CHAPTER I INTRODUCTION

I.1 Background

In the medical field, precision is life critical. A notable case involved a leading medical device manufacturer struggling to meet production standards for a high-precision orthopaedic hip implant (NASLW, 2025). The component, made from biocompatible titanium alloy (Ti-6Al-4V), demanded exceptionally tight tolerances of ±5 microns and featured complex 3D geometry with thin walls. Their previous supplier failed to maintain these specifications consistently, resulting in dimensional inaccuracies and repeated production rework. These issues not only led to regulatory delays and elevated manufacturing costs but also introduced potential risks during clinical trials. This case underscores the urgent need for advanced thermal control and process optimization in medical implant machining, where overheating can compromise both dimensional accuracy and biocompatibility.

Thermal control is important in machining processes, as excessive heat can lead to a number of issues including dimensional inaccuracies, compromised surface integrity and accelerated tool wear (Deng, Chen, et al., 2020). The generation of heat at the tool–workpiece interface is inherent to material removal, and without proper thermal regulation, thermal expansion of the tool or workpiece can occur resulting in dimensional deviations from design specifications. Therefore, managing heat generation is essential to maintain tight tolerances and ensure consistent part quality in precision machining applications.

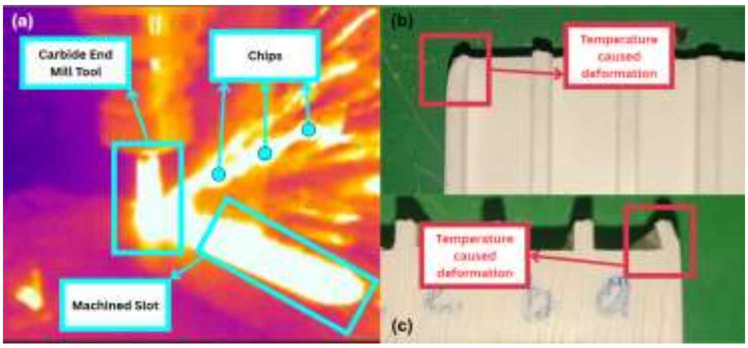

Figure I-1 Thermal and physical signs of overheating during machining.

Notes: (a) FLIR image shows heat at the tool–workpiece interface. (b) and (c) PTFE photos show edge melting and smearing.

The visual evidence presented in Figure I-1 reinforces the importance of thermal regulation during machining. The FLIR thermal imaging in Figure I-1 (a) highlights concentrated heat zones at the tool-workpiece interface, while the accompanying photo in Figure I-1 (b) and (c) reveals clear signs of material deformation on the experimented object. This deformation, likely caused by excessive localized heat, exemplifies the consequences of poor thermal control, particularly when machining heat-sensitive materials. These thermal challenges become even more pronounced when machining materials with inherently poor heat dissipation properties. One such material is Polytetrafluoroethylene (PTFE), whose low thermal conductivity amplifies the risks associated with poor temperature control.

Table I-1 Thermal conductivity in various materials.

Notes: Polymers like PTFE have very low thermal conductivity (0.25–0.30 W/m·K) compared to metals such as copper (up to 401 W/m·K), highlighting significant disparity in heat dissipation.

Number	**Polymers**	**Thermal conductivity (W/m·K)**	**Metals**	**Thermal conductivity coefficient (W/m·K)**
1	*Polyetheretherketone* (PEEK)	0.25 – 0.30	Alumunium	205 – 237
2	*Polyehylene* (PE)	0.40 – 0.50	Copper	385 – 401
3	*Polytetrafluoroethylene* (PTFE)	0.25 - 0.30	Steel (Low Carbon)	50 – 60
4	*Polyvinyl Chloride* (PVC)	0.19 – 0.22	Brass	109 – 125
5	*Polyamide* (Nylon)	0.24 – 0.30	Titanium	21 - 22

Polytetrafluoroethylene (PTFE), a high-performance polymer known for its low friction and chemical resistance, presents unique challenges in machining due to its inherently low thermal conductivity, as shown in Table I-1. Polymers, including PTFE, possess thermal conductivity coefficients significantly lower than metals, ranging from 0.25 to 0.30 W/m·K (Chen et al., 2016a), which makes them highly susceptible to temperature fluctuations during machining. This poor thermal conductivity can lead to localized temperature buildup, potentially causing thermal deformation and making effective temperature regulation crucial. These concerns are particularly important given PTFE's widespread use in aerospace components, medical implants, seals, gaskets, and high-performance electrical insulation, where dimensional accuracy and surface integrity are critical. In addition to the thermal sensitivity of PTFE itself, attention must also be given to the thermal behavior of the cutting tool, which is equally affected by the heat generated during machining.

