UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ANALYSIS RESPONSE DATA (SURFACE ROUGHNESS) OF TURNING TITANIUM ALLOY WITH MQL AND CRYOGENIC COOLANTS

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MASTER OF MANUFACTURING ENGINEERING (INDUSTRIAL ENGINEERING)

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Faculty of Technology and Manufacturing Industry Engineering

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**A master project submitted
in partial fulfillment of the requirements for the degree of
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DECLARATION

I declare that this master project entitled "Analysis Response Data (Surface Roughness) of Turning Titanium Alloy with MQL and Cryogenic Coolants " is the result of my own research except as cited in the references. The master project has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :...

Name : Ikhwan Nasir bin Ibrahim

Date :...

APPROVAL

I hereby declare that I have read this master project and in my opinion this master project is sufficient in terms of scope and quality as a partial fulfillment of Master of Manufacturing Engineering (Industrial Engineering)

Signature : ....

Supervisor Name : Associate Professor Dr. Mohd Amri bin Sulaiman

Date : ....

DEDICATION

All the praises and thanks to Allah S.W.T for His Guideness and Enlightment.

I dedicate my dissertation with heartfelt gratitude to my beloved family and dear friends. I wish to express my deepest appreciation to my loving parents, Mrs. Mahiran and Mr. Ibrahim. Though they are no longer with me, their cherished memories continue to guide and shape my life. Their words of encouragement and unwavering insistence on perseverance remain ever-present in my thoughts. I extend my heartfelt gratitude to my spouse, Mrs. Fathen Natasha, for her unwavering support and encouragement throughout the challenging moments of my master's studies and daily life. Her assistance in completing this project, her guidance on how to move forward, and her thoughtful feedback have been invaluable. I am deeply grateful for her presence in my life. To my two wonderful children, your presence fills my life with immense joy and inspiration. You remind me daily of the value of perseverance and dedication, motivating me to strive for the best in all that I do. To my dear friends and cherished companions, thank you for being by my side through both the challenges and the triumphs. Your unwavering support and friendship have been invaluable throughout this journey.

ABSTRACT

Titanium alloys are valued for their exceptional strength-to-weight ratio, which remains stable even at high temperatures. In the aerospace industry, when manufacturing critical structural components to ensure high reliability, surface roughness plays a key role in assessing the quality of the finished machined surfaces. Titanium alloys are known for their excellent mechanical properties, but their machinability is challenging due to poor thermal conductivity and rapid tool wear. Advanced cooling techniques like MQL and cryogenic cooling offer potential solutions to these issues. This project compares the influence of Minimum Quantity Lubrication (MQL) and cryogenic CO2 cooling together with cutting parameter contribution on the surface roughness of titanium alloy (Ti-6Al-4V ELI) during the turning process. The study involved conducting experiments on titanium alloy (Ti-6Al-4V ELI) cylindrical bar using CNC lathe with uncoated carbide insert by varying cutting speeds, feed rates, and depths of cut. Surface roughness measurements were taken in real time using a portable surface roughness tester. The experimental design followed the Response Surface Methodology (RSM) using Box-Behnken by Design Expert 6.0.8 software, which enabled to determine the significant factors onto the output. The results demonstrated that MQL consistently provided superior surface quality under most machining conditions and feed rate emerged as the most critical factor with lower feed rates producing better surface finishes. This research underscores the importance of adopting advanced cooling techniques in machining processes, particularly for aerospace and biomedical applications where precision and surface integrity are critical.

