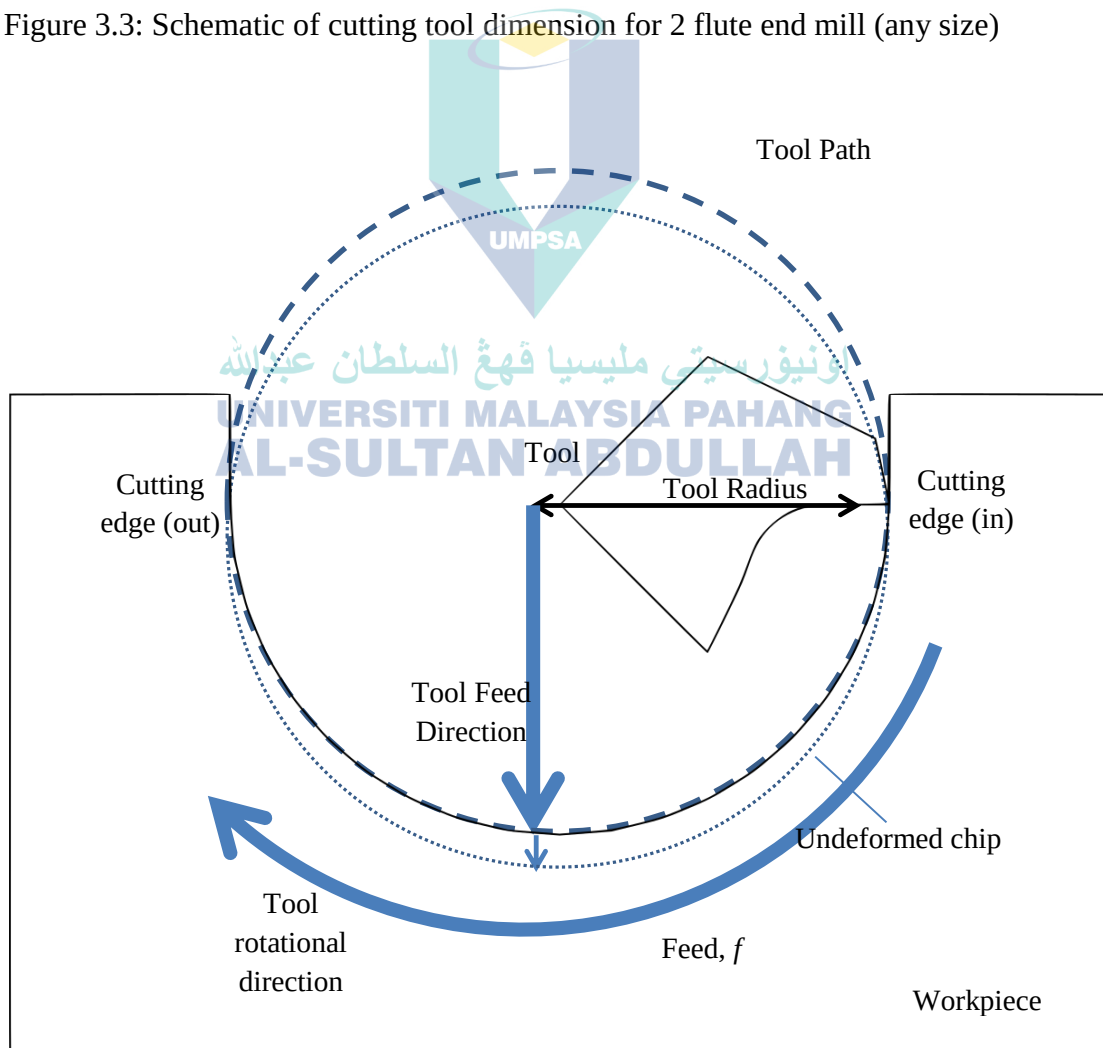


Figure 3.4: Simplified model of 2D micromilling cutting for FEM simulation

3.2.1 Assumptions in the 2D Finite Element Model and Their Potential Impact on Simulation Outcomes

The 2D finite element model, while computationally efficient, incorporates several assumptions that may influence the accuracy and reliability of its simulation results. Table 3.1 shows the key assumptions and their potential impacts considered in the study.

Table 3.1 The key assumptions and their potential impacts

No	Key Assumption	Description	Potential Impact
i.	Workpiece material is homogenous and isotropic.	Assumes the workpiece material is homogeneous and isotropic, ignoring microstructural variations such as grain boundaries.	Leads to inaccuracies in stress, deformation, and thermal predictions, particularly for heterogeneous materials.
ii.	The tool geometry is simplified.	Considers a single-tooth cutting edge and neglects multi-flute interactions and tool wear.	Overlooks dynamic interactions between tool edges and effects on cutting forces and heat generation.
iii.	The two dimensional model is plane strain conditions.	Assumes two-dimensional conditions that do not fully represent the three-dimensional micromilling process.	May underestimate or overestimate material flow, chip formation mechanics, and stress distributions.
iv.	The friction modeling	Simplifies for friction with constant coefficients.	Reduces accuracy in predictions for tool temperature and residual stresses.

Table 3.1 Continued

No	Key Assumption	Description	Potential Impact
v.	The thermal modeling	Simplifies models for heat generation without full thermal diffusion.	Reduces accuracy in predictions for tool temperature and residual stresses.
vi.	Neglect of Microstructural Effects	Omits grain-scale and strain-rate-dependent behaviors for computational simplicity.	Causes errors in simulating strain hardening, phase changes, or grain-level plasticity effects.
vii.	Tool-Workpiece Interaction Dynamics	Does not fully integrate tool deflection, vibration, and wear into the model.	Limits accuracy in simulating cutting forces and surface finish under real-world conditions.
viii.	Chip Morphology	Simplifies chip formation, assuming continuous chips without segmentation or breakage.	Affects predictions of cutting forces and temperature distributions.
ix.	Boundary Conditions	Idealizes clamping forces and workpiece rigidity without fully replicating real-world constraints.	Causes deviations in deformation and stress predictions.

3.3 Tool – workpiece model Meshing

Elements in FE analysis can be described as discrete regions that were divided from continuous regions. This procedure is called discretization or meshing. Remeshing, smoothing and refinement are a few techniques that can be employed to reduce the distortion of the elements by plastic deformation during the metal cutting simulations, specifically the capability of SFTC Deform 2D, as shown in Figure 3.3. The distortion can cause convergence rate and numerical errors, thus the adaptive mesh procedure is applied purposely to handle this problem. A new FE mesh must be generated by changing the elements size and distribution of the mesh when distortions occur. Adaptive meshing can improve the accuracy of the simulation such as milling operation, which involves complex geometry and large gradient. The refinement technique is based on increasing the local mesh density by reducing the local element size as shown. Hence, the adaptive mesh procedure must be applied in FE simulations that involve severe plastic deformation such as metal cutting. This procedure increases the accuracy of the simulation and decrease solution errors during calculation.

Tool's geometric variables are tabulated in Table 3.2. The tool was modelled and meshed as shown in Figure 3.5, and the area that is nearer to the tool tip was meshed denser than the areas that are farther. This is due to the main contact between tool and workpiece takes place at the cutting edge and it is considered as the area of interest in the study. The quantity of nodes and element for all 2D cutting tool models is 1000 nodes and 1000 elements on the tool while 5000 nodes and 4900 element's mesh for all 2D orthogonal workpiece models, to ensure high efficiency of simulation time and high accuracy results are obtainable.

Table 3.2: FEM Cutting tool geometry

Model	Tool
Rake Angle (°)	0
Relief Angle (°)	12
Tool tip radius (mm) – sharp tool	0

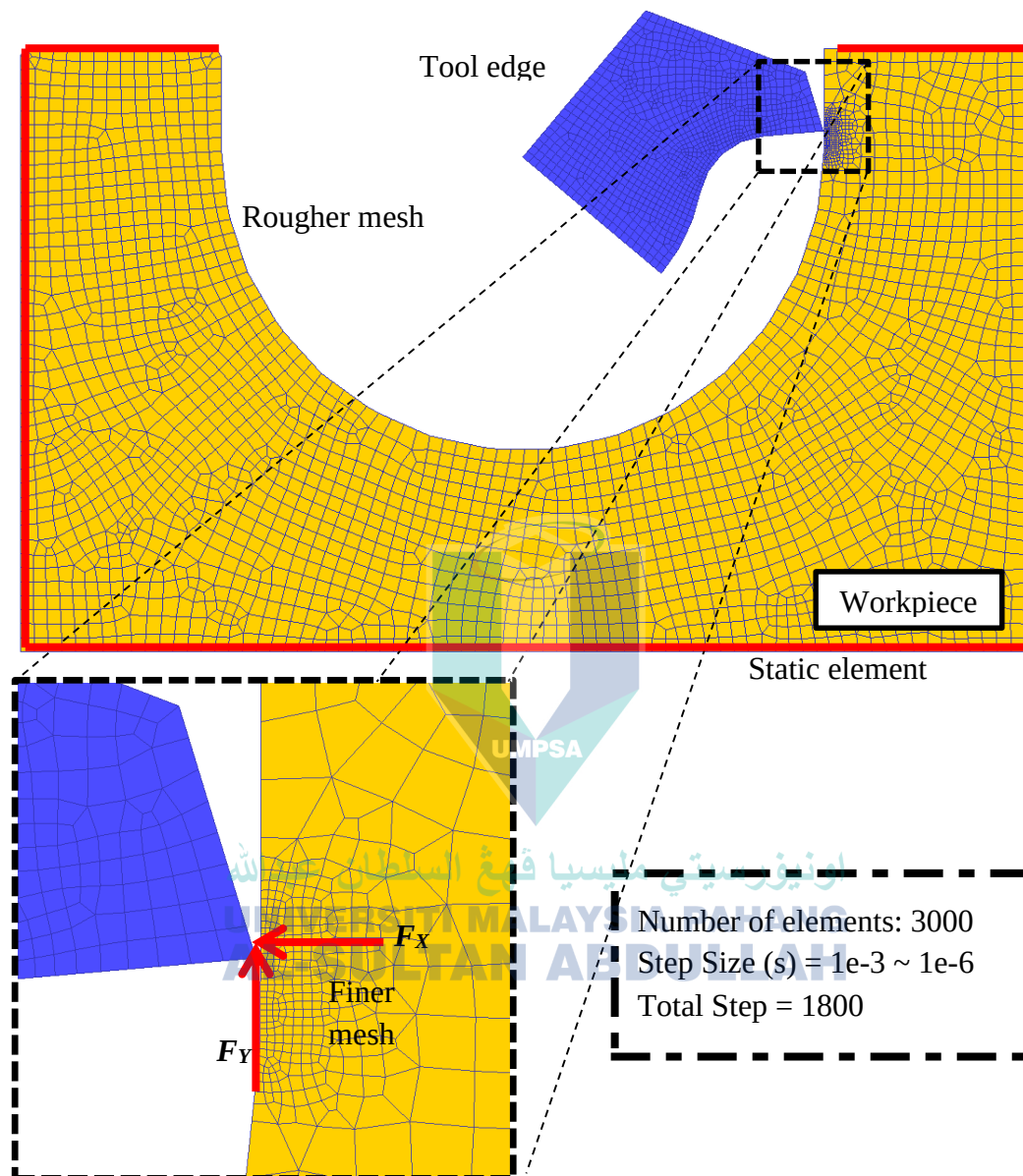


Figure 3.5 Sample of FEM model with SFTC DEFORM 2D

3.4 Material Properties

Understanding the material properties of both the tool and the workpiece is crucial in metal-cutting simulations. These properties influence the behavior of materials during the cutting process, which is critical for accurate simulations and effective machining. Here, we explain the material properties listed in Table 3.3 and their relevance to metal-cutting simulation with SFTC-DEFORM 2D. SFTC-DEFORM 2D requires precise material properties to accurately model the stress-strain behavior of materials under cutting conditions, simulate heat generation and dissipation during the cutting process, predict tool wear and failure by considering the interaction between tool and workpiece materials, and cutting parameters such as cutting speed and feed rate based on material responses. By inputting the correct material properties for WC (tool), Al-6061, and AISI 1045, SFTC-DEFORM 2D can provide reliable simulations that help in understanding the micromilling process behaviour, ultimately leading to improved machining performance and tool life.

Table 3.3 Materials Properties

Materials	WC (Tool)	Al-6061	AISI1045	Description (Wu & Cheng, 2014, Zhao et al., 2019, SFTC DEFORM 3D V11 Library)
Young Modulus, E (GPa)	650	68.9	205	Measures stiffness of a material, indicating elastic deformation under stress. WC's high modulus ensures minimal deformation, crucial for maintaining cutting edge precision.
Poisson Ratio, ν	0.25	0.33	0.29	Ratio of transverse to axial strain under stress, influencing dimensional changes. Variations affect stress distribution in simulations.
Thermal Conductivity, k (W/mK)	59	180	51.9	Measures heat conduction efficiency. Al-6061's high conductivity helps dissipate heat, reducing tool wear and improving workpiece quality.
Density, ρ (kg/m ³)	15,700	2,700	7,850	Mass per unit volume affects inertia during cutting. WC's high density influences dynamic response, suitable for high-speed cutting.
Specific Heat, c (J/kgK)	203	900	486	Heat required to raise material temperature. Al-6061's high specific heat leads to different thermal behavior compared to AISI 1045.
Hardness Vickers, $HV_{0.3}$	1800	107	200	Resistance to deformation or indentation. WC's high hardness ensures durability for cutting harder materials, whereas softer Al-6061 is easier to machine.
Friction coefficient	0.3			Indicates resistance to sliding between tool and workpiece. Used to model cutting forces and heat generation during simulations.

3.5 Simulation Process and Flow Diagram

3.5.1 Machining process simulation steps

Machining process simulation consists of three main step call pre-processor, processing, post-processor. This is explained briefly as following:

1. Pre-Processor Step

Firstly, the geometry of the cutting tool and the workpiece need to be designed using commercially available software such as SOLIDWORKS and accurate dimension of the geometry is necessary to get precise results, based on Figure 3.3.

Second step is importing the geometry data into the pre-processor of the FEA software (SFTC DEFORM-2D). The cutting condition as shown in Table 3.4 and the boundary condition needs to be input to the simulation processes. Cutting condition such as the cutting speed, axial depth (width of cut), radial depth, additional with the material properties of the workpiece and the tool are work as process input.

Third step is setting up the boundary conditions. The boundary conditions such as fixed axis, heat transfer coefficient, heat exchange zone and other boundary conditions are critical and need to be determined to ensure the simulation behaves like the experimental test.

Table 3.4 Machining Conditions for finite element analysis

Tool type	2 flutes flat end mill
Cutting tool diameter, D (mm)	0.3, 0.6, 0.9
Axial depth of cut, A_d (mm)	1.0
Revolution Speed (RPM)	5000~20000
Cutting speed, V_c (m/min)	4.7~56.6
Feed rate, f ($\mu\text{m/tooth}$)	0.25 ~ 33

After cutting conditions and boundary conditions set up, the step size and number of step is set. Higher accuracy results require finer mesh and higher precision step size compare to coarser value of meshing size. A suitable size of meshing and step is needed to be determined before depending on the computing machine's performance and

limitation. Higher machine performance and less limitation could provide better results, which mean lower error could be obtained using finer value of meshing with faster simulating times.

2. Processing Step

In this step, the simulation model that was designed in previous step is submitted to the FEA processor to initiate the processing stage. This stage is time consuming depending on the designed model, computing machining performance and limitation.

3. Post- Processing Step

After the processing step is finished, data collection and analyses are initiated to obtain the desired results. Cutting force and cutting temperature is collected at post processor of the simulation software after the simulations are completed. For both cutting force and temperature, the maximum value during the metal cutting is taken as the results. The diagram of forces and normal force F_N calculation is shown in Figure 3.6 and Equation 3.1, respectively.

