

**DISSERTATION**

**MODELLING AND OPTIMISATION OF MILLING PROCESS ON  
THIN-WALLED Ti64 UNDER CARBON DIOXIDE CRYOGENIC  
USING RESPONSE SURFACE METHODOLOGY AND GENETIC  
ALGORITHM**



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**ENGINEERING SCIENCE PROGRAM STUDY  
DOCTORAL PROGRAM  
FACULTY OF ENGINEERING  
SRIWIJAYA UNIVERSITY  
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## ENDORSEMENT PAGE

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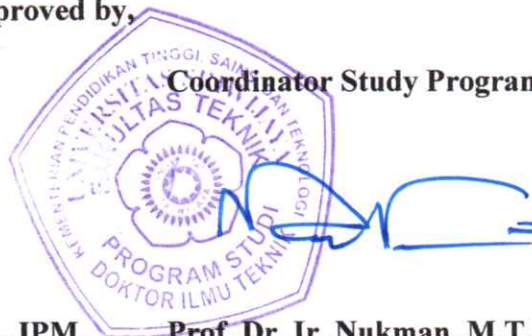
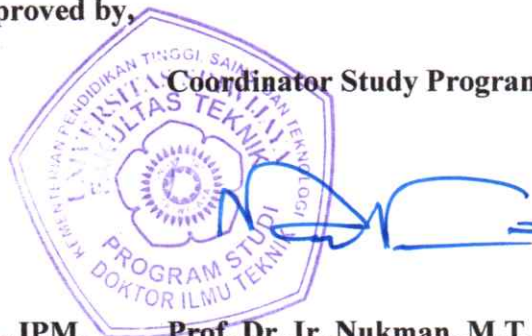
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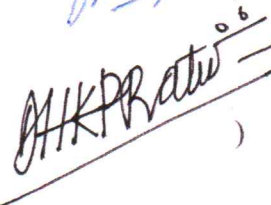
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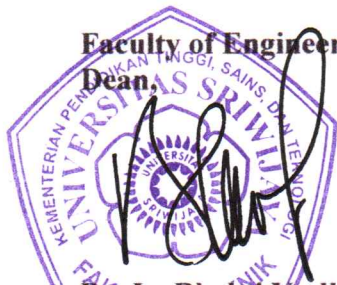
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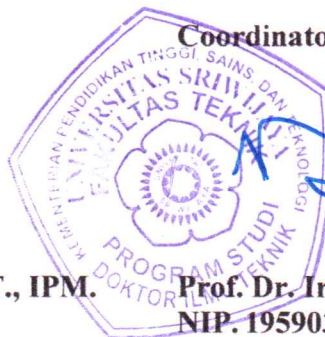
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I hereby declare that my dissertation entitled “Modelling and Optimisation of Milling Process on Thin-Walled Ti64 under Carbon Dioxide Cryogenic using Response Surface Methodology and Genetic Algorithm” is free from fabrication, falsification, plagiarism, unauthorized authorship, conflicts of interest, and multiple submissions, as stipulated in the Regulation of the Minister of Education, Culture, Research, and Technology of the Republic of Indonesia Number 39 of 2021.

Should any inconsistency with the above be found, I am willing to accept academic sanctions from Universitas Sriwijaya under the prevailing regulations.

This statement is made truthfully and sincerely.

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Sincerely,



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## PREFACE

Alhamdulillah, all praise be to Allah SWT for His blessings, guidance, and mercy that have enabled the completion of this dissertation entitled *"Modelling and Optimisation of Milling Process on Thin-Walled Ti64 under Carbon Dioxide Cryogenic using Response Surface Methodology and Genetic Algorithm."*

The dissertation report is a prerequisite for achieving a Doctoral degree in the Engineering Science Study Program at the Faculty of Engineering, Sriwijaya University. This research was conducted to address the machining challenges of aerospace-grade titanium alloys by integrating an environmentally sustainable cooling approach, CO<sub>2</sub> cryogenic cooling, with advanced optimisation techniques. Surface Methodology (RSM) was employed to develop predictive models, while the Genetic Algorithm (GA) was implemented to determine the optimal cutting conditions. The findings of this study are anticipated to offer significant contributions to both academia and industry in promoting sustainable machining practices for high-performance aerospace materials.

The completion of this report was delayed due to the COVID-19 pandemic. Nevertheless, with the unwavering support of my family, the valuable advice of my friends, and the guidance of my supervisor and co-supervisor, I was able to restore my enthusiasm and confidence, which ultimately enabled me to bring this work to completion.

