EXPERIMENTAL STUDY ON THE EFFECT OF TOOL LIFE DURING THE MACHINING OF NIMONIC C-263 ALLOY USING CRYOGENIC COOLANT

MUHAMMAD IKHWAN BIN ROSLIM

MASTER OF SCIENCE IN MANUFACTURING ENGINEERING

2024

Faculty of Industrial and Manufacturing Technology and Engineering

Experimental Study on the Effect of Tool Life During the Machining of Nimonic C-263 Alloy Using Cryogenic Coolant

Muhammad Ikhwan Bin Roslim

Master of Science in Manufacturing Engineering

2024

EXPERIMENTAL STUDY ON THE EFFECT OF TOOL LIFE DURING THE MACHINING OF NIMONIC C-263 ALLOY USING CRYOGENIC COOLANT

MUHAMMAD IKHWAN BIN ROSLIM

A thesis submitted in fulfilment of the requirement for the degree of Master of Science in Manufacturing Engineering

Faculty of Industrial and Manufacturing Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

DEDICATION

This work is wholeheartedly dedicated to my parents, Khazlina Adzam Binti Abdol Aziz@Ismail and Roslim Bin Mohamad, who have been unwavering pillars of support throughout my journey. Their boundless love, tireless encouragement, and unwavering belief in me have been the cornerstone of my achievements.

In addition to my parents, I want to express my gratitude to my extended family and friends. Their collective love and encouragement have created a nurturing environment that allowed me to pursue my aspirations with confidence. Whether it was offering valuable insights, providing a listening ear during challenging times, my family's presence has been a constant source of strength and joy. Thank you.

ABSTRACT

Nimonic C-263, a nickel-based alloy, has gained prominence in aerospace and high-temperature applications due to its exceptional properties. However, its low thermal conductivity poses challenges during machining, leading to rapid tool wear and reduced tool life. Traditional flood lubrication methods have been insufficient in addressing these issues. The difficulty in machining Nimonic C-263 alloy arises from the extreme heat generated due to its low thermal conductivity, impacting tool wear and fatigue life. Conventional flood lubrication methods have proven inadequate in mitigating the challenges posed by machining this alloy. This research focuses on evaluating the impact of cutting parameters on tool life during turning of Nimonic C-263 superalloy using cryogenic coolant, specifically Carbon dioxide (CO2) gas. A Physical Vapor Deposition (PVD) cemented carbide insert is employed as the cutting tool on a Computer Numerical Control (CNC) Haas ST-20 lathe machine. Response Surface Methodology (RSM) is utilized to design experiments that investigate the influence of feed rate, cutting speed, and depth of cut on the longevity of coated carbide inserts. The tool life calculation was based on tool wear progression and the cumulative tool travels per minutes. The study reveals that cutting speed significantly influences tool life, followed by feed rate and depth of cut according to Analysis of Variance (ANOVA). The experiment demonstrates that the Physical Vapor Deposition (PVD) coated carbide insert exhibits a maximum tool life of 26.81 minutes and a minimum of 3.56 minutes. The developed mathematical model validated as the percentage error 8.08%. 61 mm/s of cutting speed, 0.15 m/rev of feed rate and 0.5 mm of depth of cut are the optimum parameter of the cryogenic cooling machining of Nimonic C-263. Flank wear and fracture wear are identified as primary tool failure mode affecting cutting tools, with abrasion and diffusion being tool wear mechanisms observed.