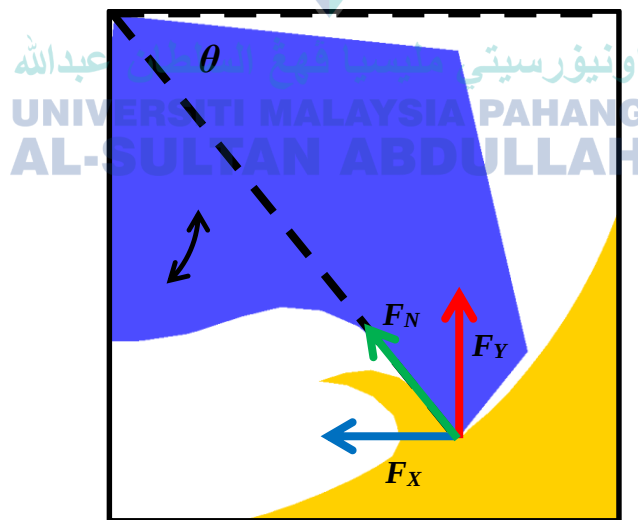


Figure 3.6 Force vector

$$F_N = F_X \sin \theta + F_Y \cos \theta \quad [3.1]$$

PHASE 2: VALIDATING THE MICROMILLING CUTTING PERFORMANCE WITH THE VERIFIED CONDITIONS FROM THE SIMULATIONS

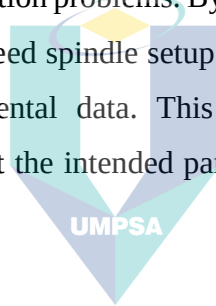
3.6 High Speed Machining Adapter Preparation and Micromilling Process

The initial phase of this methodology focuses on detailing the micromilling process for validating the simulation's estimated results. At the study's early stage, a prototype of the high-speed machining adapter was fabricated to adapt the available CNC machine for obtaining high-precision results. The development of this prototype required careful material selection, precision manufacturing techniques, and rigorous quality control measures to ensure adherence to design specifications and performance criteria. The experimental setup is critical for testing the high-speed machining adapter's performance under realistic machining conditions. The experiments will utilize a Makino KE55 Vertical Milling CNC machine, chosen for its precision and stability. This machine automates the feed rate and performs various simple 3D machining processes, as illustrated in Figure 3.7. However, the machine's maximum spindle speed is limited to 4000 RPM, as shown in Table 3.5. To overcome this limitation, a high-speed machining spindle adapter was fabricated and assembled to enhance spindle speed capability.

The high-speed machining spindle adapter is designed with standardized interfaces to ensure compatibility with various CNC models, as depicted in Figure 3.8. The mounting process emphasizes the importance of precise alignment and secure fastening. Ensuring the adapter is perfectly aligned with the spindle axis eliminates offsets that could cause vibrations or inaccuracies during machining. Secure fastening is achieved using high-strength bolts and clamps to firmly attach the adapter to the CNC machine, minimizing any risk of movement or detachment during high-speed operations. Detailed explanations of each component and the high-speed spindle's specifications are provided in Tables 3.6 and 3.7, respectively. To ensure the reliability of experimental data, a comprehensive calibration process was undertaken. The initial alignment check involved the use of a precision dial indicator to verify concentricity and proper alignment with the CNC spindle axis. This step was critical for minimizing radial runout and maintaining consistent tool positioning. Dynamic balancing of the spindle and adapter

assembly was performed using a balancing machine to mitigate vibrations during high-speed operations. Following the assembly, initial test cuts were conducted on standard materials to evaluate the spindle's performance under load. During these tests, variations in cutting force and tool path were closely monitored to identify any misalignment or instability.

Error-checking measures further enhanced the spindle setup's reliability. Vibration analysis was carried out using an accelerometer to measure operational vibrations. Any detected anomalies were addressed promptly through assembly adjustments or recalibration. Thermal monitoring was conducted using infrared sensors to ensure the spindle temperature remained within acceptable limits, thereby preventing thermal distortion or alignment shifts. Additionally, tool wear inspections were performed post-operation to evaluate wear patterns, which could indicate underlying issues such as alignment or vibration problems. By integrating these calibration and error-checking processes, the high-speed spindle setup was meticulously optimized to deliver accurate and reliable experimental data. This rigorous approach ensures that the machining results closely reflect the intended parameters, enhancing the validity of the research outcomes.



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

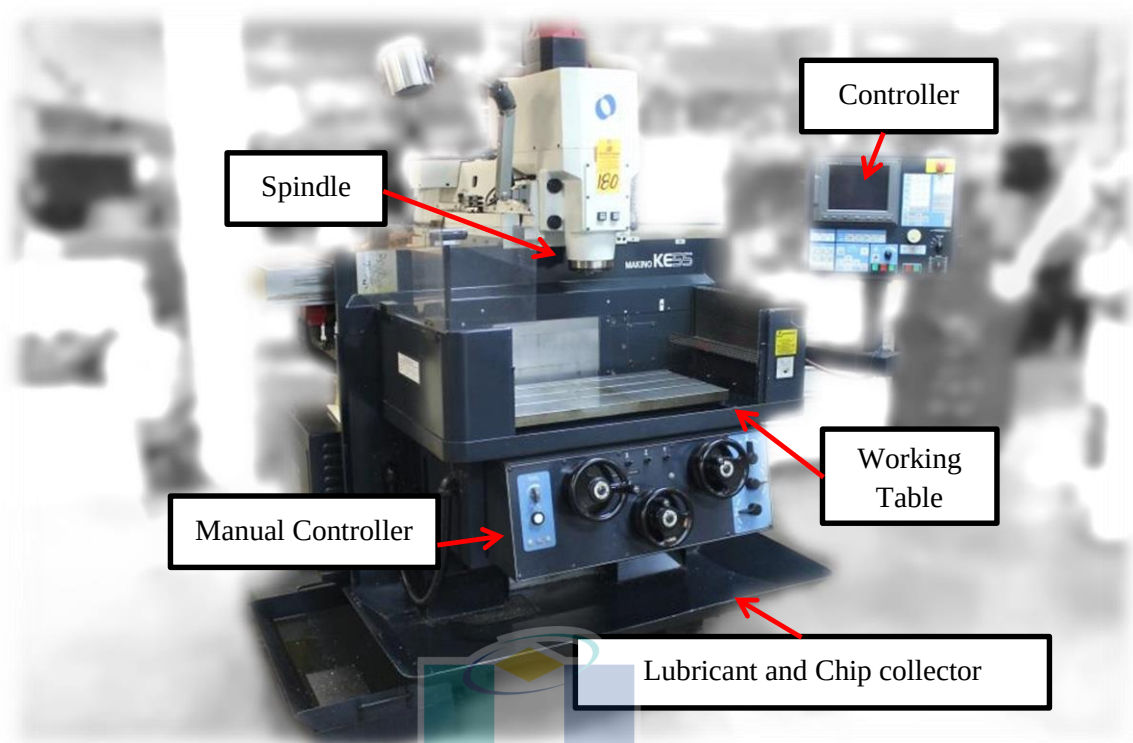


Figure 3.7: MAKINO KE55 Vertical Milling Machine

Table 3.5 MAKINO KE55 Vertical Milling Machine Specification

Specification	Details
Machine Model	Makino KE-55 CNC Vertical Mill (1996)
Control System	Fanuc CNC Control
Weight	3000 kg
Dimensions (Main Unit)	Length: 2.13 m, Width: 1.93 m, Height: 2.06 m
Table Size	0.80 m X 0.37 m
Machine Travels (X/Y/Z)	0.55 m X 0.32 m X 0.35m
Rapid Traverse Rate (X/Y/Z)	11.94 / 11.94 / 5.00 m/min
Max Table Load	250 kg
Spindle Taper	BT 40
Spindle Speed	4,000 RPM Max
Spindle Drive	5.60 kW
Electric Power Requirement	220 Volt 3 Phase

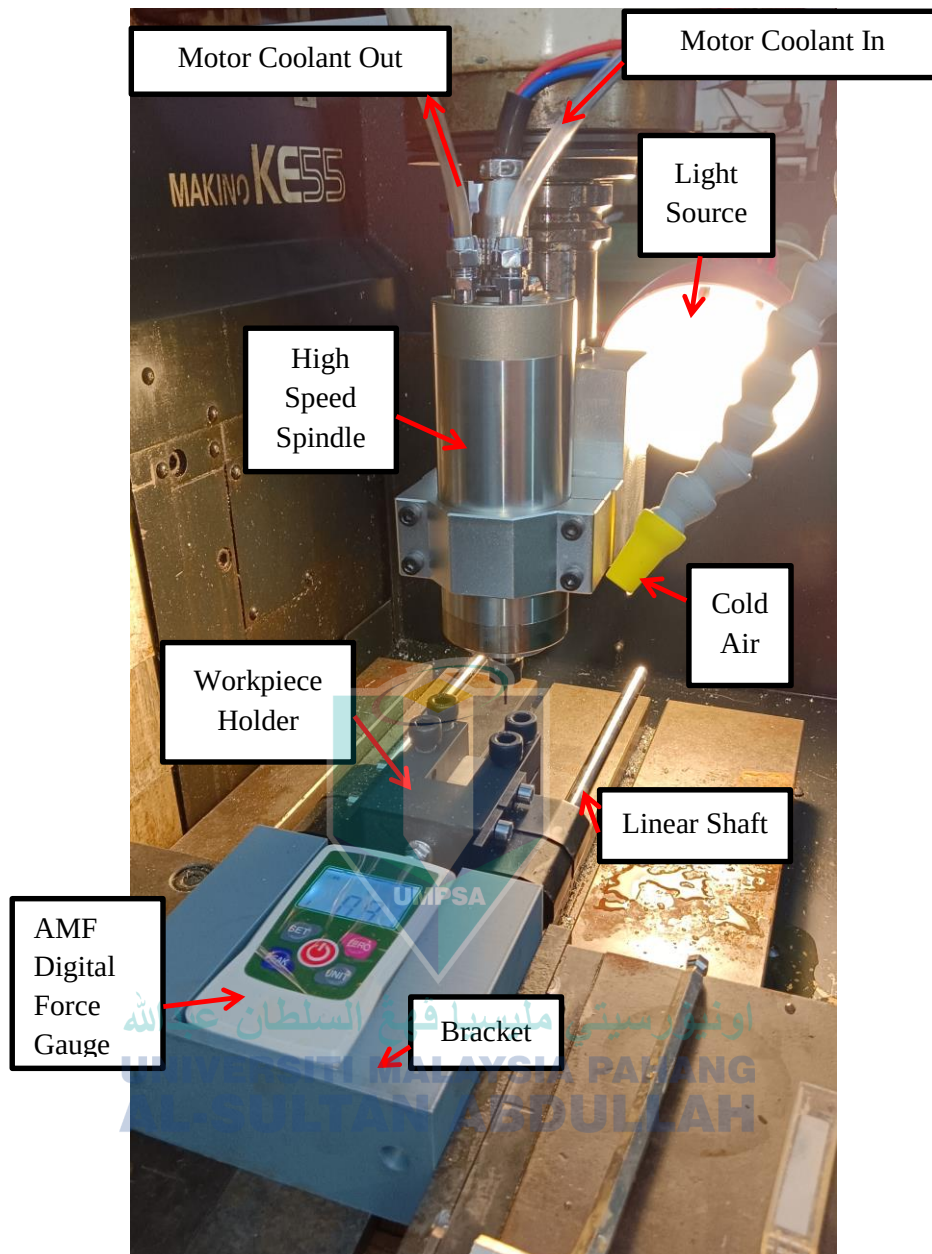


Figure 3.8: High Speed Spindle Adapter

Table 3.6 Detail description of each components

Component	Description
Motor Coolant In	This is the inlet for the coolant that helps regulate the temperature of the motor during high-speed operations. The coolant prevents overheating and ensures the motor operates efficiently.
Motor Coolant Out	The outlet where the coolant exits after passing through the motor. This component is crucial for maintaining a consistent temperature within the motor during machining processes.
High-Speed Spindle	The main rotating component that holds and drives the cutting tool. This spindle is designed to operate at high speeds, allowing for precise and efficient micromilling operations.
Bracket	A support structure that holds various components in place, including the high-speed spindle. It ensures stability and alignment during the machining process, contributing to the overall precision.
Workpiece Holder	The component that securely holds the workpiece in place during machining. It is designed to withstand the forces applied during the cutting process while keeping the workpiece stationary.
Cold Air	A cooling system that directs cold air onto the tool and workpiece, helping to manage heat generated during machining. This cooling is essential for maintaining tool life and workpiece quality.
Light Source	Provides illumination for the machining area, ensuring that the operator can clearly see the workpiece and tool during the operation. This visibility is crucial for monitoring and making adjustments during machining.

Table 3.7 Specification of high speed spindle

Specification	Details
Model	GDZ65-800A-158MM-ER11
Rated Power	800W
Speed	24000 RPM
Voltage	220V/110V
Current	5A
Frequency	400Hz
Number of Bearings	4
Maximum Torque	0.31Nm
Weight	2.5 kg
Size	65mm diameter, 158mm length
Axis End Link	ER11
Cooling Method	Water Cooling

Figure 3.9a illustrates a crucial aspect of the micromilling experimental setup, specifically designed to measure cutting forces during the machining process. The setup includes an AMF Digital Force Gauge, which is responsible for capturing real-time data on the forces exerted during micromilling. This data is vital for analyzing the milling process's performance and ensuring operational precision. The workpiece, representing the material being machined, is securely fixed in place to maintain consistency in the milling process, thereby allowing accurate force measurements and other parameters. Additionally, a workpiece holder/clamp is employed to hold the workpiece firmly, preventing any movement that could lead to inaccuracies in both the cutting force measurements and the overall machining results. The workpiece holder/clamp is linearly slide-able on the linear shaft, to prevent unneeded vibrations.

Figure 3.9b depicts the crucial relative positioning of the micromilling tool and the workpiece during the machining process. The micromilling tool, designed for high

precision and small-scale cutting, must be precisely aligned with the workpiece to ensure that the machining path is accurately followed. The workpiece holder plays a vital role in this setup by securing the workpiece in the correct orientation and position relative to the milling tool, ensuring that the tool engages with the workpiece as intended, thus maintaining the accuracy and consistency of the cut throughout the operation. Additionally, the schematic diagram of the machining process is depicted in the Figure 3.10.

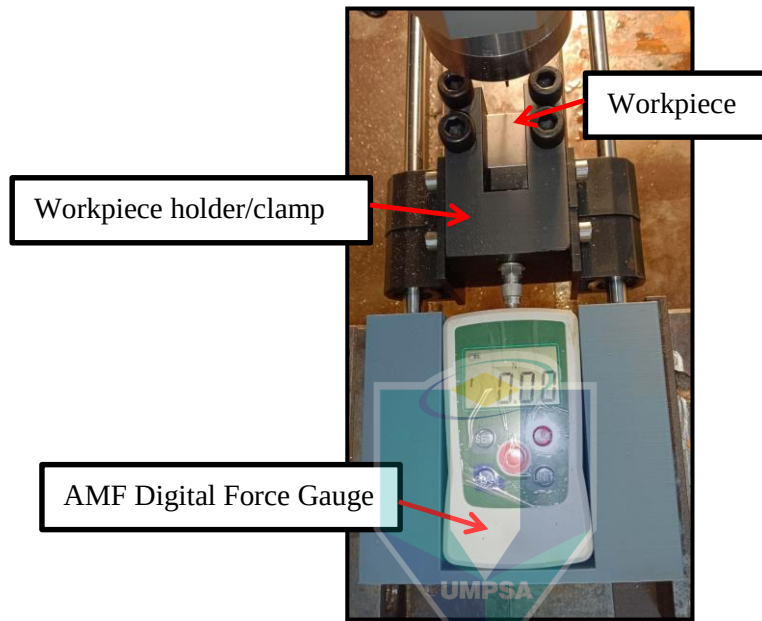


Figure 3.9a: Force gauge and workpiece position and clamp (upper view)