ANALISIS DATA RESPONS (KEKASARAN PERMUKAAN) MELARIK ALOI TITANIUM DENGAN MQL DAN PENYEJUK KRIOGENIK

ABSTRAK

Aloi titanium dihargai kerana nisbah kekuatan kepada beratnya yang luar biasa, yang kekal stabil walaupun pada suhu tinggi. Dalam industri aeroangkasa, apabila menghasilkan komponen struktur kritikal untuk memastikan kebolehpercayaan yang tinggi, kekasaran permukaan memainkan peranan penting dalam menilai kualiti permukaan yang telah diproses. Aloi titanium terkenal dengan sifat mekanikalnya yang cemerlang, tetapi kebolehnesinannya mencabar disebabkan oleh kekonduksian terma yang lemah dan kehausan alat yang cepat. Teknik penyejukan maju seperti MQL dan penyejukan kriogenik menawarkan penyelesaian berpotensi kepada masalah ini. Projek ini membandingkan pengaruh Pelinciran Kuantiti Minimum (MQL) dan penyejukan CO2 kriogenik bersama dengan sumbangan parameter pemotongan terhadap kekasaran permukaan aloi titanium (Ti-6Al-4V ELI) semasa proses pengilangan. Kajian ini melibatkan eksperimen ke atas bar silinder aloi titanium (Ti-6Al-4V ELI) menggunakan mesin pelarik CNC dengan sisipan karbida tanpa salutan dengan memvariasikan kelajuan pemotongan, kadar suapan, dan kedalaman pemotongan. Pengukuran kekasaran permukaan diambil secara langsung menggunakan alat penguji kekasaran permukaan mudah alih. Reka bentuk eksperimen mengikuti Kaedah Permukaan Respons (RSM) menggunakan Box-Behnken melalui perisian Design Expert 6.0.8, yang membolehkan menentukan faktor-faktor yang signifikan terhadap output. Hasilnya menunjukkan bahawa MQL secara konsisten memberikan kualiti permukaan yang lebih baik di bawah kebanyakan keadaan pemesinan dan kadar suapan muncul sebagai faktor yang paling kritikal dengan kadar suapan yang lebih rendah menghasilkan kemasan permukaan yang lebih baik. Penyelidikan ini menekankan kepentingan menggunakan teknik penyejukan maju dalam proses pemesinan, terutamanya untuk aplikasi aeroangkasa dan bioperubatan di mana ketepatan dan integriti permukaan adalah kritikal.

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LIST OF ABBREVIATIONS

UTeM	-	Universiti Teknikal Malaysia Melaka
AM	-	Additive Manufacturing
CO2	-	Carbon Dioxide
DOE	-	Design of Experiment
doc	-	Depth of Cut
ELI	-	Extra Low Interstitial
LN2	-	Liquid Nitrogen
MQL	-	Minimal Quantity Lubrication
PCBN	-	Polycrystalline Cubic Boron Nitride
PVD	-	Physical Vapor Deposition
RSM	-	Response Surface Methodology

LIST OF SYMBOLS

Al	-	Aluminum
C	-	Carbon
Fe	-	Iron
f	-	Feed Rate
H	-	Hydrogen
N	-	Nitrogen
O	-	Oxygen
Ra	-	Surface Roughness
V	-	Cutting Speed
Ti	-	Titanium
°C	-	Degree Celsius

CHAPTER 1

INTRODUCTION

1.1 Background

Titanium alloys represent a significant category of materials that combine excellent mechanical properties with various applications, from aerospace to biomedical devices. Known for their outstanding strength-to-weight ratio, corrosion resistance, and ability to withstand high temperatures, titanium alloys have a low density, approximately half that of steel, making them ideal for applications where weight is critical (Peters et al., 2003). Despite their benefits, titanium alloys present significant challenges in machining due to their poor thermal properties, rapid tool wear, and susceptibility to galling during processing. Recent studies have identified several cooling techniques that improve productivity, surface integrity, and tool life when machining titanium alloys. Notably, cryogenic cooling methods, such as the use of liquid nitrogen, have shown promising results in enhancing tool life and reducing thermal effects during high-speed cutting (Aramcharoen, 2016). Furthermore, adopting minimal quantity cooling lubrication (MQL) strategies introduces an environmentally friendly option that supports effective heat dissipation and reduces adverse environmental impacts (Pervaiz et al., 2017). These advanced cooling techniques collectively contribute to the enhanced machinability of titanium alloys, offering both operational and environmental benefits.

In the turning process of titanium alloys, surface roughness is a critical quality characteristic that significantly impacts the performance and longevity of machined parts, especially in high-stress applications like aerospace and biomedical implants. Research focuses on optimizing the cutting parameters to achieve the best possible surface finish. Feed rate is consistently found to be the most influential factor on surface roughness in the turning of titanium alloys. Higher feed rates generally increase roughness, while higher cutting speeds and greater depths of cut tend to improve the surface finish. The use of response surface methodology allows for the development of predictive models that relate these parameters to surface roughness outcomes, helping optimize the turning process for better results (Ramesh, Karunamoorthy, & Palanikumar, 2012). The choice of tool material and coatings also plays a significant role. Uncoated tools may perform better at lower cutting speeds, whereas PVD-coated tools are more suitable for high-speed conditions, helping minimize surface roughness while maintaining machining effectiveness (Ramana & Aditya, 2017). The selection and application of coolants also play a pivotal role in enhancing tool life and machining efficiency. Various studies have demonstrated that different coolant methods, such as high-pressure coolant, minimum quantity lubrication (MQL), and cryogenic techniques, significantly affect the machinability of titanium alloys.