KAJIAN UJIKAJI KE ATAS KESAN JANGKA HAYAT SEMASA PEMESINAN ALOI NIMONIC C-263 MENGGUNAKAN PENYEJUK KRIOGENIK

ABSTRAK

Nimonic C-263, sejenis aloi berasaskan nikel, telah mendapat keutamaan dalam aplikasi aeroangkasa dan suhu tinggi disebabkan sifat-sifatnya yang luar biasa. Walau bagaimanapun, kekonduksian haba yang rendah menyebabkan cabaran semasa pemesinan, menyebabkan haus alat yang cepat dan mengurangkan jangka hayat alat. Kaedah pelinciran banjir tradisional tidak mencukupi dalam menangani isu-isu ini. Kesukaran dalam pemesinan aloi Nimonic C-263 timbul daripada haba yang melampau yang dihasilkan disebabkan kekonduksian haba yang rendah, memberi kesan kepada haus alat dan jangka hayat kelesuan. Kaedah pelinciran banjir konvensional terbukti tidak mencukupi dalam mengurangkan cabaran yang dihadapi semasa memotong aloi ini. Penyelidikan ini memberi tumpuan kepada menilai kesan parameter pemotongan ke atas jangka hayat alat semasa pusingan Nimonic C-263 superaloi menggunakan bahan penyejuk kriogenik, khususnya gas Karbon dioksida (CO_2). Sisipan karbida simen salutan Wap Fizikal (PVD) digunakan sebagai alat pemotong pada mesin larik Kawalan Berangka Komputer (CNC) Haas ST-20. Kaedah Permukaan Tindak Balas (RSM) digunakan untuk mereka bentuk eksperimen yang menyiasat pengaruh kadar suapan, kelajuan pemotongan, dan kedalaman potongan ke atas ketahanan sisipan karbida bersalut. Pengiraan jangka hayat alat berdasarkan kemajuan haus alat dan jumlah perjalanan alat per minit. Kajian ini mendedahkan bahawa kelajuan pemotongan sangat mempengaruhi jangka hayat alat, diikuti oleh kadar suapan dan kedalaman potongan mengikut Analisis Varians (ANOVA). Eksperimen menunjukkan bahawa mata alat karbida bersalut Pemendapan Wap Fizikal (PVD) mempamerkan jangka hayat alat maksimum 26.81 minit dan minimum 3.56 minit. Model matematik yang dibangunkan disahkan sebagai ralat peratus 8.08%. 61 mm/s kelajuan pemotongan, 0.15 mm/rev kadar suapan dan 0.5 mm kedalaman potongan adalah parameter optimum pemesinan penyejukan kriogenik Nimonic C-263. Haus rusuk dan haus pecah dikenal pasti sebagai mod kegagalan alat utama yang menjejaskan alat pemotong, dengan lelasan dan resapan sebagai mekanisme haus alatan diperhatikan.

ACKNOWLEDGEMENT

All praise is due to Allah (S.W.T), whose divine will has enabled me to successfully complete this research paper. I send peace and blessings upon our Prophet Muhammad Sallallahu A'laihi Wa Sallam (S.A.W), a great leader in the world. Without his exemplary patience and courage, I would not have had the strength and role model to navigate the challenges and achieve success in all my endeavours.

I extend my heartfelt appreciation to Universiti Teknikal Malaysia Melaka (UTeM), particularly the Faculty of Industrial and Manufacturing Technology and Engineering (FTKIP) and the School of Postgraduate Studies (SPS), for granting me the invaluable opportunity to conduct my research and for facilitating my growth as a researcher.

Foremost among my expressions of gratitude are reserved for my family, especially my beloved parents. Your unwavering support sacrifices and willingness to lend a listening ear to my problems and stories have made you my best friends. May Allah bestow His blessings upon both of you for your boundless love and encouragement.

I would like to convey my deepest gratitude to my supervisors, Ir. Dr. Mohamad Ridzuan Bin Jamli, and Associate Prof. Dr. Mohd Amri Bin Sulaiman. Their wisdom, guidance, patience, advice, and unwavering assistance have been the guiding lights throughout this two-year journey. I am profoundly indebted to them for their continual moral support and encouragement."

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANOVA	-	Analysis of Variance
BUE	-	Build – Up Edge
CBN	-	Cubic Boron Nitride
CNC	-	Computer Numerical Control
CVD	-	Chemical Vapor Deposition
DOE	-	Design of Experiment
FESEM	-	Field Emission Scanning Electron Microscopy
HSS	-	High Speed Steel
ISO	-	International Organization for Standardization
JIS	-	Japanese Industrial Standards
MQL	-	Minimum Quantity Lubrication
PVD	-	Physical Vapour Deposition
RSM	-	Response Surface Method