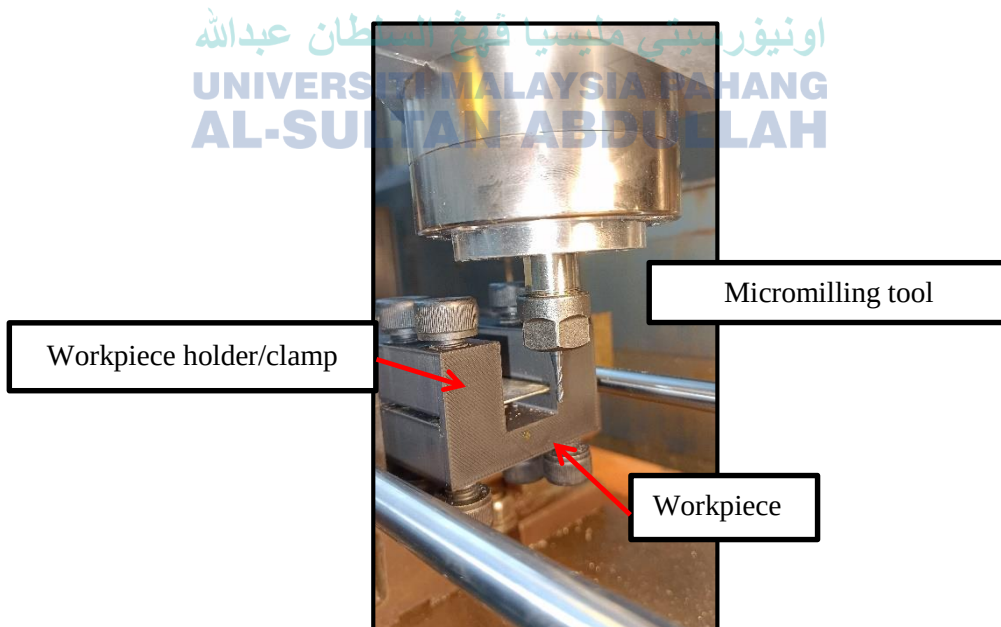


Figure 3.9b: Tool and workpiece position during machining (side view)

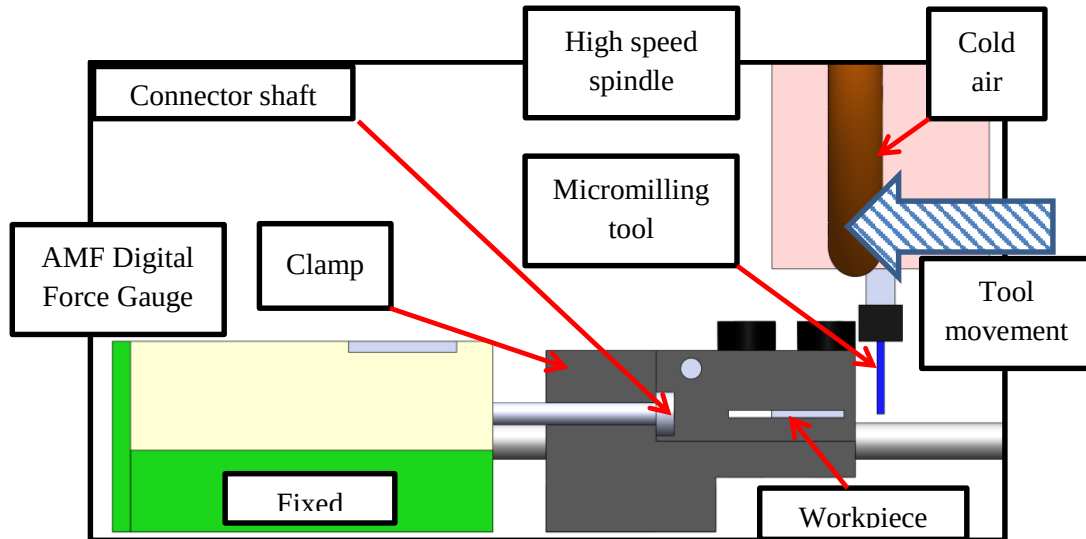


Figure 3.10: Schematic diagram of machining process

The chosen tool are tungsten carbide micromilling with Titanium Aluminium Nitride (TiAlN) tool from Shenzhen Bwin Precision Tools Co., Ltd., that are preferred for durability and ability to withstand various material. The material properties of cutting tool and workpiece are shown in Table 3.8.

Table 3.8 Materials properties of cutting tool and workpiece

Materials	WC (Tool)	TiAlN (Coating)	Al-6061	AISI1045
Young Modulus, E (GPa)	640		68.9	205
Poisson Ratio, ϵ	0.22		0.33	0.29
Thermal Conductivity, k (W/mK)	110		167	51.9
Density, ρ (kg/m ³)	15,000		2,700	7,850
Specific Heat, c (J/kgK)	203		900	486
Hardness Vickers, $HV_{0.3}$	1800	2800	107	200
Thickness (μm)		2.5~3		
Oxidation Temp. ($^{\circ}\text{C}$)		800		
Friction Coefficient		0.3		

Additionally, the geometry of the micromilling tool is shown in Figure 3.11 along with its geometrical dimension tabulated in Table 3.9



Figure 3.11 Micromilling tool geometry

Table 3.9 Specification of the micromilling tool for the experiment

Specification	Flute Dia (ϕ)	Flute Length (C)	Shank Dia (D_s)	Overall Length (L)
<i>D0.3 × L50</i>	0.3	0.6	4	50
<i>D0.6 × L50</i>	0.6	1.2	4	50
<i>D0.9 × L50</i>	0.9	1.8	4	50

3.7 Machining Condition

The machining conditions for the validation experiment of the micromilling process outlined in Table 3.9. These conditions include the type of tool, cutting tool diameter, axial depth of cut, revolution speed, cutting speed, and feed rate per tooth.

Table 3.10 Machining Conditions for micromilling validation experiment

Conditions	Parameter
Tool type	2 flutes flat end mill
Cutting tool diameter, D (mm)	0.3, 0.6, 0.9
Axial depth of cut, A_d (mm)	0.3, 0.6, 1.0

Table 3.10 Continued

Conditions	Parameter
Revolutions Speed Per Minute (RPM)	20000
Cutting speed, V_c (m/min)	5.7~113
Feed rate, f ($\mu\text{m}/\text{tooth}$)	0.25 ~ 33

The specified machining conditions are chosen to study the effects of various parameters on the micromilling process. By varying the tool diameter, axial depth of cut, spindle speed, cutting speed, and feed rate, the experiment can present the real behaviour of micromilling process over various diameter and materials. These parameters also provide a basis for validating the finite element analysis (FEA) models, ensuring that the simulated results align with the actual machining performance. To achieve the pre-set machining condition, Makino KE55 controller are utilized to generate feed rate in mm/min (as shown in Figure 3.11), while a variable Frequency Drive (VFD) controller are utilized to control the Revolutions Speed Per Minute [RPM], as shown in Figure 3.12. Table 3.11 shows the input setting to achieve the required parameter.



Figure 3.12 Makino KE55 Control Board



Figure 3.13 Sunfar E300 VFD Controller (Max Frequency: 400Hz)

Table 3.11 Input Value and Output Parameter at 20000RPM (VFD controller (333Hz))

Feed rate, F (mm/min)	Feed per tooth f ($\mu\text{m/tooth}$)
10	0.25
100	2.50
200	5.00
400	10.0

3.8 Data Collection for the Validation Experiment

The data collection phase of the validation experiment is critical for assessing the performance of the micromilling process under various conditions. This subchapter outlines the procedures for gathering essential data points, which include cutting force measurements, tool breakage detection, tool machining distance, and the evaluation of machined surface quality (such as burr formation and profile accuracy). These data points are integral to validating the finite element analysis (FEA) simulations and ensuring that the results align with real-world machining outcomes. Validation criteria have been established to ensure rigorous comparison between experimental and simulation data, including a maximum deviation of 15% in cutting forces, a 95% confidence interval for statistical significance, and specific surface quality parameters.

Detecting tool breakage is crucial for maintaining the integrity of the micromilling process and preventing damage to the workpiece or machine. The detection process includes visual inspection and real-time monitoring. Visual inspections involve examining the tools before and after each machining operation to identify signs of breakage or significant wear. High-magnification optical devices are utilized for detailed analysis, enabling the detection of minute flaws that might compromise machining accuracy. Real-time monitoring of cutting force data using a force gauge complements visual inspections. Sudden drops in cutting force are indicative of potential tool breakage, and any deviations exceeding the 15% threshold are promptly investigated to mitigate risks and ensure process reliability.

Tool machining distance, defined as the total distance the tool travels while cutting before showing signs of wear or breakage, is a critical metric for assessing tool durability and process stability. This distance is calculated based on the tool's feed rate and the total machining time, with the CNC machine's control system accurately tracking the toolpath and recording the total distance covered. To validate the accuracy of finite element analysis (FEA) predictions, a maximum allowable deviation of 15% between experimental and simulated toolpath lengths is established as a validation criterion.

The quality of the machined surface, including burr formation and profile dimensional accuracy, serves as a key indicator of the process's success. Burr formation

is assessed using optical microscopy or scanning electron microscopy (SEM) to achieve precise measurements. Burr sizes that exceed specified tolerances are flagged as deviations, as they can adversely affect dimensional accuracy and surface finish. Profile dimensions are evaluated against design specifications using high-precision metrology tools, ensuring compliance within a 95% confidence interval to establish statistical significance.

The validation methodology integrates these metrics to ensure a robust comparison between simulation results and experimental data. A maximum deviation of 15% in cutting force measurements between experimental and simulated data is deemed acceptable. Statistical analysis is conducted to evaluate results within a 95% confidence interval, providing a rigorous assessment of observed differences. Surface quality metrics, including burr size and profile accuracy, are compared against predefined tolerances derived from simulation predictions and machining standards. This comprehensive approach ensures that the FEA models accurately reflect real-world micromilling outcomes, enhancing their reliability and applicability.

3.9 Summary

The methodology chapter outlines a comprehensive approach to achieving the research objectives through a two-phase process that integrates advanced simulation with experimental validation. In Phase 1, the development of finite element analysis (FEA) models using SFTC DEFORM 2D enables precise simulations of micromilling processes, focusing on critical factors such as tool geometry, material properties, and cutting conditions. This phase provides a solid foundation for understanding the micromilling behavior across various tool diameters, ensuring that the simulated results are both accurate and reliable. Phase 2 builds upon these simulations by conducting rigorous experimental procedures to validate the findings. The experimental setup, including the fabrication of a high-speed machining adapter and the selection of appropriate micromilling tools, ensures that the experiments closely mirror real-world conditions. This phase is crucial for confirming the simulation predictions and refining the models, ultimately leading to improved micromilling processes.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The aim of this chapter is to present and analyse the results obtained from the simulation and experimental phases of this study. The chapter is structured to provide a detailed examination of the micromilling behaviour of aluminium and mild steel, focusing particularly on the critical machining forces that must be managed to prevent tool breakage. The findings are divided into two main sections: the first focuses on the results derived from the finite element analysis (FEA) simulations conducted using the SFTC DEFORM 2D software, while the second section presents the experimental validation of these simulations. Throughout this chapter, the results are critically compared to assess the accuracy of the simulations and their alignment with real-world machining outcomes.

The discussion not only highlights the consistency between simulated and experimental data but also delves into the discrepancies observed, offering explanations and potential areas for further investigation. By thoroughly analysing the machining forces and other critical parameters, this chapter provides a comprehensive understanding of the micromilling process, particularly the challenges associated with machining materials of varying hardness and toughness, such as aluminium and mild steel. The findings presented here form the basis for understanding the micromilling processes, ensuring both precision and efficiency in manufacturing small-scale, high-precision components.

PHASE 1: ANALYZING MICROMILLING BEHAVIOR FOR VARIOUS TOOL DIAMETERS USING FEM SIMULATIONS IN SFTC DEFORM 2D

4.2 Behaviour of micromilling of Aluminium Al6061 and Mild Steel AISI1045 simulated by Finite Element Method (FEM)

The analysis of micromilling behavior with varying tool diameters plays a critical role in optimizing cutting performance and understanding the influence of geometric parameters on stress distribution, cutting forces, and temperature. Simulations using finite element methods (FEM) in SFTC DEFORM 2D were conducted for tool diameters of 0.3 mm, 0.6 mm, and 0.9 mm under similar machining conditions to evaluate their impact on the micromilling process. The analysis of stress distribution during the micromilling of aluminium Al6061 is a critical aspect of understanding the material's behavior under machining conditions. Al6061, an alloy widely used in aerospace, automotive, and electronics industries, is favored for its high strength-to-weight ratio, excellent corrosion resistance, and good machinability. Figure 4.1 represents the sample of stress distribution obtained through finite element analysis (FEA) during the micromilling of aluminium alloy Al6061. The stress distribution shown in the figure highlights the regions of maximum stress, which are critical in determining the likelihood of tool breakage or excessive wear. The gradient of stress from high to low in the image indicates how the material responds to the cutting forces, with the highest stress concentrations occurring at the point where the cutting tool engages with the workpiece. This is consistent with findings in previous studies, which have shown that tool geometry, cutting speed, and feed rate play significant roles in influencing stress distribution during micromilling (Zhou et al., 2020).

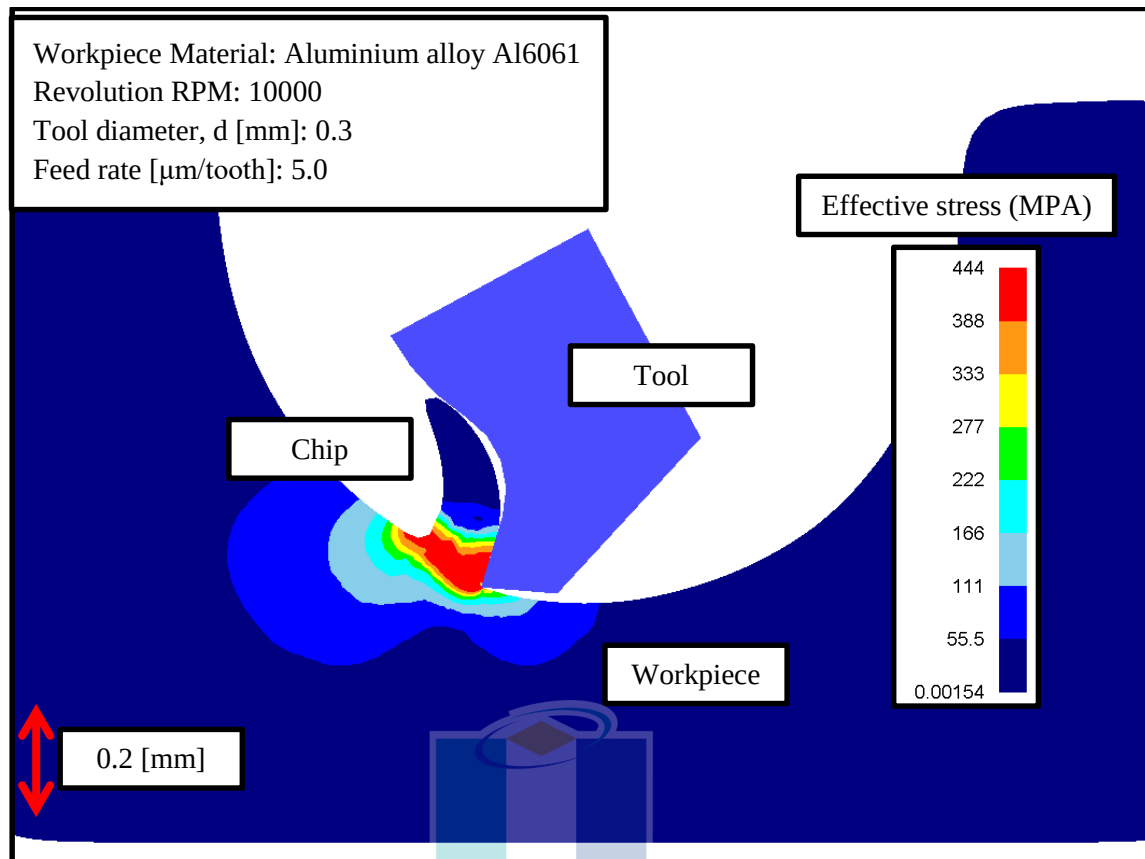


Figure 4.1 Estimated stress distribution by FEA for micromilling aluminium Al6061

Similarly, Figure 4.2 illustrates the estimated stress distribution during the micromilling of mild steel AISI1045, as simulated using finite element analysis (FEA). The stress concentration observed near the cutting edge of the tool highlights the intense mechanical interactions between the tool and the workpiece. The effective stress reaches up to 1350 MPa, indicating the significant forces involved in cutting harder materials like mild steel compared to softer materials such as aluminium. This stress distribution is critical in understanding the challenges faced when machining tougher materials, where higher cutting forces can lead to increased tool wear, deflection, and potential failure if not managed properly. Previous studies have emphasized the need to understand the effect of cutting parameters such as spindle speed, feed rate, and depth of cut to minimize these stresses, thereby extending tool life and improving surface finish quality. For instance, research conducted on the micromilling of various steel alloys supports the finding that controlling these parameters is essential to prevent excessive stress build-up, which could compromise machining accuracy and tool integrity.