The temperature of the cutting tool plays a direct and significant role in tool wear and overall process stability (Swan et al., 2018). Elevated tool temperatures can drastically reduce tool life, which then requires frequent tool changes and increasing manufacturing costs. Moreover, uncontrolled thermal expansion can lead to deviations from specified tolerances, impacting the quality of the machined part (Li et al., 2021). Therefore, understanding and controlling tool temperature is vital for optimizing machining performance. These temperature induced challenges underscore the need for machining strategies that actively reduce thermal load at the tool-workpiece interface. One such method is trochoidal milling, which offers substantial thermal advantages over conventional techniques.

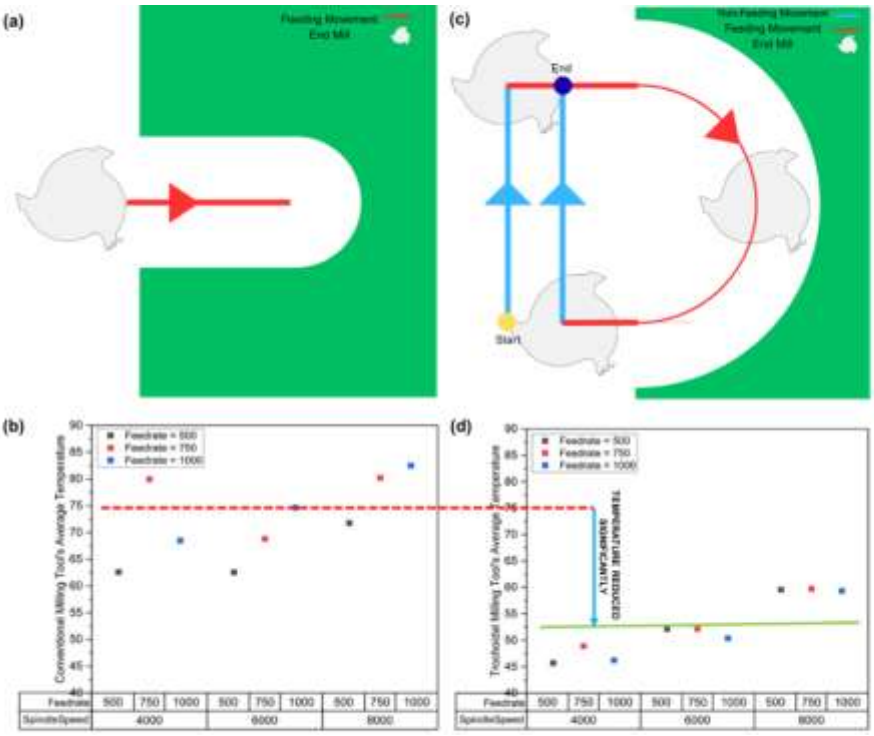

Figure I-2 Comparison of trochoidal and conventional milling strategies.

Notes: (a & b) Trochoidal milling toolpath with intermittent cutting and feed (red lines) alongside average tool temperature across varying feed rates and spindle speeds. (c & d) Conventional milling toolpath showing continuous feed (red line) with corresponding average tool temperature across different feed rates and spindle speeds.

Trochoidal milling, a machining technique that employs circular tool paths, offers significant thermal advantages over conventional milling (Deng, Mo, et al., 2020). Unlike conventional milling where the tool maintains continuous engagement with the material, trochoidal milling involves intermittent cutting (Otkur & Lazoglu, 2007), where the tool periodically engages and disengages from the workpiece as shown in Figure I-2 (c). The figure preceding this paragraph presents initial experimental comparisons between conventional and trochoidal milling, providing foundational insight into their respective thermal behaviors. This intermittent action allows for better heat dissipation and can lead to lower cutting forces and temperatures, thereby improving temperature regulation and enhancing tool life. Comparative analyses shown in Figure I-2 (b) and (d) demonstrate that trochoidal milling consistently results in lower temperatures compared to conventional milling under identical conditions, reinforcing its superior thermal performance. To address these thermal challenges at the tool-workpiece interface, trochoidal milling is best to use for improving heat management and enhance process stability.