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Palembang, 30 August 2025

The Author

## SUMMARY

This dissertation presents an in-depth investigation into the cryogenic machining performance of thin-walled Ti6Al4V (Ti64) alloy using carbon dioxide (CO<sub>2</sub>) as a sustainable cooling medium. The research aims to improve surface quality while minimizing environmental impact by replacing conventional cutting fluids with cryogenic CO<sub>2</sub>. Both uncoated and AlCrN-coated carbide end mills were used to assess the influence of key machining parameters including cutting speed ( $V_c$ ), feed rate ( $f_z$ ), radial depth of cut ( $a_r$ ), and axial depth of cut ( $a_x$ ) on surface roughness (Ra). A Central Composite Design (CCD) with 30 experimental runs was implemented, and surface roughness was measured at multiple axial depths on each workpiece. The optimization and modeling were carried out using Response Surface Methodology (RSM) and Genetic Algorithm (GA), with the aim of predicting optimal cutting conditions and minimizing Ra. For uncoated tools, the RSM model predicted a minimum surface roughness of 0.158  $\mu\text{m}$ , while GA slightly improved it to 0.1568  $\mu\text{m}$  after 64 generations. In contrast, coated tools significantly enhanced machining performance, producing a minimum Ra of 0.132  $\mu\text{m}$  through RSM and further reduced to 0.12725  $\mu\text{m}$  by GA within 96 generations, representing an 18.8% improvement over uncoated tools. The feed rate was found to be the most influential factor in both tool conditions, while cutting speed also contributed positively to surface quality. Although RSM models yielded higher predictive accuracy based on lower Mean Square Error (MSE), GA consistently produced lower Ra values, demonstrating superior global optimization capabilities. The application of AlCrN coating also helped suppress tool wear and thermal degradation, contributing to smoother surface finishes and greater process stability. Overall, the combination of CO<sub>2</sub> cryogenic cooling, advanced tool coating, and hybrid optimization techniques (RSM-GA) proves to be highly effective for the precision machining of thin-walled Ti64 alloy. This approach not only enhances surface integrity and tool life but also supports the broader goal of sustainable manufacturing by reducing dependence on traditional oil-based coolants. The findings offer valuable insights for machining difficult-to-cut aerospace materials and provide a foundation for integrating green technologies into high-performance manufacturing systems. This research contributes to the evolving field of intelligent, eco-friendly machining and sets the stage for further exploration of cryogenic processes in advanced material applications.

**Keywords:** Titanium Alloy, Thin-Walled, Surface Roughness, Cryogenic, RSM, GA



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# **CHAPTER 1**

## **INTRODUCTION**

### **1.1 Overview**

This study investigates the machining performance of thin-walled Ti64 alloy under carbon dioxide-based cryogenic cooling. Both coated and uncoated cutting tools are considered in the experimental setup. To analyze the influence of key machining variables on surface quality and process efficiency, Response Surface Methodology (RSM) and Genetic Algorithm (GA) are employed in combination, serving both as modelling frameworks and optimisation techniques to determine the most effective parameter settings..

### **1.2 Background of the Problems**

The manufacturing industry continually seeks to improve productivity while maintaining high product quality. One of the primary challenges in metal cutting processes is the generation of excessive heat at the tool and workpiece interface. This thermal buildup can negatively affect dimensional accuracy, accelerate tool wear, and degrade surface finish. Although conventional cutting fluids are widely used to manage this heat, their effectiveness diminishes at elevated cutting speeds, particularly because they struggle to reach the critical contact zone (Dhar, et al., 2006). Moreover, traditional oil-based coolants pose environmental and health risks. Their disposal can lead to soil and water contamination, and their use increases operational costs due to the need for complex storage, circulation, and filtration systems. Consequently, there is a growing demand for more sustainable and efficient cooling methods in machining operations.(Dilip Jerold and Pradeep Kumar, 2011).

Cryogenic cooling has emerged as a viable alternative. Utilizing extremely low-temperature substances such as liquid nitrogen or carbon dioxide, this approach efficiently removes heat from the cutting zone (Tazehkandi, et al., 2015). Carbon dioxide at  $-78.5^{\circ}\text{C}$  and liquid nitrogen at  $-196^{\circ}\text{C}$  can significantly enhance tool life and surface quality by maintaining lower temperatures during the cutting process (MacHai and Biermann, 2011; Pusavec, et al., 2014)

With increased global emphasis on environmentally friendly manufacturing, green machining practices are becoming more prevalent. Cutting fluids can contribute up to 20% of total production costs, making their reduction economically attractive. While complete elimination of cutting fluids is not yet feasible, cryogenic methods offer a path toward cleaner machining without compromising performance. (Maruda, et al., 2016; Fernández, et al., 2014).