Minimum Quantity Lubrication (MQL) is an innovative technology in the machining industry that aims to minimize the environmental and health impacts associated with traditional flood coolant systems while improving machining performance. MQL, also known as micro-lubrication, emerged as a response to the environmental and health challenges posed by conventional flood cooling methods, which use large quantities of coolant. The primary idea behind MQL is to use significantly reduced quantities of lubricant, typically in the form of an aerosol or mist directed precisely at the cutting zone (Boubekri & Shaikh, 2014). Initially, MQL employed simple oil-based fluids, but recent advancements have introduced nanofluids and eco-friendly lubricants like vegetable oils, which further reduce the ecological footprint and improve thermal conductivity and lubrication properties (Lv et al., 2018; Fernando et al., 2019). MQL has found applications across various machining operations, including drilling, milling, and turning, particularly in industries like automotive and aerospace, where precision and environmental considerations are paramount (Filipovic & Stephenson, 2006). MQL significantly reduces the volume of coolant used, which decreases chemical waste and exposure, contributing to a safer and cleaner work environment (Boubekri & Shaikh, 2014). By reducing coolant use, MQL lowers the costs of coolant purchase, maintenance, and disposal. The precision application of lubricant reduces wastage (Filipovic & Stephenson, 2006). MQL can improve tool life and surface finish by directly providing efficient lubrication and cooling to the tool-workpiece interface. This targeted approach helps manage the heat and reduce tool wear effectively (Lv et al., 2018).

Cryogenic cooling in machining is a sophisticated technique involving liquefied gases such as liquid nitrogen (LN2) and carbon dioxide (CO2) to significantly reduce the temperatures in the cutting zone. This method has gained attention due to its potential to enhance machining performance by improving tool life, reducing tool wear, and achieving a better surface finish. Cryogenic CO2 cooling involves using carbon dioxide in its solid or gaseous state to reduce the machining zone temperatures significantly. This method has become a focus of interest due to CO2's properties of sublimating directly from solid to gas, which absorbs a considerable amount of heat from the surrounding environment, thus cooling the tool and workpiece effectively. The development of CO2 cryogenic cooling systems has evolved with improvements in delivery mechanisms that ensure precise application and effective management of the coolant. The systems are designed to maximize the heat absorption characteristics of CO2, minimizing thermal damage to the cutting tools and improving the machinability of difficult-to-cut materials (Proud et al., 2022; Pereira et al., 2022). Studies have shown that cryogenic CO2 can significantly reduce cutting temperatures, leading to lower tool wear and improved surface finish. This cooling method is particularly effective in machining heat-resistant alloys, where traditional coolants might not be effective (Tapoglou et al., 2017). Using CO2 as a cryogenic coolant aligns with sustainable manufacturing goals by reducing the reliance on oil-based coolants, which pose environmental and health risks. CO2 is non-toxic and provides an eco-friendly alternative, contributing to safer workplace conditions and reduced environmental impact. The adoption of CO2 cryogenic cooling can lead to cost savings by extending tool life and reducing the frequency of tool changes. Additionally, the reduced need for disposal of hazardous waste associated with traditional coolants can lead to further economic benefits (Jerold & Kumar, 2012).

1.2 Problem Statement

Titanium alloys are extensively utilized in the aerospace industry owing to their superior strength-to-weight ratio and ability to withstand high temperatures. These properties make titanium alloys ideal for critical aerospace components such as engine parts, airframes, and landing gear. However, the very properties that make titanium alloys valuable also make them challenging to machine. The high strength of the material leads to significant tool wear, and its low thermal conductivity causes high temperatures during machining, which can adversely affect the tool life and the quality of the machined surface.