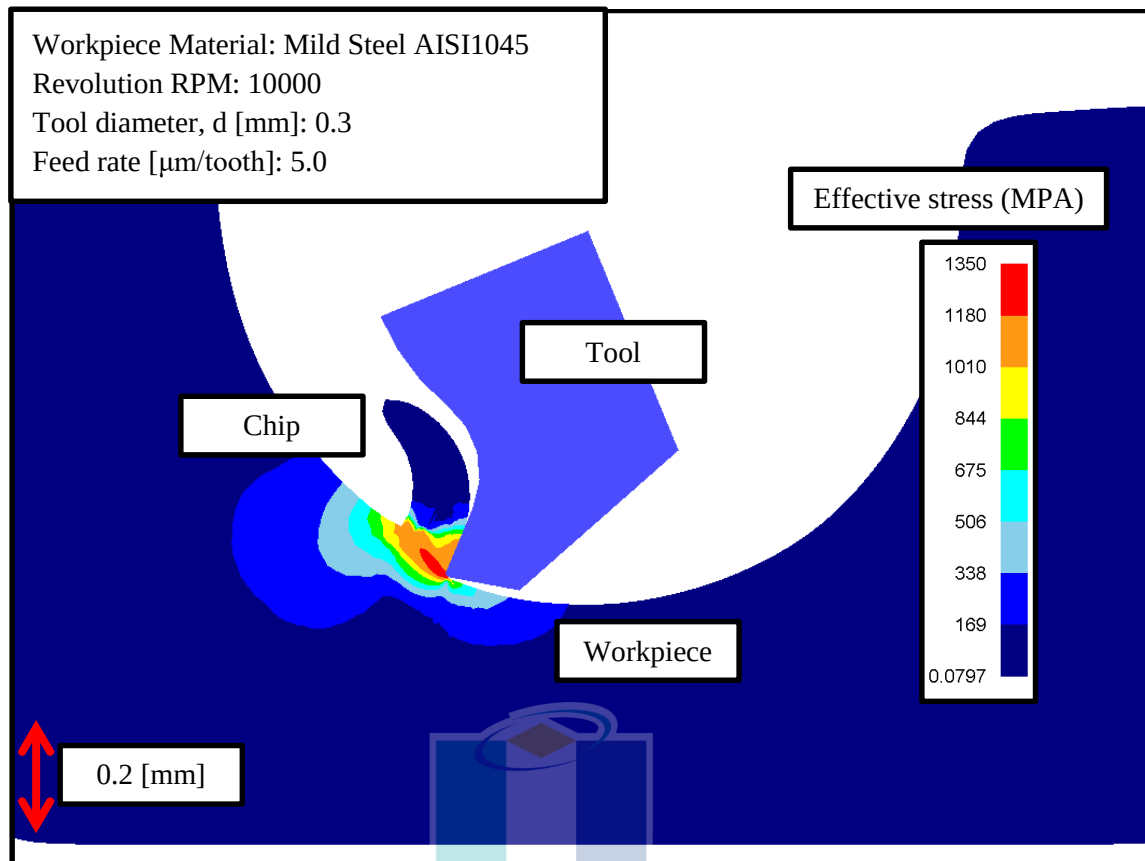


Figure 4.2 Estimated stress distribution by FEA for micromilling mild steel 1045

Furthermore, Figure 4.3 illustrates a comparative analysis of stress distribution magnitudes between aluminium Al6061 and mild steel AISI1045 during micromilling operations. The visual comparison highlights a significant difference in stress levels, with the mild steel exhibiting much higher stress concentrations. This discrepancy is primarily attributed to the inherent material properties of mild steel, such as its higher hardness and yield strength, which demand greater cutting forces during machining. The stress concentration is notably more intense in the mild steel, indicating a higher resistance to deformation and, consequently, increased tool wear and machining challenges. Furthermore, previous studies have reported that machining harder materials like steel often results in elevated stress levels, which can exacerbate tool wear and reduce surface quality if not managed properly. In contrast, aluminium, being softer, generates lower stress levels, making it easier to machine but still requiring precise control to avoid issues like burr formation.

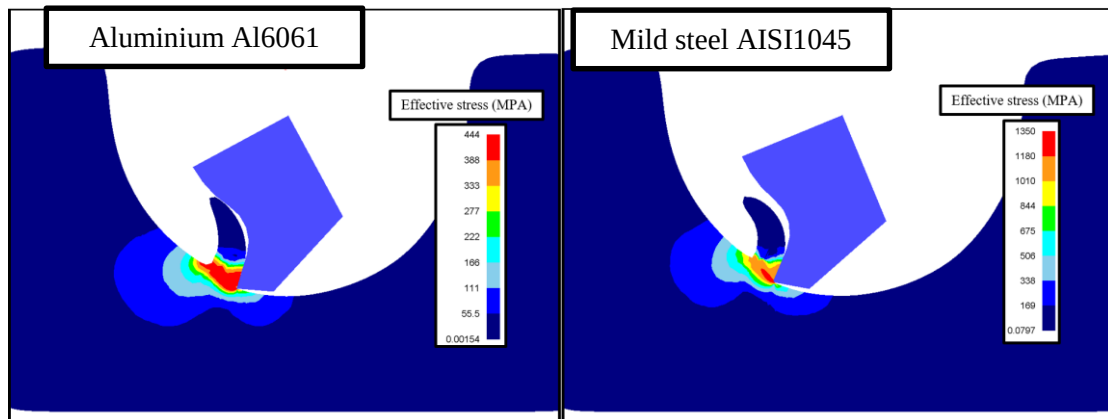


Figure 4.3 Comparison of the simulated stress magnitude between aluminium and mild steel micromilling process

4.3 Micromilling cutting force profile estimated by SFTC DEFORM 2D

Cutting forces play a significant role in determining the quality and efficiency of micromilling operations. These forces directly influence tool wear, surface integrity, and overall machining stability. In micromilling, the small size of the tool, the high precision required for the process exacerbate the challenges associated with controlling and predicting cutting forces. Accurately estimating these forces is essential to understand the effect of cutting parameters, reducing tool deflection, and improving the surface finish of the machined components. Figure 4.4 shows the sample of aluminium Al6061 micromilling process cutting force profile, estimated by SFTC DEFORM 2D software.

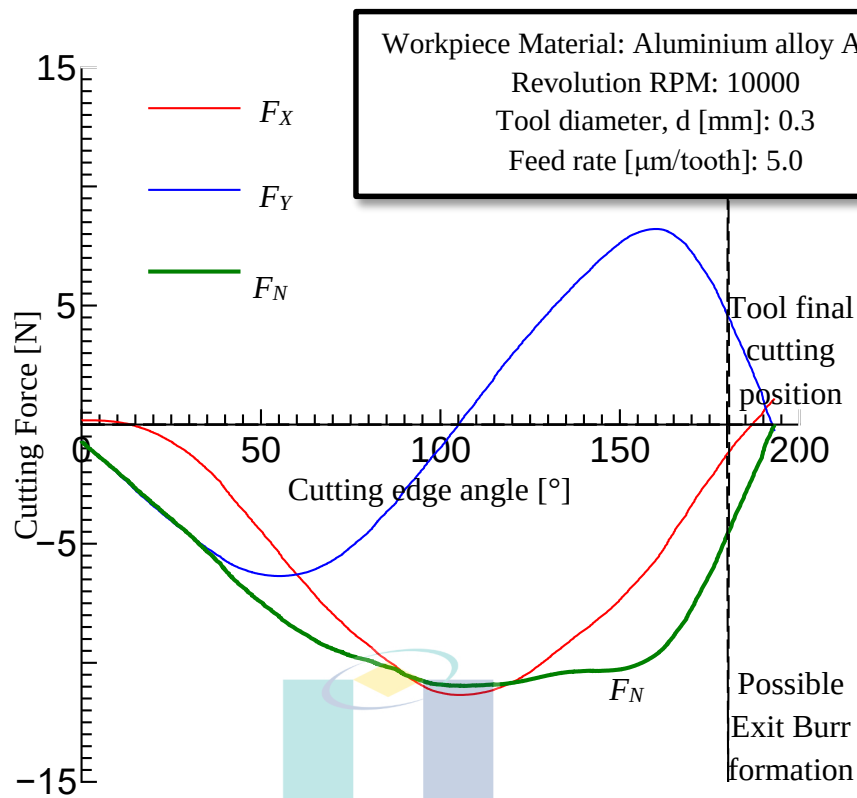


Figure 4.4 Sample of aluminium Al6061 micromilling process cutting force profile, estimated by SFTC DEFORM 2D software

According to Figure 4.4, the cutting forces F_x and F_y , representing the forces in the x- and y-directions, respectively, vary with the cutting edge angle during the micromilling process, estimated by SFTC Deform 2D software. These forces are critical in understanding how the tool interacts with the workpiece throughout the cutting process. Notably, as the cutting edge angle increases, both force components show distinct peaks and troughs, indicating the varying resistance encountered by the tool as it cuts through the material. The final cutting position of the tool and the point of exit burr formation are also highlighted, indicating the end of the cutting process where the tool exits the material, often leading to the formation of burrs due to the sudden release of cutting forces.

Based on Figure 4.4, it can be understood that, the profile provides essential insights into the machining dynamics and potential challenges in the process, such as the

effect of burrs at the tool exit. Burr formation is a common issue in micromilling that can degrade surface quality and precision, and generating unwanted force, as shown in Figure 4.5. Studies by Zhang et al. (2023) and Wu & Lin (2021), proposed that controlling cutting forces through improvised tool paths and cutting conditions can significantly improve surface finish and reduce burr formation in micromilling. Furthermore, the sinusoidal nature of the cutting forces reflects the cyclic loading that the tool experiences, which can be critical in assessing tool wear and life. Understanding this force profile is crucial for predicting tool failure and improving the design of micromilling operations, especially when machining materials with varying hardness and toughness (Zhang et al., 2023).

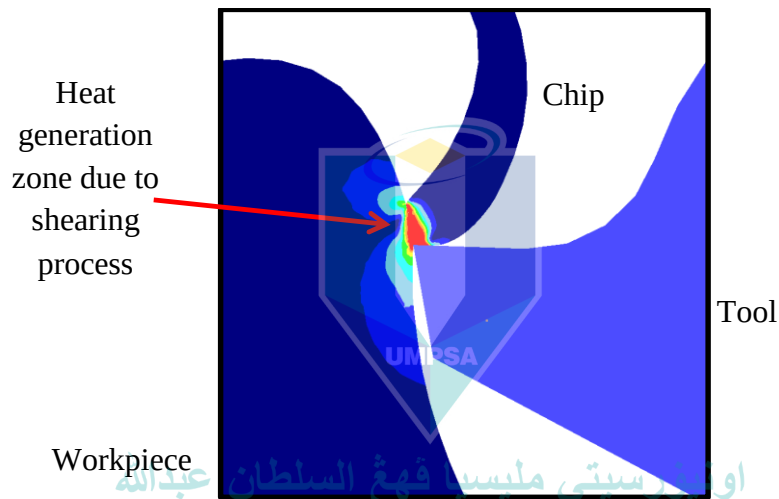


Figure 4.5 Possible burr estimated during at the tool exit

4.4 Influence of various cutting speed on cutting force and temperature in micromilling estimated by FEM

In micromilling, machining forces can vary significantly depending on the material being machined and the specific conditions under which the process is carried out. Figure 4.6 shows the estimated cutting force and cutting temperature for aluminium machining with fixed cutting speed, v_c of 18.9 [m/min], increasing feed rate, f [mm/tooth], for micromilling tool diameter D , 0.3[mm]. From the figure, it can be observed that as the feed rate increases, both the cutting force and temperature rise significantly. This

increase in force can lead to higher stresses on the tool, potentially accelerating tool wear and increasing the risk of tool breakage.

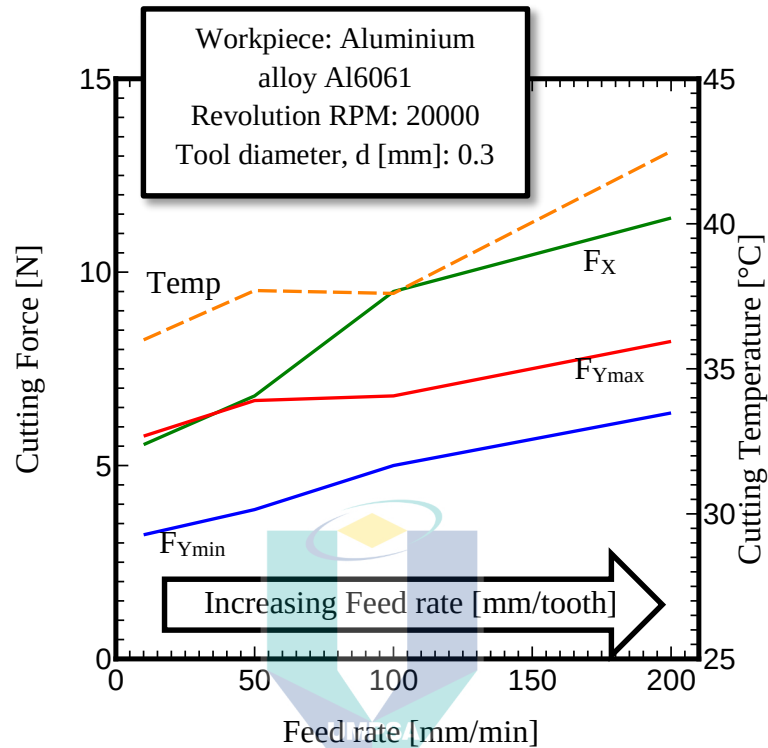


Figure 4.6 Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 18.9 [m/min], for micromilling tool diameter D , 0.3[mm].

This relationship between feed rate, cutting force, and temperature is critical in micromilling, as higher cutting forces can lead to increased tool wear and potential damage to the workpiece, while elevated temperatures can affect the material properties of both the tool and the workpiece, leading to potential thermal damage or deformation. The findings in this graph align with previous studies that emphasize the importance of setting the best feed rates to balance cutting efficiency with tool longevity and workpiece quality. Previous studies by Sheheryar et al. (2022) highlights the need for careful calibration of feed rates to manage cutting forces effectively, which is critical in maintaining tool life and ensuring high-quality surface finishes in micromilling operations. Moreover, the increase in cutting temperature with higher feed rates has also been documented in the literature. For instance, a study by Liu et al. (2022) indicates that higher feed rates can lead to increased frictional heat generation at the tool-workpiece

interface, which not only raises the cutting temperature but also accelerates tool wear and can degrade the quality of the machined surface. Similarly, Figures 4.7 and 4.8 shows the estimated cutting force and cutting temperature for aluminium machining with increasing feed rate, f [mm/tooth], for micromilling tool diameter D , 0.3[mm], and fixed cutting speed, v_c of 9.43 [m/min] and 4.7 [m/min], respectively. As the cutting speed decreases, the rise in cutting forces becomes less pronounced. At a cutting speed of 9.8 m/min (Figure 4.7), the forces are lower compared to Figure 4.6, and the maximum cutting temperature is slightly reduced, staying below 40°C. The lowest cutting speed of 4.7 m/min in Figure 4.8 exhibits the lowest cutting forces and temperatures, underscoring the trade-off between speed and thermal management. The findings suggest that while higher cutting speeds can enhance productivity, they also introduce challenges in managing cutting forces and temperatures, which can impact tool life and surface quality. Lower cutting speeds, on the other hand, offer better control over these variables but may reduce overall process efficiency. This balance is crucial in micromilling, where precision and tool integrity are paramount.