Though cryogenic machining has historical roots Reitz first reported the use of  $\text{CO}_2$  in 1919 it has seen renewed interest due to advancements in delivery systems and a greater focus on sustainability (Jawahir, et al., 2016). Compared to conventional coolants, cryogenic cooling offers superior thermal control, lower ecological impact, and potential cost reductions (Dilip Jerold and Pradeep Kumar, 2012). Numerous studies confirm that liquid nitrogen effectively reduces tool wear when machining materials like AISI 4140, while  $\text{CO}_2$  has demonstrated excellent performance in facilitating chip removal. Surface quality remains a key indicator of machining success, with attributes such as residual stress and roughness serving as critical benchmarks. These are influenced by factors including machining technique, tool type, and process parameters. (Kaynak and Gharibi, 2018).

Surface quality plays a vital role in assessing the durability and performance of machined components throughout their service life (Kenda, et al., 2011; Ulutan and Ozel, 2011). It is commonly evaluated using parameters such as surface roughness and residual stress, which offer insights into the functional performance of a machined surface (Pusavec, et al., 2011; Umbrello, et al., 2012). Several factors can influence surface quality, including the selected cutting process, the type and condition of machine tools, the cutting parameters



applied, and the specific machining environment. These elements must be carefully controlled to ensure optimal surface integrity and product reliability (Benardos and Vosniakos, 2003).

To systematically improve machining processes, researchers have moved away from empirical approaches toward data-driven modelling and optimisation. RSM provides a structured method for developing mathematical models that describe the interactions among process variables. GA, in turn, is well-suited for exploring large solution spaces to identify optimal parameter combinations. (Mokhtari Homami, et al., 2014; Pereira and Delijaicov, 2019). Statistical modelling and computational techniques estimate the machining process's surface integrity variables using a cryogenic cooling system (Jawahir, et al., 2016). Instead of relying solely on trial-and-error experimentation, machining processes can be optimized through mathematical modelling. Statistical and computational tools like RSM and GA are useful in predicting outcomes and guiding decision-making. These methods are especially relevant when machining advanced materials like titanium alloys, which are commonly used in aerospace applications.

### **1.3 Statement of The Problems**

Thin-walled components are widely used in aerospace, energy, and precision engineering due to their high strength to weight ratio and structural flexibility. Typically fabricated through additive manufacturing, these parts require high-precision finishing processes to meet functional requirements. However, machining thin-walled structures made of titanium alloys presents challenges such as deformation, poor surface finish, and rapid tool wear. (Isaev, et al., 2016). The selection of appropriate cutting tools and cooling strategies becomes crucial in addressing these issues. Both coated and uncoated tools behave differently under cryogenic conditions, influencing the machining response. Therefore, it is essential to establish predictive models and optimize

machining parameters to improve overall process reliability. This study employs RSM and GA not only to model the machining performance but also to achieve multi-parameter optimisation.

#### **1.4 Objectives of The Study**

This study aims to:

1. Develop predictive models using RSM to evaluate the effects of machining parameters on CO<sub>2</sub>-based cryogenic machining of thin-walled Ti64 alloy, utilizing both coated and uncoated cutting tools..
2. Apply RSM and GA to identify the optimal combination of process parameters for improved machining outcomes.
3. Validate the accuracy of the predictive models through experimental trials, using mean square error (MSE) as the performance metric.

#### **1.5 Significance of The Study**

This study contributes to the field of sustainable manufacturing by examining the role of CO<sub>2</sub>-based cryogenic cooling in machining thin-walled Ti64 alloy. The findings demonstrate the potential of cryogenic systems to enhance surface finish, extend tool life, and reduce reliance on conventional lubricants. Furthermore, the combined use of RSM and GA provides a structured and effective approach to process optimisation, aligning with current trends in smart and green manufacturing.

## 1.6 Scopes of The Study

The scope of this study encompasses the application of CO<sub>2</sub> cryogenic cooling in machining aerospace-grade Ti-64 alloy. The research focuses on evaluating the influence of cutting speed ( $V_c$ ), feed rate ( $f_z$ ), radial depth of cut ( $a_r$ ), and axial depth of cut ( $a_x$ ) on surface roughness ( $R_a$ ). Both RSM and GA are used to construct predictive models and determine the optimal settings for these parameters. Limitations include the exclusion of other performance indicators such as cutting forces or temperature distributions, which may be addressed in future studies.

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