LIST OF SYMBOLS

%	-	Percentage
°C	-	Degree Celsius
2FI	-	Two-Factor Interaction
Al2O3	-	Watt
C	-	Carbon
Co	-	Cobalt
CO_2	-	Carbon Dioxide
Cr	-	Chromium
m/min	-	Meter Per Minute
mm	-	Millimetre
mm/rev	-	Millimetre Per Revolution
N_2	-	Nitrogen
TiAlN	-	Titanium Aluminium Nitride
TiCN	-	Titanium Carbon Nitride
TiN	-	Titanium Nitride
V_b	-	Tool Wear
W	-	Tungsten

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis:

Roslim, M.I., Jamli, M.R., Ismail, A.E., and Rahman, M.A.A., 2022. Experimental Analysis on Machining Properties in Turning of Nimonic C-263. International Journal of Engineering Trends and Technology, 70 (11), 144–153.

Roslim, M. I., Jamli, M. R. and Sulaiman, M. A., 2023. Wear Mechanisms on Turning of Nimonic C-263 Under Cryogenic Conditions. Turkiye, 3rd Global Conference on Engineering Research, p. 6.

Roslim, M. I., Sulaiman, M. A, Jamli, M. R. Ismail, A.E., and Rahman, M.A.A., 2023. Effect of Surface Roughness in Dry Machining of Nimonic C-263. Material Energy Engineering for Sustainable Advancement Conference.

CHAPTER 1

INTRODUCTION

This chapter discusses the project background, problem statement, purpose, scope, importance and report's organization.

1.1 Project Background

Recently, a variety of applications for nickel-based superalloys have emerged, particularly in gas turbines and vital parts of aircraft engines as shown in Figure 1.1. (Thakur et al., 2016; Wang et al., 2017; Nasr et al., 2020) and mentioned that these alloys can be used in the defence, nuclear power, aerospace, as well as power plant industries as of their exceptional mechanical capabilities at excellent temperature strength, which includes tensile strength, high hardness, thermal stability, oxidation as well as thermal fatigue resistance to corrosion. Even in long-term, hot situations with tremendous stress, they can still work successfully. The aerospace industry was among the forerunners in the development of superalloy because jet engines which are stronger and more efficient, may result from the ability of the engine to tolerate greater temperatures (Kale and Khanna, 2017).

The excellent mechanical properties of Nimonic C-263, as well as other nickel-based alloys at high temperatures, including greater strength and increased hardness, have led to increased attention on their machining process (Tu et al., 2022). Nimonic C-263, in particular, is known for its admirable mechanical properties, including tensile strength, thermal fatigue resistance to corrosion, thermal stability, high hardness, as well as oxidation, which makes it a popular choice in the defence, aerospace as well as nuclear industries. Regardless of its excellent properties, Nimonic C-263 is a hard-to-cut material that has poor machinability, as mentioned by Jadhav et al. (2020). Due to the development of multiple phases at high temperatures, a chemical affinity for tool materials, a tendency to work harden, as well as the presence of hard and abrasive particles in its microstructure, the Nimonic C-263 material presents a variety of challenges during machining (Koyilada et al., 2016).