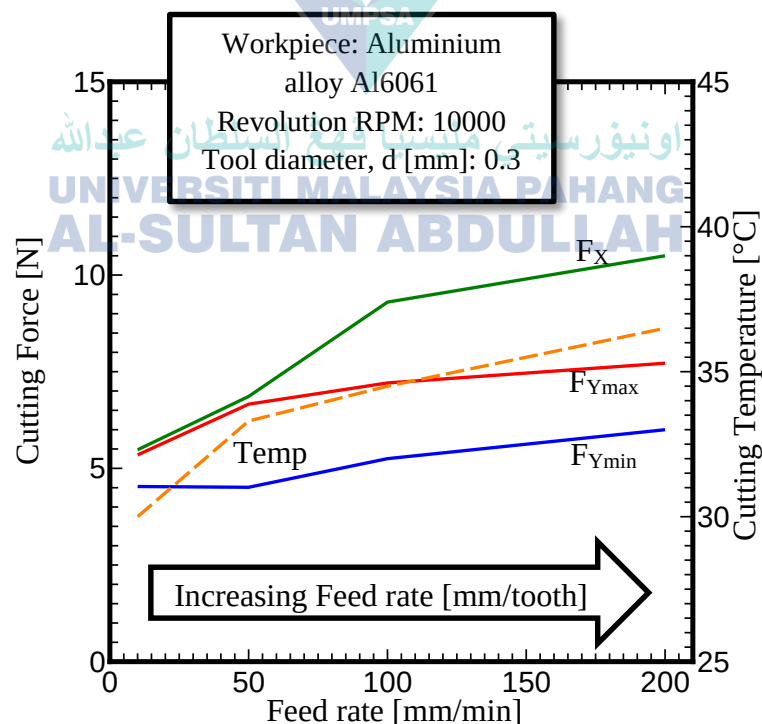


Figure 4.7 Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 9.42 [m/min], for micromilling tool diameter D , 0.3[mm].

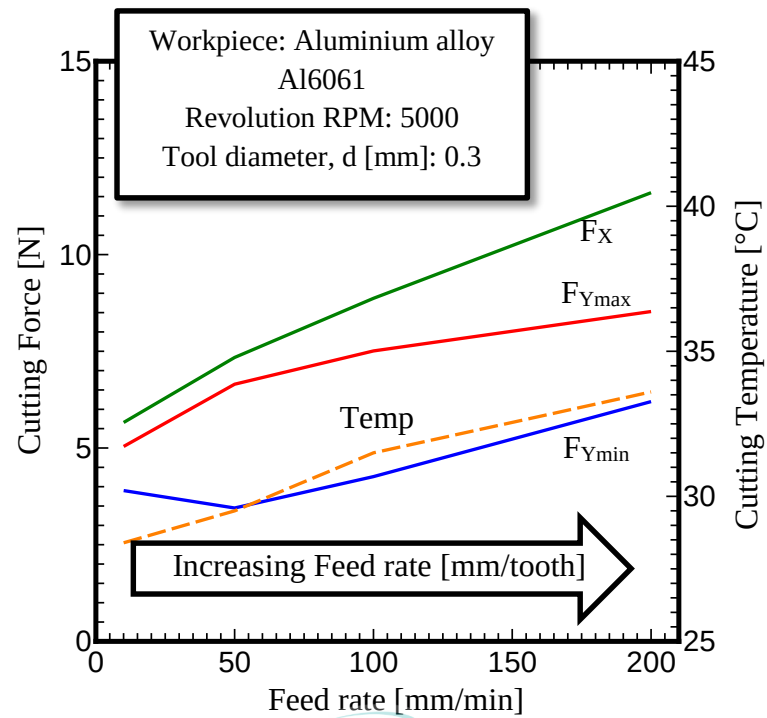
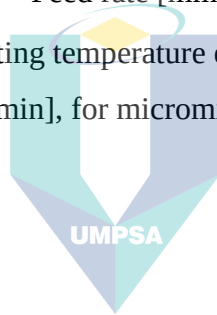


Figure 4.8 Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 4.7 [m/min], for micromilling tool diameter D , 0.3[mm].



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

4.5 Influence of various tool diameter on cutting force and temperature in micromilling estimated by FEM

Figures 4.9 and 4.10 present the estimated cutting forces and cutting temperatures for aluminium micromilling under varying feed rates using tools of different diameters, 0.6 and 0.9 [mm] tool diameter, respectively. As observed, both cutting force (F_x) and cutting temperature increase with the feed rate in both cases, which is consistent with the general trend observed in micromilling processes. In Figure 4.9, the cutting forces (F_x) and cutting temperature exhibit a linear increase as the feed rate progresses. This linear relationship suggests that the tool and material interaction in this range is relatively stable, with no significant sudden increases in force or temperature, implying efficient material removal without excessive tool wear. The increase in $F_{y_{max}}$ and $F_{y_{min}}$ is also steady, indicating minimal tool deflection and good dimensional control, which is critical in maintaining surface integrity and achieving precision in micromilling.

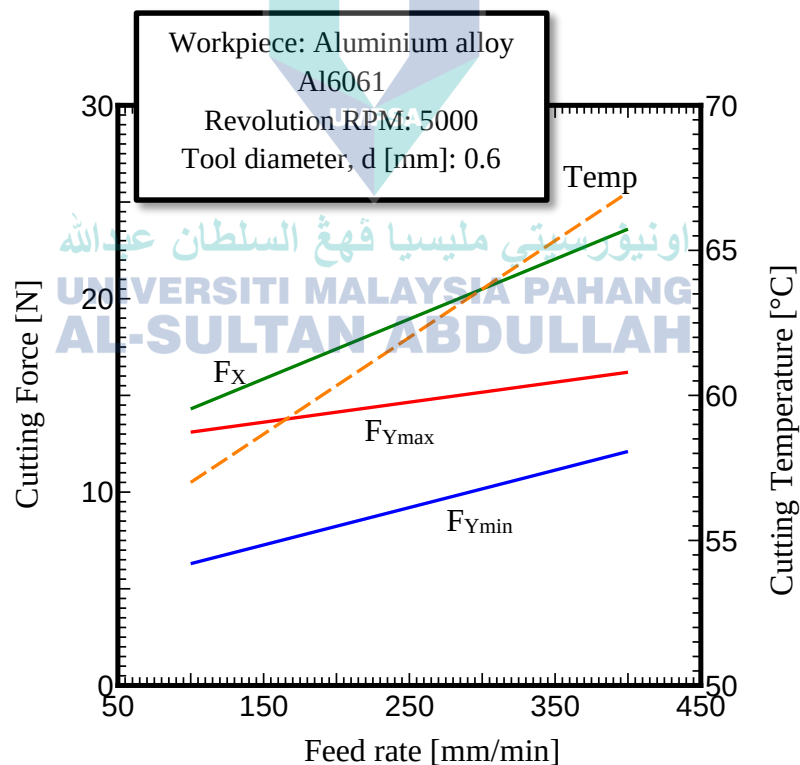


Figure 4.9 Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 9.42 [m/min], for micromilling tool diameter D , 0.6[mm].

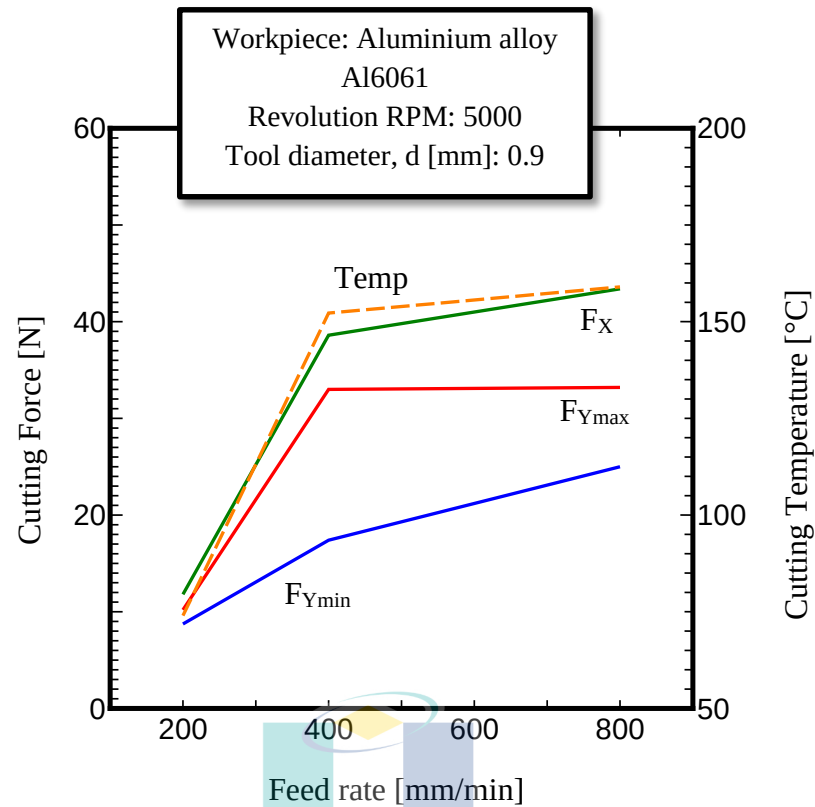


Figure 4.10 Cutting force and cutting temperature estimation for aluminium machining with cutting speed, v_c of 14.1[m/min], for micromilling tool diameter D , 0.9[mm].

However, in Figure 4.10, with a larger tool diameter of 0.9 mm and a higher cutting speed, the cutting forces and temperatures rise more sharply as the feed rate increases. Particularly notable is the rapid increase in temperature beyond the feed rate, 300 [mm/min], suggesting a higher rate of heat generation and less efficient heat dissipation, which could lead to accelerated tool wear and thermal damage to the workpiece. This behaviour can be attributed to the larger engagement area of the tool with the material, leading to higher frictional forces and, consequently, greater heat generation. The geometrical effect of the larger tool diameter also means that more material is removed per tooth engagement, which increases the load on the tool, thereby amplifying the forces and temperatures generated during machining. The findings are consistent with previous studies on micromilling, where it has been demonstrated that larger tool diameters and higher feed rates tend to increase cutting forces and temperatures (Liu et al., 2022).

4.6 Influence of various workpiece material on cutting force and temperature in micromilling estimated by FEM

Figures 4.11 and 4.12 present the force and temperature estimations for micromilling mild steel AISI1045, compared with similar processes for aluminium, providing crucial insights into the differing behaviours of these materials under identical machining conditions. In Figure 4.11, the results are shown for a cutting speed of 18.8 m/min with a tool diameter of 0.3 mm. It is evident that the cutting forces for mild steel are significantly higher than those for aluminium (dashed line). This difference can be attributed to the greater toughness of mild steel, which requires more force to cut through. The temperature during machining, is also higher for mild steel than for aluminium. This is consistent with findings in other studies, such as those by Zhou et al. (2020), which have highlighted the increased energy required for cutting stronger materials, leading to higher temperatures.

Figure 4.12, which shows results for a larger tool diameter of 0.6 [mm] at a cutting speed of 37.7 [m/min], further emphasizes these differences. Here, the cutting forces and temperatures for mild steel are again higher than those for aluminium, with the discrepancy increasing as the feed rate increases. The solid lines for mild steel exhibit a steeper slope, indicating a more pronounced rise in both cutting force and temperature with increasing feed rate. This behaviour suggests that mild steel not only requires more force to machine but also generates more heat, potentially leading to issues like tool wear and thermal damage if not properly managed (Platt et al., 2020). The higher forces and temperatures associated with mild steel necessitate careful consideration of tool material, cooling strategies, and feed rate adjustments to maintain tool life and machining precision. The findings from these figures align with previous research that emphasizes the importance of tailored machining parameters for different materials to improve efficiency and product quality in micromilling operations (Platt et al., 2020).

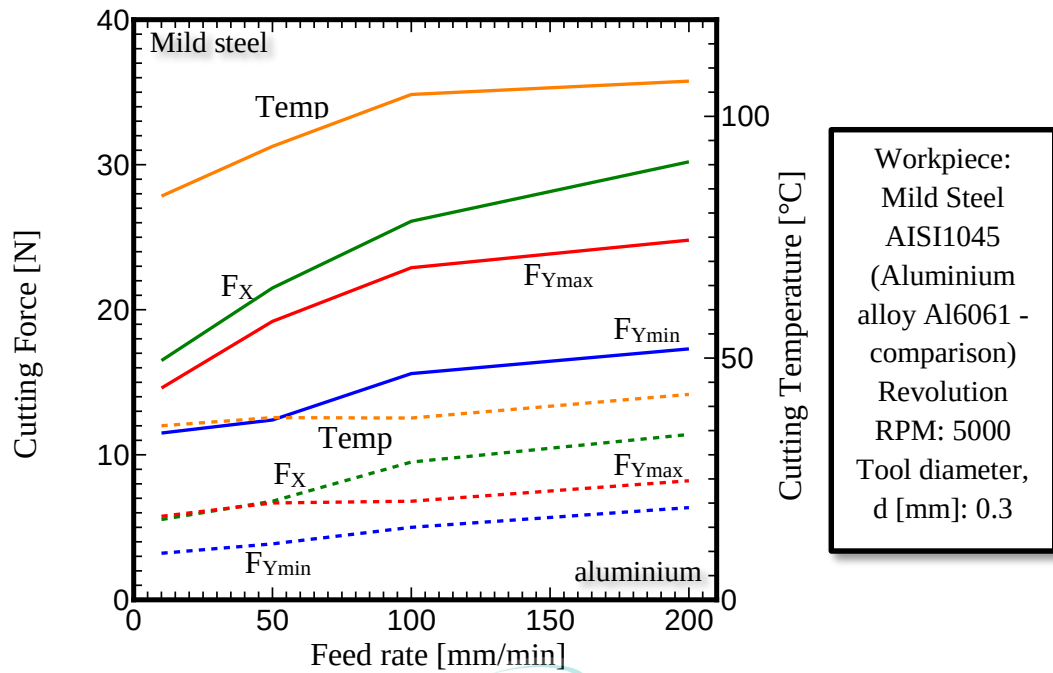


Figure 4.11 Force and temperature estimation for mild steel AISI1045 machining with cutting speed, v_c of 4.7 [m/min], for micromilling tool diameter D, 0.3[mm].

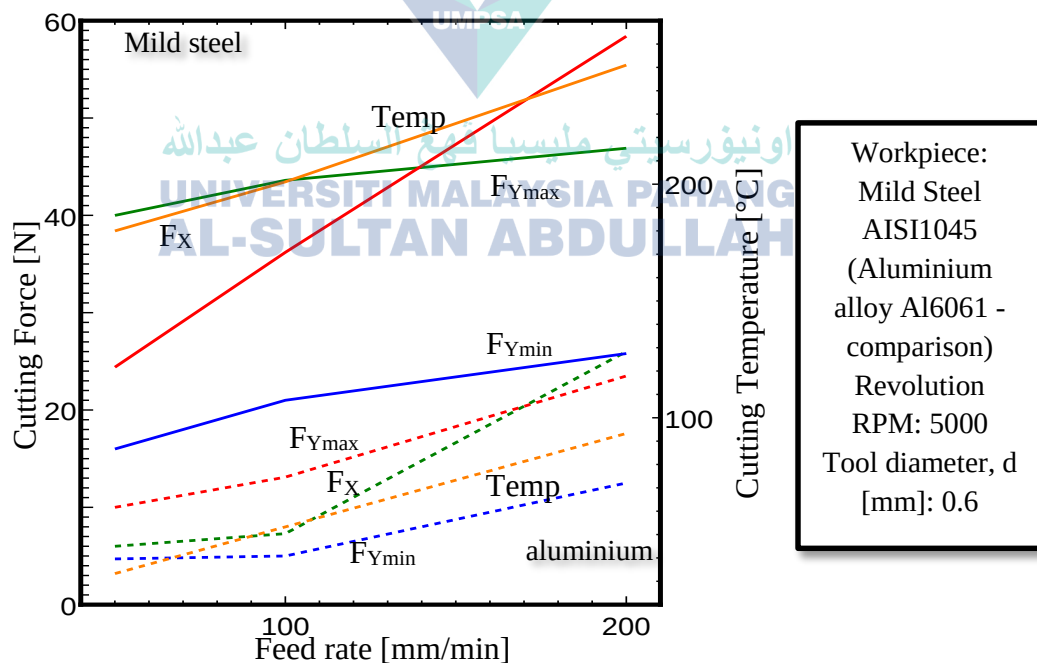


Figure 4.12 Force and temperature estimation for mild steel AISI1045 machining with cutting speed, v_c of 9.4 [m/min], for micromilling tool diameter D, 0.6[mm].

From the Phase 1, several finding can be summarize as following:

- As feed rate increases, both cutting force and temperature rise significantly.
- Larger tool diameters (0.6mm and 0.9mm) result in higher cutting forces and temperatures compared to smaller diameters (0.3mm).
- The increase in forces and temperatures is more pronounced with larger tool diameters as feed rate increases.
- Mild steel AISI1045 requires significantly higher cutting forces and generates higher temperatures compared to aluminium alloy Al6061 under the same machining conditions.
- The difference in cutting forces and temperatures between mild steel and aluminium becomes more pronounced as feed rate increases.