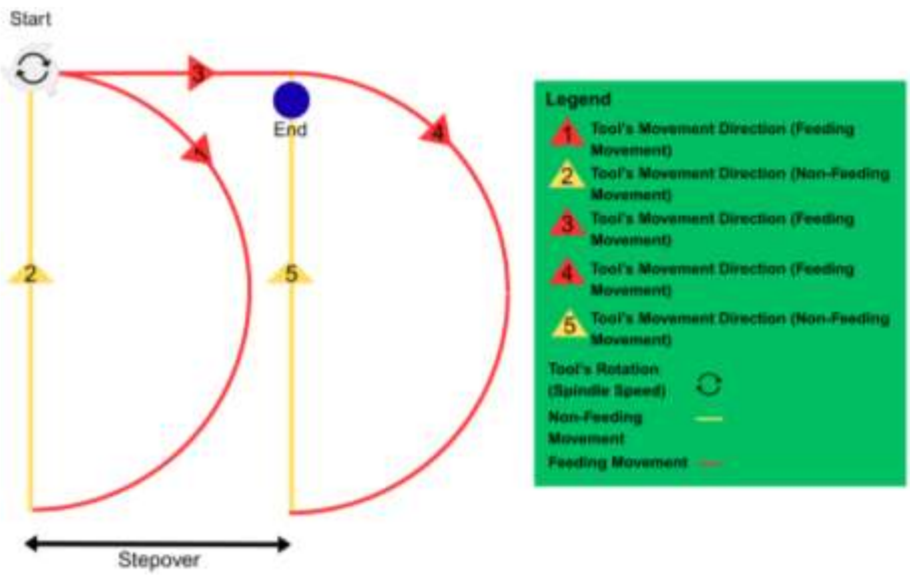

Figure I-3 Schematic of trochoidal toolpath showing interaction of spindle speed (RPM), feed rate (mm/min), and stepover (mm).

Notes: All parameters affect cutting velocity, chip load, radial engagement, and heat generation.

Trochoidal milling offers significant thermal advantages, which can only be fully leveraged by understanding the influence of key machining parameters, feed rate, spindle speed, and stepover affect tool temperature. These parameters directly influence heat generation at the cutting interface. For instance, higher feed rates can increase cutting forces and elevate temperatures, while excessive rates might paradoxically reduce tool temperature due to improved chip evacuation. Spindle speed, by determining cutting velocity, is a primary driver of heat generation, with higher speeds consistently leading to increased temperatures. Stepover, which dictates the radial engagement, affects the contact area and energy input per pass (Wagih, 2023). As the combined effects of these parameters can produce varied and sometimes unexpected thermal outcomes, a systematic approach is needed to quantify and predict their impact on tool's temperature during machining.

In addition to cutting parameters, the milling direction which are up versus down milling also influences thermal behavior at the tool interface. In up milling, the tool enters with zero chip thickness, leading to higher frictional contact at the start of cut, which tends to increase tool temperature. In contrast, down milling begins with a full chip load and often transfers more heat into the chip itself, potentially resulting in slightly lower average tool temperatures. While the differences are often modest, a study reported that up milling tends to produce slightly higher tool temperatures (Ma et al., 2015). These insights are important for fully understanding the thermal profile of trochoidal milling, which inherently alternates between tool engagement and disengagement and can operate under both milling directions.

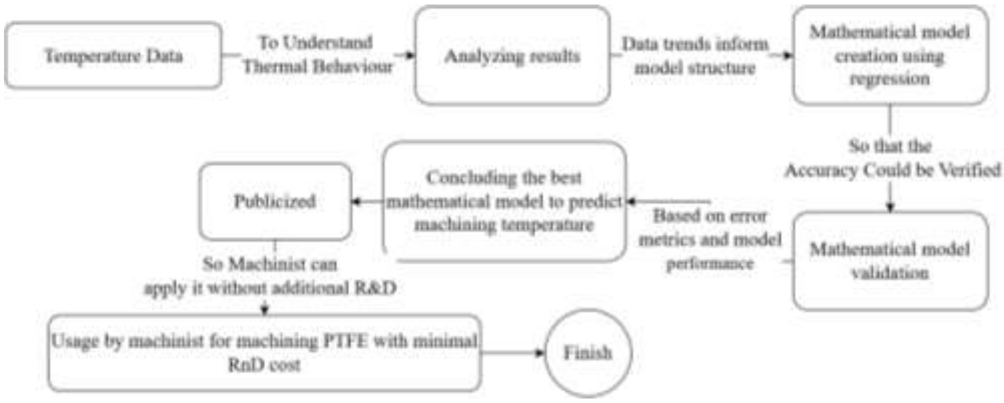

Figure I-4 Flowchart of developing a predictive model for tool temperature in PTFE machining

Notes: Starting from data collection, followed by analysis, regression modeling, validation, and model selection. The finalized model aids machinists in optimizing PTFE machining with reduced R&D effort.

Given the intricate interplay of these parameters and the thermal sensitivity of materials like PTFE, there is a clear rationale for creating a predictive model to assist machinists. Such a model would equip machinists and process planners with a reliable, data-driven tool to anticipate cutting tool temperatures during trochoidal milling operations, as shown in Figure I-4. The novelty of this study lies in its specific focus on modeling tool temperature, rather than workpiece temperature during trochoidal milling of PTFE, a topic that remains underexplored in current literature. While most existing models focus on temperature prediction in conventional milling or for metallic materials, this research uniquely targets low thermal conductivity polymers under trochoidal toolpaths. By formulating the problem around identifying the thermal influence of feed rate, spindle speed, and stepover, and translating it into a mathematical model, this study addresses a critical gap that bridges experimental thermal analysis with predictive modeling in advanced polymer machining. This predictive capability enables the selection of optimal machining parameters, helping to prevent thermal overload, minimize tool degradation, and improve overall process consistency and part quality. This research aligns with industrial engineering principles by integrating mathematical modeling and experimental validation to promote efficient and sustainable manufacturing practices.

I.2 Problem Formulation

Based on the previous sub-chapter, the following problems can be formulated for this experiment:

1. What is the relationship between cutting parameters (feed rate, spindle speed, stepover) and tool temperature in trochoidal milling?
2. How can this relationship be mathematically modeled for prediction?

I.3 Objective

The primary objectives of this study are:

1. To analyze the impact of feed rate, spindle speed, and stepover on tool temperature during trochoidal milling
2. To develop a mathematical model that predicts tool temperature based on these parameters

I.4 Significance of the study

This study provides meaningful contributions both academically and practically in the context of modern machining. From a practical standpoint, it equips machinists and process planners with a reliable, data-driven tool to predict the temperature of the cutting tool during trochoidal milling operations. This is particularly useful when machining thermally sensitive materials like PTFE, where temperature spikes can lead to dimensional inaccuracy, poor surface integrity, or rapid tool degradation. By understanding the influence of feed rate, spindle speed, and stepover on tool temperature, users can select optimal machining parameters to avoid thermal overload, reduce tool wear, and improve overall process consistency.

From an academic and industrial engineering perspective, this research supports the development of predictive models that enhance process control, thermal management, and productivity optimization. It aligns with industrial engineering principles by integrating mathematical modeling, experimental validation, and real-world application to promote sustainable and efficient manufacturing.

The findings may also serve as a reference for future studies involving heat-sensitive polymer machining, as well as a foundation for developing more comprehensive digital manufacturing systems that incorporate thermal forecasting.

I.5 Limitations and Assumptions

In this experiment it includes limitations and assumptions which has been the focus according to the objective of this research, as follows:

1. Material condition has the same characteristics from all directions.
2. All assigned parameters are stable and constant.
3. Developed mathematical model is empirical and based on trends. It does not account for dimensional homogeneity.
4. The model is only valid within specific ranges of feed rate, spindle speed, and stepover used in the experiments.
5. The findings are specific to PTFE and may not apply to other polymers or metals without further validation

I.6 Writing Structure

This final project contains chapters filled with elaboration and explanation on the activities done while the research is undergoing. The purpose of writing each chapter is to discuss specific explanation based on the chapter's title.

CHAPTER I INTRODUCTION

This chapter introduces the parameters that are discussed in trochoidal milling to manage machining temperature. The chapter outlines the problem formulation, objectives, benefits, and systematic approach of the research.

CHAPTER II LITERATURE REVIEW

The second chapter discusses relevant literature and theoretical foundations that highlight the importance of optimizing machining parameters for trochoidal milling. It emphasizes the need for effective tool's temperature management, providing the reason for choosing Full Factorial as the experimental method.

CHAPTER III RESEARCH METHODOLOGY

This chapter presents the methods used to solve the problem, describing the integrated system and defining the boundaries and assumptions of the study. The chapter.

CHAPTER IV DATA COLLECTION AND PROCESSING

In this chapter, the data collection process has been based on the methods outlined in the previous chapters. The gathered data has been used to observe and measure the effects of parameter changes on heat generation. The data will also be constructed into a mathematical prediction model.

CHAPTER V ANALYSIS

This chapter analyzes the data collected, focusing on the impact of varieties of machining parameters of trochoidal milling on temperature. The results has been examined to evaluate how changes in machining parameters affect the overall performance of the process. The constructed mathematical model has been analyzed and compared to the validation data for further confirmation.

CHAPTER VI CONCLUSION AND SUGGESTION

The last chapter discusses the result of analysis to be reformed to a conclusion in the hope that it could provide solution from the problem formulation. In this chapter, suggestions will also be provided so that future studies can be improved.