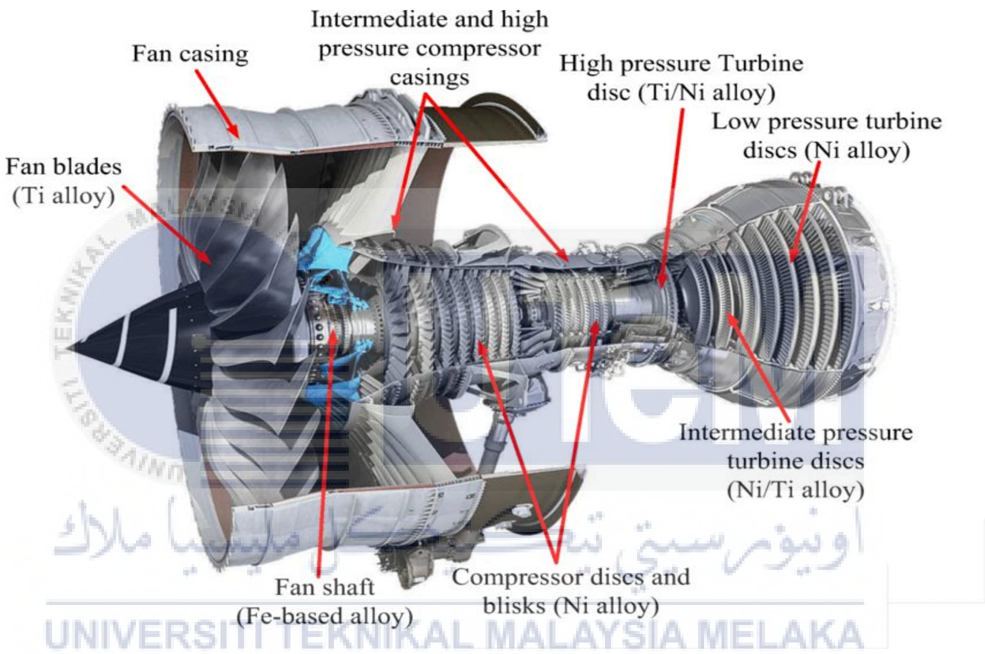

Figure 1.1 Engine parts made from nickel-based superalloy (Yin et al., 2020)

Work hardening and low thermal conductivity result in a heat concentration at the contact point between the cutting tool chip and the chip, resulting in thermomechanical stress. Materials with low thermal conductivity tend to retain heat rather than dissipate it efficiently. This leads to a rapid increase in temperature at the cutting edge of the tool during machining processes. Elevated temperatures accelerate tool wear by promoting thermal degradation and reducing the tool's hardness and wear resistance. As a result, the tool will deteriorate quickly. This has an impact on tool life and results in significant surface deterioration (Velmurugan et al., 2018). Because of the low thermal conductivity of nickel-based alloys, the cutting tool generates greater heat, particularly during harsh machining. The heat created while cutting raises the temperature of the cutting tool, which directly impacts the workpiece's surface quality and increases tool wear, which can lead to a reduction in cutting tool life. This wear can result in dimensional inaccuracy, surface damage, and severe corrosion cases on the workpiece, ultimately affecting the overall quality of the machined part (Ogedengbe et al., 2019). The temperature at the cutting tip, between the cutting tool and the workpiece, can reach 1000°C or higher, which influences not only the rate of tool wear but also the surface integrity of the workpiece, including residual stress, hardness, and surface roughness (Zhu et al., 2022).

In order to prolong the life of the cutting tool, it is essential to take the necessary measures to limit the heat generated on the tool and workpiece surface. It is recommended to use cutting fluid for cooling and lubrication while machining nickel-based alloys in order to dissipate the heat generated during machining, hence reducing tool wear and extending tool life. Exploring various types of cooling techniques can further aid in reducing the temperature in the cutting zone (Babu et al., 2024). Techniques such as cryogenic cooling, minimum quantity lubrication (MQL) and air/oil mist cooling have shown promise in effectively managing heat during machining processes as shown in Figure 1.2.

Cryogenic cooling involves the use of extremely cold gases or liquids to cool the cutting zone rapidly, minimizing heat generation and enhancing tool life. On the other hand, MQL systems deliver a small amount of lubricant directly to the cutting zone, reducing friction and heat buildup while minimizing fluid usage. Additionally, air/oil mist cooling combines compressed air with a fine mist of oil to provide efficient cooling and lubrication, offering benefits similar to traditional cutting fluids but with reduced environmental impact and cost (Boubekri and Shaikh, 2014).