In aerospace manufacturing, the quality of machined components is paramount as it directly influences the reliability and functionality of the aerospace vehicles. Surface finish, in particular, is a critical quality parameter. A superior surface finish enhances the fatigue resistance, corrosion resistance, and overall performance of the titanium alloy components. Achieving an optimal surface finish requires precise control over the machining parameters, among which the choice of coolant plays a crucial role.

Traditionally, the machining of titanium alloys has relied heavily on flood cooling with substantial amounts of cutting fluids. While effective in reducing tool wear and controlling heat, these fluids pose significant environmental and health hazards. The chemicals in these fluids can be harmful to workers, leading to skin and respiratory issues, and their disposal raises environmental concerns due to potential contamination of water sources and soil. This scenario necessitates the exploration of safer and more environmentally friendly cooling methods.

In response to the drawbacks of traditional flood cooling, advanced techniques such as Minimum Quantity Lubrication (MQL) and cryogenic cooling using CO2 have been developed. MQL involves the use of a minimal amount of lubricant, which is precisely applied to the cutting zone, significantly reducing the amount of fluid used and the associated disposal problems. Cryogenic cooling, on the other hand, uses liquefied gases like CO2 to cool the cutting area drastically. This approach not only decreases the amount of heat transferred to the tool and workpiece but also completely removes the need for chemical coolants.

Despite the potential benefits of MQL and cryogenic CO_2, comprehensive comparative data on their effectiveness in machining titanium alloys is scarce. Each method has its advantages and trade-offs in terms of tool life, surface finish quality, environmental impact, and operational costs. There is a critical need to systematically investigate and compare these two cooling techniques under controlled and standardized conditions to determine their suitability for aerospace titanium alloy machining. Such a study would help in understanding whether the higher initial costs associated with setting up cryogenic cooling systems provide a balanced payoff in terms of better surface quality and reduced environmental impact, or if the simpler MQL approach offers a more cost-effective solution without significantly compromising the machining quality.

1.3 Research Question

Research questions are formulated to acquire the relevant data necessary to accomplish the objectives. The study encompasses three research inquiries:

i) How do Minimum Quantity Lubrication (MQL) and cryogenic CO_2 cooling methods compare in their effects on the surface roughness of titanium alloy Ti-6Al-4V ELI during the turning process?

ii) How do different cutting parameters (cutting speed, feed rate, depth of cut) affect the surface roughness when using MQL and cryogenic CO_2 cooling methods?

1.4 Research Objective

The objectives of this study are as follows:

i) To conduct a comprehensive comparative analysis between Minimum Quantity Lubrication (MQL) and cryogenic CO2 coolant in the machining of titanium alloys, focusing on their effects on surface roughness.

ii) To analyze the cutting parameter contribution onto surface roughness for both MQL and cryogenic coolant.

1.5 Scope of Research

This study will specifically examine the use of MQL and cryogenic coolants in the machining of the titanium alloy Ti-6Al-4V ELI. The machining process will be performed using the straight turning method at the Universiti Teknikal Malaysia Melaka (UTeM) laboratory, utilizing the CNC Lathe Haas SL-20. The research will investigate how the characteristics of MQL and cryogenic cooling can enhance the surface roughness of the material. Surface roughness measurements will be taken using a portable device. The machining parameters evaluated will include cutting speed (ranging from 120 to 220 m/min), feed rate (ranging from 0.1 to 0.2 mm/rev), and depth of cut (ranging from 0.4 to 0.6 mm).

1.6 Master Project Outline

This master project report consists of five chapters, summarizing the study based on the provided objectives and proposed approach:

- Chapter 1: Introduction - This chapter provides an overview of the study's background, research problems, research questions, objectives, and scope
- Chapter 2: Literature review - This chapter includes relevant prior studies on the current applications of MQL and cryogenic cooling in the titanium alloy turning process.
- Chapter 3: Methodology - This chapter describes the study's approach toward achieving the objectives stated in Chapter 1, detailing the preparation of the experiment, testing methods, and studies of each sample.
- Chapter 4: Results and Discussion - This chapter presents the results obtained from the experiments and provides a detailed discussion of the findings. This includes the analysis of the impact of cutting parameters toward surface roughness for both types of coolants, along with the validation through model graphs using RSM.
- Chapter 5: Conclusion and Recommendations - This chapter summarizes the key findings of the research, discusses their implications for industrial applications, and provides recommendations for future research and practical improvements in the turning process for titanium alloy surface roughness quality.