MACHINING PERFORMANCE ANALYSIS DURING ROUGHING MACHINING STRATEGY OF POCKETING PROFILES USING TiSiN COATED END MILL- AEROSPACE PART

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FACULTY OF INDUSTRIAL AND MANUFACTURING TECHNOLOGY AND ENGINEERING

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DECLARATION

I declare that this thesis entitled is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : Thaneswaran

Name : Thaneswaran Balu

Date : 10/1/2024

APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Manufacturing Engineering Technology (Process & Technology) with Honours.

Signature	:	
Supervisor Name	:	Ts. Hassan Bin Attan
Date	:	10/1/2024

DEDICATION

To all the engineers who strive to improve our world through innovation and problem solving, this thesis is dedicated to you.

Engineering is a field that demands relentless curiosity, creativity, and perseverance. It requires individuals who are passionate about making a difference in society by developing solutions to complex challenges. This thesis embodies these ideals and aims to contribute towards achieving more efficient and cost-effective manufacturing processes using robotics technology.I would like to acknowledge the countless hours spent researching, designing, testing, and refining engineering solutions that have made significant impacts across various industries worldwide. Your work inspires me daily as I aspire to follow in your footsteps.This dedication serves as a tribute to all engineers who devote their lives towards improving human life quality through innovative design thinking. May we continue striving for excellence together while contributing positively towards our collective future.

ABSTRACT

The aerospace industry's relentless pursuit of advanced materials and manufacturing processes to optimize component production efficiency has led to the prominence of Aluminum 6061, recognized for its lightweight and high-strength attributes. In this context, the role of cutting tools and coatings in machining processes becomes crucial. Titanium Silicon Nitride (TiSiN) coatings have demonstrated significant potential in enhancing tool durability and performance during the machining of aluminum alloys.Despite acknowledging the benefits of TiSiN-coated end mills, a nuanced exploration into the intricate interplay between machining parameters, tool wear, and surface roughness in the context of Aluminum 6061 is imperative. This research aims to fill this critical gap by delving into the optimization of machining parameters, with a focus on roughing strategies for pocketing profiles, using TiSiN-coated end mills. The problem statement highlights the challenges faced in machining Aluminum 6061, emphasizing the need for precise optimization. The lack of a comprehensive investigation into the interaction between machining parameters and TiSiN coatings inhibits the realization of their full potential, hindering the development of a systematic methodology for maximizing tool life and achieving superior surface finishes. The research objectives are structured to address the identified challenges. The investigation aims to understand the effect of machining parameters, specifically cutting speed and feed per tooth, on machining results, surface finish, and tool wear during roughing of pocketing profiles for aerospace parts. Additionally, the research seeks to determine the most optimum machining parameters for TiSiN-coated end mills in the roughing operation of pocketing features. The scope of the research involves milling Aluminum 6061 T651 using a 10mm 4-flute TiSiN-coated end mill, utilizing a DMG MORI DMU 60 Evo CNC machine programmed with CATIA V5. The focus is on open pocket profiles, examining the influence of cutting speed and feed per tooth, and emphasizing the achievement of optimal surface roughness while monitoring tool wear on the end mill face.This research endeavors to contribute valuable insights that not only advance the understanding of machining dynamics but also provide practical guidelines for enhancing the performance and economic viability of aerospace manufacturing processes, thereby addressing the industry's evolving machining requirements.

ABSTRAK

Usaha berterusan industri aeroangkasa terhadap bahan termaju dan proses pembuatan untuk mengoptimumkan kecekapan pengeluaran komponen telah membawa kepada keunggulan Aluminium 6061, yang diiktiraf kerana sifatnya yang ringan dan berkekuatan tinggi. Dalam konteks ini, peranan alat pemotong dan salutan dalam proses pemesinan menjadi penting. Salutan Titanium Silicon Nitride (TiSiN) telah menunjukkan potensi yang ketara dalam meningkatkan ketahanan dan prestasi alat semasa pemesinan aloi aluminium. Walaupun mengakui kebaikan kilang akhir bersalut TiSiN, penerokaan bernuansa ke dalam interaksi rumit antara parameter pemesinan, kehausan alat dan kekasaran permukaan dalam konteks Aluminium 6061 adalah penting. Penyelidikan ini bertujuan untuk mengisi jurang kritikal ini dengan mendalami pengoptimuman parameter pemesinan, dengan tumpuan pada strategi kasar untuk profil poket, menggunakan kilang akhir bersalut TiSiN. Pernyataan masalah menyerlahkan cabaran yang dihadapi dalam pemesinan Aluminium 6061, menekankan keperluan untuk pengoptimuman yang tepat. Kekurangan penyiasatan menyeluruh terhadap interaksi antara parameter pemesinan dan salutan TiSiN menghalang realisasi potensi penuhnya, menghalang pembangunan metodologi sistematik untuk memaksimumkan hayat alat dan mencapai kemasan permukaan yang unggul. Objektif kajian disusun untuk menangani cabaran yang dikenal pasti. Penyiasatan bertujuan untuk memahami kesan parameter pemesinan, khususnya kelajuan pemotongan dan suapan setiap gigi, pada hasil pemesinan, kemasan permukaan, dan haus alatan semasa mengasarkan profil poket untuk bahagian aeroangkasa. Selain itu, penyelidikan ini bertujuan untuk menentukan parameter pemesinan yang paling optimum untuk kilang akhir bersalut TiSiN dalam operasi kasar bagi ciri poket. Skop penyelidikan melibatkan pengilangan Aluminium 6061 T651 menggunakan kilang akhir bersalut TiSiN 10mm 4 seruling, menggunakan mesin CNC DMG MORI DMU 60 Evo yang diprogramkan dengan CATIA V5. Tumpuan adalah pada profil poket terbuka, mengkaji pengaruh kelajuan pemotongan dan suapan setiap gigi, dan menekankan pencapaian kekasaran permukaan yang optimum semasa memantau haus alat pada muka pengisar akhir. Penyelidikan ini berusaha untuk menyumbangkan pandangan berharga yang bukan sahaja memajukan pemahaman dinamik pemesinan tetapi juga menyediakan garis panduan praktikal untuk meningkatkan prestasi dan daya maju ekonomi proses pembuatan aeroangkasa, dengan itu menangani keperluan pemesinan industri yang berkembang.

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I extend my sincere thanks to the staff members at Universiti Teknikal Malaysia Melaka for their support and resources that facilitated the research process. Their collaborative efforts have enriched the academic environment and contributed to the quality of this thesis.

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This thesis stands as a testament to the collective efforts and support from these individuals, and I am truly blessed to have had such an exceptional team surrounding me.

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LIST OF SYMBOLS AND ABBREVIATIONS

Vc	-	Cutting Speed
Vf	-	Feed rate
Fz	-	Feed per tooth
N	-	Spindle Speed
DoE	-	Design of Experiment
CAD	-	Computer Aided Design
CAM	-	Computer Aided Manufacturing
CNC	-	Computer Numerical Control
ADOC	-	Axial Depth of Cut
RDOC	-	Radial Depth of Cut
Al	-	Aluminum
Ra	-	Arithmetic average roughness
Rz	-	Vertical distance between max and min height of the profile
Rq	-	Root means square roughness
RPM	-	Revolutions per minute
ANOVA	-	Analysis of Variance
RSM	-	Response surface methodology
mm	-	Millimeters
min	-	Minutes
sec	-	Seconds
D	-	Diameter
ft	-	Feet
TL	-	Total length
CL	-	Cutting length
Zc	-	Number of effective teeth
IGES	-	Initial Graphics Exchange Specification

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CHAPTER 1

INTRODUCTION

1.1 Background

In the aerospace industry, the pursuit of advanced materials and manufacturing processes is paramount to achieving optimal performance and efficiency in component production. Aluminum 6061, renowned for its lightweight characteristics and high strength, has emerged as a key material in aerospace applications. The demand for precision in machining this alloy has underscored the significance of selecting appropriate cutting tools and refining machining parameters.

In tandem with material advancements, the application of specialized coatings on cutting tools has become integral to optimizing machining performance. Titanium Silicon Nitride (TiSiN) coatings, in particular, have exhibited remarkable potential in enhancing tool durability and performance during the machining of aluminum alloys. TiSiN's unique properties, including increased hardness, oxidation resistance, and low friction, position it as a promising solution for overcoming challenges associated with machining aluminum alloys.

However, while the benefits of TiSiN-coated end mills are acknowledged, a nuanced exploration into the intricate interplay between machining parameters, tool wear, and surface roughness—specifically in the context of Aluminum 6061—is imperative. This exploration is essential for maximizing the advantages offered by TiSiN coatings and advancing the efficiency and precision of aerospace component manufacturing.

Against this backdrop, this research aims to delve into the optimization of machining parameters for Aluminum 6061 using TiSiN-coated end mills, with a particular focus on roughing strategies for pocketing profiles. By addressing this research gap, we aim to contribute valuable insights that not only advance the understanding of the machining dynamics involved but also provide practical guidelines for enhancing the performance and economic viability of aerospace manufacturing processes.

1.2 Problem Statement

The The machining of Aluminum 6061, a pivotal material in aerospace component manufacturing, is confronted with challenges that necessitate precise optimization for enhanced efficiency and cost-effectiveness. While Titanium Silicon Nitride (TiSiN) coatings on end mills have shown promise in augmenting tool performance during aluminum alloy machining, a critical gap exists in our understanding of their application specifically in the context of Aluminum 6061.

The current lack of a comprehensive investigation into the interaction between machining parameters, tool wear, and surface roughness during roughing strategies for pocketing profiles in Aluminum 6061 inhibits the realization of the full potential of TiSiN-coated end mills. This knowledge gap impedes the development of a systematic methodology for maximizing tool life and achieving superior surface finishes in the machining of Aluminum 6061.

Consequently, the aerospace manufacturing sector faces a challenge in optimizing the machining process for Aluminum 6061, hindering efforts to enhance productivity and reduce production costs. Addressing this problem is not only essential for the efficient utilization of TiSiN-coated end mills but also crucial for advancing the overall precision and economic viability of aluminum alloy machining in aerospace applications. This research endeavors to bridge this critical gap and provide practical solutions for the aerospace industry's evolving machining requirements.

1.3 Research Objective

Building upon the identified challenges in the machining of Aluminum 6061 with TiSiN-coated end mills, this research aims to address these issues through a set of focused objectives:

a) To investigate the effect of machining parameters namely cutting speed and feed per tooth with respect to the machining results, surface finish and tool wear during roughing of pocketing profiles for a sample of aerospace part.

b) To determine the most optimum machining parameters (cutting speed and feed per tooth) for TiSiN-Coated endmill in roughing operation of pocketing features for a sample of aerospace part.

1.4 Scope of Research

The scope of this research are as follows:

- Investigating the milling process of Aluminum 6061 T651 using a 10mm 4-flute TiSiN-coated endmill.
- Utilizing a DMG MORI DMU 60 Evo CNC machine and programming with CATIA V5.
- Examining the influence of cutting speed and feed per tooth on open pocket profiles.
- Focusing on achieving optimal surface roughness (Ra & Rz) and monitoring tool wear on the endmill face.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The literature review is a crucial part of this research, examining existing knowledge on aerospace machining techniques. Its main goal is to establish a foundation for the study, delving into the history, advancements, and challenges in aerospace machining. By reviewing literature, the research aims to understand precision machining, tool coatings, and machining materials like Aluminium 6061, focusing on aspects such as dimensional accuracy and tool wear. This review helps identify gaps in knowledge, recognize trends, and refine experimental designs. In essence, the literature review is the intellectual backbone, informing and justifying the research while setting the stage for impactful contributions to aerospace machining.

2.2 Aerospace Machining Techniques

2.2.1 Overview of Aerospace Machining

Aerospace Aerospace machining has undergone significant evolution, transitioning from traditional methods to advanced techniques, driven by the imperative for precision, efficiency, and adaptability to complex aerospace materials. The historical development of machining techniques within the aerospace industry reveals a progression from conventional methods to the integration of cutting-edge technologies, such as CNC machining, hybrid assisted machining, and predictive maintenance.

Traditionally, aerospace manufacturing relied on processes like turning, milling, and drilling for shaping metallic components. The pursuit of higher precision and efficiency led to the adoption of Computer Numerical Control (CNC) machining, revolutionizing the industry by enabling automated control of machining tools, resulting in improved accuracy and repeatability (Zhou & Pan, 2022).

The evolution of machining techniques within the aerospace industry extends to the integration of advanced technologies to enhance the machinability of aerospace materials. For example, the implementation of hybrid simultaneous laser- and ultrasonic-assisted machining has shown promise in improving the machinability of aerospace alloys such as Ti-6Al-4V (Dominguez-Caballero et al., 2023). These advanced techniques leverage the synergistic effects of multiple energy sources to enhance material removal rates, surface integrity, and tool life, addressing challenges posed by the high strength and heat-resistant nature of aerospace materials.

Furthermore, the aerospace industry has embraced data-driven approaches and machine learning for predictive maintenance in machining processes. This shift towards predictive maintenance aims to optimize machine tool performance, minimize downtime, and enhance overall productivity (Jimenez-Cortadi et al., 2019). By leveraging data fusion and machine learning, aerospace manufacturers can anticipate and prevent potential machining issues, ensuring the reliability and efficiency of the manufacturing processes.

Moreover, the development of CNC grinding machines tailored for specific aerospace applications, such as the 3+2-axis grinding of profile rotary milling cutters, demonstrates the industry's commitment to advancing machining technologies to meet the stringent requirements of aerospace manufacturing (Milutinović et al., 2022). These specialized machines enable the precise and efficient production of complex tooling components critical for aerospace applications.

Aerospace machining techniques have also evolved to address challenges posed by composite materials used in aerospace applications. Research on the machining of hybrid metal-polymer composites and the comparative analysis of machining technologies for carbon fiber-reinforced polymers (CFRPs) reflects the industry's efforts to develop specialized processes for working with composite materials (Trzepieciński et al., 2021; Pereszlai & Geier, 2020).

In conclusion, the historical development of machining techniques within the aerospace industry reflects a transition from traditional methods to the integration of advanced technologies such as CNC machining, hybrid assisted machining, predictive maintenance, and specialized grinding machines. These advancements have been driven by the industry's need for precision, efficiency, and the ability to work with complex aerospace materials, ultimately contributing to the production of high-quality components for aerospace applications.

2.2.2 Importance of Precision Machining in Aerospace

Precision machining is a cornerstone in the aerospace industry, where the imperative for high-quality and intricate components is paramount. The aerospace sector places stringent requirements on dimensional accuracy, surface finish, and material integrity, making precision machining integral to manufacturing processes. The evolution of machining techniques, transitioning from traditional methods to advanced technologies, has been motivated by the aerospace industry's unwavering need for precision and reliability in the production of aerospace components.

The adoption of Computer Numerical Control (CNC) machining stands out as pivotal in meeting the precision demands of aerospace manufacturing. CNC machining facilitates the automated control of machining tools, ensuring consistent and accurate production of complex aerospace components. This transition has significantly enhanced the industry's capacity to achieve tight tolerances and intricate geometries, both critical for aerospace applications.

Moreover, the integration of advanced technologies, such as laser- and ultrasonic-assisted machining, has further elevated the precision and surface integrity of aerospace components. These techniques leverage multiple energy sources to enhance material removal rates, surface finish, and tool life, effectively addressing challenges posed by the high-strength and heat-resistant nature of aerospace materials (Dominguez-Caballero et al., 2023).

The importance of precision machining in aerospace is exemplified by the industry's focus on digital twin modeling methods for machining aerospace components. Digital twin technology enables the creation of virtual replicas of physical components, facilitating real-time monitoring, analysis, and optimization of machining processes. This approach ensures high precision and accuracy in aerospace manufacturing, meeting the industry's exacting standards (Liu et al., 2021).

Additionally, the aerospace industry's emphasis on precision control design for components, such as spiral bevel gears, underscores the criticality of precision in achieving minimal transmission error and robust performance. The reverse-adjustment algorithm of tooth surface precision control design reflects the industry's commitment to ensuring precise and reliable operation of aerospace systems (Chen et al., 2022).

The importance of precision machining in aerospace is further underscored by the industry's focus on predictive maintenance and process optimization. By leveraging data-driven approaches and machine learning, aerospace manufacturers can anticipate and prevent potential machining issues, ensuring the reliability and efficiency of manufacturing processes.

In conclusion, precision machining holds paramount importance in the aerospace industry, where the demand for high precision and intricate components is critical. The industry's commitment to achieving the highest levels of precision and reliability, as reflected in the adoption of advanced technologies and meticulous quality control measures, ensures the production of aerospace components that meet the most exacting standards.

2.2.3 Challenges Specific to Aerospace Machining

Aerospace machining presents unique challenges due to the stringent requirements for precision, material characteristics, and the complexity of aerospace components. The machining of aerospace materials such as titanium alloys, additively manufactured alloys, and composite materials poses specific challenges that demand innovative solutions and advanced machining techniques.

One of the primary challenges in aerospace machining is the machinability of titanium alloys. Titanium alloys, known for their high strength-to-weight ratio and corrosion resistance, present difficulties due to their limited ductility and high chemical reactivity. Conventional machining methods struggle with titanium alloys, leading to tool wear, high process forces, and elevated process temperatures Williams & Boyer (2020) Frame et al., 2019). The brittleness of TiAl-based intermetallic compounds further complicates the machining process, requiring specialized approaches to overcome these challenges (Liu et al., 2020).

Additively manufactured titanium alloys, such as Ti-6Al-4V, introduce additional complexities in machining. The challenges in machining additively manufactured titanium alloys are not comprehensively documented in the literature, necessitating a focused effort to address the specific issues associated with these materials (Zhang et al., 2023). The microstructure and dynamic compressive properties of selective laser melted Ti–6Al–4V alloy also pose challenges, requiring rapid response manufacturing methods to mitigate costs and ensure high-quality aerospace components (Liu et al., 2021).

Composite materials, widely used in aerospace applications for their high strength-to-weight ratio, present machining challenges due to the differences in the chemical and physical properties of the reinforcement particles and the matrix. Conventional machining of metal matrix composites is particularly challenging due to the hardness of the ceramic reinforcement particles and the soft-metal matrix, necessitating specialized machining techniques to achieve the required precision and surface finish (Marimuthu et al., 2019).

Furthermore, the machining of nickel-based superalloys, such as Inconel alloys, used in aerospace components, presents challenges due to their high strength, heat resistance, and work hardening characteristics. Improving the machinability of aerospace-grade Inconel alloys requires innovative approaches such as ultrasonically assisted hybrid machining to reduce cutting forces and improve surface roughness (Bai et al., 2018).

The use of natural fiber-reinforced composites in aerospace applications introduces challenges in machining due to insufficient interlocking between the matrix and fibers, demanding a comprehensive understanding of machining characteristics and appropriate input parameters to overcome these limitations (Mahakur et al., 2021).

In addition to material-specific challenges, the machining of aerospace components requires addressing issues related to surface integrity, thermal management, and fault tolerance. Thermal analysis of fault-tolerant electrical machines for aerospace actuators highlights the importance of specific design choices and control strategies to ensure safe operation, even in faulty conditions (Madonna et al., 2018). Moreover, achieving precise dimensional tolerance and surface finish in aerospace components requires addressing the influence of tool quality, crater volume in wire electrical discharge machining, and the influence of machining atmosphere on surface integrity (Prasanthan et al., 2022; Wang et al., 2020; Ma et al., 2022).

In conclusion, aerospace machining presents a myriad of challenges, from the machinability of specific materials such as titanium alloys and composites to the need for precise dimensional tolerance, thermal management, and fault tolerance in aerospace components. Addressing these challenges requires the development and application of advanced machining techniques, innovative materials, and comprehensive understanding of the specific requirements of aerospace manufacturing.

2.3 Roughing Machining Strategies

2.3.1 Types of Roughing Machining

Roughing In aerospace manufacturing, roughing machining employs strategies like high-speed machining, trochoidal milling, and adaptive roughing. High-speed machining involves faster cutting, reducing forces, heat, and tool wear (Krishnaraj et al., 2014). Trochoidal milling optimizes material removal with an efficient toolpath (Xu & Wang, 2022). Adaptive roughing dynamically adjusts parameters for consistent cutting forces and optimal material removal (Villeta et al., 2011).

These strategies address challenges related to surface integrity and roughness. High-speed machining and trochoidal milling minimize detrimental effects on material (Shokrani et al., 2016), meeting aerospace's stringent dimensional and surface requirements (Villeta et al., 2011). Material-specific considerations, like cryogenic machining for titanium alloys, highlight the impact of roughing strategies on surface quality (Rotella et al., 2013; Shokrani et al., 2016).

In conclusion, selecting roughing strategies is critical in aerospace manufacturing, directly impacting component quality, efficiency, and integrity. High-speed machining, trochoidal milling, and adaptive roughing offer unique advantages in addressing material removal challenges while meeting industry standards.

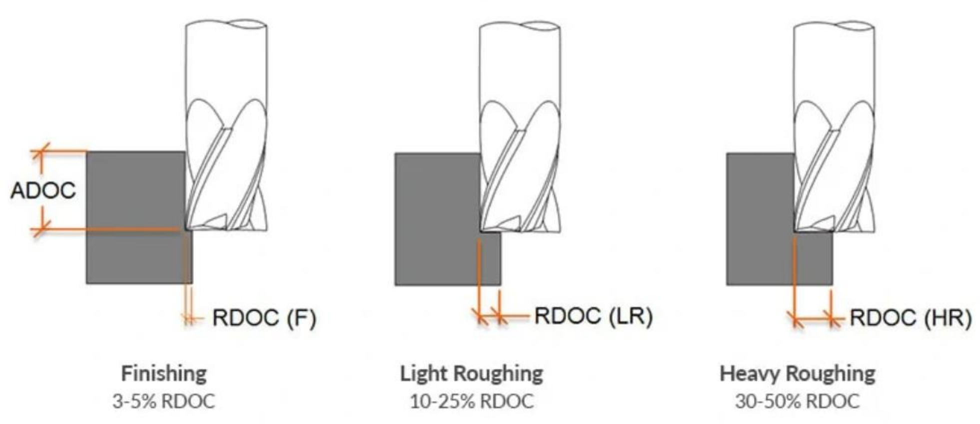


Figure 2.1 Finishing operation vs roughing operation (Harvey Performance, 2017)

2.3.2 Applications of Roughing Strategies in Aerospace

In aerospace component manufacturing, material removal is a critical process influencing performance and safety. Roughing strategies are indispensable due to the need for high precision and complex geometries, especially in materials like titanium alloys known for their strength and corrosion resistance (Gomez-Gallegos et al., 2018; Zhang et al., 2023). Challenges such as tool wear and surface roughness in machining these materials are effectively addressed through optimized roughing strategies (Ying-fei et al., 2016; Ribeiro et al., 2017).

Efficient machining processes, minimizing tool wear and surface roughness, are achieved by optimizing cutting parameters, tool paths, and selecting appropriate techniques (Imani et al., 2019; Xu et al., 2020). Advanced modeling and artificial intelligence predict milling forces and surface roughness, optimizing roughing processes (Imani et al., 2019). Novel tool path generation methods, like trochoidal tool paths, further enhance efficiency by improving material removal rates and reducing tool wear (Chang et al., 2023).

Roughing strategies address aerospace industry challenges related to machining complex surfaces and achieving high-quality finishing. By preparing workpieces for finishing operations, they ensure dimensional accuracy and surface integrity of final components (Ramos et al., 2003; Tong et al., 2015). Coupled with advanced machining techniques such as abrasive flow finishing and controlled depth abrasive water jet machining, roughing strategies contribute to achieving required surface quality (Sambharia & Mali, 2017; Özcan et al., 2021; Choopani et al., 2022). These strategies not only address challenges in achieving fine surface finishes on complex geometries but also enhance cost-effectiveness by reducing the need for extensive finishing operations.

In conclusion, roughing strategies are pivotal in aerospace manufacturing, facilitating efficient material removal, minimizing tool wear, and addressing challenges associated with complex materials and geometries. Optimization through advanced modeling and simulation methods significantly improves their efficiency and effectiveness in aerospace component manufacturing.

2.3.3 Impact on Machining Efficiency

Machining efficiency is a critical factor in aerospace manufacturing, influencing production costs, energy consumption, and tool life. Various roughing strategies significantly contribute to overall efficiency. The selection of cutting strategies, parameters, and manufacturing techniques can notably affect energy consumption, surface quality, and production costs (Rodríguez-Alabanda et al., 2018).

Metal additive manufacturing in aerospace impacts production costs by reducing material waste and lead times (Blakey-Milner et al., 2021). Regulatory frameworks influence the implementation of additive manufacturing, impacting manufacturing efficiency (Uriondo et al., 2015).

Surface roughness is crucial, affecting energy consumption and tool wear. Studies show that optimizing cutting strategies and parameters can improve surface roughness and reduce energy consumption (Rodríguez-Alabanda et al., 2018). The relationship between tool wear, surface quality, and cutting parameters is intricate (Pimenov et al., 2017). Artificial intelligence predicts required surface roughness, demonstrating the potential of advanced technologies to optimize processes (Pimenov et al., 2017).

Energy consumption is critical, and predictions and minimization of surface roughness in milling operations lead to reduced energy usage (Eyvazian et al., 2021). Consideration of factors beyond cutting parameters, such as spindle vibration, is crucial for optimizing machining efficiency (Zhang & To, 2016). Cryogenic cooling conditions substantially reduce tool wear, contributing to improved efficiency (Sivalingam, 2023).

In conclusion, roughing strategies intricately impact aerospace manufacturing efficiency, influencing tool life, energy consumption, and production costs. The integration of advanced technologies and considerations like surface roughness and energy consumption is vital for optimizing efficiency and enhancing productivity in aerospace manufacturing.

2.4 Pocketing Strategies in Machining

2.4.1 Overview of Pocketing Machining

Pocketing machining, a fundamental process in manufacturing, involves the removal of material to create internal features like pockets or cavities. In aerospace machining, the demand for intricate internal features necessitates specialized techniques. Different from other methods, pocketing employs specific tool paths and cutting parameters for efficient material removal (Aggarwal & Xirouchakis, 2012).

Pocket milling finds extensive use in aerospace for components like dies, molds, and aerospace parts (Aggarwal & Xirouchakis, 2012). High-performance milling techniques are explored for thin-walled elements, emphasizing the role of pocketing in creating intricate features (Zawada-Michałowska, 2022). Studies on increased milling forces due to tool wear stress the importance of precise tool path generation and machining strategies in pocketing operations (Oliaei, 2015).

Research focuses on developing advanced tool path generation methods for pocket machining. Curvilinear tool path generation with implicit moving boundaries enhances efficiency and accuracy (Xiong et al., 2011). The use of curvilinear tool-path methods demonstrates the intricacies involved in pocketing strategies, morphing smooth paths to conform to pocket boundaries (Bieterman & Sandstrom, 2003).

Optimization problems related to zigzag pocket machining complexity highlight the challenges in tool path generation (Arkin et al., 2000). The development of a double spiral tool-path generation and linking method addresses challenges associated with machining intricate pocket geometries (Zhou et al., 2016).

In summary, pocketing is pivotal for creating internal features in aerospace components. Optimal cutting conditions, advanced tool path generation, and considerations for tool wear on machining forces are crucial. The widespread application of pocket milling in the aerospace industry underscores its significance in producing complex and precise internal features.

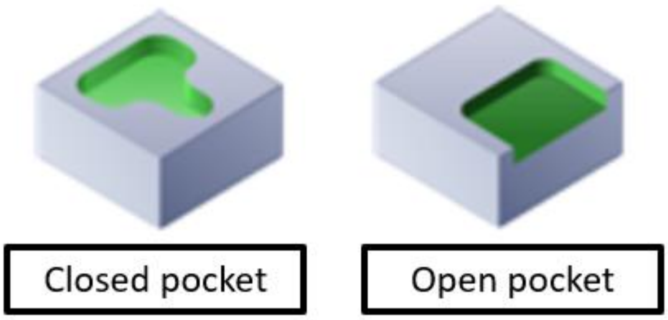


Figure 2.2 Closed Pocket vs Open Pocket

2.4.2 Types of Pocketing Strategies

Pocketing strategies in machining vary to meet specific requirements. Traditional methods involve material removal with conventional tool paths and cutting parameters. Abdulrazaq et al. (2019) optimizes parameters like material removal rate (MRR) and surface roughness in traditional pocket milling.

On the other hand, high-efficiency strategies, exemplified by trochoidal milling, aim at increased productivity and precision. Chang et al. (2023) propose a double-NURBS approach to optimize tool paths, enhancing engagement angles, efficiency, and reducing tool wear—particularly beneficial in aerospace applications requiring high precision.

These strategies address aerospace challenges differently. Traditional methods offer reliability, while high-efficiency strategies like trochoidal milling provide advanced precision and productivity. In aerospace, where intricate internal features are common, the choice of pocketing strategy is crucial for achieving desired precision, efficiency, and surface quality.

In conclusion, diverse pocketing strategies, including traditional and high-efficiency approaches like trochoidal milling, offer tailored solutions for aerospace applications. Ongoing research underscores their significance in meeting evolving demands in aerospace component manufacturing.

2.4.3 Influence of Pocketing Strategies on Machining Performance

Pocketing strategies significantly influence machining performance, impacting material removal rates, tool engagement, wear, and surface finish. Research by Vladescu et al. (2016) highlights how pocketing reduces wear and friction through various mechanisms, including an increase in oil film thickness (Vladescu et al., 2017). Observations by Oliaei (2015) emphasize the role of pocketing in extending machining time without interruption.

The effects of cutter path strategies on surface roughness have been explored, providing insights into surface finish (Göloğlu & Sakarya, 2008). Studies by Ghayoor et al. (2019) demonstrate the impact of pocketing on homogenized stiffness and failure initiation in composites. Gao et al. (2022) reveal how pocket shape influences wear characteristics in self-lubricating bearing cages.

Abdo et al. (2020) underscore the practical relevance of studying pocketing strategies, emphasizing pocket milling as a widely used operation. Investigations by Dahiwal et al. (2020) reveal the substantial impact of pocket wear on cage wear in solid-lubricated rolling bearings. Zavos & Nikolakopoulos (2018) present experimental results indicating reduced friction and oil consumption with pocketed rings.

Research efforts focus on validating cutting force simulations and optimizing machining operations through pocketing strategies (Chang et al., 2023). Multi-response optimization methods, as applied by Abdo et al. (2020), highlight trade-offs in minimizing machining time and maximizing material removal rate. Comparative studies by Ozoegwu & Ezugwu (2015) provide insights into the efficiency of different pocketing approaches.

In conclusion, understanding the multifaceted influence of pocketing strategies on machining performance is essential for optimizing operations and enhancing overall efficiency.

2.4.4 Advances and Innovations in Pocketing Techniques

Recent innovations in pocketing techniques have profoundly impacted aerospace machining. Multi-objective optimization, as demonstrated by Slama et al. (2022), addresses energy savings and machining costs simultaneously. This approach is crucial for aerospace machining, prioritizing precision and efficiency.

Another notable innovation is the optimization of toolpaths with circular cycle transitions for sharp corners in pocket milling (Wu et al., 2016). This advancement ensures efficient machining of complex geometries common in aerospace components, contributing to improved manufacturing quality and efficiency.

Significant time minimization in pocketing, particularly through zigzag passes along the stability limit, has been developed by Ozoegwu & Ezugwu (2015). This is especially relevant in aerospace machining, where minimizing machining time enhances productivity and meets demanding industry requirements.

The study by Zheng et al. (2023) on distortion in thin-wall aluminum parts due to initial residual stress and toolpath strategy represents a cutting-edge advancement. This research addresses the specific challenges of aerospace machining, ensuring dimensional accuracy and integrity in machined aerospace components with thin-wall structures.

In conclusion, recent advances in pocketing techniques, including multi-objective optimization, toolpath optimization, and addressing residual stress-induced distortion, significantly contribute to the precision, efficiency, and overall quality of machined aerospace components.

2.5 TiSIN Coated End Mills in Machining

2.5.1 Introduction to Coated End Mills

Coated end mills play a pivotal role in modern machining, where applying coatings on cutting tools has become standard practice to boost performance and longevity. The primary goals of these coatings are to improve tool life, enhance wear resistance, and reduce friction during cutting processes (Sousa & Silva, 2020), especially in demanding applications like aerospace component manufacturing.

Coated end mills, often produced using methods like physical vapor deposition (PVD) (Twardowska et al., 2022), are prevalent in the machining industry. Titanium nitride (TiN) coatings, for example, are applied to carbide inserts for end milling operations, improving the feasibility of machining challenging materials (Shah et al., 2022). Explorations into multilayer diamond coatings in micro-end milling highlight their potential in enhancing the performance of coated end mills for machining cemented carbides (Silva et al., 2021).

Research focuses on optimizing coating characteristics, such as enhancing multi-scale self-organization processes during machining through bi-nano-multilayer coating optimization (Fox-Rabinovitch et al., 2022). The application of nickel cubic boron nitride coatings via electroless nickel co-deposition demonstrates the diverse materials and methods being explored for coated end mill cutting tools (Norsilawati et al., 2022).

Experimental investigations assess the performance of coated end mills. Studies on ductile mode micro-milling of ZrO2 ceramics with diamond-coated end mills and comparative studies on wear and tool life emphasize the advantages of coatings like TiN in enhancing tool performance (Bao et al., 2018; Yawara & Intanon, 2019).

Efficiency in end milling of titanium alloys significantly increases with the use of tools featuring composite nano-structured coatings (Vereschaka et al., 2018). Micro-mechanical characterization and wear performance studies on coatings like TiAlN/NbN PVD coatings provide valuable data on wear behavior during end milling of austenitic stainless steel (Varghese et al., 2018).

In conclusion, coatings on end mills are critical for modern machining, enhancing tool performance, extending tool life, and improving efficiency. The ongoing efforts to optimize coated end mills for various machining operations, including those involving challenging materials, demonstrate the industry's commitment to continuous improvement.

2.5.2 TiSIN Coating Properties

TiSiN (titanium silicon nitride) coating has gained prominence in machining for its distinctive properties, contributing to improved tool performance, exceptional wear resistance, high-temperature stability, and suitability for aerospace materials (Akhter et al., 2021). Exceptional wear resistance is a notable feature, enhancing tool durability during challenging machining, particularly with aerospace alloys (Aamir et al., 2021).

Research on TiSiN nanocomposite coatings has explored wear and friction behaviors, highlighting the impact of substrate bias on scratch, wear, and indentation responses (Šulhánek et al., 2023). Studies on AlTiSiN/TiSiN nanocomposite coatings emphasize understanding high-temperature oxidation behavior, crucial in aerospace applications (Bočáková et al., 2022). The influence of multilayer architecture on WNx/TiSiN coatings indicates potential for tailoring properties to specific machining requirements (Sert et al., 2022).

TiSiN coatings demonstrate superior oxidation resistance, making them suitable for high-temperature aerospace applications (Luo et al., 2022). Tribological properties evaluated in ambient air and vacuum environments confirm high wear resistance, particularly in ambient air conditions (Colombo-Pulgarín et al., 2021). The impact abrasive wear property of CrAlN/TiSiN multilayer coatings at elevated temperatures has been studied, providing insights into performance under challenging conditions (Belguith et al., 2019).

Mechanical and chemical characterization on LPBF processed IN718 substrates highlights the importance of wear-resistant coatings in abrasive environments (Grzesik & Małecka, 2021). Studies on meso-scale milling of Inconel 718 alloy emphasize the need for coatings with high-temperature stability and wear resistance like TiSiN (Zahid et al., 2022).

Experimental investigations into tool wear and its effect on TiSiN-coated ball-end mill geometry in high-speed milling provide insights into wear behavior and performance, contributing to understanding mechanical properties and durability in machining applications (Özkan et al., 2023). Studies on the oxidation behavior and notch wear formation of TiAlN-coated tools offer insights into oxidation resistance under various environmental conditions (Aamir et al., 2021).

In conclusion, TiSiN coating's wear resistance, high-temperature stability, and suitability for aerospace materials make it valuable in modern machining, especially in the aerospace industry. Extensive research has provided valuable insights into TiSiN's unique properties and its potential for enhancing tool performance in demanding machining environments.

2.5.3 Wear Resistance

Wear resistance is pivotal in aerospace machining, influencing tool life, change frequency, and downtime. TiSiN (titanium silicon nitride) coating stands out for its remarkable wear resistance, making it ideal for demanding aerospace applications.

Studies on the impact abrasive wear property of CrAlN/TiSiN multilayer coating reveal outstanding wear resistance due to the formation of amorphous Si_3N_4 at elevated temperatures (Luo et al., 2022). Tribological assessments of in-situ PVD TiAlN, TiSiN, and TiAlN/TiSiN coatings show TiSiN's highest wear resistance in ambient air conditions (Sert et al., 2022).

In micro-milling applications, TiSiN coating protects substrates from plastic deformation, reducing wear and extending tool life (Bhoi et al., 2022). Investigations into TiSiN nanocomposite coatings, considering substrate bias, provide insights into wear resistance under different processing conditions (Akhter et al., 2021).

Evaluation of TiSiN coating in high-temperature dry sliding wear behavior demonstrates its potential for enhancing wear resistance in cutting tools (Altas et al., 2019). Mechanical and chemical characterization of TiN and AlTiSiN coatings on LPBF processed IN718 substrate provides valuable insights into wear-resistant properties, especially in abrasive environments (Colombo-Pulgarín et al., 2021).

The exceptional wear resistance of TiSiN coating is crucial in aerospace machining, ensuring prolonged tool life, reduced changes, and minimized downtime. Its valuable attributes make it an asset in aerospace component manufacturing, where precision and durability are paramount for structural integrity and reliability.

In conclusion, TiSiN coating's wear resistance significantly improves tool performance in aerospace machining, offering prolonged tool life and reduced downtime. Research and characterization underscore its unique properties and potential for enhancing wear resistance in demanding machining environments, particularly in the aerospace industry.

2.5.4 Heat Resistance

TiSiN (titanium silicon nitride) coating is pivotal in high-speed machining, where elevated temperatures pose challenges to cutting edge integrity. Extensive research demonstrates the exceptional heat resistance of TiSiN, contributing to enhanced tool performance and durability in demanding machining environments.

Studies on the impact abrasive wear property of CrAlN/TiSiN multilayer coating highlight outstanding heat resistance due to the formation of amorphous Si3N4, allowing TiSiN to withstand abrasive forces at elevated temperatures (Luo et al., 2022). Tribological evaluations of in-situ PVD TiAlN, TiSiN, and TiAlN/TiSiN coatings confirm TiSiN's highest wear resistance in ambient air conditions, emphasizing its ability to maintain integrity at elevated temperatures (Sert et al., 2022).

Research on TiSiN/TaVN nanomultilayers showcases super-hardness, crucial for cutting edge integrity during high-speed operations (Yan et al., 2023). The multilayer structure of TiSiN coating, with a nano-composite outer layer containing Si3N4 nanocrystals, contributes to exceptional heat resistance, particularly suitable for high-temperature machining applications (Kantoríková & Moravec, 2022).

TiSiN coating's ability to maintain integrity at elevated temperatures is crucial for high-speed cutting, impacting tool performance and durability. Its exceptional heat resistance contributes to prolonged tool life, reduced changes, and minimized downtime, especially in aerospace component manufacturing where high-speed cutting generates substantial heat.

In conclusion, TiSiN coating's heat resistance is vital for maintaining cutting edge integrity in high-speed machining, enhancing tool performance and durability. Research and characterization highlight its unique properties and potential for enhancing heat resistance in demanding machining environments, particularly in the aerospace industry.

2.5.5 Suitability for Aerospace Materials

TiSiN-coated end mills play a crucial role in addressing the challenges posed by high-strength alloys and composites commonly found in aerospace components. Their exceptional heat resistance is a key advantage in high-speed cutting operations, ensuring the maintenance of cutting edge integrity during machining. Research highlights the desirability of TiSiN coatings for efficient machining under high service conditions (Özkan et al., 2023).

The wear resistance of TiSiN coatings is particularly advantageous when machining aerospace materials with hardness and abrasiveness. This property contributes to prolonged tool life and reduced tool changes, essential for handling challenging materials. TiSiN coatings have been noted for their ability to withstand abrasive forces, enhancing overall tool performance (Giasin et al., 2020).

Demonstrated compatibility of TiSiN-coated end mills with aerospace materials is evident in various studies. Investigations on alloys like Al2024 emphasize the importance of coating materials in achieving stringent geometric tolerances required in aerospace components (Aamir et al., 2021). Tribological property evaluations under various conditions further confirm the suitability of TiSiN coatings for aerospace material machining (Sert et al., 2022).

Beyond performance benefits, the use of TiSiN-coated end mills aligns with sustainable manufacturing practices. These coatings contribute to improved tool performance, reducing the need for frequent tool changes and minimizing material waste. This alignment supports the aerospace industry's focus on sustainability goals (Özbek et al., 2022).

In conclusion, TiSiN-coated end mills demonstrate exceptional heat and wear resistance, making them well-suited for machining aerospace materials. Their use contributes to improved tool performance, extended tool life, and enhanced machining efficiency, addressing specific requirements in aerospace material machining and supporting sustainable manufacturing practices.

2.6 Machining of Aluminium 6061

2.6.1 Properties of Aluminium 6061

Aluminium 6061 stands out as a versatile and extensively employed material in aerospace manufacturing, owing to its exceptional physical and mechanical attributes. The alloy's high strength-to-weight ratio, coupled with excellent corrosion resistance and ease of machining, positions it as a favored choice for various aerospace components, fostering its broad adoption in the industry.

The high strength-to-weight ratio of Aluminium 6061 is a pivotal advantage in aerospace applications, where lightweight materials are crucial for enhancing fuel efficiency and overall performance. This characteristic enables the alloy to provide structural strength while minimizing overall weight, making it an ideal selection for critical components like airframes. This capability allows aerospace manufacturers to attain the necessary structural integrity while optimizing fuel efficiency, aligning with Wang et al. (2018).

Moreover, the outstanding corrosion resistance of Aluminium 6061 is of paramount importance in aerospace applications, where components face exposure to harsh environmental conditions such as moisture, salt, and corrosive agents. The alloy's ability to withstand corrosion ensures the durability and reliability of aerospace components, contributing significantly to the safety and performance of aircraft and spacecraft (Xu et al., 2020).

The ease of machining is another notable advantage of Aluminium 6061 in aerospace manufacturing. Its high machinability facilitates efficient and precise manufacturing processes, enabling the production of intricate aerospace components with tight tolerances and superior surface finishes. This property contributes to cost-effective and streamlined production, meeting the stringent requirements of the aerospace industry (Wang et al., 2023).

In addition to its physical and mechanical attributes, Aluminium 6061 exhibits excellent thermal conductivity, making it well-suited for applications where heat dissipation is critical. This property is particularly advantageous in aerospace components subjected to thermal stress and varying temperature conditions, enhancing the overall reliability and performance of aerospace systems (Sivaprakasam et al., 2022).

The exceptional properties of Aluminium 6061 have led to its widespread use in diverse aerospace applications, encompassing structural components, aircraft fittings, and spacecraft parts. The alloy's combination of high strength, lightweight characteristics, corrosion resistance, ease of machining, and thermal conductivity positions it as a highly suitable material for meeting the rigorous demands of the aerospace industry.

In conclusion, the physical and mechanical properties of Aluminium 6061 make it an optimal choice for aerospace manufacturing, contributing to the development of lightweight, durable, and high-performance aerospace components. These attributes not only meet but also advance the stringent requirements of the aerospace industry, playing a crucial role in the ongoing evolution of aerospace technology.

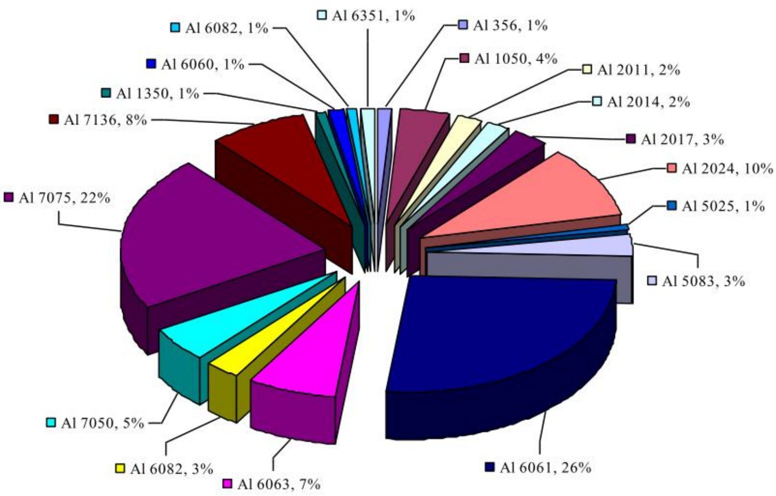


Figure 2.3 The aluminum alloys used as a percentage in the aerospace industry in the 2005-2019 period. (Titu, 2020)

2.6.2 Challenges in Machining Aluminium

Machining aluminium 6061 introduces distinctive challenges due to its material properties, including heat generation during cutting, potential chip adhesion, and considerations for tool selection and machining parameters. The incorporation of reinforcing materials, harder and stiffer than the matrix, adds complexity compared to conventional materials (Muthukrishnan & Davim, 2009). Addressing distortion in machined aluminium alloy parts poses a serious challenge, with residual stresses from processing steps being a primary cause (Maria et al., 2022). Additionally, burr removal in aluminium 6061 machining involves abrasive particle impact and liquid cavitation, with a minor role for the latter (Kumar et al., 2022).

Temperature optimization becomes crucial in aluminium 6061 machining, and the impact of parameters on temperature has been assessed through analysis of variance (Gutema et al., 2022). Reinforcement incorporation in aluminium 6061 composites enhances mechanical characteristics, aligning with the constant demand for technological advancement (Kaliappan et al., 2022). Aging effects on the machinability of 6061 aluminium alloy have been studied, revealing a significant impact of aging on alloy machinability (Demir & Gündüz, 2009).

Furthermore, the investigation into the mechanical and wear behavior of graphene-reinforced aluminium alloy 6061 metal matrix composites indicates diminishing elongation percentage with increased reinforcement in the matrix (Kumar et al., 2020). A comprehensive review of heat treatment's influence on the mechanical properties of aluminium alloys, including the 6xxx series, emphasizes key parameters affecting the alloys' mechanical properties (Chauhan, 2017).

In conclusion, machining aluminium 6061 presents multifaceted challenges, encompassing heat generation, chip adhesion, and the intricate selection of tools and machining parameters. The complexity is heightened by the inclusion of reinforcing materials, demanding a deeper understanding of processing conditions, temperature optimization, and the effects of aging and heat treatment to effectively address these challenges.

2.6.3 Cutting Speeds and Feed Rates

In the evaluation of cutting speeds and feed rates for machining Aluminium 6061, a delicate balance is crucial to efficiently remove material while preventing excessive heat buildup and tool wear. Gutema et al. (2022) identified that a cutting speed of 98.0 m/min and a feed rate of 0.26 mm/rev resulted in the minimum temperature during machining of Aluminium 6061. Nor et al. (2019) emphasized the significance of cutting speed, depth of cut, and their optimal combinations for efficient machining. Shrinivasa & Prakash (2022) highlighted the considerable impact of cutting speed on tool wear, underscoring the need for careful parameter consideration. List et al. (2005) delved into wear mechanisms during dry machining of aluminum alloys, emphasizing the importance of appropriate cutting speeds and feed rates to mitigate tool wear.

Demir & Gündüz (2009) discussed the effects of aging on the machinability of Aluminium 6061, stressing the need to consider material properties in determining optimal cutting parameters. Odedeyi et al. (2021) investigated the effects of cutting parameters on machining output variables, emphasizing the influence of cutting speed, feed rate, and depth of cut on surface roughness and acoustic emission potentials. Additionally, Premnath et al. (2014) concluded that feed rate significantly affects tool wear, further emphasizing its importance in machining operations.

Consideration of the cutting environment and tool coatings is also essential. Buranská et al. (2019) focused on the effects of the cutting environment on bore roughness and cylindricity, emphasizing the need to optimize cutting parameters for specific machining environments. Więckowski et al. (2019) discussed the resistance to abrasive wear of different coatings, highlighting the importance of selecting appropriate tool coatings to enhance tool life and machining efficiency.

In conclusion, achieving optimal cutting speeds and feed rates for machining Aluminium 6061 requires a comprehensive understanding of material properties, wear mechanisms, and the influence of cutting parameters on machining output variables. Careful consideration of these factors, along with the cutting environment and tool coatings, is essential to strike a delicate balance between efficient material removal and mitigating issues such as heat buildup and tool wear.

2.6.4 Tool Selection for Aluminium

To effectively machine Aluminium 6061, several considerations must be taken into account when selecting cutting tools and coatings. The choice of machining parameters, tool materials, and coatings significantly impacts the tool life, performance, and surface finish. The evaluation of specific cutting energy coefficients, as well as the impact of chip thickness, tool wear, and cutting environment, is crucial in determining the most effective tool selection (Balogun et al., 2014). Additionally, the development of an energy consumption map for orthogonal machining of Al 6061-T6 alloy aids in identifying the machining parameters that result in the lowest specific cutting energy consumption, leading to potential energy savings (Warsi et al., 2017). Furthermore, the optimization of temperature using response surface methodology and desirability analysis is essential in determining the ideal parameter levels and assessing the significant impact of parameters on the machining process (Gutema et al., 2022).

The selection of cutting tools and coatings plays a vital role in enhancing tool life and performance. Experimental and mathematical modeling for the prediction of tool wear on the machining of Aluminium 6061 Alloy by high-speed steel tools provides insights into the impact of various machining parameters such as spindle speed, feed rate, axial depth of cut, and radial depth of cut on tool wear (Okokpujie et al., 2017). Moreover, the performance of cryo-treated and untreated cutting tools in the machining of aerospace aluminium alloy emphasizes the importance of the optimum selection of cost-effective cutting tools and cutting parameters (Adin, 2023). Coatings such as TiSIN and hybrid Ti-MoS2 coatings have been studied for their effectiveness in enhancing tool life and machining performance (Brzezinka et al., 2017; Ramírez et al., 2022). These coatings have shown promising results in improving tool performance and surface quality.

In conclusion, the selection of cutting tools and coatings for machining Aluminium 6061 is a critical aspect that significantly influences the machining process. The evaluation of specific cutting energy coefficients, optimization of machining parameters, and the use of advanced coatings such as TiSIN and hybrid Ti-MoS2 are essential in enhancing tool life, performance, and surface finish.

2.7 Surface Finish Evaluation

2.7.1 Significance of Surface Finish

Surface finish evaluation is critical in aerospace components due to its impact on safety, efficiency, and reliability. Specific surface finishes influence the functionality and durability of components, such as those in fuel systems or airframes (Bedi & Rana, 2021). Advanced finishing techniques, like magnetic field-assisted processes, are gaining importance in aerospace, emphasizing the need for precise evaluation methods (Souza et al., 2022).

Unique surface finish requirements in aerospace applications are crucial for meeting safety and efficiency standards. Control of surface lay on cobalt-chromium alloy using magnetic abrasive finishing affects wettability, essential for aerospace components (Graziano et al., 2014). Surface integrity in aerospace materials, like Ti-6Al-4V, requires comprehensive evaluation due to combinations of additive and subtractive manufacturing processes (Bejjani et al., 2020).

The aerospace industry demands stringent standards for surface finishes to ensure reliability and safety. Titanium alloys for aerospace applications require specific surface finishes for damage tolerance, oxidation behavior, and producibility (Peters et al., 2003).

The effect of different build orientations on surface finishes in additive manufacturing processes for aerospace components is crucial for consolidation and properties (Alsalla & Liu, 2018). Post-processing of direct metal deposited AlCrCoCuFeNi HEA using centrifugal barrel finishing demonstrates advanced surface improvement methods in aerospace materials (Modikwe et al., 2022).

In conclusion, precise evaluation methods and advanced finishing techniques are crucial in achieving specific surface finishes for enhanced performance and meeting the stringent standards of the aerospace industry.

2.7.2 Impact on Aerodynamics and Fatigue Life

Achieving the desired surface finish in aerospace components is crucial for optimizing aerodynamic performance, enhancing fatigue life, and ensuring the overall aesthetics and functionality of machined parts. Surface finish directly affects the aerodynamic performance of aerospace components by influencing the flow of air over the surface, leading to changes in drag and lift forces (Haridas et al., 2017). Moreover, surface finish plays a crucial role in the fatigue life of components, especially in high-stress applications such as aerospace, where even minor surface imperfections can act as stress concentration points, accelerating fatigue crack initiation and propagation (Elangeswaran et al., 2020). Additionally, the aesthetics and functionality of machined parts are greatly influenced by surface finish, affecting the part's appearance, corrosion resistance, and wear characteristics.

The significance of surface finish in aerospace components is further underscored by the findings of Atzeni et al. (2022), who explored the effects of abrasive fluidized bed (AFB) processing on the surface morphology and fatigue behavior of additive manufactured cobalt-chrome parts. Their study highlighted the crucial role of surface finish in determining fatigue life, emphasizing the need for precise control over surface morphology to enhance the performance and longevity of aerospace components. Furthermore, the work of Elangeswaran et al. (2020) demonstrated the sensitivity of fatigue behavior to surface roughness, particularly in high-strength materials such as maraging steel, underscoring the critical role of surface finish in determining the fatigue performance of aerospace materials.

Surface finish also impacts the aerodynamic performance of aerospace components, as highlighted by Kaynak and Kitay (2018), who emphasized the importance of accurate determination of surface roughness in aerospace engineering. The control of surface roughness is essential for minimizing aerodynamic drag and optimizing the performance of aerospace structures. Moreover, the study by Haridas et al. (2017) revealed that finish machining resulted in significantly lower surface roughness of additively manufactured stainless steel, indicating the potential for improved aerodynamic performance through precise surface finishing.

In conclusion, achieving the desired surface finish in aerospace components is crucial for optimizing aerodynamic performance, enhancing fatigue life, and ensuring the overall aesthetics and functionality of machined parts. The studies reviewed underscore the multifaceted impact of surface finish on aerospace components, emphasizing the need for advanced surface finishing techniques to meet the stringent requirements of the aerospace industry.

2.7.3 Methods of Surface Finish Measurement

In aerospace machining, various instruments and techniques, such as profilometers, Mitutoyo Surf-Testers, and optical interferometry, are employed for surface finish measurement. The parameters Ra (average roughness) and Rz (maximum peak-to-valley height) are crucial in evaluating surface finish. Surface roughness significantly influences material properties and performance, particularly in aerospace applications. For instance, Britton et al. (1999) investigated the effect of surface finish on gear tooth friction, revealing its impact on frictional losses.

Additionally, the study by Woodling & Moraru (2005) highlighted the complex influence of surface properties on the effectiveness of pulsed light treatment for inactivating Listeria innocua on stainless-steel surfaces, emphasizing the broader implications of surface properties in various applications.

Profilometers, widely recognized as the most standardized method for determining surface roughness, have been extensively used for surface roughness measurement (Rapone et al., 2022). The study by Sm et al. (2013) exemplified this by evaluating the surface characteristics of dental nanocomposites using profilometry, showcasing the broad applicability of profilometers in assessing surface properties.

Furthermore, the significance of surface finish measurement extends to additive manufacturing, as emphasized by Soja et al. (2020). Their work described bulk surface finishing methods for producing end-use selective laser melting parts, emphasizing the relevance of surface finish in different manufacturing processes. Similarly, Lebea et al. (2021) underscored the challenge of evaluating surface finish in additive manufacturing, particularly for samples with complex geometries, further highlighting the importance of surface finish measurement in diverse manufacturing applications.

In conclusion, the measurement of surface finish in aerospace machining is indispensable for ensuring the quality and performance of machined components. Instruments such as profilometers, Mitutoyo Surf-Testers, and optical interferometry, along with techniques like bulk surface finishing methods, play a vital role in assessing surface roughness. The parameters Ra and Rz offer valuable insights, contributing to the comprehensive evaluation of surface finish in aerospace machining.

2.7.4 Parameters for Evaluating Surface Finish

Surface finish evaluation is integral to determining the quality and performance of machined components, with critical parameters including surface roughness, geometric tolerances, adherence to industry standards, and process optimization. Surface roughness, measured by parameters like Ra and Rz, offers insights into surface texture and irregularities. Baseren's (2004) study on dental materials highlighted variations in surface roughness among different restorative materials, emphasizing its significance in evaluating surface finish.

Geometric tolerances are equally crucial for the qualitative assessment of machined parts. Khoshanjam et al. (2022) emphasized the importance of geometric tolerances in ensuring consistency and quality during the evaluation of machining parts.

Adherence to industry standards and specifications is paramount, especially in aerospace components. Atzeni et al. (2021) compared the surface finishing of additive manufactured Ti-6Al-4V alloy with industry standards, underlining the necessity of meeting specified standards for aerospace materials. Scamans et al. (2013) indicated the industry's reliance on specific surface finish requirements, calling for additional finishing lines to meet the increasing demand for surface treatment of aluminum automotive sheets.

The role of parameters in maintaining consistency and quality throughout the production process is evident in various studies. Euzenat et al. (2020) successfully simulated surface topography for an entire manufacturing process, demonstrating the crucial role of parameters in ensuring consistent and high-quality surface finish. Additionally, Fatima et al. (2021) highlighted the optimization of process parameters in turning nuclear-grade steel alloy, emphasizing the significance of parameter control in achieving sustainable manufacturing and high-quality surface finish.

In conclusion, the evaluation of surface finish involves a comprehensive analysis of parameters such as surface roughness, geometric tolerances, industry standards, and process optimization. These parameters collectively contribute to ensuring the quality, consistency, and adherence to industry specifications in aerospace components and other manufacturing applications.

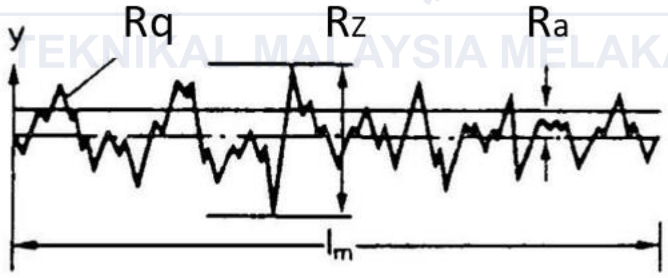


Figure 2.4 Pictorial representation of surface roughness (Stahli USA 2023)

(https://www.stahliusa.com/stahli-publication/the-technique-of-lapping/surface-finish-quality)

2.8 Tool Wear Analysis

2.8.1 Types of Tool Wear

Tool wear in aerospace machining encompasses abrasive wear, adhesive wear, flank wear, rake wear, and cutting edge breakage. Abrasive wear, resulting from mechanical interaction, is particularly critical in machining hard and abrasive aerospace materials like titanium alloys (Zhang et al., 2022; Arrazola et al., 2009). Adhesive wear involves material transfer, leading to built-up edge formation and eventual tool failure (Hao et al., 2012).

These wear types present challenges in machining, affecting surface finish, dimensional accuracy, and tool life. Abrasive wear degrades cutting tool edges, impacting machining efficiency, especially with titanium alloys and superalloys (Wu et al., 2018; Graves et al., 2020). Adhesive wear, causing built-up edge, affects workpiece surface integrity and increases cutting forces, impacting tool life and machining quality (Li et al., 2006). Flank wear, rake wear, and cutting edge breakage directly influence tool life, production costs, and productivity (Du et al., 2021).

Researchers propose various monitoring and prediction methods to address these challenges. Convolutional neural networks classify tool wear levels for control limits (Dai et al., 2021). Variational mode decomposition and ensemble learning establish nonlinear mappings for tool wear condition monitoring (Yuan et al., 2020). Continual learning-based methods enhance tool wear prediction accuracy in changing cutting conditions, improving efficiency in aerospace machining (Hua et al., 2021).

In summary, tool wear types in aerospace machining pose challenges, impacting tool life, surface finish, and production costs. Advanced monitoring and prediction methods offer solutions to enhance efficiency and reliability.

2.8.2 Factors Contributing to Tool Wear

Factors Tool wear in aerospace machining results from a complex interplay of parameters, including cutting speeds, feed rates, tool materials, and workpiece properties. Extensive literature documents the influence of these factors on tool wear.

Cutting speed significantly affects wear, with higher speeds leading to elevated temperature, increasing abrasion, diffusion, and oxidation (Debnath et al., 2016). Similarly, increased feed rates contribute to more substantial wear (Wei et al., 2020). Workpiece material properties, such as microstructure and composition, impact wear behavior (Hoier et al., 2019).

The choice of tool material is critical, influencing wear resistance. Studies emphasize the importance of wear-resistant coatings and materials capable of chemical interaction to reduce wear rates (Grigoriev et al., 2021). Cutting tool geometry, including rake angle and cutting edge angle, influences wear in high-speed milling operations (Ma et al., 2017).

Cutting fluids and lubrication mitigate wear by reducing friction and dissipating heat, extending tool life (Chinnasamy et al., 2017). Dry cutting conditions, in contrast, increase friction, leading to elevated abrasion, diffusion, and oxidation, accelerating wear (Debnath et al., 2016).

The tool-workpiece interaction, considering contact stresses, sliding velocity, and cutting temperature, significantly affects wear on interfaces (Zhang et al., 2015). Abrasive particles in workpiece materials contribute to wear (Darmawan et al., 2012).

In conclusion, factors contributing to tool wear in aerospace machining are diverse and interconnected. Cutting speeds, feed rates, tool materials, workpiece properties, and their complex interactions play pivotal roles. Understanding these dynamics is crucial for developing strategies to minimize wear and enhance efficiency in aerospace machining processes.

2.8.3 Impact on Machining Cost and Efficiency

Tool wear in machining processes substantially impacts both cost and efficiency. Frequent tool replacement increases operational costs and downtime, adversely affecting productivity and component quality (Mhalsekar et al., 2010). Tool life, a critical factor, influences costs and productivity significantly (Kayhan & Budak, 2009). Direct effects of tool wear include compromised surface finish, dimensional precision, and increased costs in the final product (Mhalsekar et al., 2010).

Furthermore, tool wear induces vibrations that negatively impact the interface between the machining tool and the workpiece, influencing machining quality (Xu et al., 2023). This connection between tool wear and component quality is evident, impacting not only tool life but also final product dimensions and surface integrity (Soori & Arezoo, 2023).

Optimizing cutting parameters becomes crucial in increasing tool life and machining efficiency, emphasizing the role of operational parameters in mitigating tool wear-related costs (Hao et al., 2012). Studies highlight that tool wear constitutes a significant portion of machining costs and influences process efficiency (Farahnakian et al., 2016). Exploration of spindle speed's impact on coated tool wear underscores the importance of operational conditions in managing tool wear and machining efficiency (Ma et al., 2016). Investigating the wear mechanism of cutting tools in milling processes indicates improved tool life and reduced machining temperature under specific conditions (Muhamad et al., 2022).

Intelligent methods for tool wear estimation and monitoring aim to ensure machining accuracy while minimizing tool replacement frequency, which can reduce production efficiency and increase costs (Rajeev et al., 2017). The development of tool condition monitoring systems in the aerospace industry seeks to provide real-time diagnostics and data sharing, optimizing tool management and enhancing manufacturing performance (Bombiński et al., 2021).

In conclusion, tool wear significantly impacts aerospace machining's overall cost and efficiency, influencing component quality, operational costs, and productivity. Therefore, strategies such as optimizing operational parameters, implementing intelligent monitoring systems, and real-time diagnostics are crucial for mitigating the impact of tool wear on machining cost and efficiency.

2.8.4 Strategies for Tool Life Improvement

Enhancing tool life in aerospace machining is vital for boosting productivity and reducing costs. Several investigated approaches include advanced coatings, cutting parameter optimization, and environmentally conscious strategies.

The architectural development of nano-multilayer PVD coatings has demonstrated a substantial increase in tool life and improved mechanical properties (Chowdhury et al., 2018). Optimizing initial cutting conditions is emphasized for enhancing tool life when machining materials like Inconel 718 (Memarianpour et al., 2021). Integrated methods, such as Taguchi, RSM, and MOPSO, for CNC machining parameters optimization stress the importance of understanding interactions between cutting parameters (Li et al., 2016).

Alternative approaches suggested for improving tool life include enhancing cutting materials, utilizing coated inserts at low cutting speeds and high feed rates, and designing tools for interrupted cutting (Yamamoto et al., 2018). A focus on improving tool life in the metal cutting industry contributes to higher productivity and better finishes (Selvam et al., 2019). Coating application has shown a significant improvement in tool behavior and performance, resulting in greater productivity and longer tool life (Forero et al., 2022).

Optimization of cutting parameters is a key focus. Multi-objective optimization in turning austenitic stainless steel decreases surface roughness and specific energy consumption while increasing material removal rate (Su et al., 2020). Optimized cutting parameters lead to increased tool life and machining efficiency (Batista et al., 2006). An optimization model for cutting path and parameters minimizes carbon emissions and cost in a NC milling process, emphasizing environmentally conscious machining strategies (Yang et al., 2022).

The use of advanced coatings, such as TiN and TiAlN, contributes to improved tool life, productivity, and product quality (Sarwar & Haider, 2011). Adaptive nano-multilayered coatings have been shown to achieve better tool life (Manoj & Gandhi, 2018).

In conclusion, improving tool life in aerospace machining involves a multifaceted approach, including advanced coatings, cutting parameter optimization, and environmentally conscious strategies. These collectively aim to enhance tool longevity, increase productivity, and improve the overall efficiency of aerospace machining processes.

2.8.5 Tool Wear Trend Analysis

In Tool wear trend analysis is a crucial aspect of machining operations, essential for maintaining efficiency, product quality, and cost-effectiveness. Different methods are employed for assessing and predicting tool wear, encompassing visual inspection, wear land measurements, and the use of condition monitoring systems.

Visual inspection is fundamental, involving direct observation of the tool's condition to identify wear signs like flank wear, crater wear, and edge deformation. Kerr et al. (2005) highlight its real-time feedback for timely interventions in tool replacement or reconditioning. Wear land measurements quantify wear land dimensions, offering valuable data for assessing wear progression and estimating tool life (Sagar et al., 2020).

Condition monitoring systems play a crucial role. Sun et al. (2020) integrate deep learning methods for in-process tool condition forecasting, enabling real-time assessment and prediction based on sensor data and machining parameters. Sun and Yeh (2018) develop an on-machine insert condition monitoring system using machine vision for automated inspection and monitoring of insert wear during machining.

Advanced technologies like artificial neural networks and machine learning algorithms contribute to tool wear trend analysis. Dong et al. (2021) utilize particle swarm optimization-back propagation neural networks and discrete wavelet transformation-genetic algorithm-back propagation neural networks for monitoring woodworking tool wear conditions based on power signals, demonstrating their potential for accurate wear condition assessment. Liao et al. (2015) propose a multi-scale hybrid hidden Markov model for tool wear condition monitoring, capturing the long-term dynamical degradation of tool wear condition.

In conclusion, the comprehensive assessment and prediction of tool wear trends are essential for optimizing machining processes and ensuring manufacturing efficiency. The integration of visual inspection, wear land measurements, advanced condition monitoring systems, and artificial intelligence and machine learning techniques allows proactive maintenance and decision-making to mitigate the impact of tool wear on machining operations.

2.9 Design of Experiment (Taguchi L4 Method)

2.9.1 Introduction to Taguchi Methods

The Taguchi method, pioneered by Genichi Taguchi, is a widely adopted statistical design of experiments (DOE) technique prevalent in engineering, manufacturing, and industrial processes. This methodology aims to optimize product and process robustness and efficiency by systematically identifying and controlling key factors influencing quality and performance. Noteworthy applications span diverse areas such as wood machining (Tiryaki et al., 2015), industrial chemical processes (Davis & John, 2018), and the design optimization of submersible permanent magnet synchronous motors (Cui et al., 2020). These applications showcase the method's versatility in addressing quality and performance improvement across domains.

Fundamental principles of the Taguchi approach involve the use of orthogonal arrays for efficient experimentation and analysis of the effects of multiple factors on a process or product. This methodology permits the evaluation of numerous factors with relatively few experiments, resulting in significant time and cost savings. Emphasizing robustness, the Taguchi method seeks to minimize performance variation due to external factors or noise by identifying optimal parameter settings less sensitive to variations, thus enhancing product or process reliability and stability (Hamzaçebi, 2021).

Moreover, the Taguchi method excels in addressing multi-objective optimization problems, exemplified in the design optimization of submersible permanent magnet synchronous motors (Cui et al., 2020). Combining design of experiments (DOE) and Taguchi approaches allows consideration of multiple performance objectives while ensuring robustness against variations and uncertainties. This capability makes the Taguchi method particularly suitable for complex engineering design problems with diverse and often conflicting objectives.

In summary, the Taguchi method provides a systematic and efficient approach to experimental design, with a focus on robustness and efficiency for improving quality and performance across various domains. Its widespread application underscores its versatility and effectiveness in optimizing product and process parameters, contributing to enhanced quality, reliability, and performance.

2.9.2 Purpose in Experimental Design

The Taguchi L4 method is specifically tailored for experimental design in aerospace machining, efficiently exploring the impact of factors like cutting speed and feed rate on machining performance. This method, a variation of the Taguchi approach, proves invaluable in optimizing the aerospace machining process.

In aerospace machining, the Taguchi L4 method allows systematic exploration of cutting speed and feed rate effects with minimal experiments, crucial for achieving precision and quality in aerospace component production (Pillai et al., 2022). Its key advantage lies in identifying the optimal combination of cutting speed and feed rate, minimizing variability, and maximizing performance characteristics like surface finish and dimensional accuracy (Pillai et al., 2022; Sandhya et al., 2020).

This method aligns with aerospace machining's complex requirements, facilitating simultaneous consideration of multiple critical performance characteristics such as precision, surface finish, and dimensional accuracy (Reddy et al., 2014). Aerospace manufacturers can effectively optimize machining parameters to meet these multi-objective requirements, enhancing overall performance and component quality.

Moreover, the Taguchi L4 method offers robustness, identifying parameter settings less sensitive to variations in cutting speed and feed rate. This is crucial for consistency and repeatability in aerospace applications, ensuring compliance with stringent quality standards and reliability of aerospace components.

In summary, the Taguchi L4 method provides a systematic and efficient approach to experimental design in aerospace machining. Its advantages, including optimal parameter combinations identification, consideration of multiple performance characteristics, and robustness, enable effective optimization of cutting speed and feed rate for achieving high precision, surface finish, and dimensional accuracy in aerospace component production.

Experiment number	Column (Factor)			Response
	1 (A)	2 (B)	3 (C)	(y_i)
1	1	1	1	y_1
2	1	2	2	y_2
3	2	1	2	y_3
4	2	2	1	y_4

Figure 2.5 Taguchi L4 Array

2.9.3 Benefits in Optimizing Machining Parameters

Achieving superior outcomes in dimensional accuracy, surface finish, and reduced tool wear hinges on optimizing machining parameters. The Taguchi L4 method has gained widespread recognition for its proficiency in identifying optimal factor combinations, showcasing substantial benefits across various studies.

Applied in diverse materials such as titanium alloy, additive-manufactured Ti6Al4V alloy, hardened AISI H13 steel, ceramics, and metal matrix composites, the Taguchi L4 method effectively pinpoints influential factors affecting responses like surface roughness, material removal rate, and tool wear (Özel et al., 2004; Jenarthanan et al., 2016; Jasper et al., 2018). Systematically varying machining parameters and analyzing their effects enable the identification of optimal parameter combinations leading to improved outcomes.

The Taguchi method extends its utility to specific objectives, such as reducing tool wear and improving surface integrity. Notably, in the machining of challenging materials like Inconel 718, prone to rapid tool wear and poor surface integrity, the Taguchi method identifies optimal parameters resulting in reduced tool wear and improved surface integrity (Zhuang et al., 2015; Ma et al., 2016; Wang et al., 2016; Hamdan et al., 2014). Similarly, in the machining of metal matrix composites, the Taguchi method optimizes parameters for enhanced metal removal rate and surface finish (Jenarthanan et al., 2016; Jasper et al., 2018).

Furthermore, the Taguchi method collaborates seamlessly with optimization techniques like genetic algorithms and response surface methodology for multi-objective optimization in machining processes. This approach successfully optimizes parameters for reduced surface roughness, improved dimensional accuracy, and minimized tool wear (Mumtaz et al., 2019; Maged et al., 2018).

Beyond parameter optimization, the Taguchi method plays a crucial role in analyzing the effects of individual input parameters on responses, offering valuable insights into factors like cutting speed, feed rate, depth of cut, and tool material influencing outcomes such as surface roughness, tool wear, and material removal rate (Jenarthanan et al., 2016; Jasper et al., 2018).

In conclusion, the Taguchi L4 method delivers significant benefits in optimizing machining parameters, leading to improved dimensional accuracy, surface finish, and reduced tool wear. Its systematic approach to parameter variation and analysis facilitates the identification of optimal parameter combinations, thereby enhancing machining performance and realizing cost savings.

2.9.4 Application of Taguchi L4 Method in Aerospace Machining

The The utilization of the Taguchi L4 method in aerospace machining serves as a valuable tool for optimizing machining parameters with specific research goals. In the context of evaluating the TiSIN Coated End Mill for roughing operations and exploring machining performance parameters, the deliberate selection of factors like cutting speed and feed rate resonates with the research objectives. The Taguchi L4 method facilitates the systematic variation of these parameters, aiming to identify the optimal combination that enhances machining performance.

The rationale behind choosing cutting speed and feed rate as key factors is substantiated by their pronounced influence on machining performance. Literature reports an increase in burr thickness with higher cutting speed in orthogonal machining (Lekkala et al., 2011), and a hybrid approach combining Taguchi has been effective in optimizing machining parameters, including feed rate (Raveendran et al., 2021). Given their critical role in aerospace machining, where achieving high-quality surface finish and minimizing tool wear is paramount, these factors align seamlessly with the research goals. Additionally, their selection directly impacts the assessment of the TiSIN Coated End Mill in roughing operations, providing valuable insights for both academia and industrial practitioners.

Moreover, the Taguchi L4 method allows for the systematic exploration of the effects of cutting speed and feed rate at different levels on multiple responses, such as surface roughness, tool wear, and material removal rate. This alignment with the research goals ensures a comprehensive evaluation of the TiSIN Coated End Mill's performance, offering insights beneficial to academia and industrial practitioners. The method's utility lies in identifying the optimal parameter combination that minimizes tool wear, enhances surface finish, and improves material removal rate—critical factors in aerospace machining applications.

Furthermore, the successful application of the Taguchi L4 method in various aerospace machining studies, as demonstrated in references (Pereira et al., 2021; Kuram & Özçelik, 2016; Ekici et al., 2015), reinforces its efficacy in achieving desired machining outcomes. These studies affirm the method's versatility in optimizing parameters for aerospace alloys, titanium alloys, and composite materials, providing additional support for its application in the specific study of evaluating the TiSIN Coated End Mill in aerospace machining.

In conclusion, the application of the Taguchi L4 method in aerospace machining, particularly in evaluating the TiSIN Coated End Mill for roughing operations and exploring machining performance parameters, offers a systematic approach to optimize cutting speed and feed rate. This method aligns seamlessly with research goals, contributing valuable knowledge to academia and industrial practitioners within the aerospace sector.

2.9.5 Selection of Factors and Levels

The selection of factors and levels in the Taguchi L4 method plays a pivotal role in achieving the objectives of the study, particularly concerning the evaluation of the TiSIN Coated End Mill during roughing operations and the examination of machining performance parameters. Emphasizing the significance of cutting speed and feed rate, this review underscores their critical impact on surface roughness, tool wear, and material removal rate across various machining processes (Muhammad et al., 2021; Sheheryar et al., 2022).

To align with the research goals effectively, the chosen factors mirror the essential parameters influencing the TiSIN Coated End Mill's performance in roughing operations. Notably, the practical variation in the levels of cutting speed and feed rate ensures the Taguchi L4 method captures real-world machining scenarios, enhancing the study's applicability for industrial practitioners (Muhammad et al., 2021; Sheheryar et al., 2022).

The systematic variation of factors and levels, facilitated by the Taguchi L4 method, proves invaluable in identifying optimal combinations leading to enhanced machining performance. This methodical approach aligns seamlessly with the research objectives of investigating machining performance parameters, providing both academia and industrial practitioners with comprehensive insights (Muhammad et al., 2021; Sheheryar et al., 2022).

The efficacy of the Taguchi L4 method in optimizing machining parameters, as demonstrated in analogous studies focused on tool wear, surface roughness, and material removal rate, further substantiates its suitability for the current investigation. This alignment underscores the rationale behind the specific selection of factors and levels, showcasing the method's established success in similar contexts (Muhammad et al., 2021; Sheheryar et al., 2022).

In conclusion, the meticulous selection of factors and levels in the Taguchi L4 method for evaluating the TiSIN Coated End Mill in roughing operations is anchored in the critical influence of cutting speed and feed rate on machining performance. These chosen parameters harmonize with the research goals and the characteristics of the aerospace machining process, presenting valuable insights for both academic and industrial practitioners in the aerospace field.

2.9.6 Analysis of Experimental Results

The analysis of experimental results obtained through the Taguchi L4 method holds paramount importance in gaining insights into the optimal combination of factors for achieving desired machining performance. The interpretation of data and insights derived from experimental results plays a crucial role in comprehending the effects of selected parameters and levels on the machining process.

In the specific study evaluating the TiSIN Coated End Mill in roughing operations and investigating machining performance parameters, the analysis involves interpreting multiple responses, including material removal rate, surface roughness, and tool wear. Employing statistical techniques such as analysis of variance (ANOVA) and signal-to-noise (S/N) ratio, the data is systematically analyzed to identify the most influential factors and their optimal levels (Jung & Kwon, 2010; Chen et al., 2009; Sundaram et al., 2007).

Insights drawn from experimental results facilitate the determination of the optimal combination of factors for achieving desired machining performance. For instance, in studies on electrodischarge machining parameters for ZrO2 ceramic and ultrasonic-assisted micro EDM, the Taguchi method revealed significant effects of specific parameters, leading to the identification of optimal combinations for improved machining performance (Chen et al., 2009; Sundaram et al., 2007).

The Taguchi L4 method's systematic approach allows for identifying the most influential factors and their levels, guiding the selection of optimal parameter combinations. This proves particularly valuable in the context of evaluating the TiSIN Coated End Mill, aligning with the research goals (Banh et al., 2017; Shivaprasad & Das, 2021).

Furthermore, the Taguchi L4 method's success in various machining studies, focusing on tool wear, surface roughness, and material removal rate, demonstrates its effectiveness in providing insights into optimal combinations for desired machining performance (Aslani et al., 2020; Kam & Demirtaş, 2021). The consistent identification of optimal parameter combinations through the Taguchi method contributes valuable knowledge for both academia and industrial practitioners.

In conclusion, the analysis of experimental results through the Taguchi L4 method is pivotal for interpreting data and extracting insights into the optimal combination of factors, thereby guiding improvements in machining performance and contributing to the machining field's knowledge base.

2.10 Summary

The literature review offers a comprehensive overview of aerospace machining techniques, focusing on precision machining, tool coatings, and machining materials such as Aluminium 6061. The main goals of the literature review are to establish a foundation for the study, identify gaps in knowledge, recognize trends, and refine experimental designs in aerospace machining. It serves as the intellectual backbone, informing and justifying the research while setting the stage for impactful contributions to aerospace machining.

The review discusses the evolution of aerospace machining from traditional methods to advanced techniques, driven by the imperative for precision, efficiency, and adaptability to complex aerospace materials. It highlights the historical development of machining techniques within the aerospace industry, revealing a progression from conventional methods to the integration of cutting-edge technologies, such as CNC machining, hybrid assisted machining, and predictive maintenance.

Key advancements in aerospace machining, as discussed in the literature review, include the use of advanced coatings such as TiN and TiAlN, which contribute to improved tool life, productivity, and product quality. Additionally, adaptive nano-multilayered coatings have been shown to achieve better tool life. The review emphasizes the multifaceted approach to improving tool life in aerospace machining, including advanced coatings, cutting parameter optimization, and environmentally conscious strategies to enhance tool longevity, increase productivity, and improve overall efficiency.

Furthermore, the literature review addresses the critical role of surface finish in aerospace machining, emphasizing its impact on fatigue behavior, aerodynamic performance, and overall functionality of machined parts. It discusses the methods of surface finish measurement in aerospace machining, including the use of various instruments and techniques such as profilometers, Mitutoyo Surf-Testers, and optical interferometry.

The review also delves into the importance of tool wear trend analysis in maintaining efficiency, product quality, and cost-effectiveness in machining operations. It discusses different methods employed for assessing and predicting tool wear, encompassing visual inspection, wear land measurements, and the use of condition monitoring systems. Advanced technologies like artificial neural networks and machine learning algorithms are highlighted for their contribution to tool wear trend analysis, enabling proactive maintenance and decision-making to mitigate the impact of tool wear on machining operations.

Moreover, the literature review introduces the Taguchi method as a widely adopted statistical design of experiments (DOE) technique prevalent in engineering, manufacturing, and industrial processes. It emphasizes the method's systematic approach to optimizing product and process robustness and efficiency by identifying and controlling key factors influencing quality and performance.

In conclusion, the literature review provides valuable insights into the multifaceted aspects of aerospace machining, including advancements in tool coatings, surface finish, tool wear trend analysis, and the application of the Taguchi method in optimizing machining processes. It serves as a comprehensive resource for researchers, practitioners, and enthusiasts seeking to enhance their understanding of precision machining in the aerospace industry.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the focus shifts to the methodology employed in the investigation titled 'Machining Performance Analysis During Roughing Machining Strategy Of Pocketing Profiles Using Tisin Coated End Mill- Aerospace Part.' A systematic approach was adopted, involving distinct stages to ensure precision and effectiveness in the analysis. The initial phase employed the Taguchi method, specifically the Design of Experiments (DOE), to determine critical machining parameters, including cutting speed and feed rate. Subsequently, a CAD model representative of an aerospace part featuring pocketing profiles was selected. The following stages encompassed the creation of a machining program in Catia V5 and the execution of the machining process itself. This chapter details the structured methodology employed to achieve the project's objective: the precise machining of the Aero-Structural Component using predetermined parameters. Each stage is intricately connected, ensuring a comprehensive and systematic exploration of the machining performance analysis in the context of roughing machining strategy for pocketing profiles, utilizing a TiSIN coated end mill in the aerospace sector.

3.2 Process Flowchart

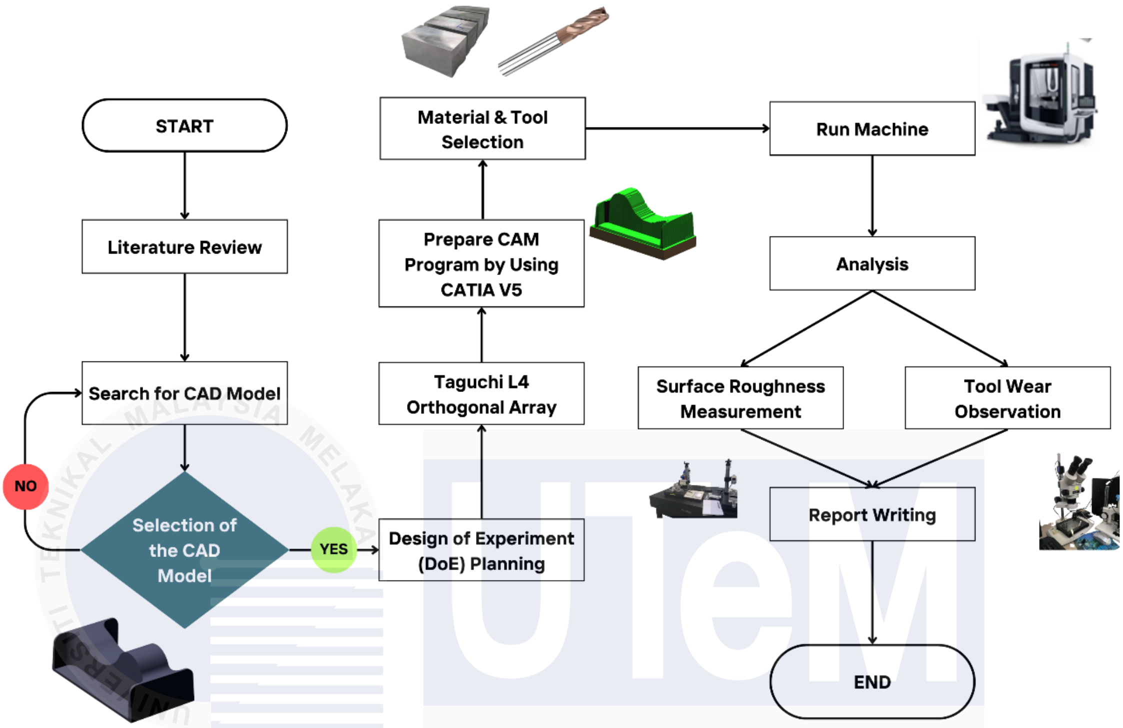


Figure 3.1 Process Flowchart

3.3 CAD Model Selection

In the process of exploring aerospace parts CAD models for the experiment, the search was conducted on GrabCAD websites, revealing numerous aerospace components. However, the primary focus of this research is on parts exhibiting pocketing profiles, both closed and open pockets, to analyze surface roughness in these specific features. Among the various aerospace parts identified, discussions with the supervisor led to the selection of the GE Engine Bracket, depicted in Figure 3.2.

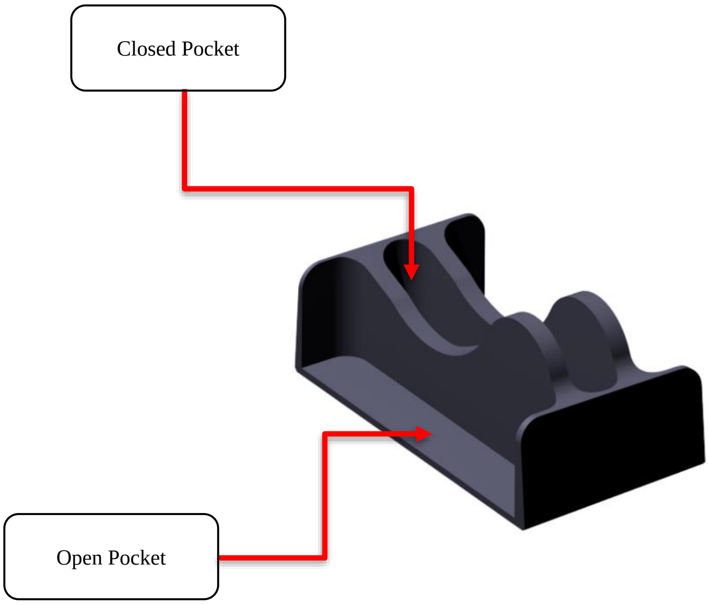


Figure 3.2 GE Engine Bracket

Upon conducting a phase analysis of the CAD model, it became evident that its dimensions exceeded the initially expected size. To address this misalignment with practical considerations, such as the raw stock material dimensions, a decision was made to scale down the CAD model. Consequently, the dimensions of the CAD model were adjusted to 0.6 using SolidWorks 2023 software for improved size compatibility. Furthermore, in the trial machining phase, the closed pocket process posed challenges as the endmill struggled to effectively dispose of chips, resulting in extensive damage to the endmill. Consequently, the decision was made to forego closed pockets and concentrate solely on open pockets for the machining process.

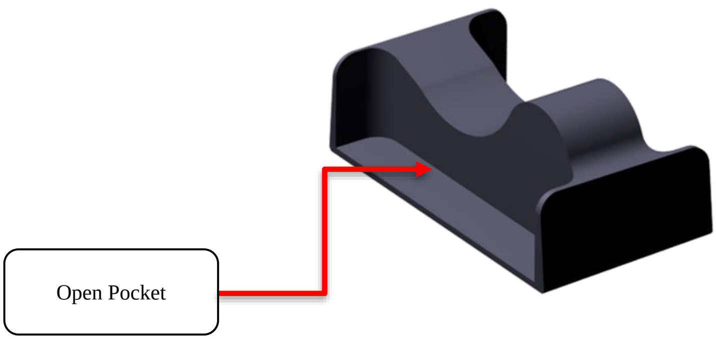


Figure 3.3 Modified GE Bracket

3.4 CAM Program Preparation

This experiment presented a valuable opportunity to enhance proficiency in utilizing CATIA V5 software. To successfully execute this experiment, the preparation of the CAM program using CATIA V5 software is imperative. However, the focal point of this CAM program preparation lies specifically in roughing. Emphasizing the importance of machining parameters is crucial to attaining the primary objective of this experiment. The subsequent section will meticulously detail the step-by-step process of CAM program preparation, focusing on roughing operations.

3.4.1 Stock Preparation

Preparing the stock stands as a crucial step before commencing the CAM program. To initiate the stock creation, the first step involves sketching on the face of the part, as illustrated in Figure 3.4. Following the completion of the sketch, the subsequent action entails padding the sketch, leading to the extrusion and formation of the stock, as depicted in Figure 3.5.

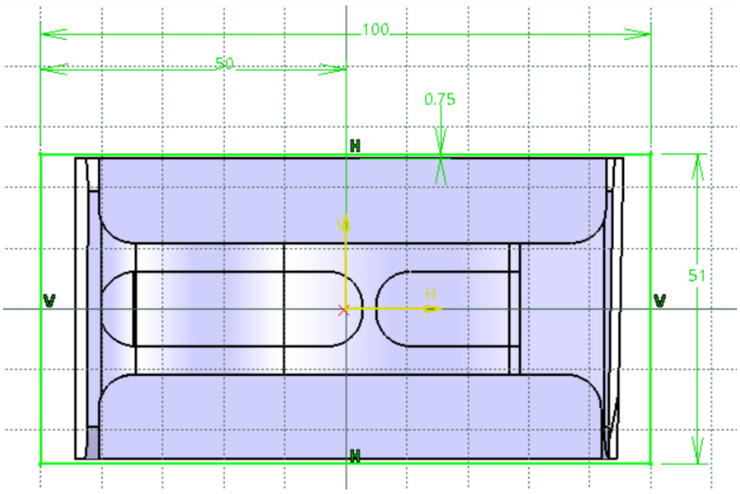


Figure 3.4 Sketch on Face of The Part

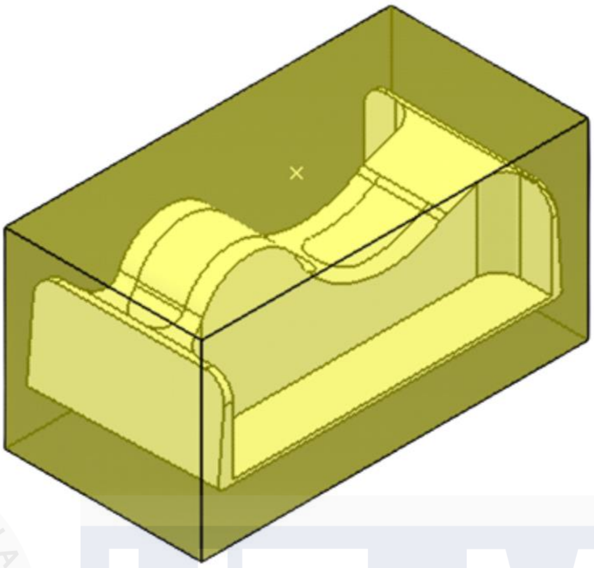


Figure 3.5 Stock in CATIA V5 Software

Before progressing to the subsequent stage, it is imperative for the stock to possess an axis system, as illustrated in Figure 3.6. This axis system comprises an origin point and three orthogonal axes, providing a foundational reference for subsequent operations.

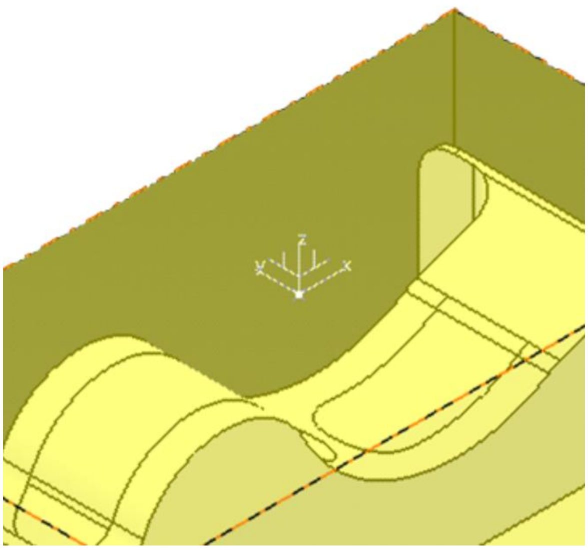


Figure 3.6 Axis System on Stock

3.4.2 Plane System Creation

The plane system holds significant importance as a prerequisite for advancing into more sophisticated machining processes. These planes serve as essential reference points or supports when generating various components. Within the plane system, two pivotal reference planes are identified: the safety plane and the approach plane, as illustrated in Figure 3.7. The safety plane denotes the cutting tool's safety position, ensuring secure operations, while the approach plane signifies the cutting tool's designated approach position, contributing to precise machining procedures.

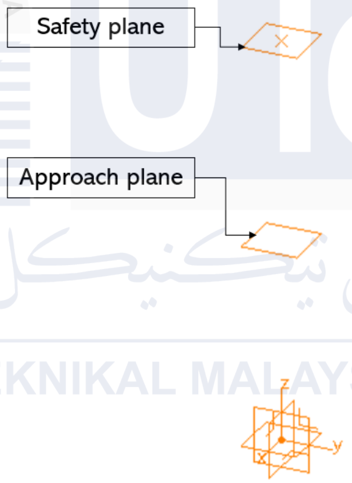


Figure 3.7 Plane System with Axis System

3.4.3 Assembly Process

Once the plane system and stock creation on the parts are completed, the subsequent step involves assembling the plane system and stock. The assembly procedure for combining the plane system and stock will be illustrated based on Figure 3.8. This step is crucial in establishing the spatial relationship between the reference planes and the machined stock, providing a foundation for the subsequent stages in the CAM program.

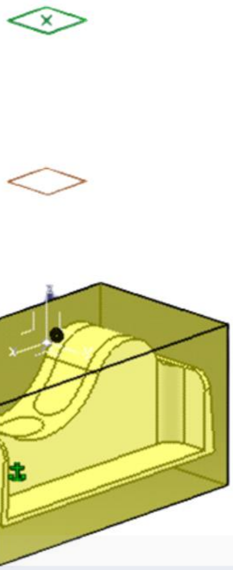


Figure 3.8 Assembly of Plane System & Stock

3.4.4 Advanced Machining Process

The advanced machining process represents a crucial phase in programming the CAM program, encompassing various steps such as part operation setup, cutting tool selection, and the configuration of machining strategies. The initial step in this comprehensive process involves the setup of the part operation, as illustrated in Figure 3.9. This setup encompasses the selection of the machine to be employed, defining the reference machining axis system, and specifying both part and stock selections, thereby facilitating the program's understanding of the programmer's requirements.

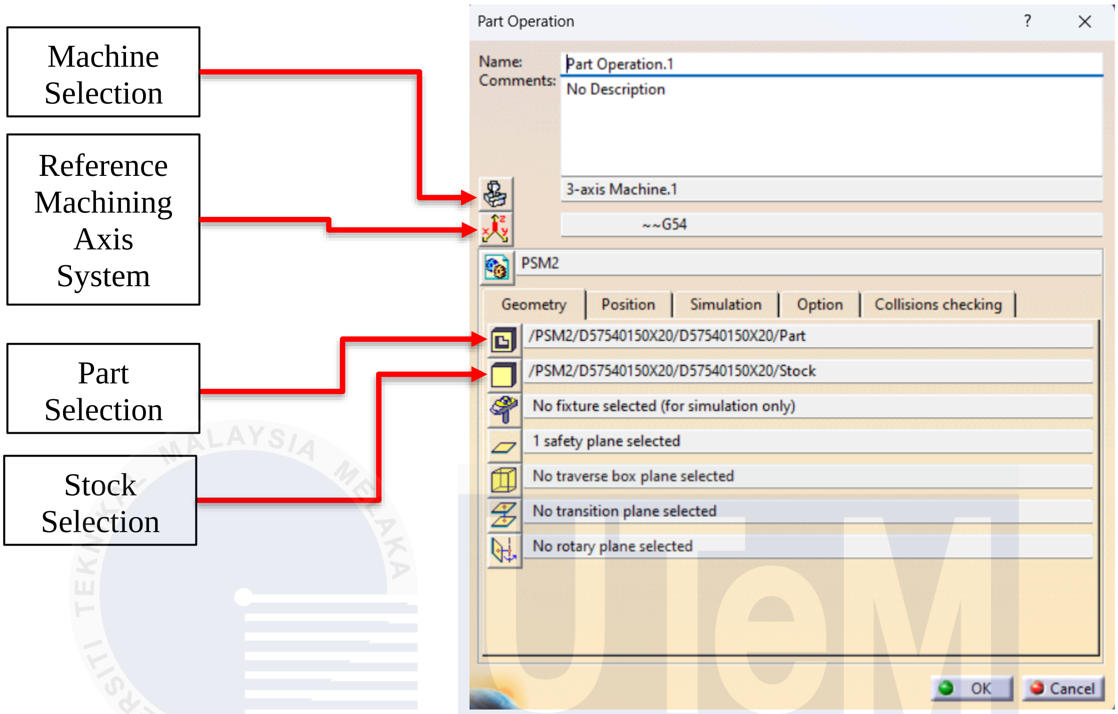


Figure 3.9 Part Operation Setup

Subsequently, the next step entails the selection of a cutting tool from the resources list, detailed in Figure 3.10. This list provides information on the machine and cutting tool utilized, in this case, the 3-axis Machine and End mill D10, respectively.

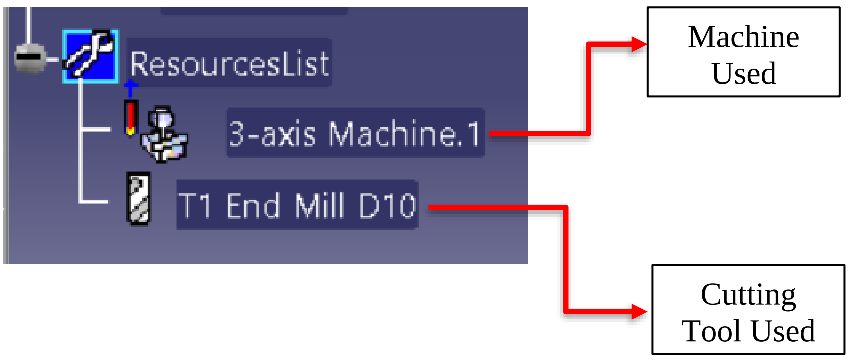


Figure 3.10 Resources List

Following the cutting tool selection, the process proceeds to roughing, where the roughing strategy parameters are distributed across five tabs. The roughing operation in CATIA V5 is visually represented in Figure 3.11. By default, all five tabs are displayed with their respective parameters, as outlined in Table 3.4.1. This systematic approach ensures a comprehensive and well-defined setup for the subsequent machining operations.

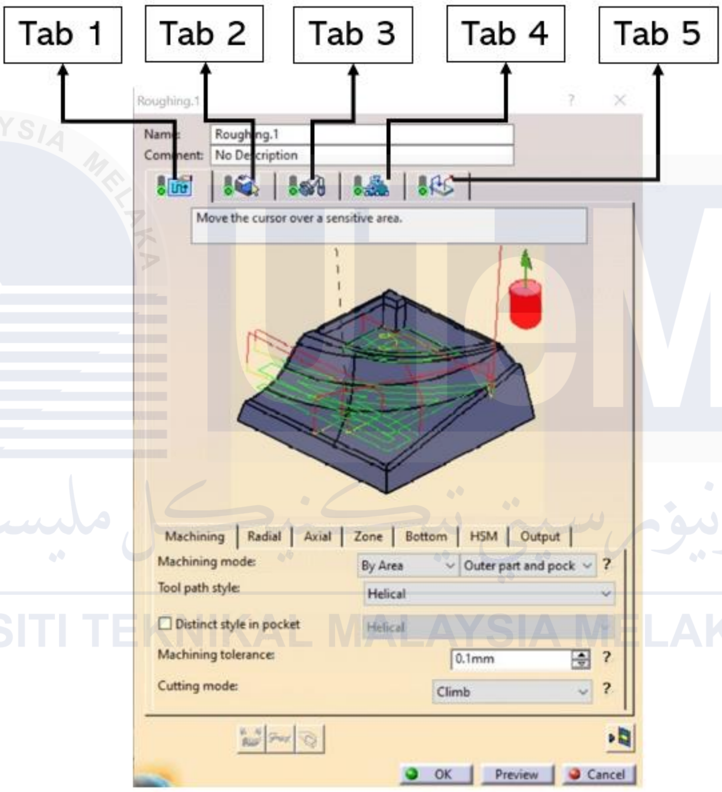
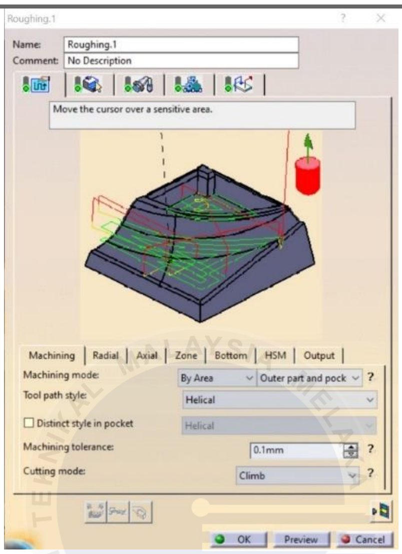
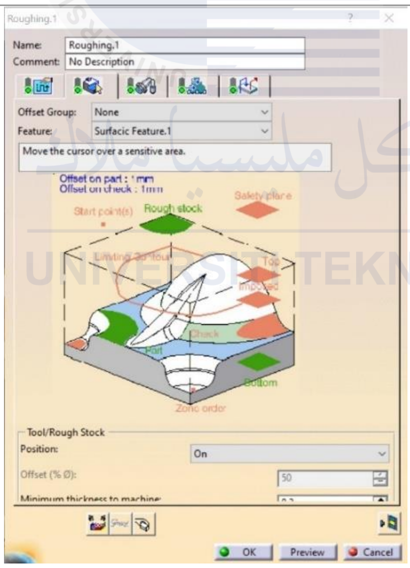
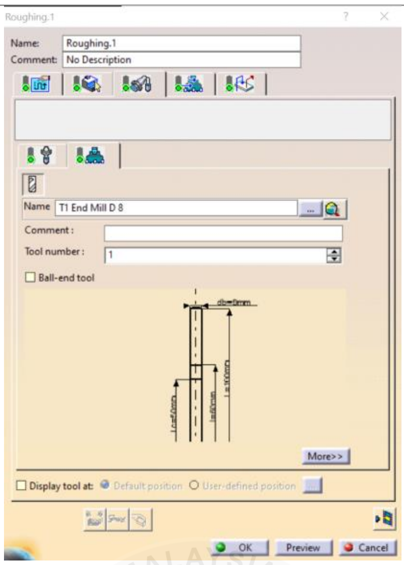
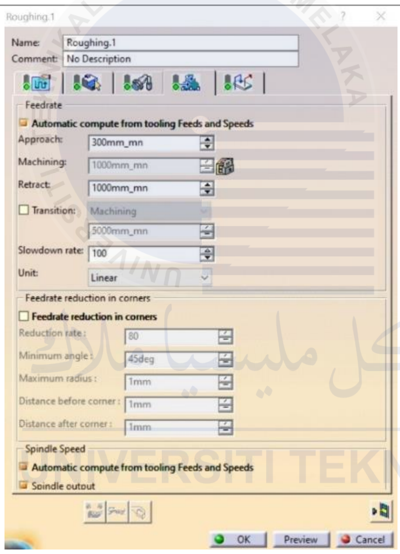
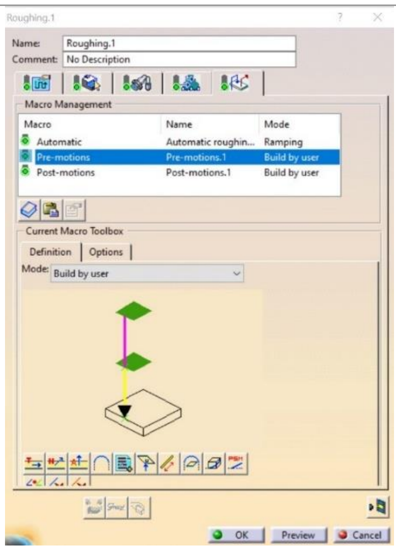


Figure 3.11 Roughing Operation in CATIA V5

Table 3.1 Tabs of Roughing Process

Tab number	Figure	Description
1		Tab 1 defines machining strategies for processing parts, covering axial, radial, and other approaches. It crucially influences material removal during roughing, impacting tool path and efficiency. Parameters set in Tab 1 shape the overall effectiveness of the roughing strategy for machining parts.
2		Tab 2 in the roughing process defines aspects like rough stock, part geometry, and part bottom. It's crucial for the program to understand the requirements, aiding precise machining. Parameters specify initial stock shape, part geometry, and bottom features, guiding the CAM program for efficient material removal and meeting design criteria.

3		Tab 3 in the roughing process focuses on selecting and configuring the cutting tool, crucial for material removal. Parameters include the type, dimensions, and relevant characteristics. Choices made in this tab ensure the suitability of the tool for roughing, considering factors like diameter and length.
4		Tab 4 in the roughing process sets crucial machining parameters—feed rate and spindle speed. Feed rate controls tool advancement, and spindle speed manages spindle rotation. Customization of approach and retract feed rates is also available, influencing tool movements during entry and exit for optimized efficiency and precision.
5		Tab 5 in the roughing process focuses on the macro plane, defining the approach and safety planes crucial for spatial orientation. It sets pre-motions (approach) and post-motions (retract) to position the tool before and after roughing. These settings in Tab 5 enhance overall coordination and precision in the machining process.

Once the five tabs of the roughing process have been configured, the next step involves running the simulation to visualize and verify the roughing operation. The simulation provides a dynamic representation of how the cutting tool engages with the workpiece based on the parameters and strategies set in the previous tabs. In this context, Figure 3.12 displays the simulation result, offering a visual representation of the roughing process.

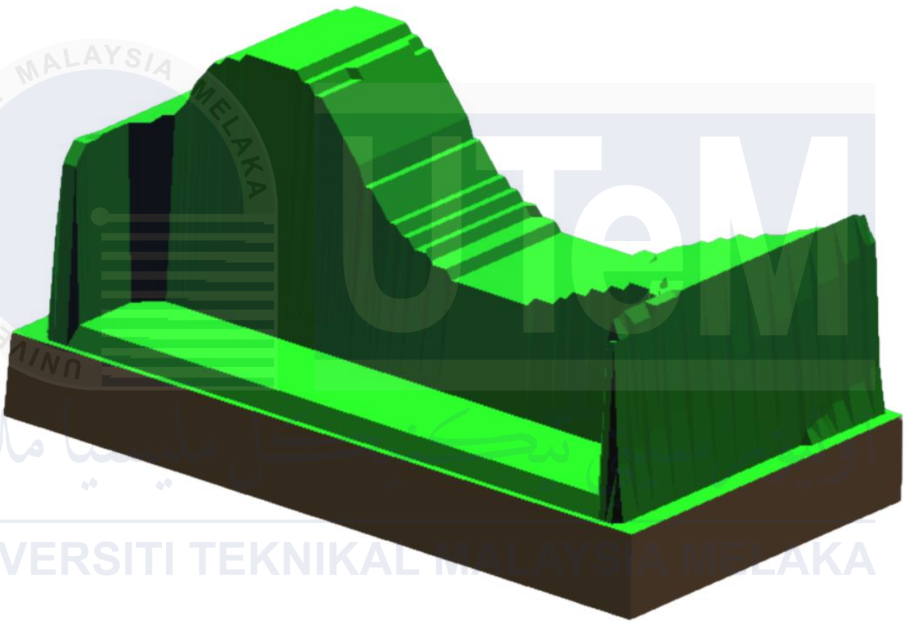


Figure 3.12 Simulation Result of Roughing Process

3.5 Machine Specifications

For this experiment, the designated machine is the DMGMORI DMU 60 Evo, as depicted in Figure 3.13. This machine is a CNC 5-Axis Milling Machine, chosen for its suitability for the specific requirements of the experiment. The specifications of the machine are detailed in Table 3.5.1, providing key information about its capabilities and features. The selection of a suitable machine is critical in ensuring that the CAM program aligns with the capabilities and constraints of the chosen equipment, ultimately influencing the success and accuracy of the machining operations.

Figure 3.13 DMG MORI DMU 60 eVo CNC 5-Axis Milling Machine

Table 3.2 Specification of DMG MORI DMU 60 eVo CNC 5-Axis Milling Machine

Parameters	**Specifications**
Spindle speed range	20-24000 rpm
Maximum spindle speed	24000 rpm
Maximum feed speed	50 m/min or 164 ft/min
Maximum X-axis travel distance	600 mm
Maximum Y-axis travel distance	500 mm
Maximum Z-axis travel distance	500 mm

3.6 Tool Geometry

In this experiment, the chosen cutting tool is a specific type: a TiSIN coated end mill carbide with a diameter of 10mm, featuring 4 flutes and a standard helix angle of 40°, as illustrated in Figure 3.14. Despite the singular type of cutting tool, a total of 4 cutting tools were employed in the experiment, following the utilization of the Taguchi method L4. The detailed drawing of the cutting tool can be observed in Figure 3.15, providing a visual representation of its dimensions and design.

Figure 3.14 TiSIN Coated Carbide Endmill, D10, 4 Flutes & Helix Angle 40°

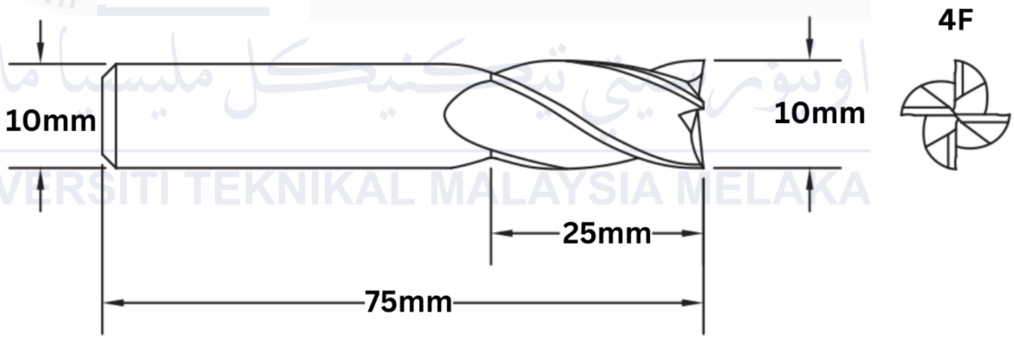


Figure 3.15 Drawing of Cutting Tool

Table 3.3 Cutting Tool Specification

Type of cutting tool	Diameter (mm)	Number of flutes	Helix angle (°)	Cutting length (mm)	Total length (mm)
End mill	10.0	4	40	25.0	75.0

The specifications of the cutting tool, including its diameter, number of flutes, and helix angle, are comprehensively outlined in Table 3.6.1. This information is crucial for precisely configuring the CAM program and ensuring that the toolpaths generated align with the characteristics of the selected cutting tool.

3.7 Material Details

In this experiment, the chosen material is Aluminum Alloys from the 6xxx series, specifically Al-6061 T651, as indicated in Figure 3.16. The 6xxx series aluminum alloys are characterized by their composition, primarily consisting of aluminum, magnesium, and silicon as the major alloying elements. The Al-6061 alloy, in particular, typically contains approximately 97.9% aluminum, 1% magnesium, and 0.6% silicon. This alloy is widely used in various applications due to its favorable combination of strength, corrosion resistance, and machinability. The selection of Al-6061 T651 for the experiment ensures that the machining processes are conducted on a material with known properties and characteristics.

Figure 3.16 Aluminium Alloys AI-6061 T651

3.8 Machining Parameters

The machining parameters used during the roughing of aluminum alloy 6xxx series material were determined using the DOE method, specifically the Taguchi method with an L4 orthogonal array. Minitab software was employed to set the number of runs and identify the two factors considered in this roughing process. The selected machining parameters, as outlined in Table 3.8.1, were generated based on the Taguchi L4 approach. These parameters include cutting speed (V_c), spindle speed (N), feed per tooth (f_z) and feed rate (V_f). The relationships between these machining parameters are given by the following formulas:

Feed rate:

$$v_f = f_z \times n \times z_c \tag{3.1}$$

Cutting speed:

$$v_c = \frac{\pi \times D \times N}{1000} \tag{3.2}$$

Spindle speed:

$$N = \frac{v_c \times 1000}{\pi \times D} \tag{3.3}$$

Feed per tooth:

$$f_z = \frac{v_f}{N \times z_c} \tag{3.4}$$

These equations enable a comprehensive understanding and calculation of the machining conditions for the roughing process, contributing to the effective implementation of the experimental design based on the Taguchi L4 orthogonal array.

Table 3.4 Taguchi L4 Array

Run	Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)
1	Low	Low
2	Low	High
3	High	Low
4	High	High

Table 3.5 Machining Parameters Used in This Experiment

Run	Cutting speed, Vc (m/min)	Spindle speed, N (RPM)	Feed per tooth, fz (mm)	Feed rate, Vf (mm/min)
1	150	4774	0.05	955
2	150	4774	0.10	1910
3	200	6365	0.05	1273
4	200	6365	0.10	2546

3.9 Surface Roughness Measurement

The measurement of surface roughness (Ra) & (Rz) on the machined parts was performed using a surface roughness tester, specifically the Surftest SJ-410 manufactured by Mitutoyo. This instrument is a widely used type of surface roughness tester in the current industry for inspecting the surface quality of machined materials. The SJ-410 is equipped with the capability to measure surfaces using various parameters.

As depicted in Figure 3.17, the key component of the Surftest SJ-410 is the stylus, a small sensor employed to gauge the roughness of a surface. The stylus traverses a distance of 4mm during each measurement. For each measurement, the device takes five reading points, and the average reading is used to determine the Ra value, which is a commonly utilized parameter for characterizing surface roughness. This method ensures a comprehensive and reliable assessment of the machined parts' surface quality, contributing to the evaluation and optimization of the roughing process for aluminum alloy 6xxx series material.

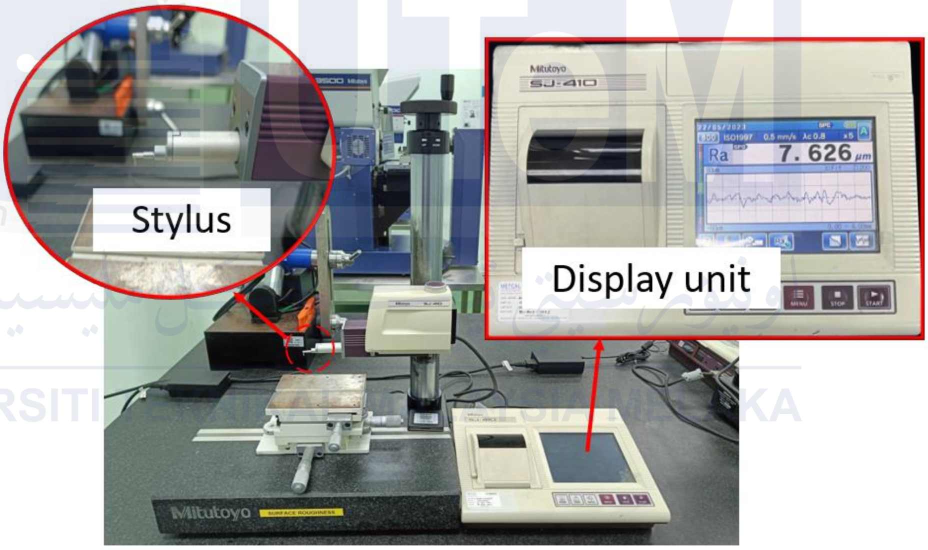


Figure 3.17 Surface Roughness Tester Surftest SJ-410

3.10 Observation of Tool Wear & Surface Quality

After the machining process, the tool wear of the 4 cutting tools and the surface quality of each machined part will be examined using the Meiji EMZ-13TR trinocular zoom stereo microscope. This microscope offers a magnification range from 1x to 100x, enabling detailed analysis of tool wear and surface quality based on the cutting parameters.

To facilitate the observation and documentation of the cutting tool condition, the E-max software is employed. This software is connected to the microscope and allows for the capture of images, providing a visual record of the tool wear under different cutting conditions. The setup for the observation of tool wear, as illustrated in Figure 3.18, outlines the configuration for a systematic and detailed examination of the cutting tools.

This integrated approach involving optical microscopy and image capture with E-max enhances the ability to assess tool wear and surface quality, contributing valuable insights into the performance of the cutting tools under various experimental conditions.

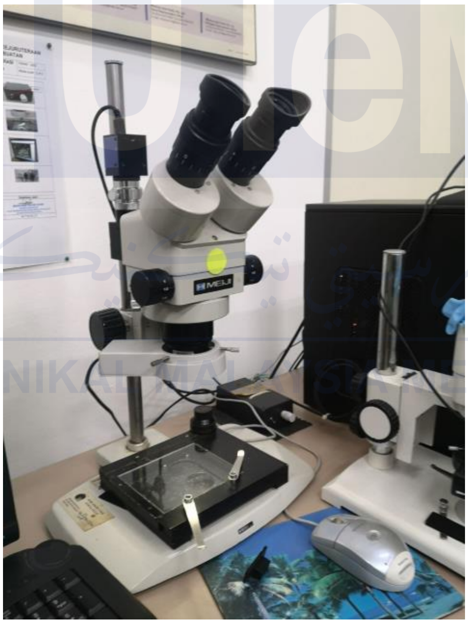


Figure 3.18 Meiji EMZ-13TR Trinocular Zoom Stereo Microscope

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, the examination revolves around analyzing the outcomes derived from the experiment, specifically honing in on surface roughness and tool wear. The challenges associated with this analysis are meticulously explored. The primary objective is to identify optimal machining parameters and comprehensively understand their impact on both surface quality and tool wear. The subsequent discussion will intricately investigate the determination of optimal machining parameters tailored for roughing pocketing profiles within the aerospace industry. Ultimately, the conclusion of this chapter aims to pinpoint and expound upon the optimal machining parameters that prove most conducive to achieving superior results in surface quality and minimizing tool wear.

4.2 Surface Roughness

Achieving a high-quality surface finish on machined aluminum material in aerospace part production is crucial, and surface roughness plays a pivotal role in this regard. Various factors, including cutting speed, spindle speed, and feed rate, contribute to influencing the surface finish. The initial analysis in this experiment focuses on surface roughness analysis, conducted using the Surftest SJ-410 surface roughness tester manufactured by Mitutoyo, as detailed in Section 3.9. The analysis provides Ra and Rz values for the open pocket.

The surface roughness analysis is segmented into two main sections: face roughness and side wall roughness. Face roughness values are obtained from five points on both the left and right faces, totaling 10 points for face roughness. Similarly, for side wall roughness, values are acquired from five points on both the left and right side walls, amounting to a total of 10 points for side wall roughness. In total, 20 points are considered, and the average value across these 20 points serves as the determinant for the overall surface roughness.

4.2.1 Face Roughness

The points utilized for obtaining face roughness values are visually represented in Figures 4.1 and 4.2. These figures offer a visual guide to the exact locations on both the left and right faces where measurements were conducted to evaluate the face roughness of the machined aluminum material.

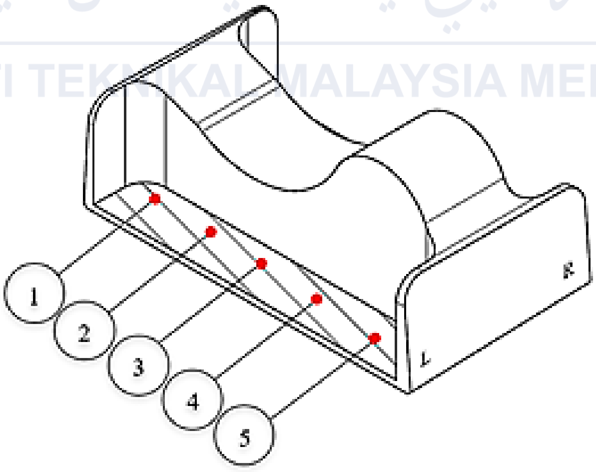


Figure 4.1 Illustrates Points Taken From Left Side

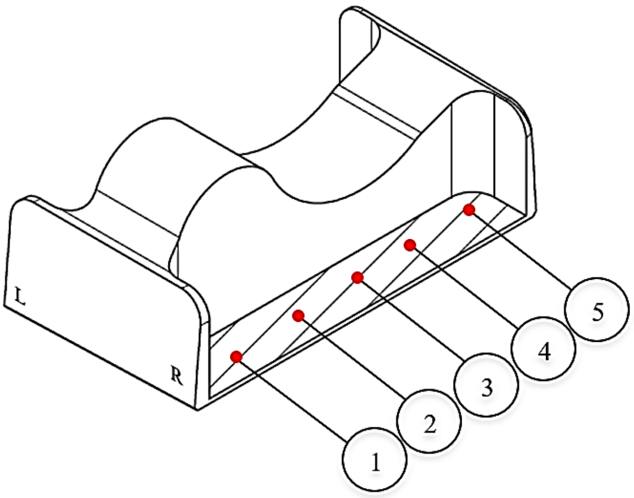


Figure 4.2 Illustrates Points Taken From Right Side

The surface roughness (Ra) was measured for the left and right surfaces, with five measurements taken for each run. The results obtained from this analysis are presented in Table 4.1. The average Ra for the left surface ranged from 0.1336µm to 0.3042µm, while for the right surface, it ranged from 0.1456µm to 0.3098µm. The overall average Ra across all combinations and runs ranged from 0.2493µm to 0.2999µm.

The data indicates that the combination of cutting speed and feed per tooth has a significant impact on surface roughness. Generally, higher cutting speeds and lower feed per tooth resulted in lower surface roughness. This trend is evident when comparing the average Ra values for different combinations. For example, the combination with Vc=200m/min and fz=0.05mm resulted in lower average Ra compared to the combination with Vc=150m/min and fz=0.1mm. Additionally, the variation in surface roughness between the left and right surfaces for each run suggests potential asymmetry in the machining process.

In conclusion, the data highlights the influence of cutting parameters on surface roughness in machining processes. The data demonstrates the importance of carefully selecting cutting speed and feed per tooth to achieve the desired surface quality. This information is essential for optimizing machining operations and improving the overall quality of manufactured components.

Table 4.1 Shows The Data of Surface Roughness,Ra on Face Surface

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	***Surface Roughness, Ra (µm)***												
			Left Point						**Right Point**						**Overall Average**
			1	**2**	**3**	**4**	**5**	**Average**	**1**	**2**	**3**	**4**	**5**	**Average**	
150	0.05	1	0.244	0.245	0.232	0.271	0.214	**0.2412**	0.26	0.324	0.351	0.316	0.298	**0.3098**	**0.2755**
150	0.1	2	0.227	0.27	0.271	0.487	0.266	**0.3042**	0.283	0.326	0.28	0.255	0.334	**0.2956**	**0.2999**
200	0.05	3	0.116	0.153	0.13	0.134	0.135	**0.1336**	0.186	0.162	0.145	0.128	0.167	**0.1576**	**0.1456**
200	0.1	4	0.37	0.187	0.211	0.23	0.256	**0.2508**	0.375	0.215	0.202	0.205	0.242	**0.2478**	**0.2493**

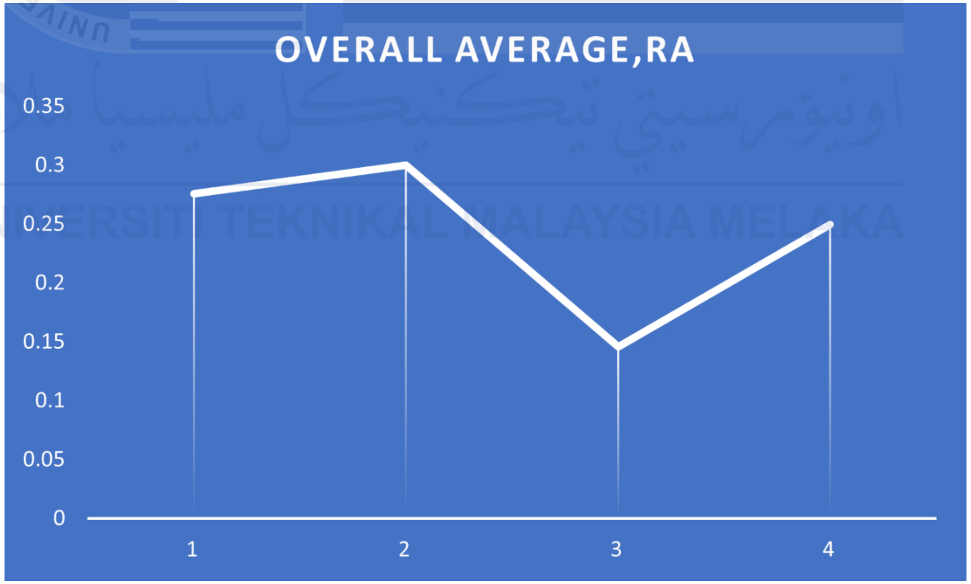


Figure 4.3 shows Overall Average Surface Roughness, Ra (µm) Graph

The surface roughness (Rz) was measured for the left and right surfaces, with five measurements taken for each run. The results obtained from this analysis are presented in Table 4.2.The results indicate that the surface roughness values vary based on the cutting speed and feed per tooth. Lower cutting speeds and finer feed per tooth tend to result in lower surface roughness, as evidenced by the lower average Rz values in the corresponding runs. Conversely, higher cutting speeds and coarser feed per tooth resulted in higher surface roughness values.

The findings highlight the importance of selecting appropriate cutting parameters to achieve the desired surface finish in machining processes. By optimizing the cutting speed and feed per tooth, manufacturers can effectively control and minimize surface roughness, which is crucial for ensuring the quality and performance of machined components.

In summary, the data demonstrates the relationship between cutting speed, feed per tooth, and surface roughness in a machining operation, emphasizing the need for careful consideration and optimization of these parameters to achieve the desired surface finish and overall quality of machined products.

Table 4.2 Shows The Data of Surface Roughness,Rz on Face Surface

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	*Surface Roughness, Rz (µm)*												
			Left Point						Right Point						Overall Average
			1	2	3	4	5	Average	1	2	3	4	5	Average	
150	0.05	1	1.298	1.254	1.134	1.293	1.342	**1.2642**	1.423	1.561	1.818	1.775	1.732	1.6618	**1.463**
150	0.1	2	1.592	1.517	1.749	2.982	1.902	**1.9484**	1.683	3.092	2.023	1.393	2.686	2.1754	**2.0619**
200	0.05	3	0.739	0.925	0.695	0.715	0.779	**0.7706**	1.032	0.945	0.748	0.721	0.933	0.8758	**0.8232**
200	0.1	4	1.808	1.123	1.173	1.386	1.26	**1.35**	1.723	1.222	1.189	1.096	1.382	1.3224	**1.3362**

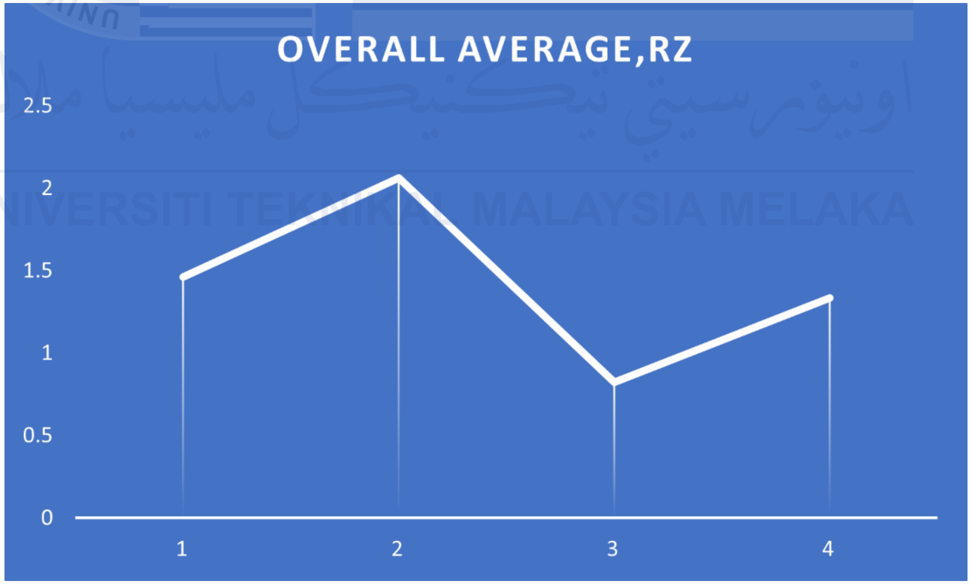


Figure 4.4 Shows Overall Average Surface Roughness, Rz (µm) Graph

The presented data on Ra and Rz values for machined aluminum surfaces reveals a consistent trend in the influence of cutting parameters on surface roughness. Both Ra and Rz values indicate that lower cutting speeds and finer feed per tooth generally lead to lower surface roughness, while higher cutting speeds and coarser feed per tooth result in higher roughness values.

The analysis emphasizes the significance of selecting appropriate cutting parameters to achieve the desired surface finish in machining processes. The average Ra and Rz values across various combinations and runs consistently support the idea that optimizing cutting speed and feed per tooth is crucial for controlling and minimizing surface roughness. This optimization is essential for enhancing the overall quality and performance of machined components.

Furthermore, the microscopic images presented in Figure 4.5, 4.6, 4.7, 4.8 provide a visual representation of the surface characteristics at specific points, reinforcing the importance of careful consideration and optimization of cutting parameters to achieve the desired surface quality.

In conclusion, both Ra and Rz data underscore the relationship between cutting speed, feed per tooth, and surface roughness in machining operations. The findings highlight the need for manufacturers to attentively select and optimize cutting parameters to achieve the desired surface finish and ensure the overall quality of machined products.

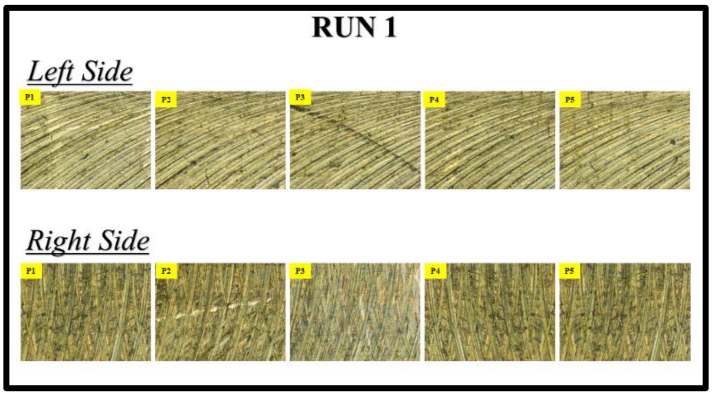


Figure 4.5 Microscopic Image Face Surface, Run 1

Figure 4.6 Microscopic Image Face Surface, Run 2

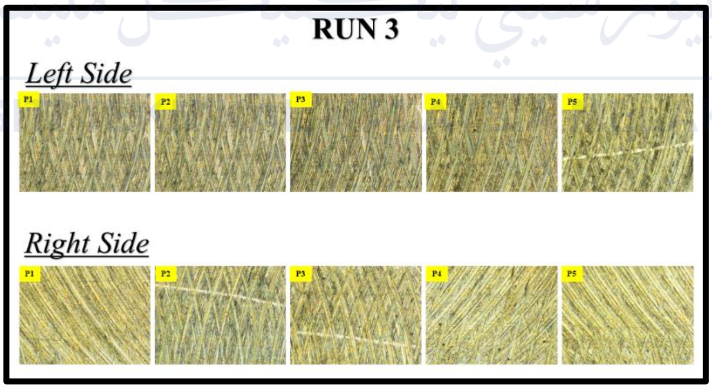


Figure 4.7 Microscopic Image Face Surface, Run 3

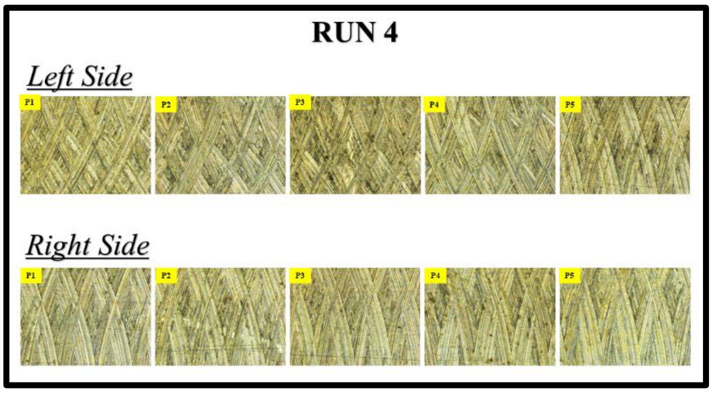


Figure 4.8 Microscopic Image Face Surface, Run 4

4.2.2 Side Wall Roughness

The points utilized for obtaining side wall roughness values are visually represented in Figures 4.9 and 4.10. These figures offer a visual guide to the exact locations on both the left and right faces where measurements were conducted to evaluate the side wall roughness of the machined aluminum material.

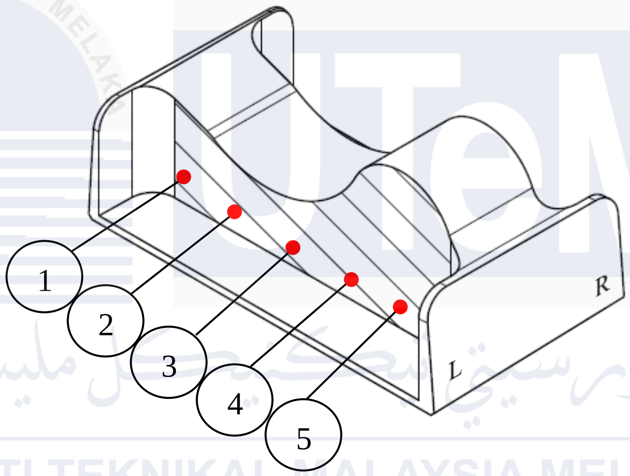


Figure 4.9 Illustrates Points Taken From Left Side

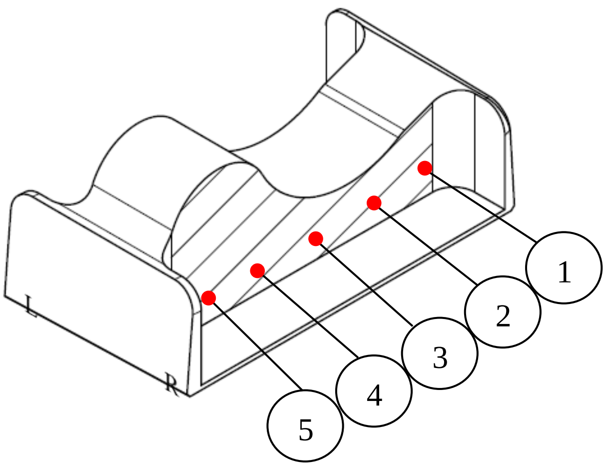


Figure 4.10 Illustrates Points Taken From Right Side

The Table 4.3 displays the cutting speed (Vc) in meters per minute, feed per tooth (fz) in millimeters, run numbers, and the corresponding surface roughness values for each run. The surface roughness values are recorded separately for the left and right sides, with an average calculated for each set of runs and an overall average for all runs.

For instance, at a cutting speed of 150 m/min and a feed per tooth of 0.05 mm in the first run, the surface roughness on the left side was 0.69 µm, while on the right side, it was 0.533 µm. The overall average surface roughness for this set of conditions was 0.591 µm.

Similarly, at a cutting speed of 150 m/min and a feed per tooth of 0.1 mm in the second run, the surface roughness on the left side was 0.784 µm, and on the right side, it was 0.884 µm. The overall average surface roughness for this set of conditions was 0.7232 µm.

At a cutting speed of 200 m/min and a feed per tooth of 0.05 mm in the third run, the surface roughness on the left side was 0.584 µm, and on the right side, it was 0.578 µm. The overall average surface roughness for this set of conditions was 0.5758 µm.

Finally, at a cutting speed of 200 m/min and a feed per tooth of 0.1 mm in the fourth run, the surface roughness on the left side was 0.645 µm, and on the right side, it was 0.74 µm. The overall average surface roughness for this set of conditions was 0.7456 µm.

In summary, the data provides a detailed insight into the influence of cutting speed and feed per tooth on surface roughness during machining. It demonstrates a clear correlation between these parameters and surface roughness, indicating that higher cutting speeds and larger feed per tooth values generally result in higher surface roughness.

Table 4.3 Shows The Data of Surface Roughness,Ra on Side Wall Surface

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	*Surface Roughness, Ra (µm)*												
			Left						Right						Overall Average
			1	2	3	4	5	Average	1	2	3	4	5	Average	
150	0.05	1	0.69	0.357	0.302	0.496	0.522	**0.4734**	0.533	0.863	0.779	0.739	0.629	**0.7086**	**0.591**
150	0.1	2	0.784	0.539	0.579	0.686	0.444	**0.6064**	0.884	0.868	0.697	0.818	0.933	**0.84**	**0.7232**
200	0.05	3	0.584	0.576	0.758	0.749	0.703	**0.674**	0.578	0.448	0.438	0.467	0.457	**0.4776**	**0.5758**
200	0.1	4	0.645	0.764	0.869	0.874	0.659	**0.7622**	0.74	0.607	0.69	0.751	0.857	**0.729**	**0.7456**

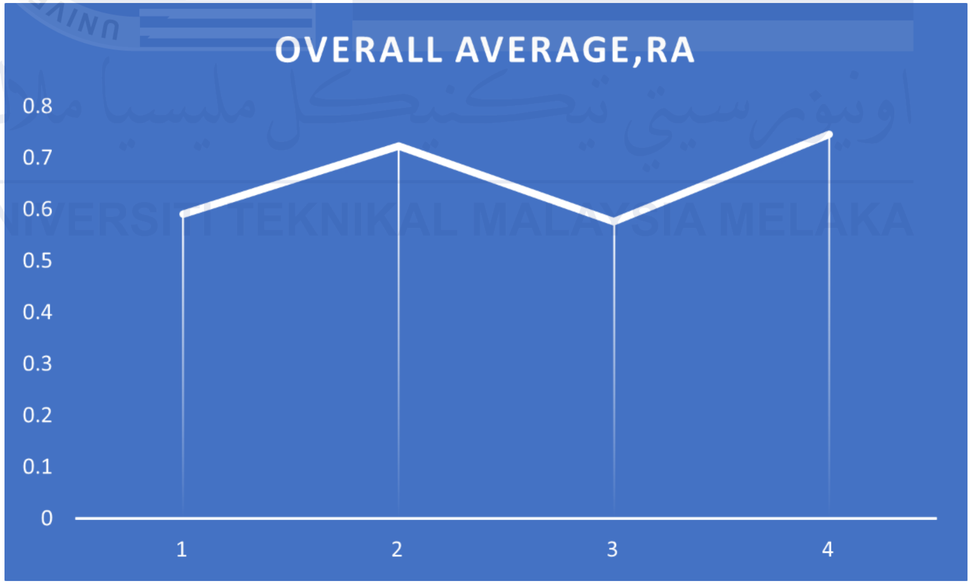


Figure 4.11 Shows Overall Average Surface Roughness, Ra (µm) Graph

The Table 4.4 shows that as the cutting speed and feed per tooth values change, there is a corresponding effect on the surface roughness of the machined surfaces. For instance, at a cutting speed of 150 m/min and a feed per tooth of 0.05 mm, the surface roughness ranges from 2.251 µm to 4.775 µm for different runs and points. Similarly, at a cutting speed of 200 m/min and a feed per tooth of 0.1 mm, the surface roughness ranges from 3.0084 µm to 4.956 µm for different runs and points.

The recorded data also includes the average surface roughness values for each set of cutting parameters. For example, at a cutting speed of 150 m/min and a feed per tooth of 0.1 mm, the average surface roughness is 4.3361 µm, while at a cutting speed of 200 m/min and a feed per tooth of 0.05 mm, the average surface roughness is 3.5301 µm.

From the data, it is evident that higher cutting speeds and lower feed per tooth values generally result in lower surface roughness, indicating a smoother machined surface. Conversely, lower cutting speeds and higher feed per tooth values tend to produce rougher surfaces with higher Rz values.

In summary, the data illustrates the impact of cutting speed and feed per tooth values on surface roughness, highlighting the importance of selecting appropriate cutting parameters to achieve the desired surface quality in machining operations. The results provide valuable insights for machining processes and can be used to optimize cutting parameters to achieve the desired surface roughness for specific applications.

Table 4.4 Shows The Data of Surface Roughness,Rz on Side Wall Surface

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	*Surface Roughness, Rz (µm)*												
			Left Points						**Right Points**						**Overall Average**
			1	**2**	**3**	**4**	**5**	**Average**	**1**	**2**	**3**	**4**	**5**	**Average**	
150	0.05	1	4.812	2.632	2.251	3.056	2.899	**3.13**	3.223	4.467	4.775	4.653	3.63	4.1496	**3.6398**
150	0.1	2	4.747	3.515	3.309	3.323	2.878	**3.5544**	4.879	5.119	4.836	5.228	5.527	5.1178	**4.3361**
200	0.05	3	3.352	3.89	4.466	3.957	4.594	**4.0518**	3.564	3.142	2.619	2.939	2.778	3.0084	**3.5301**
200	0.1	4	3.376	4.501	4.992	4.888	4.434	**4.4382**	3.746	3.837	4.271	4.168	4.956	4.1956	**4.3169**

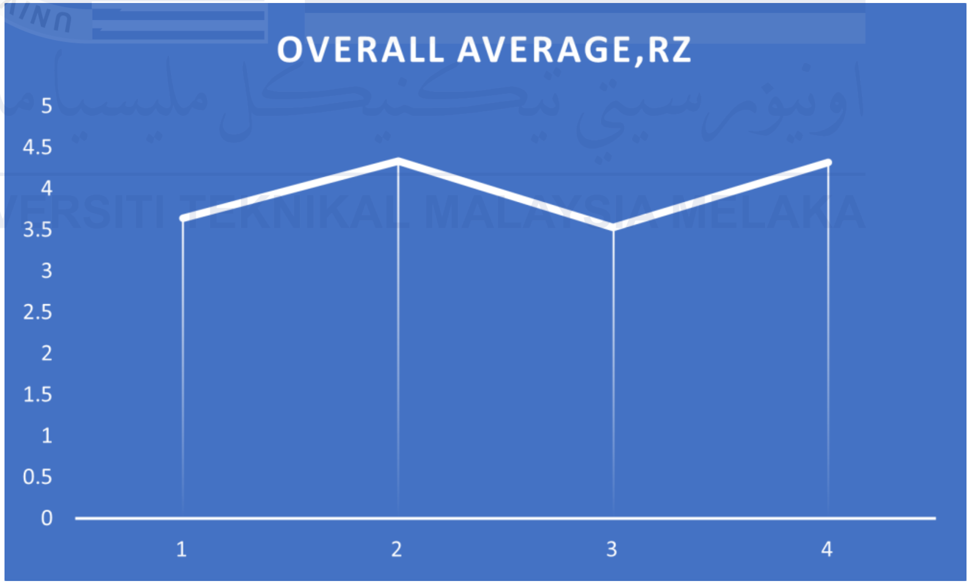


Figure 4.12 Shows Overall Average Surface Roughness, Rz (µm) Graph

The examination of both Ra and Rz data sets consistently reveals a direct correlation between cutting speed, feed per tooth, and surface roughness. Higher cutting speeds paired with lower feed per tooth values tend to yield lower surface roughness, while lower cutting speeds and higher feed per tooth values result in a rougher machined surface. This robust correlation is evident across different runs and points, establishing a foundation for understanding the nuanced impact of cutting parameters on surface quality.

Detailed insights from Ra values highlight the influence of cutting speed and feed per tooth on surface roughness, showcasing a discernible trend. Generally, higher cutting speeds and larger feed per tooth values lead to higher surface roughness. The parallel analysis using Rz values further accentuates this trend, indicating that higher cutting speeds and lower feed per tooth values result in a smoother machined surface. The range of surface roughness values for various runs and points provides a comprehensive view of the nuanced impact of cutting parameters on surface quality.

Both Ra and Rz measurements include average surface roughness values for specific combinations of cutting speed and feed per tooth. These averages serve as concise summaries, enabling a quick comparison and assessment of surface quality. The averages reinforce the overarching trend, highlighting the need for careful consideration and optimization of cutting parameters to achieve the desired surface finish consistently.

The inclusion of microscopic images in Figure 4.13, 4.14, 4.15, 4.16 serves to visually reinforce the numerical findings. These images provide a direct representation of surface characteristics at specific points, underlining the importance of meticulous consideration and optimization of cutting parameters. The visual evidence enhances the understanding of the complex relationship between cutting parameters and the resulting surface quality. The conclusive insight derived from the combined analysis of Ra and Rz data emphasizes the critical role of careful selection and optimization of cutting parameters.

In conclusion, the synergy between cutting parameters and surface roughness in machining processes is a multifaceted relationship that demands careful consideration. The insights gained from both Ra and Rz analyses provide manufacturers with valuable guidance for optimizing machining operations, ensuring the desired surface quality, and elevating the overall excellence of manufactured components.

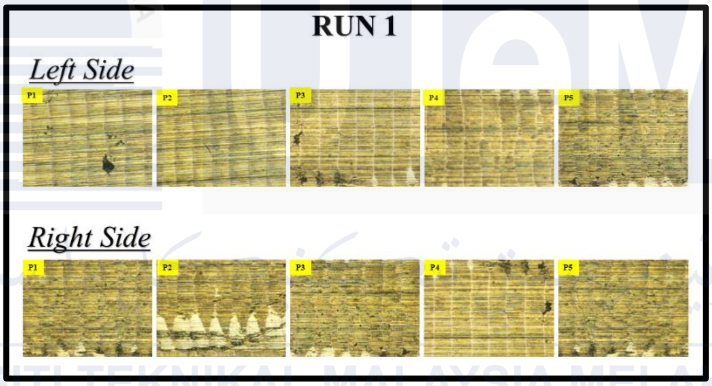


Figure 4.13 Microscopic Image Side Wall Surface, Run 1

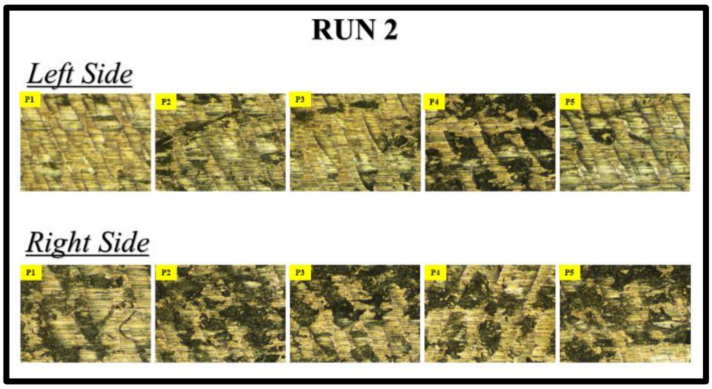


Figure 4.14 Microscopic Image Side Wall Surface, Run 2

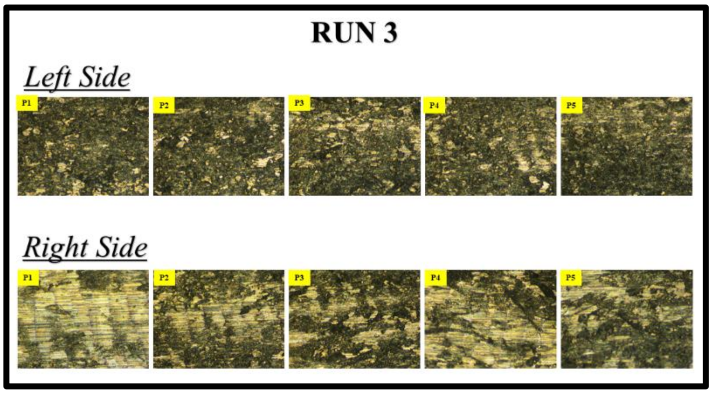


Figure 4.15 Microscopic Image Side Wall Surface, Run 3

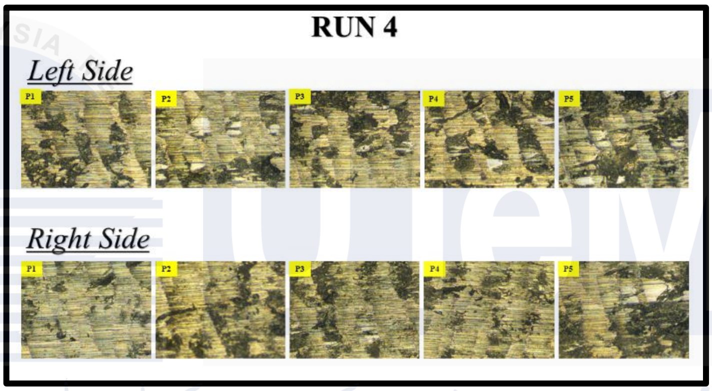


Figure 4.16 Microscopic Image Side Wall Surface, Run 4

4.2.3 Overall Surface Roughness

The Table 4.5 displays four sets of data points with varying cutting speeds and feed per tooth values, along with their corresponding run number and overall surface roughness measurements.

The results indicate that as the cutting speed increases from 150 m/min to 200 m/min, there is a decrease in overall surface roughness. Specifically, at a cutting speed of 150 m/min, the surface roughness values are 0.43325 (run 1) and 0.51155 (run 2) for feed per tooth values of 0.05 mm and 0.1 mm respectively. On the other hand, at a cutting speed of 200 m/min, the surface roughness values are 0.3607 (run 3) and 0.49745 (run 4) for the same feed per tooth values.

The data also suggests that the feed per tooth has an impact on the overall surface roughness. When comparing runs 1 and 3, both conducted at a cutting speed of 150 m/min but with different feed per tooth values (0.05 mm and 0.1 mm), it is evident that the lower feed per tooth results in a higher surface roughness. Similarly, comparing runs 2 and 4, conducted at a cutting speed of 200 m/min, the lower feed per tooth value leads to a higher surface roughness.

These findings highlight the importance of optimizing cutting speed and feed per tooth parameters in machining processes to achieve the desired surface finish. The results demonstrate that higher cutting speeds and lower feed per tooth values contribute to reduced surface roughness, indicating a smoother surface finish.

Table 4.5 Shows The Data of Overall Average Surface Roughness,Ra

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	Overall Surface Roughness (Ra)
150	0.05	1	**0.43325**
150	0.1	2	**0.51155**
200	0.05	3	**0.3607**
200	0.1	4	**0.49745**

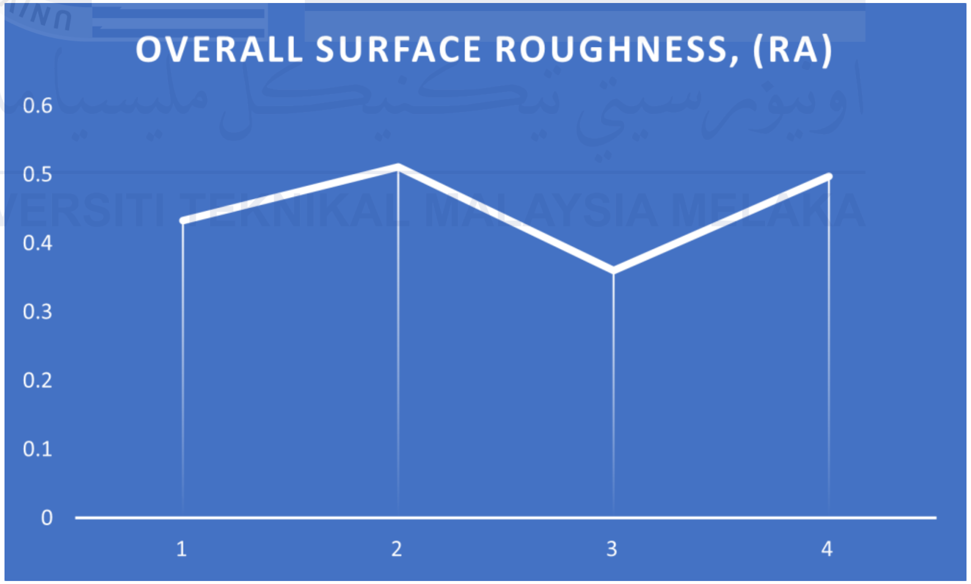


Figure 4.17 Shows Overall Average Surface Roughness, Ra (μm) Graph

The Table 4.6 displays four different combinations of cutting speed and feed per tooth, along with their corresponding runs and overall surface roughness (Rz) values.

The cutting speed (Vc) is represented in meters per minute (m/min), and the feed per tooth (fz) is measured in millimeters (mm). The run column indicates the specific combination of cutting speed and feed per tooth, while the overall surface roughness (Rz) values represent the quality of the machined surface.

In the first row, a cutting speed of 150 m/min and a feed per tooth of 0.05 mm resulted in a run labeled as 1, with an overall surface roughness (Rz) value of 2.5514. The second row shows that maintaining the cutting speed at 150 m/min but increasing the feed per tooth to 0.1 mm led to a run labeled as 2, with a higher overall surface roughness value of 3.199.

Moving to the third row, a higher cutting speed of 200 m/min and a feed per tooth of 0.05 mm resulted in a run labeled as 3, with a lower overall surface roughness (Rz) value of 2.17665. Finally, the fourth row demonstrates the impact of increasing both the cutting speed to 200 m/min and the feed per tooth to 0.1 mm, resulting in a run labeled as 4 and an overall surface roughness (Rz) value of 2.82655.

The data illustrates the relationship between cutting parameters and surface roughness, highlighting that variations in cutting speed and feed per tooth can significantly influence the quality of the machined surface. Specifically, higher cutting speeds and lower feed per tooth values appear to contribute to reduced overall surface roughness, as evidenced by the lower Rz values in the third row compared to the first two rows.

Table 4.6 Shows The Data of Overall Average Surface Roughness,Rz

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	Overall Surface Roughness (Rz)
150	0.05	1	**2.5514**
150	0.1	2	**3.199**
200	0.05	3	**2.17665**
200	0.1	4	**2.82655**

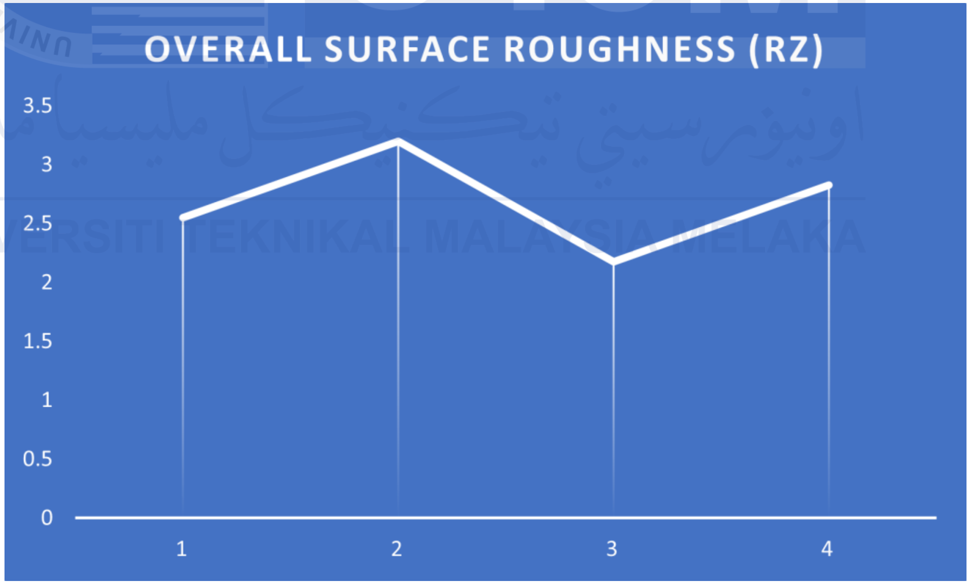


Figure 4.18 shows Overall Average Surface Roughness, Rz (µm) Graph

4.2.4 Taguchi Analysis: Ra versus Cutting Speed, Feed Per Tooth

The Table 4.7 outlines the signal-to-noise ratios (smaller is better) for each factor at two different levels. For Cutting Speed, the signal-to-noise ratio at Level 1 is 6.544, and at Level 2, it is 7.461. A smaller ratio is indicative of better performance, and in this case, Level 1 outperforms Level 2. The difference between the two levels, represented by the Delta value, is 0.917. The Rank column assigns a rank of 2 to Cutting Speed, signifying its relative performance compared to the other factor.

In contrast, Feed per Tooth demonstrates a signal-to-noise ratio of 8.061 at Level 1 and 5.944 at Level 2. Here, Level 2 exhibits the smaller ratio, indicating superior performance. The Delta value for Feed per Tooth is 2.118, reflecting a more substantial difference in performance between the two levels. The Rank column assigns a rank of 1 to Feed per Tooth, highlighting its greater influence on surface roughness compared to Cutting Speed.

In summary, based on the Taguchi Analysis, Cutting Speed performs better at Level 1, while Feed per Tooth exhibits superior performance at Level 2. The Delta values and ranking provide quantitative insights into the relative impact of these factors on surface roughness, aiding in the optimization of machining parameters for desired outcomes.

Table 4.7 Shows The Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting Speed	Feed Per Tooth
1	6.544	8.061
2	7.461	5.944
Delta	0.917	2.118
Rank	2	1

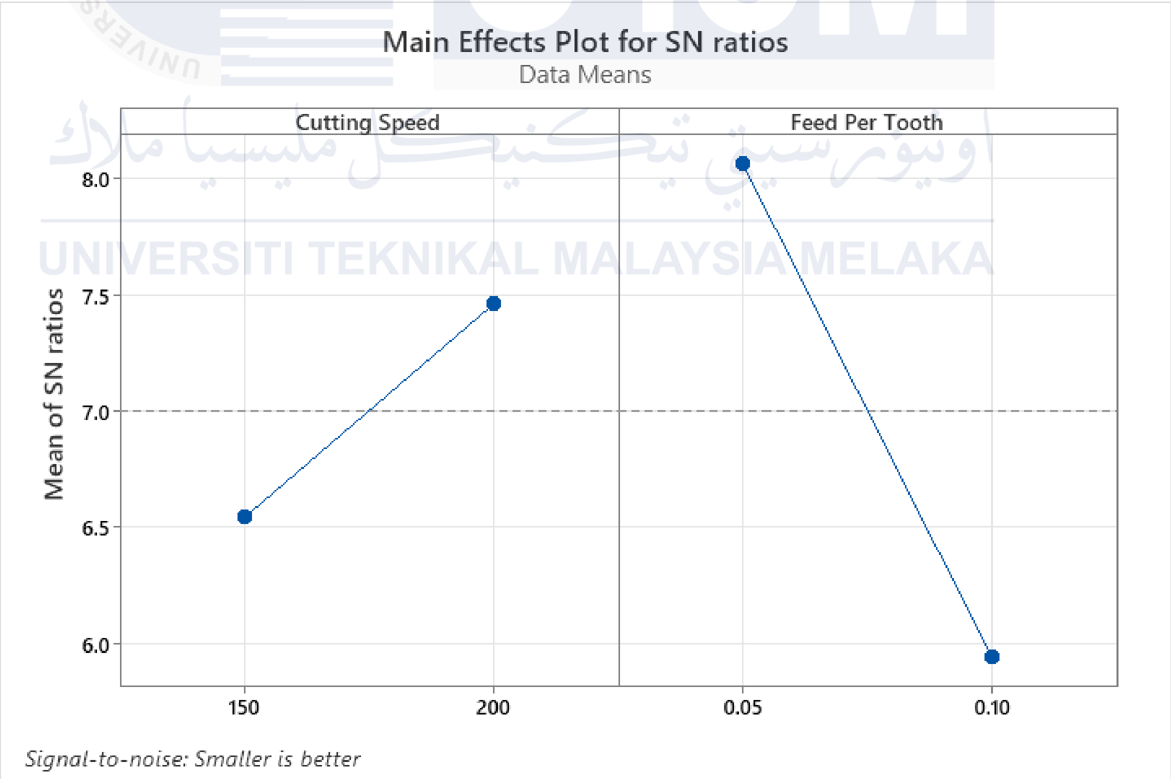


Figure 4.19 shows Main Effects Plot for S/N Ratios

4.2.5 Taguchi Analysis: Rz versus Cutting Speed, Feed Per Tooth

The Table 4.8 shows the signal-to-noise ratios for the two factors at two levels each. The signal-to-noise ratio is a measure of the amount of variation present in the data, with a smaller value indicating less variation and hence better performance. The values in the table indicate the performance of the cutting speed and feed per tooth at each level, with negative values representing better performance.

For cutting speed, the signal-to-noise ratio at level 1 is -9.118, while at level 2, it is -7.89. This indicates that the cutting speed performs better at level 1 compared to level 2. Similarly, for feed per tooth, the signal-to-noise ratio at level 1 is -7.446, and at level 2, it is -9.563, suggesting that feed per tooth performs better at level 1 than at level 2.

The delta values represent the difference in performance between the two levels of each factor. For cutting speed, the delta is 1.227, indicating that the difference in performance between the two levels is 1.227. For feed per tooth, the delta is 2.117, suggesting a larger difference in performance between the two levels.

Furthermore, the rank column shows the ranking of the factors based on their performance. In this analysis, feed per tooth is ranked 1, indicating that it has a greater impact on surface roughness (Rz) compared to cutting speed, which is ranked 2.

In conclusion, the Taguchi analysis reveals that feed per tooth has a more significant impact on surface roughness (Rz) than cutting speed in the machining process. This information is crucial for optimizing the machining parameters to achieve the desired surface quality.

Table 4.8 Shows The Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting Speed	Feed Per Tooth
1	-9.118	-7.446
2	-7.890	-9.563
Delta	1.227	2.117
Rank	2	1

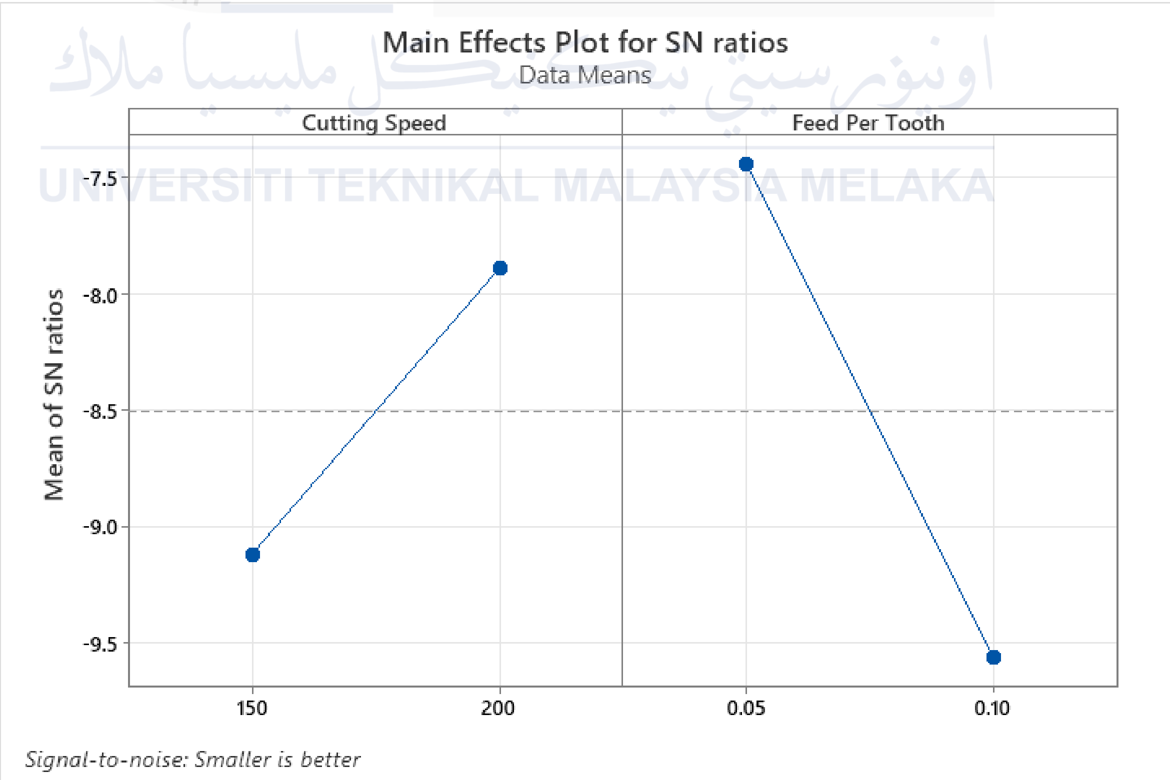


Figure 4.20 shows Main Effects Plot for S/N Ratios

4.3 Tool Wear

In the investigation of tool wear, graphical data was systematically collected using the Meiji EMZ-13TR trinocular zoom stereo microscope. The data acquisition process involved capturing top-view images. Each cutting tool underwent a thorough analysis at four specific quadrants: the 1st quadrant, 2nd quadrant, 3rd quadrant, and 4th quadrant. To visually represent the selected points for tool wear analysis, Figure 4.21 has been included. This figure visually illustrates the specific locations where the examination of tool wear characteristics occurred, providing a comprehensive overview of wear patterns observed from different perspectives on the cutting tools.

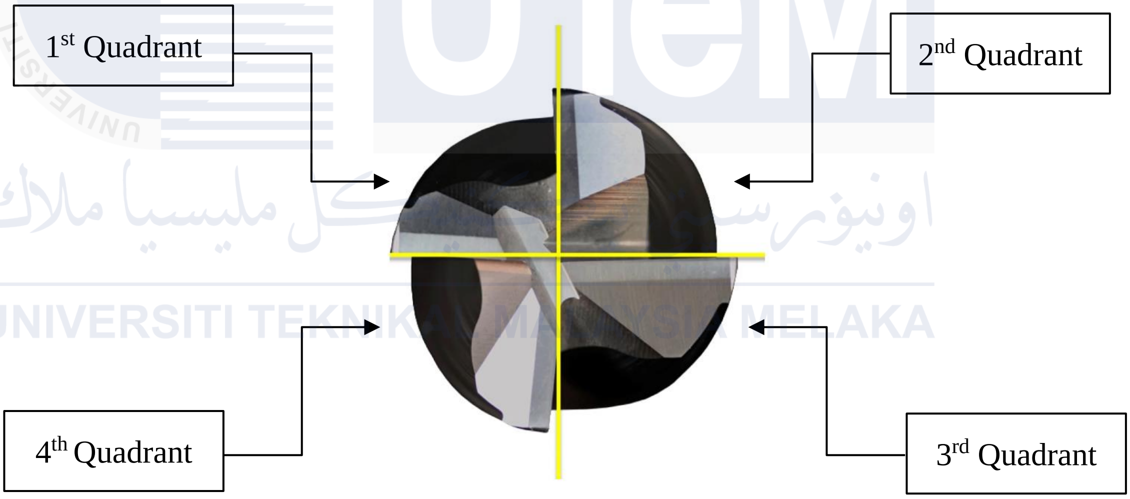
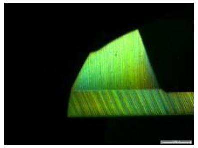
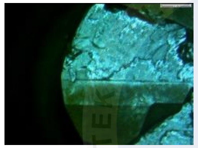
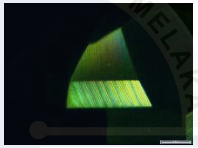
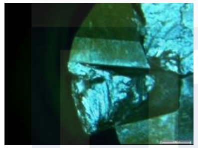
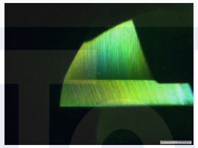
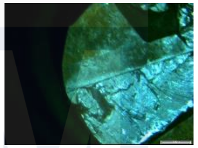
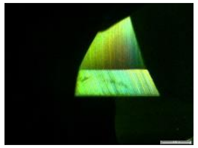
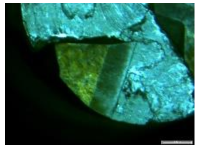
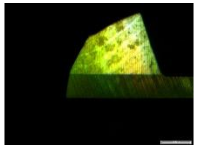
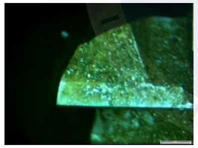
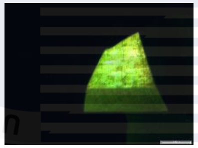
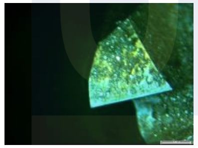
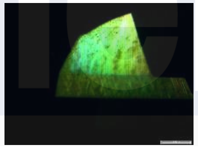
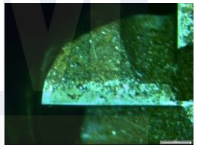
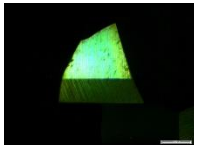
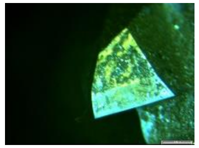
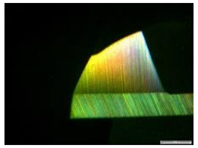
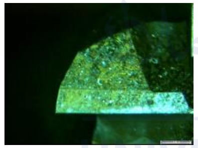
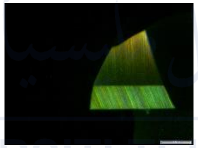
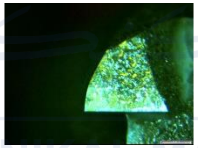
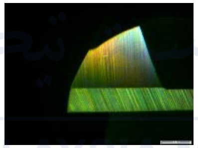
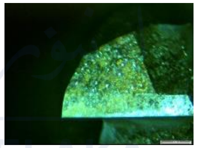
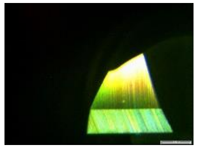
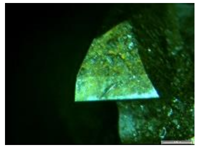
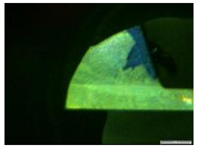
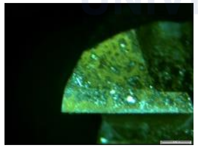
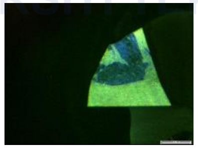
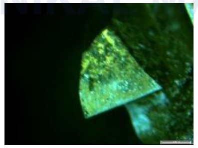
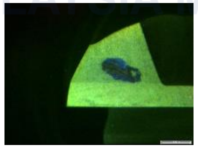
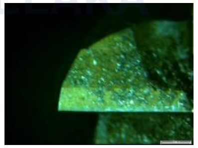
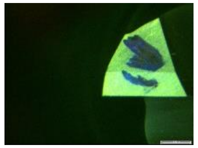
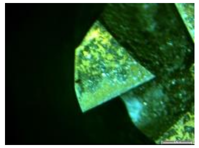


Figure 4.21 illustrates the location examined for tool wear

4.3.1 Data Analysis

The intricate examination of tool wear in the endmill, employed during the experimental run, confronts complexities arising from challenges encountered in the initial phase of the experiment. Notably, the endmill used in Run 1 tasked with milling a closed pocket, encountered impediments in chip evacuation, leading to the occurrence of aluminum material melting and adhering to the tool surface. Due to that, the tool wear of endmill cannot be evaluated. A detailed microscopic analysis conducted across quadrants discerns nuanced patterns in tool wear distribution. In the 1st quadrant, the endmill utilized in run 3 exhibits the most conspicuous tool wear, with subsequent positions occupied by endmills from runs 2 and 4. Transitioning to the 2nd quadrant, a comparable level of tool wear is discerned between runs 2 and 3, while the endmill from run 4 displays the least wear. The 3rd quadrant microscopy indicates that the endmill in run 3 manifests the most pronounced wear, with endmills from runs 2 and 4 following a similar pattern. Lastly, the 4th quadrant analysis delineates that the endmill in run 2 manifests the highest degree of tool wear, with endmills from runs 3 and 4 sequentially trailing in wear intensity.

Table 4.9 Shows The Before & After of The Endmill Used for Each Run

Run	1st Quadrant		2nd Quadrant		3rd Quadrant		4th Quadrant	
	Before	After	Before	After	Before	After	Before	After
1								
2								
3								
4								

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Effect of Cutting Parameters on Surface Roughness

The analysis of Ra and Rz values highlights that higher cutting speeds and lower feed per tooth values consistently lead to lower surface roughness. For instance, Vc=200m/min and fz=0.05mm consistently result in lower average Ra and Rz compared to Vc=150m/min and fz=0.1mm. Microscopic images in Figures 4.5-4.8 visually validate these trends. The examination of overall surface roughness (Table 4.5) supports this, showing a consistent decrease as cutting speed increases from 150 m/min to 200 m/min. Taguchi analysis (Table 4.7) quantifies the impact, emphasizing the superior performance of Feed per Tooth at Level 2. In conclusion, meticulous selection of cutting parameters, especially cutting speed and feed per tooth, is crucial for achieving a consistent and desired surface finish in the machining of Aluminum 6061 with TiSiN-coated end mills.

5.2 Optimization of Machining Parameters

The pursuit of optimal machining conditions was guided by a multifaceted approach. Analysis of overall surface roughness trends, Taguchi analysis, and microscopic validation converged to identify potential optimum parameters. The quantitative metrics from Taguchi analysis pointed towards Level 2 of Cutting Speed (200 m/min) and Level 1 of Feed per Tooth (0.05 mm) as promising contributors to enhanced surface quality.

The overall surface roughness trends corroborated these findings, with higher cutting speeds generally associated with reduced surface roughness. The microscopic images further enriched this understanding, providing a visual narrative of the surface characteristics and reinforcing the significance of the selected parameters in achieving the desired surface finish.

5.3 Recommendations & Future Directions

The culmination of this research bears significant implications for the practicalities of aerospace component manufacturing. Manufacturers can leverage the gleaned insights to not only optimize surface quality but also enhance tool longevity and machining efficiency. The identified optimum parameters serve as a compass for navigating the intricate landscape of material removal, ensuring that the end result aligns with the stringent quality standards demanded by aerospace applications.

As the aerospace industry continues to evolve, future research endeavors can build upon this foundation, delving deeper into the complexities of machining parameters. Exploring additional variables, such as tool geometry or coolant application, could refine the optimization process further. Continuous improvement remains integral to adapting to the evolving landscape of materials and technologies in aerospace manufacturing.

In conclusion, this research contributes to the broader understanding of machining processes, offering practical insights and recommendations for optimizing operations in aerospace component manufacturing. The intricate dance between cutting parameters and material behavior underscores the necessity for a holistic approach, ensuring that each facet of the machining process harmonizes to produce components of the highest quality and precision

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