Based on the finding from the Phase 1, it is understood that higher machining speed is giving more significant output, higher production rate with optimal wear rate as the force still low, compared to lower machining speed as shown in Figures 4.6 – 4.8. To further the study to Phase 2, the highest possible spindle speed is chosen as RPM for all the experiment data collection, which is 20,000 RPM.

PHASE 2: VALIDATING THE MICROMILLING CUTTING PERFORMANCE WITH THE VERIFIED CONDITIONS FROM THE SIMULATIONS

4.7 New Micromilling tool geometry observed by a 3D measuring and laser microscope LEXT.

Micromilling is a high-precision machining process that relies on extremely small cutting tools, often with diameters less than 1 mm. The geometrical properties of these tools—such as the tool diameter, flute design, and overall sharpness—play a significant role in determining the efficiency and accuracy of the micromilling process, as new tools are shown in Figure 4.13. Research has shown that tool wear in micromilling is a complex phenomenon influenced by several factors, including cutting forces, material hardness, and the thermal conditions during machining. Smaller tools are particularly vulnerable to rapid wear due to their limited ability to dissipate heat and the high cutting forces relative to their size. Figure 4.14 presented new tool geometries designed for micromilling, highlighting advancements in tool design to improve performance in micro-scale machining processes. The geometries shown reflect the latest innovations aimed at reducing tool wear, improving cutting efficiency, and enhancing surface quality during micromilling operations. The smaller the tool size, the difficulty of manufacturing increase as the tool geometry itself is not easily obtainable, or similar to the higher diameter version. Additionally, it is widely acknowledged that smaller tool sizes in micromilling significantly reduce the axial and radial depths of cut, thereby affecting productivity, especially when scaling up for larger production runs. As a result, micromilling requires specialized strategies to ensure optimal cutting conditions and to mitigate the negative effects of reduced tool size on productivity. Recent studies emphasize the need for advanced cutting strategies that optimize feed rates, cutting speeds, and tool paths to prolong tool life and maintain high precision in micromilling operations (Balázs et al., 2021).

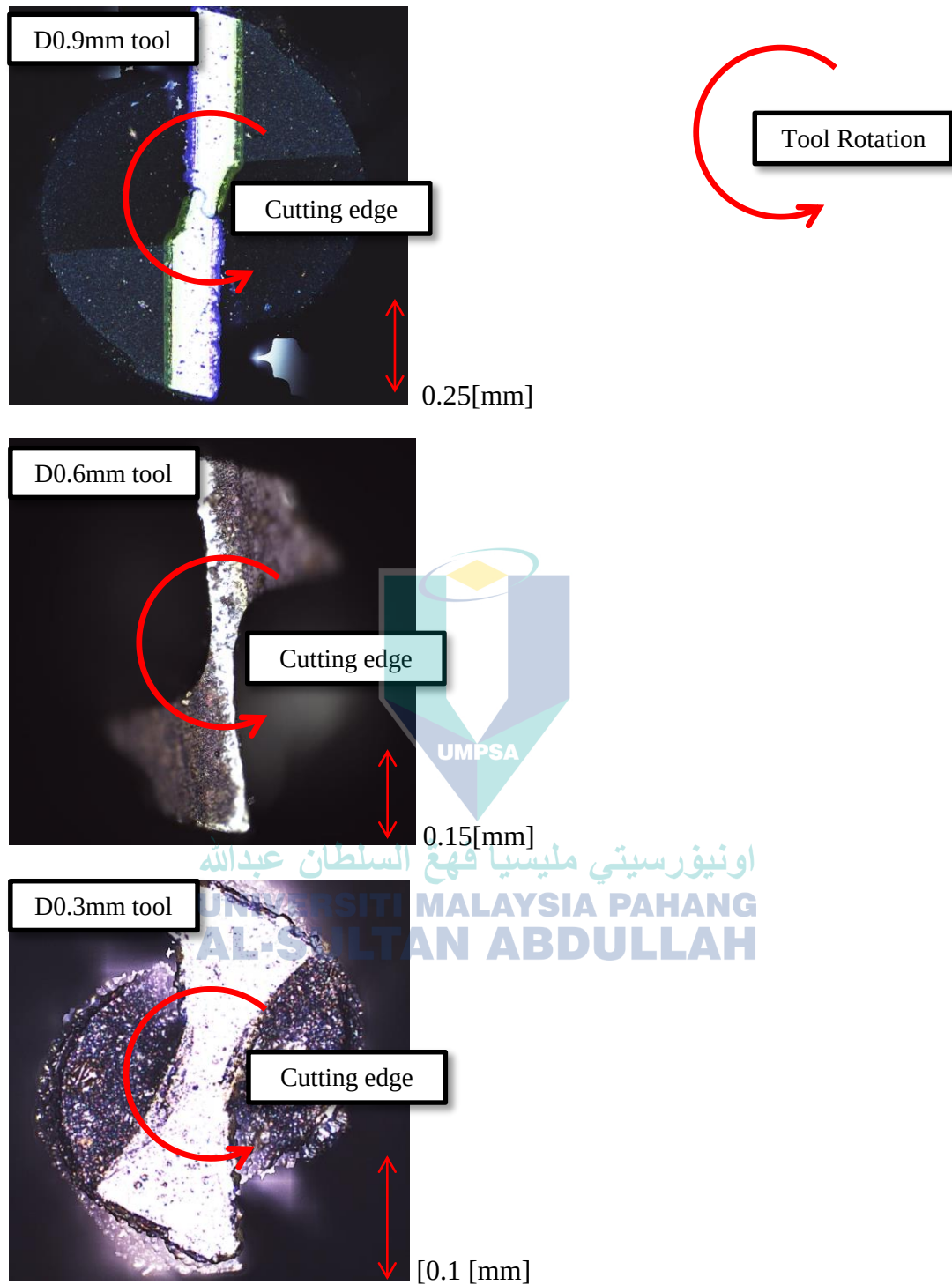
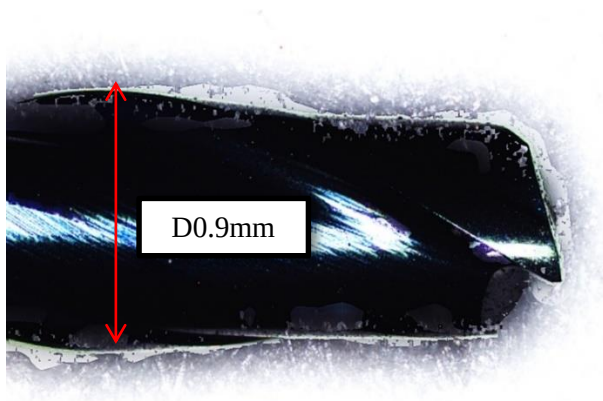
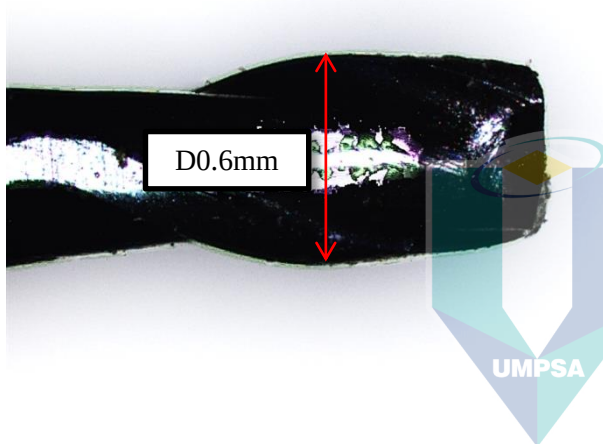


Figure 4.13 New tool geometries (front view)



[0.9 mm tool]



[0.6 mm tool]



[0.3 mm tool]

Figure 4.14 New tool geometries (side view)

4.8 Cutting force performance of micromilling tool on various cutting conditions

Figure 4.15 shows the relationship between tool diameter [mm] with cutting force per unit thickness [N/mm] during machining aluminium Al-6061 and mild steel AISI1045. For aluminium, the cutting force increases slightly as the tool diameter grows from 0.3 mm to 0.9 mm, staying within the 2 to 5 N/mm range. In contrast, the cutting force for mild steel increases sharply as the tool diameter grows, reaching around 10 N/mm at 1 mm. This difference is due to material properties: aluminium, being softer, requires less force, while mild steel's hardness and strength result in a much higher cutting force requirement as tool size increases. Recent studies support these trends, showing that tool geometry, particularly diameter, impacts cutting forces significantly, especially for harder materials like steel. Research indicates that larger tool diameters increase cutting forces more notably for materials with higher hardness, while softer materials like aluminium require lower forces even as tool diameter increases, due to increase machining load (Ercetin et al., 2023; Lee et al., 2023; Zhang & Li, 2023).

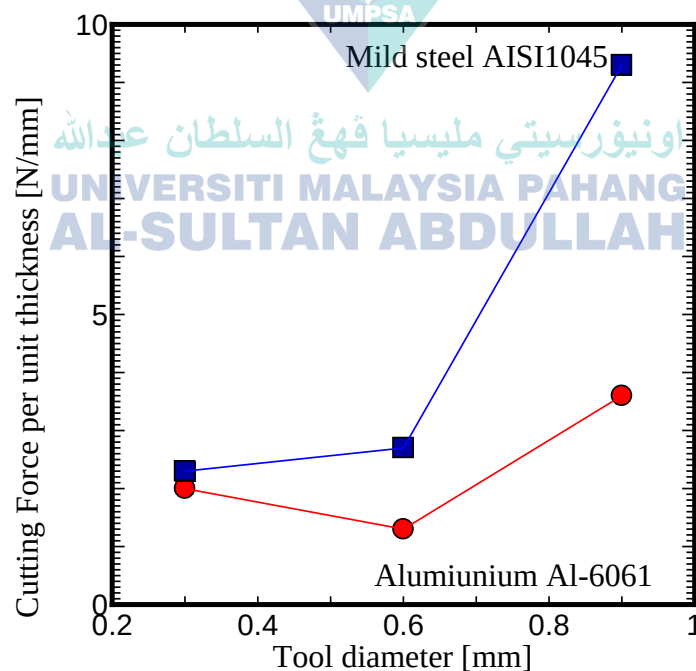


Figure 4.15 Relationship between tool diameters (mm) with cutting force (N/mm) for aluminium Al-6061 and mild steel AISI1045.

Figure 4.16 shows the relationship between tool diameter and cutting force per unit thickness for aluminium Al-6061 at two different feed rates: 10 mm/min and 200 mm/min. Additional to the information, at the higher feed rate (200 mm/min), the cutting force shows higher magnitude compared to lower feed rate (10 mm/min). This suggests that higher feed rates increase cutting force, especially for smaller and larger tool diameters, due to increased resistance from faster material removal. Research supports these findings, showing that higher feed rates typically result in higher cutting forces, especially with smaller and larger tool diameters. However, mid-range tool diameters may reduce cutting force by achieving a balance between feed rate and tool geometry (Manso et al., 2019).

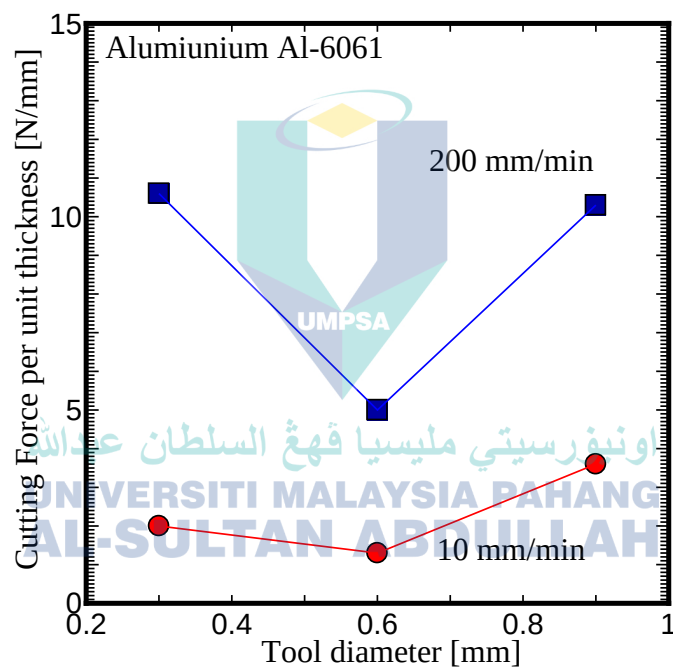


Figure 4.16 Relationship between tool diameters (mm) with cutting force (N/mm) for various feed rate (mm/min)

4.9 Validation on cutting force performance of micromilling tool with Finite Element Method

Figure 4.17 shows the comparison between FEM estimated cutting force per unit thickness [N/mm] with the experimental result for micromilling tool diameter 0.3mm. The trends reveal that, as the feed rate increases, both the FEM and EXP cutting forces per unit thickness also increase. However, the experimental results show consistently higher cutting forces than those predicted by the FEM simulation. This discrepancy between FEM and EXP results suggests that the FEM model may underestimate some factors affecting cutting force, such as tool wear, heat generation, or material behavior under real machining conditions. FEM tends to simplify assumptions about material properties and tool interactions, leading to lower force predictions. Experimental results reflect the actual cutting environment where these factors, such as thermal effects and tool deflection, contribute to higher forces O'Toole (O'Toole and Fang, 2022).

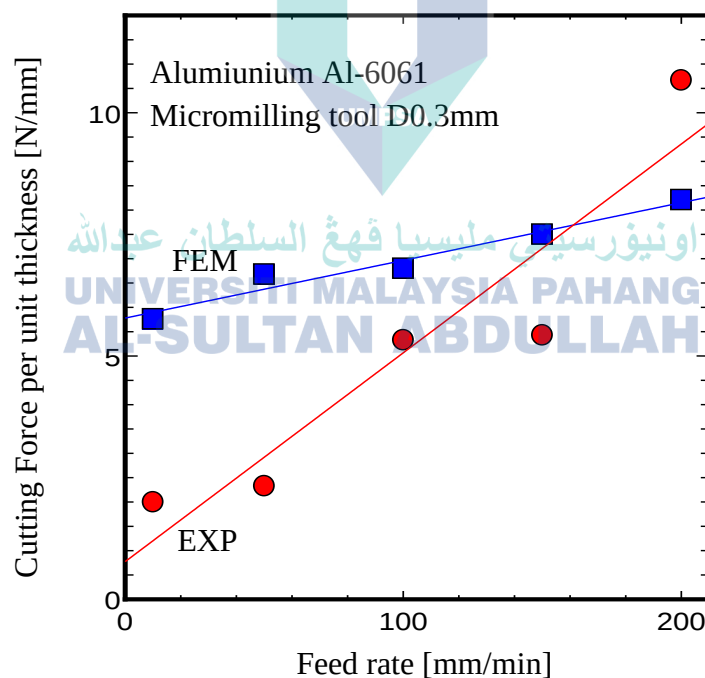


Figure 4.17 Comparison between FEM estimated cutting force per unit thickness [N/mm] with the experimental result for micromilling tool diameter 0.3mm

Recent studies confirm that FEM often underestimates cutting forces in micromilling due to its inability to fully capture the complexities of real machining conditions (O'Toole and Fang, 2022). The increasing trend of cutting force with higher feed rates is consistent with previous research, where higher feed rates generate greater resistance, leading to higher forces (Ercetin et al., 2023). Additionally, Figure 4.18 shows the comparison between FEM estimated cutting forces per unit thickness [N/mm] with the experimental result for micromilling tool diameter 0.3 to 0.9 mm with the feed rate of 200 mm/min. The experimental data show a consistent decrease in cutting force as the tool diameter increases. In contrast, the FEM model predicts a peak in cutting force around the 0.6 mm tool diameter, after which the force decreases (O'Toole and Fang, 2022; Ercetin et al., 2023).