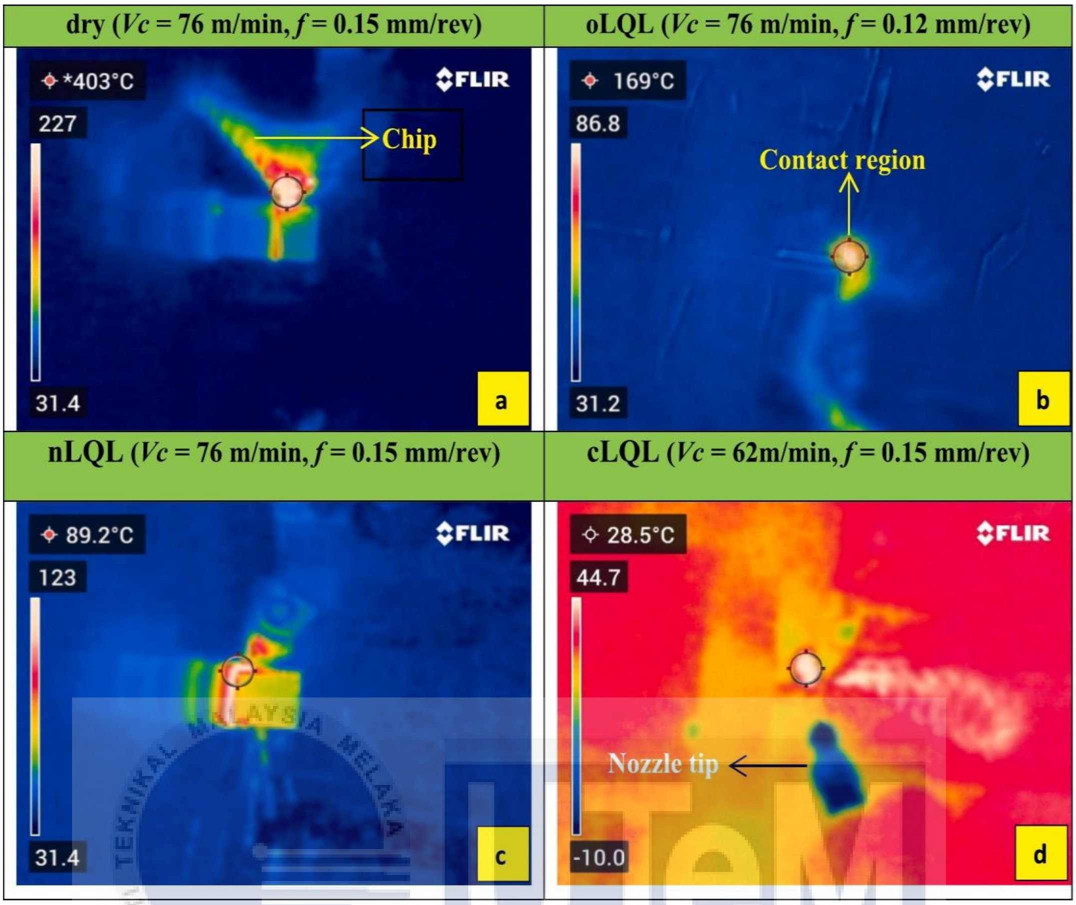

Figure 1.2 Heat generated under different cutting conditions (Babu et al., 2024)

Cryogenic cooling is an alternative to conventional cooling in machining that can boost the productivity of nickel-based alloy machining. Utilizing either liquid nitrogen (LN_2), or liquid carbon dioxide (CO_2), cryogenic machining involves freezing the cutting tool to extremely low temperatures of roughly −196 °C (Shokrani et al., 2013). Cryogenic machining is the process of metal removal operation utilizing cryogen-like liquefied nitrogen and carbon dioxide acting as coolants (Deshpande et al., 2018). In order to reject heat and reduce tool wear, cryogenic machining necessitates the incorporation of a cryogenic coolant right in the cutting zone. In a recent investigation by Babu et al. (2024), it was demonstrated that in the machining of Nimonic 80 under various machining conditions, cryogenic Low Quantity Lubrication (CLQL) emerged as a highly effective technique for prolonging tool life when compared to alternative methods. The study revealed that cryogenic machining resulted in a substantial reduction of 68% in flank wear, surpassing the performance observed with oil-based Low Quantity Lubrication (LQL) conditions at 56% and nanofluids LQL conditions at 39%. This highlights the significant advantage of employing cryogenic CLQL in enhancing tool longevity and optimizing machining processes for improved efficiency and performance.

Utilizing liquid carbon dioxide as a cryogenic medium can improve chip surface quality by eliminating particle adherence (Ross and Manimaran, 2019). Researchers and machining industries are developing interest in the use of cryogenic coolants as cutting fluids due to their eco-friendliness, recyclability, and lack of negative effects on the machining operators (Ravi and Gurusamy, 2020). Cryogenic cooling reduces the cutting temperature in the metal cutting process by using cryogenic fluids as coolants, which can greatly enhance machining quality and save the cost of manufacturing. In contrast to conventional cutting fluids, carbon dioxide (CO_2) offers a range of advantages as a coolant. CO_2 is characterized by its non-toxic and non-flammable nature, along with the absence of hazardous waste generation. Additionally, CO_2 is easily accessible and can be sourced from the by-products of various processes, rendering it a cost-efficient and environmentally sustainable coolant option as highlighted in studies by Jerold and Kumar (2011).

This study delves into the intricate relationship between tool life and the machining process of Nimonic C-263 alloy when employing cryogenic coolant. By exploring this dynamic, the research aims to not only enhance the understanding of machining practices for advanced materials but also to offer practical insights for optimizing tool longevity and efficiency in industrial applications. The anticipated findings are poised to fill a critical gap in knowledge within the field of high precision machining industry, providing a foundation for future advancements in machining technologies. Through a systematic analysis of the data collected, this study seeks to contribute valuable information that can guide decision-making processes in industries working with high-performance alloys like Nimonic C-263, ultimately driving innovation and efficiency in machining operations.

1.2 Problem Statement

A nickel-based alloy such as Nimonic C-263 has poor machinability due to its low thermal diffusivity, high strength at higher temperatures, tendency to harden, coarse and stiff particles in its microstructure, and chemical affinity towards cutting tool materials. In conventional machining, nickel-based alloys have approximately one-fifth to one-third the strength of steel due to their lower heat conductivity coefficient. The cutting heat cannot be rapidly transferred, and the temperature in the cutting zone can reach over 1200 °C instantaneously (Mohan et al., 2022). At elevated temperatures, the nickel-based alloy's elastic modulus decreases (Gowthaman and Jagadeesha, 2019). During cutting, the rebound degree of the treated surface and the contact stress, both increases. Simultaneously, the actual contact area between the tool flank and the processed face of the workpiece increased, as did tool flank wear. In addition, the cutting force, cutting performance, material brittleness, as well as tensile strength all decrease, impacting the alloy brittleness in the cutting area (Wang et al., 2017).

Traditional machining methods struggle to efficiently dissipate heat and control temperatures during cutting processes on Nimonic C-263 alloy. Cryogenic coolant emerges as a viable solution to the intricate challenges encountered in machining Nimonic C-263 alloy when compared to dry machining, flood machining, and minimum quantity lubrication (MQL) methods. Hence, to reduce the temperature, cryogenic coolant has been introduced to overcome the machining difficulties. Carbon dioxide cryogenic coolant has been introduced in this study due to its superior cooling effect rather than liquid nitrogen (Jamil et al., 2021). Carbon dioxide owing higher temperature than nitrogen can help prevent catastrophic failure during early stage of the machining. Extreme cool temperature can affect the property of the cutting insert in term of brittleness.

Other than cooling strategy, the optimization of cutting parameters in the turning machining process is crucial, as they directly impact the quality of the finished product. Cutting speed, feed rate and depth of cut are the primary variables that influence the machining process. However, there is a significant research gap in optimizing these parameters to achieve optimal productivity, quality and cost-effectiveness. Specifically, there is a need for further investigation into how to optimize cutting speed, feed rate and depth of cut to reduced tool wear and enhanced tool life, which can significantly improve the overall machining process.

Previous studies have investigated the effects of various cutting parameters on tool wear and surface integrity when turning Nimonic C-263 using different cutting tools and coolants. However, there is a lack of research specifically focusing on the use of CO_2 cryogenic coolant and its impact on tool life during the turning of this superalloy. Hence, the current study, the effect of cryogenic cooling during machining on tool life, tool wear progression and tool wear mechanisms was investigated. The PVD coated carbide insert is used during the turning process of Nimonic C-263 and carbon dioxide is used as cryogenic coolant.

1.3 Objectives

The objectives are the following:

1. To evaluate the effect of cutting parameters (cutting speed, feed rate and depth of cut) on tool life during turning of Nimonic C-263 Superalloy using cryogenic coolant.
2. To determine the optimized cutting parameters and develop mathematical model for tool life.
3. To analyse tool failure mode and tool wear mechanism on the cutting tool.