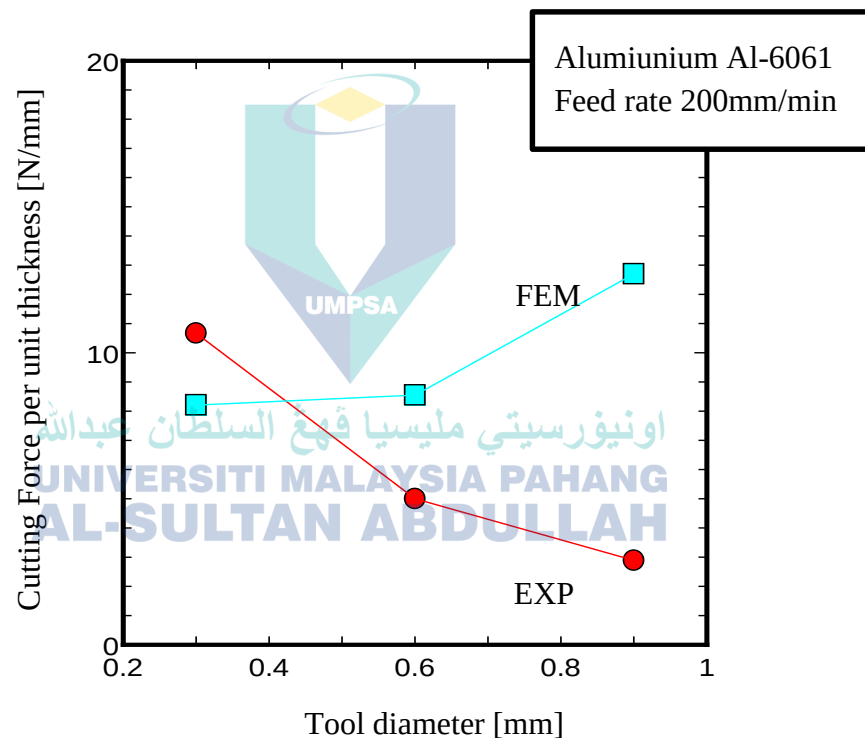


Figure 4.18 Comparison between FEM estimated cutting forces per unit thickness [N/mm] with the experimental result for micromilling tool diameter 0.3 to 0.9 mm with the feed rate of 200 mm/min.

4.10 Observation on Machining performance of micromilling tool on aluminium metal sheet to through 1 mm aluminium sheet

Figure 4.19 shows the micromilling performance of diameter 0.9 [mm] cutting tool on aluminium metal sheet with 1 [mm] thickness. The figure highlights the tool's ability to produce fine, precise cuts, which is crucial in industries where high precision is necessary. It is assumed that 0.9 mm tool is close to 1.0 mm conventional milling, the machining process can be considered as simpler (Ercetin et al., 2023).

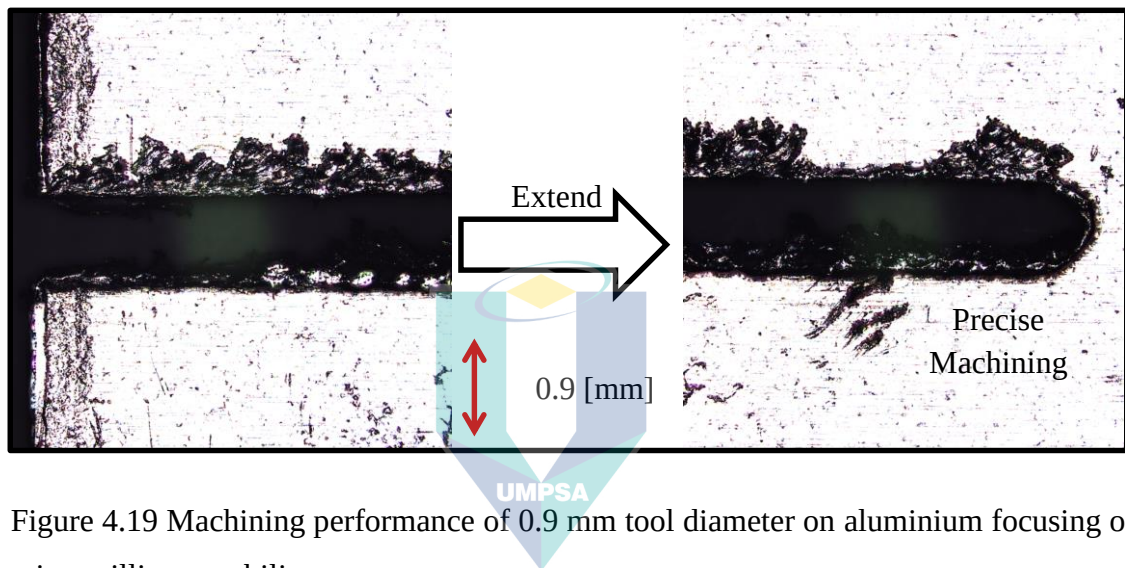


Figure 4.19 Machining performance of 0.9 mm tool diameter on aluminium focusing on micromilling capability.

اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

Machining Challenges: Burr Formation

Additionally, Figure 4.20 presented shows the machining performance of a 0.6 mm tool diameter on aluminium, specifically focusing on burr formation. Burr formation is a common issue in micromilling, especially when working with ductile materials like aluminium (Ercetin et al., 2023). Burrs are unwanted raised edges or small pieces of material that remain attached to the workpiece after the machining process. These burrs can significantly affect the quality of the machined part, leading to issues in assembly, performance, and overall aesthetics. In the context of micromilling, the size and geometry of the tool, as well as the machining parameters like feed rate, cutting speed, and depth of cut, play crucial roles in determining the extent of burr formation decreases (O'Toole

and Fang, 2022; Ercetin et al., 2023). The image shows that, despite using a relatively small tool diameter of 0.6 mm, burr formation still occurs, which indicates that further improvement of the micromilling process is necessary. This could involve adjustments to the cutting parameters or the use of specialized tools designed to minimize burrs [Balázs et al., 2021].

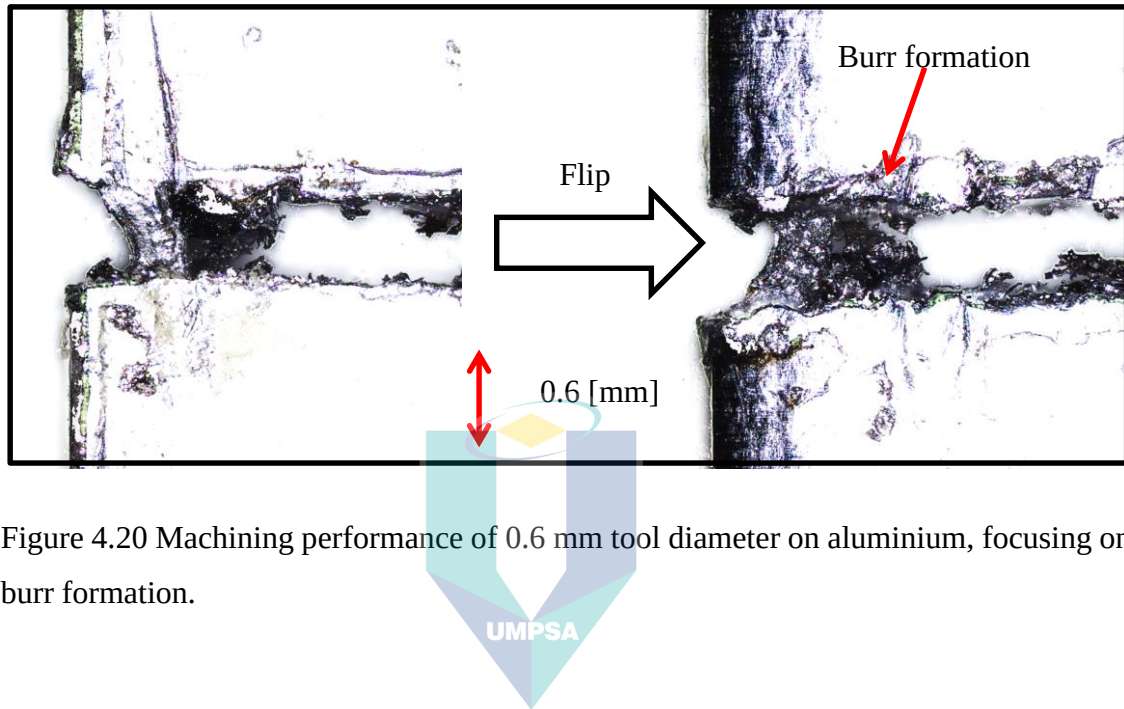


Figure 4.20 Machining performance of 0.6 mm tool diameter on aluminium, focusing on burr formation.

Tool Breakage and Depth Variation

Figure 4.21 provides crucial insights into the machining performance of a 0.3 mm tool diameter on an aluminium sheet, focusing particularly on tool breakage and the corresponding depth of microfeatures. The left figure showcases the physical wear and tear that occurs on the tool during the micromilling process. The tool's failure is evident from the irregularities and excessive burr formation along the machined surface, indicating that the small tool diameter struggled to withstand the cutting forces involved, ultimately leading to breakage. The right image further illustrates the depth profile of the micro features created during the machining process, where the red areas represent the highest points and the blue areas indicate the lowest (base). The tool's failure highlights the challenges of using ultra-small diameters under demanding conditions. On the right, the colored depth profile visualizes significant variations in the microfeatures' depth, with

red areas representing the highest points and blue areas indicating the lowest. These variations directly correlate with tool wear and performance; as the tool degrades, its ability to maintain consistent cutting depth diminishes, leading to uneven features (Liu et al., 2020; Balázs et al., 2021).

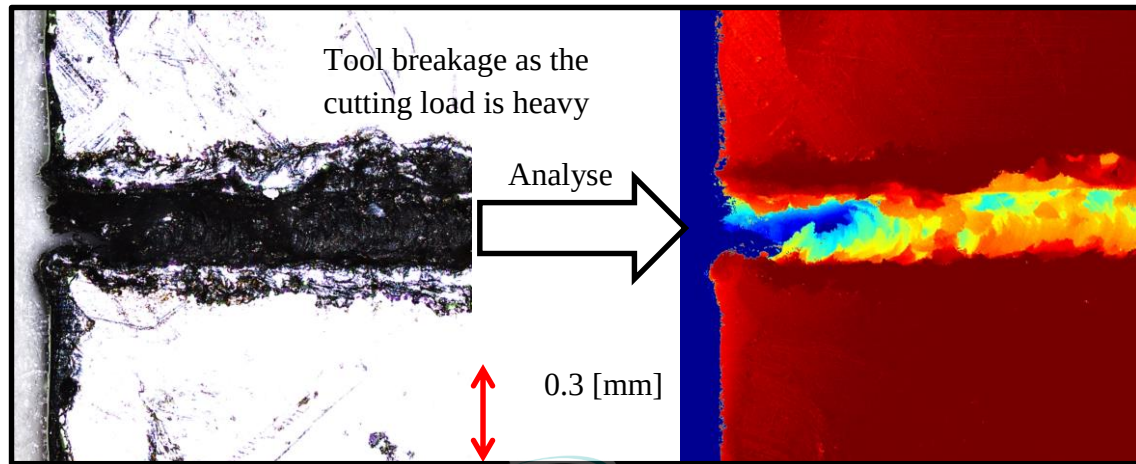


Figure 4.21 Machining performance of 0.3 mm tool diameter on aluminium, focusing on tool breakage.

The observations on tool breakage, burr formation, and depth profile variations are directly linked to the validation of verified machining conditions. Optimized cutting forces, tool geometry, and machining parameters significantly contribute to maintaining tool integrity and surface quality. For example, smaller tools with diameters below 0.5 mm, such as the 0.3 mm tool examined in this study, exhibit increased susceptibility to wear and breakage due to their limited stiffness and higher bending stresses under cutting forces (Ren et al., 2024). Deviations from verified conditions, such as improper cutting speeds or feed rates, exacerbate tool deflection, vibration, and thermal stresses, leading to catastrophic tool failure. For instance, previous study observed that smaller cutting tool diameters are prone to severe deflection and vibration under high cutting forces, directly impacting machining accuracy and tool life (Moges et al., 2018). Experimental results also validate that larger tools, such as the 0.9 mm diameter tool, demonstrate greater stability and precision under similar machining conditions, owing to their higher structural stiffness and reduced susceptibility to deflection (Wang et al., 2019). On the other hand, smaller tools demand highly optimized machining conditions, including reduced cutting forces and refined tool paths, to minimize wear and breakage while

achieving desired surface quality. This is particularly important as tools with small diameters often face increased vibrations and thermal stresses, which are more pronounced at the micro-scale (Chen et al., 2020). These experimental insights reinforce the critical importance of validated machining conditions in micromilling, especially for ultra-small diameters. The integration of advanced cutting strategies, optimized tool designs, and cooling solutions is essential to enhance performance and durability. Future research should focus on further refining these parameters to achieve a balance between productivity and precision, particularly for tools below 0.5 mm, where machining dynamics are most challenging (Wojciechowski et al., 2019).

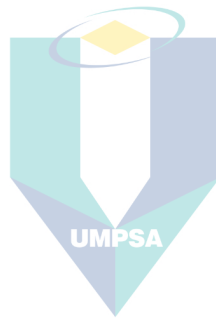
4.11 Summary

The micromilling study revealed significant insights into the behavior of different materials and tool sizes during the machining process. Finite Element Analysis (FEA) simulations demonstrated that mild steel AISI1045 experiences higher stress concentrations compared to aluminium Al6061 during micromilling. The study found a strong correlation between feed rate, cutting forces, and temperature. As the feed rate increased, both cutting force and temperature rose significantly. Higher cutting speeds led to increased cutting forces and temperatures, while lower cutting speeds offered better control over these parameters but at the cost of reduced overall process efficiency. The study also revealed that tool diameter plays a significant role in the micromilling process. Larger tool diameters (0.6mm and 0.9mm) resulted in higher cutting forces and temperatures compared to smaller diameters (0.3mm), with this effect becoming more pronounced as feed rate increased.

Material properties were found to significantly influence the micromilling process. Mild steel AISI1045 required substantially higher cutting forces and generated higher temperatures compared to aluminium alloy Al6061 under identical machining conditions. This difference became even more pronounced as the feed rate increased, highlighting the importance of material-specific machining strategies. When comparing Finite Element Method (FEM) simulations with experimental results, the study found that FEM generally underestimated cutting forces. This discrepancy was more noticeable at

lower feed rates and for harder materials like mild steel, suggesting that current FEM models may not fully capture all the complexities of the micromilling process. Further study is require to fully utilize FEM as a tool for estimation with high precision

The study also provided valuable insights into tool performance across different sizes. Larger tools (0.9mm) demonstrated better performance in producing fine, precise cuts. Medium-sized tools (0.6mm) still exhibited some issues with burr formation, while smaller tools (0.3mm) were prone to breakage and produced inconsistent cutting depths. These findings highlight the challenges associated with micromilling, particularly the issues of burr formation with smaller tool diameters and ductile materials like aluminium, and the significant problem of tool breakage for the smallest tool diameter (0.3mm).



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH

CHAPTER 5

CONCLUSIONS

5.1 Summary

This study provides a comprehensive exploration of the micromilling process, focusing on how tool diameter, material properties, and cutting conditions influence machining performance. By integrating finite element analysis (FEA) simulations with experimental validation, this study effectively bridges the gap between theoretical predictions and real-world machining outcomes. The simulation phase provided predictive insights into cutting forces, stress distributions, and thermal effects, while the experimental phase validated these predictions under practical conditions. This dual approach not only confirmed the accuracy of the simulations but also highlighted discrepancies, particularly for harder materials and smaller tool diameters, providing a foundation for refining simulation models to better reflect real-world machining dynamics. The primary objectives of the study were successfully achieved, offering valuable insights into micromilling behavior, the influence of material properties, and the efficacy of simulation models. The findings emphasize three key themes:

Micromilling Behavior: Tool diameter critically affects machining outcomes. Larger tools (0.6 mm and 0.9 mm) exhibit better stability and produce superior surface finishes with fewer burrs, while smaller tools (0.3 mm) excel in detail but face challenges such as tool breakage, deflection, and inconsistent cutting depths.

Material Influence: Aluminum (Al6061) provides greater machining flexibility with lower cutting forces and temperatures, making it suitable for diverse conditions. In contrast, mild steel (AISI1045) demands significantly higher forces, leading to accelerated tool wear and increased thermal stress, particularly for smaller tool diameters.

Simulation and Validation: FEM simulations offer critical predictive insights, particularly in estimating cutting forces, stress distributions, and temperatures. However,

discrepancies remain, particularly for harder materials and small-diameter tools, underscoring the need for refined simulation models that align more closely with experimental data.

5.2 Future works

Future work in this field should focus on several key areas:

- i. **Tool Wear Mechanisms:** Further investigation into the wear mechanisms of micro-tools, especially for smaller diameters (0.3mm and below), is crucial. This research could lead to the development of new tool materials or coatings that can withstand the high stresses involved in micromilling, particularly when machining harder materials like steel or HEAs.
- ii. **Microhardness and Machinability of HEAs:** The relationship between microhardness and machinability in high-entropy alloys presents an intriguing area for future research. Studies could focus on how variations in microhardness across different HEA compositions affect cutting forces, tool wear, and surface quality during micromilling. This could lead to the development of tailored machining strategies for specific HEA compositions.
- iii. **Real-time Monitoring and Adaptive Control:** Developing systems for real-time monitoring of tool condition and cutting forces during micromilling could significantly enhance process reliability. Future work could explore the integration of sensors and machine learning algorithms to create adaptive control systems that adjust cutting parameters on-the-fly to optimize performance and prevent tool failure.
- iv. **Simulation and Modeling:** Improving the accuracy of FEM simulations for micromilling processes, particularly in predicting cutting forces and tool wear for smaller tool diameters and harder materials, is an important area for future research. This could involve developing more sophisticated material models and incorporating micro-scale phenomena into simulation algorithms.

REFERENCES

- Aboelezz, A., Elqudsi, Y., Hassanalian, M., & Desoki, A. (2020). Wind tunnel calibration, corrections and experimental validation for fixed-wing micro air vehicles measurements. *Aviation*, 23(4).
- Altıparmak, S. C., Yardley, V. A., Shi, Z., & Lin, J. (2021). Challenges in additive manufacturing of high-strength aluminium alloys and current developments in hybrid additive manufacturing. *International Journal of Lightweight Materials and Manufacture*, 4 (2), 246-261.
- Attanasio, A. (2017). Tool run-out measurement in micro milling. *Micromachines*, 8(7), 221.
- Attanasio, A., Abeni, A., Özel, T., & Ceretti, E. (2018). Finite element simulation of high speed micro milling in the presence of tool run-out with experimental validations. *The International Journal of Advanced Manufacturing Technology*, 100(1–4), 25–35.
- Balázs, B. Z., Geier, N., Pereszlai, C., Poór, D. I., & Takács, M. (2021). Analysis of cutting force and vibration at micro-milling of a hardened steel. *Procedia CIRP*, 99, 177–182.
- Bhople, N., Mastud, S., & Satpal, S. (2021). Modelling and analysis of cutting forces while micro end milling of Ti-alloy using finite element method. *International Journal for Simulation and Multidisciplinary Design Optimization*, 12, 26.
- Bodunrin, M., Obiko, J., & Klenam, D. (2023). On the Uniaxial Compression Testing of Metallic Alloys at High Strain Rates: An Assessment of DEFORM-3D Simulation. *Applied Sciences*, 13(4), 2686.
- Brough, D., & Jouhara, H. (2020). The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery. *International Journal of Thermofluids*, 1, 100007.
- Caiazzo, F., & Alfieri, V. (2018). Simulation of Laser Heating of Aluminium and Model Validation via Two-Color Pyrometer and Shape Assessment. *Materials*, 11(9), 1506.
- Cao, Z., & Li, H. (2015). Investigation of machining stability in micro milling considering the parameter uncertainty. *Advances in Mechanical Engineering*, 7, 1687-8140.
- Chauhan, S., Trehan, R., & Singh, R. P. (2022). State of the art in finite element approaches for milling process: a review. *Advances in Manufacturing*, 11(4), 708–751.

- Chen, N., Li, H. N., Wu, J., Li, Z., Li, L., Liu, G., & He, N. (2021). Advances in micro milling: From tool fabrication to process outcomes. *International Journal of Machine Tools and Manufacture*, 160, 103670.
- Chen, Y., Wang, T., & Zhang, G. (2020). Research on Parameter Optimization of Micro-Milling Al7075 Based on Edge-Size-Effect. *Micromachines*, 11(2), 197. <https://doi.org/10.3390/mi11020197>
- Chen, Z., Wu, X., Zeng, K., Shen, J., Jiang, F., Liu, Z., & Luo, W. (2021). Investigation on the Exit Burr Formation in Micro Milling. *Micromachines*, 12(8), 952.
- Christiand, C., Kiswanto, G., Baskoro, A. S., Hasymi, Z., & Ko, T. J. (2024). Tool Wear Monitoring In Micro-Milling Based on Digital Twin Technology with an Extended Kalman Filter. *Journal of Manufacturing and Materials Processing*, 8(3), 108.
- Dadgari, A., Huo, D., & Swailes, D. (2018). Investigation on tool wear and tool life prediction in micro-milling of Ti-6Al-4V. *Nanotechnology and Precision Engineering*, 1(4), 218–225.
- Deepanraj, B., Senthilkumar, N., Hariharan, G., Tamizharasan, T., & Bezabih, T. T. (2022). Numerical Modelling, Simulation, and Analysis of the End-Milling Process Using DEFORM-3D with Experimental Validation. *Advances in Materials Science and Engineering*, 2022, 1-11
- Du, H., Wu, C., Li, D., Yip, W. S., Wang, Z., & To, S. (2023). Feasibility study on ultraprecision micro-milling of the additively manufactured NiTi alloy for generating microstructure arrays. *Journal of Materials Research and Technology*, 25, 55-67.
- Duan, X., Su, F., Gao, S., Zhu, K., Deng, B., & Zhang, Y. (2024). Relationship between energy efficiency and surface morphologies in micro-milling of SLM Inconel 718. *Journal of Materials Research and Technology*, 31, 1473–1482.
- Ercetin, A., Aslantaş, K., Özgün, Z., Perçin, M., & Chandrashekarappa, M. P. G. (2023). Optimization of Machining Parameters to Minimize Cutting Forces and Surface Roughness in Micro-Milling of Mg13Sn Alloy. *Micromachines*, 14(8), 1590.
- Giardini, C., Ceretti, E., Pola, A., Attanasio, A., & Gelfi, M. (2013). Influence of material microstructures in micromilling of Ti6Al4V alloy. *Materials*, 6(9), 4268-4283.
- Hsieh, W.-C., Chang, F.-R., Yang, C.-H., Lin, Y.-S., Wang, C.-Y., & Huang, K.-S. (2012). An Aluminium Microfluidic Chip Fabrication Using a Convenient Micromilling Process for Fluorescent Poly(DL-lactide-co-glycolide) Microparticle Generation. *Sensors*, 12(2), 1455-1467.
- Khamar, S., Kiran, M.B., Kumar, A. (2024). Advances in Micro-milling: A Critical Review. In: Dikshit, M.K., Khanna, N., Soni, A., Markopoulos, A.P. (eds)

- Khan, M. A., Jaffery, S. H. I., Khan, M. A., Faraz, M. I., & Mufti, S. (2023). Multi-objective optimization of micro-milling titanium alloy Ti-3Al-2.5V (Grade 9) using Taguchi-Grey Relation Integrated Approach. *Metals*, 13(8), 1373.
- Koklu, U., & Basmaci, G. (2017). Evaluation of Tool Path Strategy and Cooling Condition Effects on the Cutting Force and Surface Quality in Micromilling Operations. *Metals*, 7(10), 426.
- Kuram, E., & Ozcelik, B. (2014). Micro-milling performance of AISI 304 stainless steel using Taguchi method and fuzzy logic modelling. *Journal of Intelligent Manufacturing*, 27(4), 817–830.
- Lashkaripour, A., Silva, R., & Densmore, D. (2018). Desktop micromilled microfluidics. *Microfluidics and Nanofluidics*, 22(3).
- Liang, X., Wang, C., Zhang, C., & Cheung, C. F. (2022). Physical-metallurgical properties and micro-milling machinability evaluation of high entropy alloy FeCoNiCrAlx. *Journal of Materials Research and Technology*, 21, 3285–3300.
- Liu, T., Liu, Y., & Zhang, K. (2022). An improved cutting force model in micro-milling considering the comprehensive effect of tool runout, size effect, and tool wear. *The International Journal of Advanced Manufacturing Technology*, 120(1–2), 659–668.
- Liu, T., Wang, Q., & Wang, W. (2022). Micro-milling tool wear monitoring via nonlinear cutting force model. *Micromachines*, 13(6), 943.
- Mamedov, A. (2021). Micro milling process modeling: a review. *Manufacturing Review*, 8, 3.
- Manso, C. S., Thom, S., Uhlmann, E., De Assis, C. L. F., & Del Conte, E. G. (2019). Tool wear modelling using micro tool diameter reduction for micro-end-milling of tool steel H13. *The International Journal of Advanced Manufacturing Technology*, 105(5–6), 2531–2542.
- Manwar, A., Varghese, A., Bagri, S., & Joshi, S. S. (2023). Online tool condition monitoring in micromilling using LSTM. *Journal of Intelligent Manufacturing*.
- Meylan, B., Masserey, A., Boillat, E., Calderon, I., & Wasmer, K. (2022). Thermal Modelling and Experimental Validation in the Perspective of Tool Steel Laser Polishing. *Applied Sciences*, 12(17), 8409.
- Moges, T. M., Desai, K. A., & Rao, P. V. M. (2018). Modeling of cutting force, tool deflection, and surface error in micro-milling operation. *The International Journal of Advanced Manufacturing Technology*, 98(9–12), 2865–2881.

- Muhammad, A., Gupta, M. K., Mikołajczyk, T., Pimenov, D. Y., & Giasin, K. (2021). Effect of Tool Coating and Cutting Parameters on Surface Roughness and Burr Formation during Micromilling of Inconel 718. *Metals*, 11(1), 167.
- O'Toole, L., & Fang, F. Z. (2022). Optimal tool design in micro-milling of difficult-to-machine materials. *Advances in Manufacturing*, 11(2), 222–247.
- O'Toole, L., Kang, C. W., & Fang, F. Z. (2020). Precision micro-milling process: state of the art. *Advances in Manufacturing*, 9(2), 173–205.
- Platt, T., Meijer, A., & Biermann, D. (2020). Conduction-Based Thermally Assisted Micromilling Process for Cutting Difficult-to-Machine Materials. *Journal of Manufacturing and Materials Processing*, 4(2), 34.
- Platt, T., Meijer, A., Merhofe, T., & Biermann, D. (2021). Simulation-Based and Experimental Investigation of Micro End Mills with Wiper Geometry. *Micromachines*, 12(5), 496.
- Pratap, T., Patra, K., & Dyakonov, A. (2015). Modeling Cutting Force in Micro-Milling of Ti-6Al-4V Titanium Alloy. *Procedia Engineering*, 129, 134–139.
- Ren, Y., Jia, B., Wan, M., & Tian, H. (2024). Stability of Micro-Milling Tool Considering Tool Breakage. *Journal of Manufacturing and Materials Processing*, 8(3), 122.
- Sahoo, A. K., & Mishra, P. C. (2014). A response surface methodology and desirability approach for predictive modeling and optimization of cutting temperature in machining hardened steel. *International Journal of Industrial Engineering Computations*, 5(3), 407–416.
- Sharma, M. K., Alkhazaleh, H. A., Askar, S., Haroon, N. H., Almufti, S. M., & Nasar, M. R. A. (2024). FEM-supported machine learning for residual stress and cutting force analysis in micro end milling of aluminum alloys. *International Journal of Mechanics and Materials in Design*, 20(5), 1077–1098.
- Sheheryar, M., Khan, M. A., Jaffery, S. H. I., Alruqi, M., Khan, R., Bashir, M. N., & Petru, J. (2022). Multi-objective optimization of process parameters during micro-milling of nickel-based alloy Inconel 718 using Taguchi-Grey Relation Integrated Approach. *Materials*, 15(23), 8296.
- Shirzadi, A. A., Zhang, C., Mughal, M. Z., & Xia, P. (2022). Challenges and Latest Developments in Diffusion Bonding of High-Magnesium Aluminium Alloy (Al-5056/Al-5A06) to Stainless Steels. *Metals*, 12(7), 1193.
- Siregar, I., Saedon, J. B., & Adenan, M. S. (2018). Design and optimization of micromilling cutting tools. *MATEC Web of Conferences*, 220, 04003.
- Sun, Q., Cheng, X., Liu, Y., Yang, X., & Li, Y. (2017). Modeling and Simulation for Micromilling Mechanisms. *Procedia Engineering*, 174, 760–766.

- Sun, Q., Zhou, J., & Li, P. (2022). Simulations and Experiments on the Micro-Milling Process of a Thin-Walled Structure of Al6061-T6. *Materials*, 15(10), 3568.
- Tian, L., Han, X. Z., Gao, F., & Han, C. (2019). Review of micro-milling technology. *Journal of Mechanical Strength*, 41, 618-624.
- Tian, N., Zhang, G., Yan, P., Li, P., Feng, Z., & Wang, X. (2024). Simulation and Experimental Study on the Effect of Superheat on Solidification Microstructure Evolution of Billet in Continuous Casting. *Materials*, 17(3), 682.
- Ucun, İ., Aslantas, K., & Bedir, F. (2016). Finite element modeling of micro-milling: Numerical simulation and experimental validation. *Machining Science and Technology*, 20(1), 148–172.
- Ucun, İ., Aslantas, K., Özkaya, E., & Cicek, A. (2017). 3D numerical modelling of micro-milling process of Ti6Al4V alloy and experimental validation. *Advances in Materials and Processing Technologies*, 3(3), 250–260.
- Wang, H., Bai, Q., Zhang, J., Chen, S., Xu, X., & Wang, T. (2024). Tool wear monitoring strategy during micro-milling of TC4 alloy based on a fusion model of recursive feature elimination-bayesian optimization-extreme gradient boosting. *Journal of Materials Research and Technology*, 31, 398-411.
- Wang, P., Bai, Q., Cheng, K., Zhao, L., & Ding, H. (2022). Optimization of the process parameters for micro-milling thin-walled micro-parts using advanced algorithms. *The International Journal of Advanced Manufacturing Technology*, 121(9–10), 6255–6269.
- Wang, P., Bai, Q., Cheng, K., Zhao, L., Ding, H., & Zhang, Y. (2023). Machinability analysis of micro-milling thin-walled Ti-6Al-4V micro parts under dry, lubrication, and chatter mitigation conditions. *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture*, 238(1–2), 335–346.
- Wang, X., Li, W., & Chen, T. (2015). Simulation and Experimental Validation of the Hot Embossing Process of Poly(lactic-co-glycolic acid) Microstructures. *International Journal of Polymer Science*, 2015, 1–9.
- Wang, Y., Zou, B., & Huang, C. (2019). Tool wear mechanisms and micro-channels quality in micro-machining of Ti-6Al-4V alloy using the Ti(C7N3)-based cermet micro-mills. *Tribology International*, 134, 60–76.
- Wang, Z., & Sun, Y. (2024). Influence of micro-milling machining parameters on residual stresses in alumina bioceramics-a three-dimensional finite element simulation study. *PLoS ONE*, 19(11), e0313588.
- Wojciechowski, S., Matuszak, M., Powalka, B., Madajewski, M., Maruda, R., & Królczyk, G. (2019). Prediction of cutting forces during micro end milling

considering chip thickness accumulation. *International Journal of Machine Tools and Manufacture*, 147, 103466.

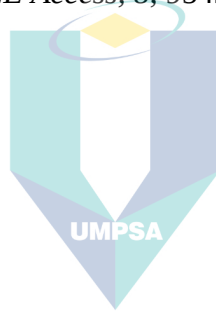
Wu, N. X., Zhu, N. X., Wu, N. G., & Ding, N. W. (2013). Data mining with big data. *IEEE Transactions on Knowledge and Data Engineering*, 26(1), 97–107.

Xia, Y., Shu, X., Zhang, Q., Pater, Z., Li, Z., Xu, H., Ma, Z., & Xu, C. (2023). Modified Arrhenius Constitutive Model and Simulation Verification of 2A12-T4 Aluminium Alloy During Hot Compression. *Journal of Materials Research and Technology*, 26, 1325-1340.

Zhang, Y., Yuan, Z., Fang, B., Gao, L., Chen, Z., & Su, G. (2023). Study on the Mechanism of Burr Formation by Simulation and Experiment in Ultrasonic Vibration-Assisted Micromilling. *Micromachines*, 14(3), 625.

Zheng, T., Song, Q., Du, Y., & Liu, Z. (2022). Development of tool wear standards and wear mechanism for micro milling Ti-6Al-4V alloy. *Metals*, 12(5), 726.

Zhou, Y., & Sun, W. (2020). "Tool Wear Condition Monitoring in Milling Process Based on Current Sensors." *IEEE Access*, 8, 95491-95502.



اونيفرسيتي مليسيا قهغ السلطان عبدالله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH