

IDENTIFICATION OF INTERNAL PROCESS PARAMETERS OF MICRO MILLING CONSIDERING MACHINED SURFACE TOPOGRAPHY

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By
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Identification of Internal Process Parameters of Micro Milling Considering Machined Surface Topography

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July 2022

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

IDENTIFICATION OF INTERNAL PROCESS PARAMETERS OF MICRO MILLING CONSIDERING MACHINED SURFACE TOPOGRAPHY

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M.S. in Mechanical Engineering

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Micro-milling is a fast and versatile machining method that can be used to manufacture three-dimensional parts of a wide range of materials with high accuracy. Modeling of micro-milling processes is complex due to size effects, where the chip thickness becomes comparable to the cutting edge radius. Furthermore, tool runout and deflection effects on the process outputs are amplified and cannot be neglected. As the process is scaled down where micrometer accuracy is required; modeling and identifying the process parameters becomes essential to optimize or monitor the process. This study presents a systematic approach to force modeling and parameter identification of micro-milling processes. Finite element analysis of tool deflection is integrated into mechanistic modeling of micro-milling forces together with considering the trochoidal trajectory of the cutting teeth, tool runout, and chip thickness accumulation due to minimum uncut chip thickness. The internal process parameters are identified using the experimental cutting forces and machined surface topography with a novel methodology. The research results are experimentally validated by slot and side micro-milling tests on commercially pure titanium, using coated carbide micro-end-mills with diameters of 0.2 and 0.4 mm, and accurate predictions of model parameters and cutting forces are obtained. The proposed force models can be used in smart manufacturing and digital twin applications to reduce the time and costs associated with process optimization. The proposed parameter identification techniques can also help to reduce the need for advanced measurement systems.

Keywords: Micro-milling, Mechanistic force modeling, Finite element analysis, Surface Topography, CP titanium.

ÖZET

MIKRO FREZELEME İŞLEMİ İÇ PARAMETRELERİNİN İŞLENMİŞ YÜZEY TOPOGRAFİSİ YARDIMIYLA BELİRLENMESİ

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Mikro frezeleme üç boyutlu parçaların hassas bir şekilde üretilmesine olanak sağlayan esnek bir işlemdir. Mikro frezelemenin modellenmesi boyut etkisi adı verilen, kesici takım köşe yarıçapı ile kesilen talaş kalınlığının yaklaşık değerde olmasından dolayı zor olarak bilinir. Dahası, takım eksen kaçıklığı ve takım eğilmesi gibi etkilerin işleme çıktıları üzerinde etkisi mikro ölçekte artmaktadır. İşleme boyutu küçüldükçe, mikrometre ölçeğinde hassasiyetin sağlanması zorlaşmaktadır. Dolayısıyla işlemenin modellenmesi ve parametrelerinin belirlenmesi önemli bir konu olarak öne çıkmaktadır. Bu çalışma mikro frezeleme esnasında oluşan kuvvetlerin modellenmesi için sistematik bir yaklaşım önermektedir. Sonlu elemanlar analizi takım eğilmesi, troikoidal kesici kenar hareketi, takımın eksen kaçıklığı ve talaş birikmesi gibi etkenler mekanistik model içinde göz önüne alınmıştır. İşlemenin iç parametreleri deneysel olarak ölçülen kesme kuvveti ve kesilmiş yüzey topografyasını kullanan yenilikçi bir yöntem belirlenmiştir. Araştırmanın sonuçları kanal ve kenar kesme deney sonuçları ile doğrulanmış ve iyi sonuçlar elde edilmiştir. Deneylerde malzeme olarak ticari saflıkta titanyum ile birlikte 0.2 ve 0.4 mm çaplarındaki mikro freze takımları kullanılmıştır. Teklif edilen yöntem akıllı imalat sistemlerinin geliştirilmesinde ve bu tip sistemlerde kullanılan pahalı ölçüm cihaz kullanımına olan ihtiyacı azaltılmasına olanak sağlayabilir.

Anahtar sözcükler: Mikro frezeleme, Mekanistik kuvvet modelleme, Sonlu elemanlar analizi, Yüzey topografisi, Ticari saflıkta titanyum.

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Chapter 1

Introduction

Milling is a fast, cheap, and versatile method of subtractive machining which can be employed to manufacture parts of a variety of materials with high precision and accuracy. The process normally features a stage over which a workpiece is fixed, while a rotating cutter (mill) is clamped to a spindle. Relative motion between the spindle and workpiece is applied by means of human or computer control to machine parts to the desired geometry. Micro-milling is a scaled down version of milling, and it is usually employed exclusively in Computer Numerical Control (CNC) machining. A global miniaturization trend is a key driver for the wide use and application of micro-milling processes in the industry.

1.1 Miniaturization in Manufacturing

Demand over miniaturized products has been growing exponentially over the last two decades [1–4]. While a variety of non-conventional manufacturing processes have been developed to specifically machine parts at the nano-scale in extremely high accuracy, i.e. lithography based processes, these methods tend to be slow, expensive, and require educated and highly skilled labor for operation. Moreover, these methods can pose constraints on material selection and geometry

of the machined parts [5]. Often, mechanical machining processes are scaled down using precisely fabricated cutting tools utilized in high precision machine centers. Complex geometry with high dimensional accuracy can be obtained using micro-mechanical machining processes, while maintaining low cost and feasibility. Therefore, micro-milling became one of the most favorable methods to micro-manufacture 3D complex parts of a wide spectrum of materials with high precision and speed [6].

1.2 Milling at the Micrometer Scale

Scaling down the milling process to the micrometer scale comes with challenges. Besides the need for high precision machine centers and cutting tools, micro-milling processes become difficult to predict due to several factors. While milling at this scale, the cutting edge of the tool can no longer be considered sharp and the chip thickness becomes in the same order of magnitude of the cutting edge radius. In the literature, this is referred to as the size effects [7,8]. Moreover, tool and spindle runout can be significant in comparison to the feed values used in micro-milling. Tool tip deflections, ploughing, elastic recovery, and chip thickness accumulation are other phenomena that drastically impact the micro-milling process outputs. To better model and predict micro-milling processes, it is important to understand how these phenomena can influence the machining process.

1.2.1 Tool and spindle runout

Eccentricity of the cutter and the spindle system can become problematic when micrometer precision is required. While tool and spindle runout are two different parameters, they are normally modeled as one accumulative runout. Runout can cause varying chip load on the teeth of the micro-end-mill (Figure 1.1a) and therefore, can produce uneven tool wear and cause instability issues and disturbance of the cutting forces, which in turn will affect the process outputs [9]. Tool runout effect in micro-milling force modeling can appear as an alternation

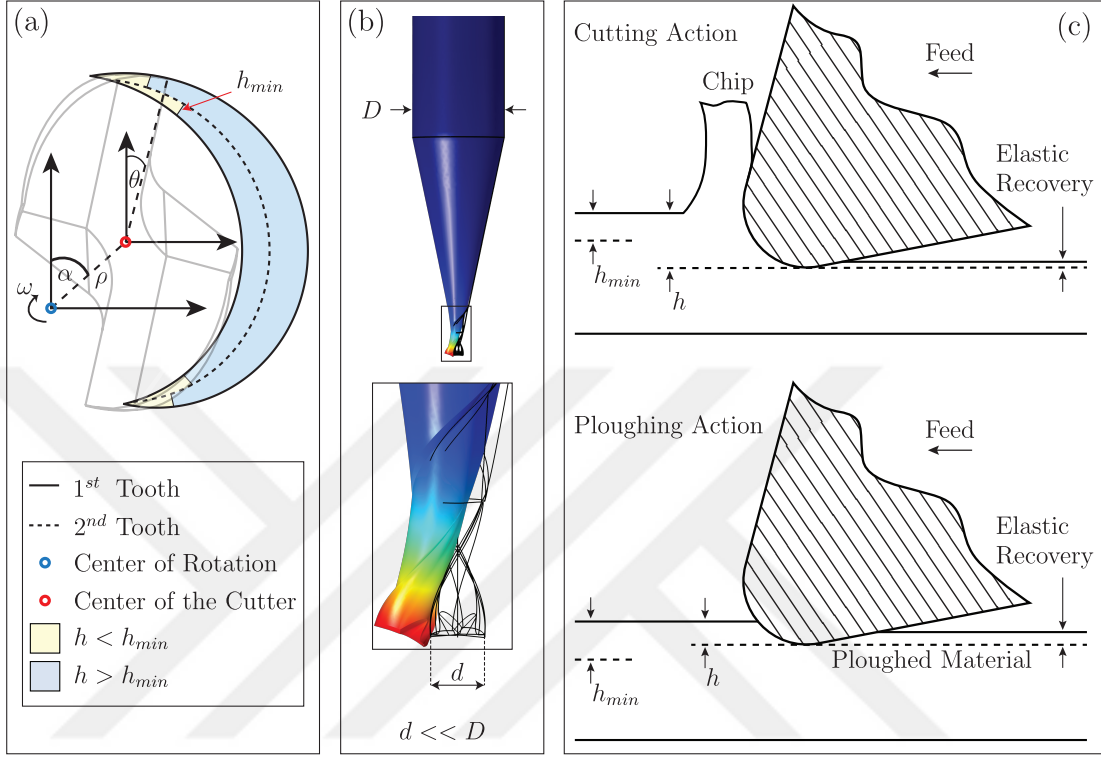


Figure 1.1: Phenomena associated with micro-milling: (a) Runout. (b) Deflection. (c) Chip accumulation due to ploughing and elastic recovery.

on the uncut chip thickness magnitude as multiple cutting teeth are engaged with the workpiece, as well as a change in the phase angles of every cutting tooth (the rotation angle over which the cutting tooth is engaged with the workpiece material). This eventually appears as peak alternation in the cutting force signal as will be seen later in this thesis.

1.2.2 Tool deflection

Deflection of the tool tip (Figure 1.1b) is another significant phenomenon associated with micro-milling [10–12]. Tools with tip diameters of less than 1 mm are commonly used in micro-milling [6]. As the tool tip diameter becomes small, cutting forces can produce significant amounts of tip deflection and can then result in geometric errors on the machined part and premature failure of the micro-end-mill [13–16].

Tool deflection can cause interplay with tool runout. For a two-fluted micro-end-mill, runout causes an increase in the uncut chip thickness for the first tooth and a subsequent decrease in the second. As a result, the forces acting on the tool will also increase for the first tooth and the tool tip will deflect more which will reduce the uncut chip thickness, and the opposite will be true for the subsequent tooth. Therefore, modeling tool deflection with runout is very important to better describe the micro-milling process.

1.2.3 Ploughing and chip thickness accumulation

In micro-machining, chip formation is normally associated with a minimum uncut chip thickness under which no chip will be generated, and the workpiece material will suffer from ploughing instead [7, 17, 18]. The material left by the passing tooth on the workpiece will then elastically recover [19, 20] and accumulate to the consequent tooth pass (Figure 1.1c), hence affecting the forces by creating an unequal condition between the cutting edges. Machining under such conditions may rapidly lead to uneven wear on the cutting edges, which increases the forces. Therefore, it is important to consider ploughing and chip thickness accumulation to produce a better estimation of the uncut chip thickness during process simulation.

1.3 Literature Review

According to Chen et al. [6], more than 2800 papers and patents studying micro-milling have been published and granted to the date of the review. Extensive research has been conducted on modeling and optimization of micro-milling processes, as well as surface generation and quality [1, 4]. A brief review on the literature studying micro-milling process modeling and surface investigation is presented in this section.

In an early study, Bao and Tansel [21] presented an analytical micro-milling force model which included the trochoidal trajectory of the cutting teeth as the micro-end-mill feeds into the workpiece. They extended the work to study the effect of tool runout in [22]. They observed the effect of tool runout on the fluctuations of the cutting force signal and predicted the cutting forces with an average error of 21%, while using a relatively large cutting tools compared to what is used today in micro-milling operations. Li et al. [23] proposed a three-dimensional cutting force model with consideration of runout, ploughing effect and minimum uncut chip thickness. Tool deflection was not considered in that study. Afazov et al. [24] presented an uncut chip thickness model considering the trochoidal trajectory and runout, and found that tool runout can significantly alter the uncut chip thickness at low feed rates. The work was later extended to include the effect of tool wear and helix lag in [25], however, tool deflection was excluded from both studies. Mamedov and Lazoglu [26] compared chip thickness models available in the literature based on force predictions. Wojciechowski et al. [27] studied chip thickness accumulation and the transition between ploughing and shearing in micro-milling. Their model also considered tool runout and deflection but excluded the effect of helix angle. Zhang et al. [20] modeled cutting forces in micro-milling with consideration of tool runout, deflection, and elastic recovery in different material removal mechanisms. In their model, the tool was approximated to a cylindrical geometry to accommodate deflection. Jing et al. [28] presented a runout model considering the spatial position of the tool in micro-milling. Elastic recovery was considered in that model, but not tool deflection.

Identification of micro milling model parameters is important to predict forces. Often, parameters such as tool and spindle runout, tool stiffness, and minimum uncut chip thickness are difficult to measure experimentally. Advanced measurement systems are required to identify the runout parameters during micro-milling [28,29]. Zhang et al. [30] proposed an analytical model for force coefficients and runout parameters calibration for helical milling processes. The parameters were calibrated using an underdetermined system of equations and an optimization method. Attanasio [31] proposed an experimental methodology requiring

micro-milling slots to identify runout parameters. Zhang et al. [32] proposed a calibration method of runout parameters for solid carbide and inserted milling cutters. Three runout types are mathematically modeled and numerically optimized with use of experimental measurement. Both of these works studied runout calibration in macro-scale milling. Li et al. [33] proposed a generic uncut chip thickness model for micro-milling processes, in which the runout parameters are identified from the force signal using least squared error. Liu et al. [34] developed a model for micro-milling where material properties and friction conditions were used to estimate the minimum chip thickness. Rezaei et al. [35] studied this issue for different materials and found that the minimum chip thickness to edge radius ratio changes between 25-49%.

Machined surface has been investigated extensively in previous research. Bolar et al. [36] presented a study on the relationship between process parameters and cutting forces and surface roughness in milling of thin-walled parts. Vogler et al. [37] modeled the centerline surface roughness in micro-milling with consideration of the minimum uncut chip thickness. Krüger and Denkena [38] modeled the influence of runout on the surface roughness based on cutting forces. Chen et al. [39] presented a surface generation model for micro-milling processes. The effects of runout and minimum uncut chip thickness were considered in their model. The effect of axial runout was later studied in [40]. In a recent study, Jing et al. [41] proposed a mathematical model for the prediction of the surface generated on the slot floor during micro-milling. In their study, the effect of elastic recovery as well as tool runout was considered during the prediction process.

1.4 Motivation and Thesis Structure

The motivation behind the work presented in this thesis stems from the industrial need for improved, reliable, and systematic approaches to model the micro-milling process and identify its internal parameters. An accurate prediction of the cutting force signal before initiation of the micro-milling process will provide an assessment on the process outputs, which will in turn reduce the costs and time

associated with trial tests prior to process initiation. During operation, such systematic approaches can be used to provide continuous monitoring and feedback on the process conditions which can help improve and optimize efficiency, geometric accuracy, surface quality, and tool life. Furthermore, the work presented in this thesis can be extended and applied in future research to ultimately enhance the modeling and prediction of micro-milling processes.

The goal in any machining operation is to satisfy finished part accuracy and surface quality requirements. However, the number of studies in this area is relatively limited. Within the framework of intelligent manufacturing, optimizing the process parameters and monitoring the process outputs through predictive models based on process physics is essential. The work presented in this thesis contributes to micro-milling force modeling and optimization. Novel approaches in the identification of the internal parameters of micro-milling processes using the cutting force signal and the machined surface topography are presented.

The structure of the thesis will be as follows: The experimental setup explaining the experimentation methodology and laboratory equipment used in the research is presented in chapter 2. Chapter 3 presents a finite element analysis of tool tip deflection which will be integrated in the cutting force models at later stages. A hybrid cutting force model for micro-milling processes is presented in chapter 4. Chapter 5 presents a model based surface investigation for the identification of runout parameters using machining marks left by the tool on the surface. An extension to the cutting force model to consider preceding passes of the cutting edges of the micro-end-mill, as well as an improvement to the prediction of tool deflection in force modeling are also presented in that chapter. Finally, a conclusion and future work suggestions are presented in chapter 6.

Chapter 2

Experimental Setup

The work presented in this thesis calls for extensive experimentation. Experiments were conducted to identify model parameters, validate the cutting force models, investigate the machined surfaces, and inspect the tool for wear and CAD modeling. The equipment used to conduct these experiments, as well as the experimental setup are presented in this chapter.

2.1 Micro Milling Setup

2.1.1 Machine center and spindle system

Micro milling tests were carried out on a Mikrotools DT-110 3-axis micro-milling center (Figure 2.1), equipped with a high precision Nakanishi NR40-5100 ATC Automatic Tool Replacement Spindle coupled to a Nakanishi EM-3060 Brushless Motor (Nakanishi, Japan). The spindle system was operated under 0.3 MPa of bearing pressure.

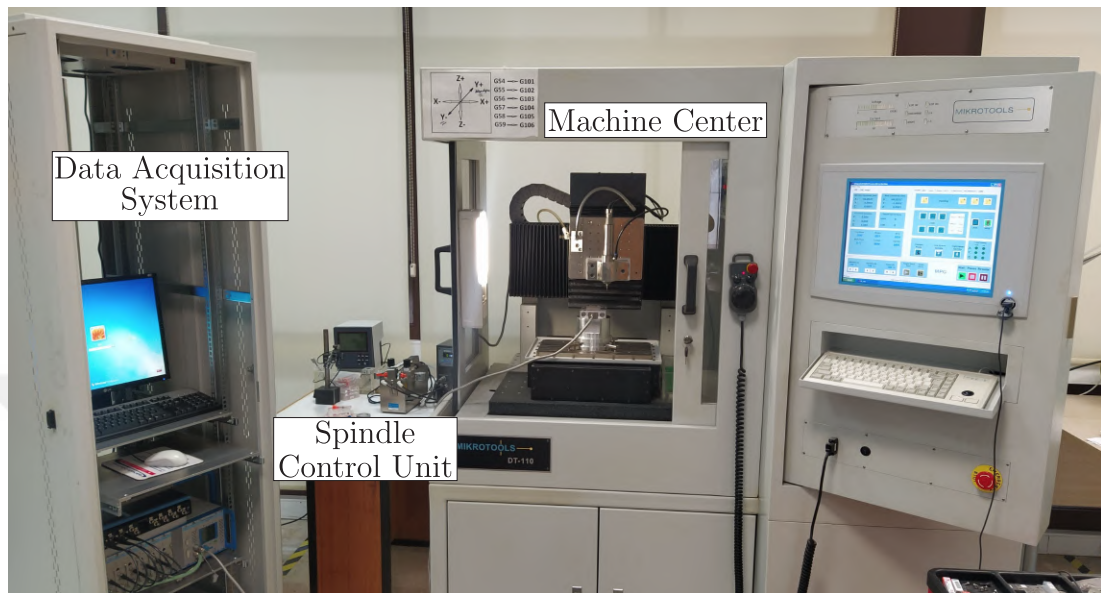


Figure 2.1: Overview of the machine center setup.

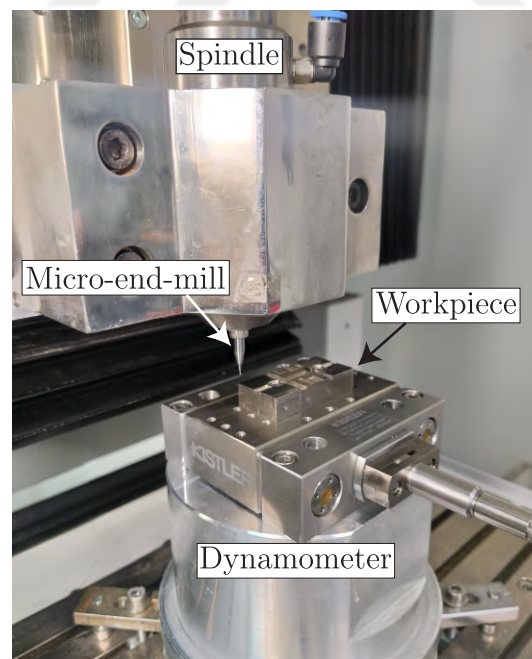


Figure 2.2: Close-up view of the workpiece, spindle system, and dynamometer.

2.1.2 Dynamometer and data acquisition system

The workpiece is bolted on a Kistler mini dynamometer 9256C1 which was secured on a mounting block attached to the machine center stage for maximum rigidity during the cutting tests (Figure 2.2). The dynamometer was connected to a multichannel charge amplifier, which is then fed into the data acquisition system that is connected to a computer. A VI program is used in NI LabView environment to record the cutting force signal at a sampling frequency of 333.3 kHz ($3 \mu\text{s}$ time sample size), which was saved to the local computer and then extracted for further processing using NI DIAdem signal processing software.

2.1.3 Tool and workpiece

A two-flute coated carbide micro-end-mill (Figure 2.3) with $400 \mu\text{m}$ diameter, $800 \mu\text{m}$ length of cut, and 30-degree helix angle (MXH230 0.4×0.8 NS Tools, Japan) was used in the micro-milling tests. The tool was clamped on the spindle at an overhang of 15 mm to reduce vibrations and deflection during cutting. A rectangular block of commercially pure titanium (cpTi) was prepared with appropriate mounting holes and used in the tests.

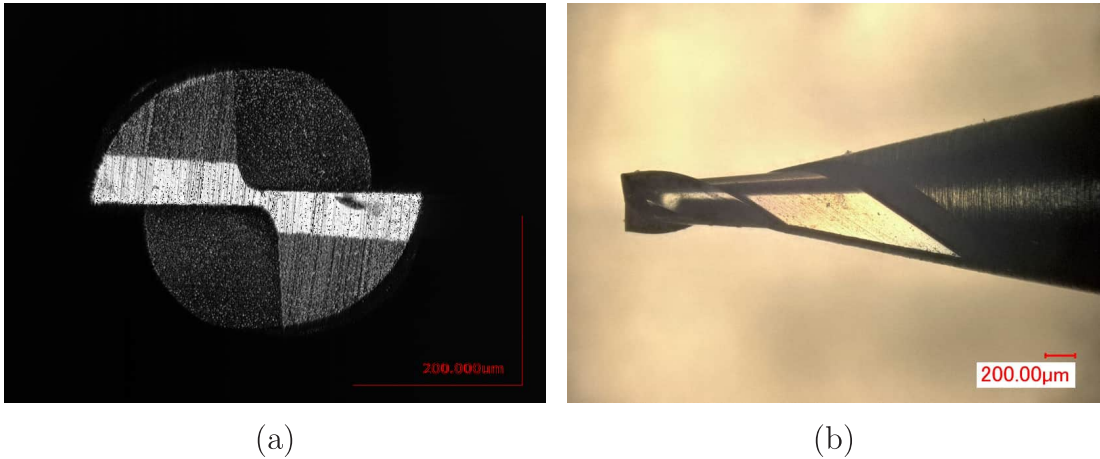


Figure 2.3: Microscope images of the micro-end-mill used in the micro-milling tests. (a) Laser image of the bottom view. (b) Optical image of the side view.

2.2 Optical and Laser Microscopy

Optical and laser microscopes were used extensively in the research presented in this thesis. A laser scanning microscope (VK-X100, Keyence, Japan) was used to investigate the machined surface marks to identify model parameters as will be discussed later in this thesis. It is also used to investigate the machined surface roughness. The laser scanning microscope is able to produce optical, laser, and optical/laser convoluted images as well as height data for 3D geometric samples with high resolution and accuracy. An optical microscope (VHX-1000, Keyence, Japan) was used in combination with the laser scanning microscope to investigate the cutting tool geometry and wear. Both microscopes are shown in Figure 2.4.

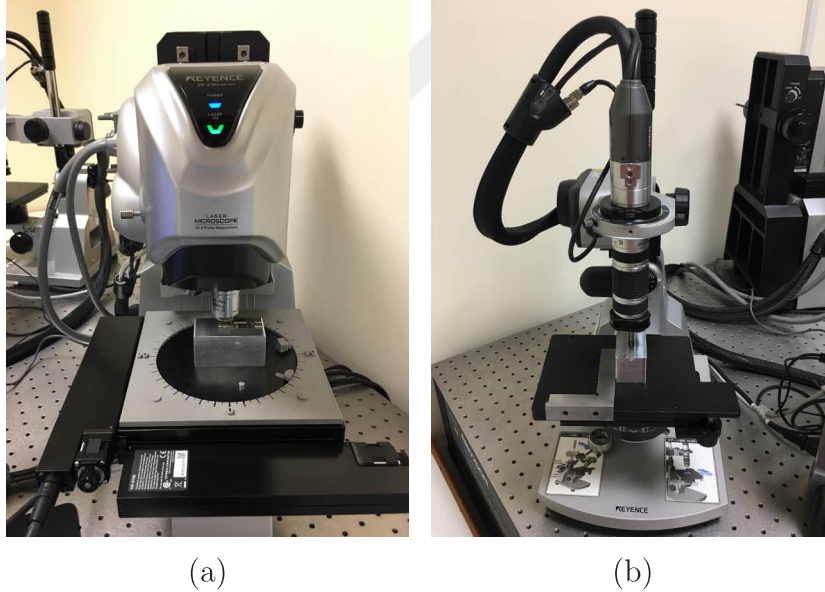


Figure 2.4: Microscopes used in the experiments. (a) VK-X100 Laser Scanning Microscope. (b) VHX-1000 Optical Microscope.

2.3 Instrumented Nano-indentation

Instrumented nano-indentation tests were carried out on the cutting tool shank using the Nano-indentation Tester TTX-NHT (CSM Instruments, USA) equipped

with a Berkovich indenter head to identify material properties, namely the modulus of elasticity and hardness. The tool was clamped horizontally as depicted in Figure 2.5, such that the cylindrical face of the shank can be tested conveniently. A linear array of 15 nano-indentation tests was conducted in compliance with ISO-14577 Nano-indentation standard. The sample was loaded to the peak force at a constant rate of 150 mN/min, and the load was held constant for a dwell period of 2 seconds. The force is then reduced to 10% of the peak value at a constant unloading rate of 150 mN/min and was held constant for a period of 80 seconds, before completely unloading at the same rate (Figure 2.6a). The depth data collected during this period can be used to determine if the thermal drift was significant and calculate the drift rate and compensate if necessary. Thermal drift was estimated as -2 nm/min, which was deemed negligible. The peak load values used during the nano-indentation tests are summarized in Table 2.1. Figure 2.6b shows examples of the resulting depth vs. force curves. Figure 2.7 shows the impression of the indenter head on the tool surface.

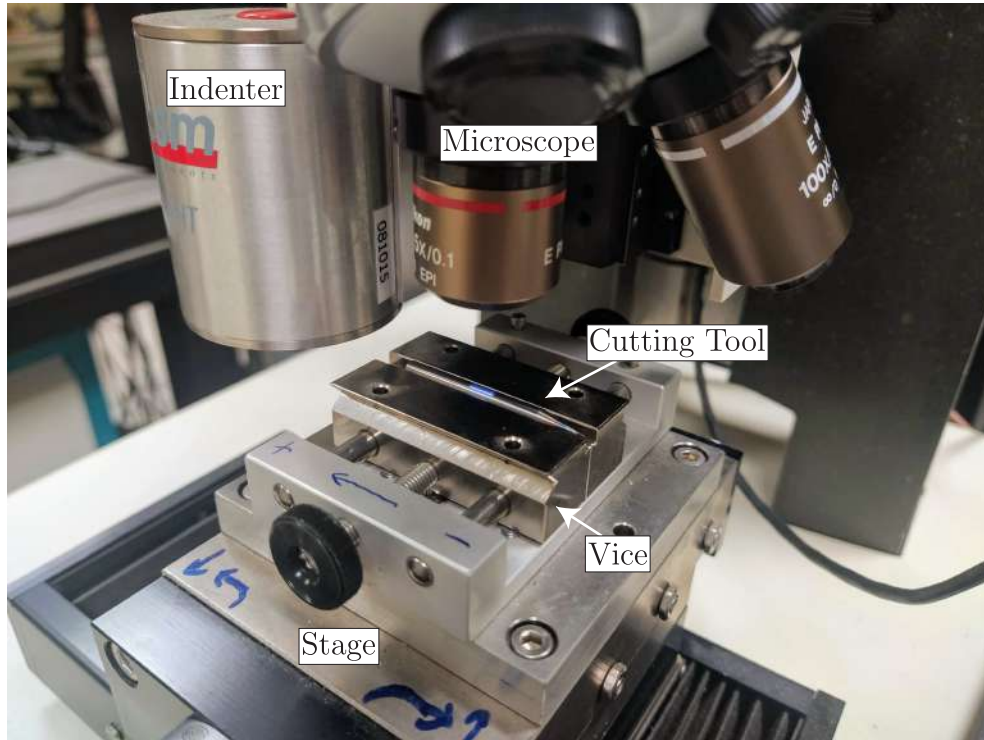


Figure 2.5: Nano-indentation testing setup.

Table 2.1 Nano-indentation testing conditions.

Test No.	No. of Indentations	Peak Load (mN)
1	5	50
2	5	100
3	5	250

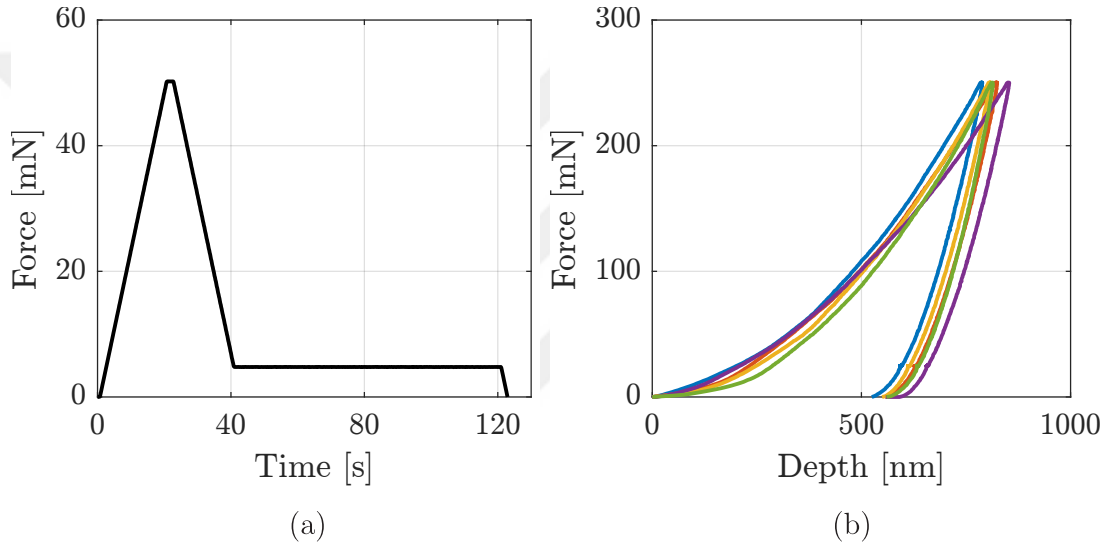


Figure 2.6: Nano-indentation (a) Loading curve. (b) Depth vs. force curves for test no. 3.

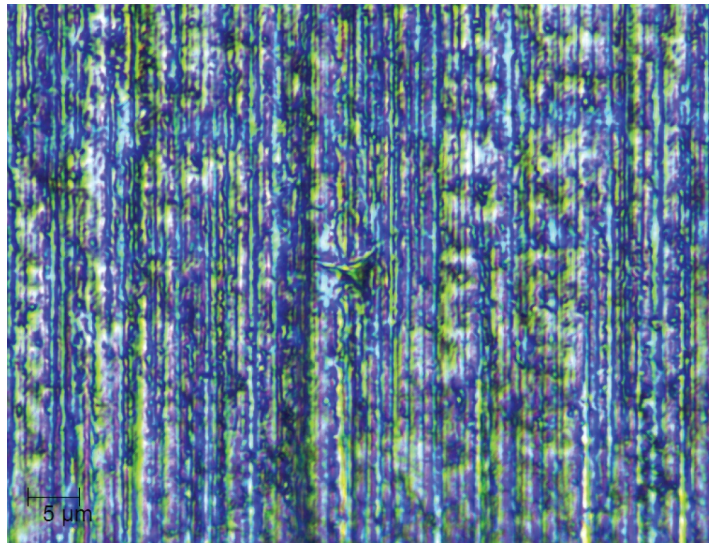


Figure 2.7: Impression of the Berkovich indenter head on the tool shank.

Chapter 3

Finite Element Analysis of Tip Deflection of the Micro-end-mill

Modeling of the tool tip deflection is a crucial step in cutting force prediction in micro-milling. Analytical modeling [10, 11, 15, 20, 42] can be applied to model tool deflection using the theory of elasticity. These models can be fast. However, an approximation of the tool geometry is necessary to use them. The tool is normally approximated as a combination of conical and multi-section cylindrical shapes, with a nominal diameter to describe the fluted section. Experimental approaches [17, 27] can also be used to model tool deflection, where a hookean spring model is applied to the tool tip with a predefined stiffness that is measured experimentally. While this approach can be accurate, measurement of the tool tip stiffness can prove to be an extremely challenging task as the tool diameter becomes smaller. To measure the tool tip stiffness, the tool tip is normally pressed against a solid carbide insert mounted on a dynamometer to measure the forces while the deflection is recorded as the stage of the machine center moves. Taking the stage readout as the actual deflection of the tool tip can introduce error. Moreover, any variation in the direction over which the force is applied can change the resulting deflection behavior of the tool tip.

Finite element analysis (FEA) can be a powerful tool to model tool deflection. With accurate modeling of the tool geometry, combined with accurate measurement of the material properties, finite element analysis can provide an accurate description of the tool tip deflection behavior. FEA can also be very versatile. In the case of changes in the tool geometry such as tool diameter, length of cut, helix angle, or the number of flutes, the finite element model can be updated in a fast and feasible manner to accommodate these changes. Therefore, FEA is applied in this work to estimate the stiffness of the tool tip which will then be incorporated in cutting force modeling.

3.1 CAD Model of the Cutting Tool

An accurate CAD model of the cutting tool is crucial in this analysis. The 3D geometry of the cutting tool was inspected thoroughly using optical and laser microscopy (see Section 2.2). A 3D model of the tool (Figure 3.1) was then created using Solidworks CAD package (Dassault Systèmes, France), and imported to COMSOL Multiphysics FE package (COMSOL Inc., USA) for further investigation. The CAD model was imported using the LiveLink for Solidworks feature which allowed an accurate import of the 3D geometry without tessellation.

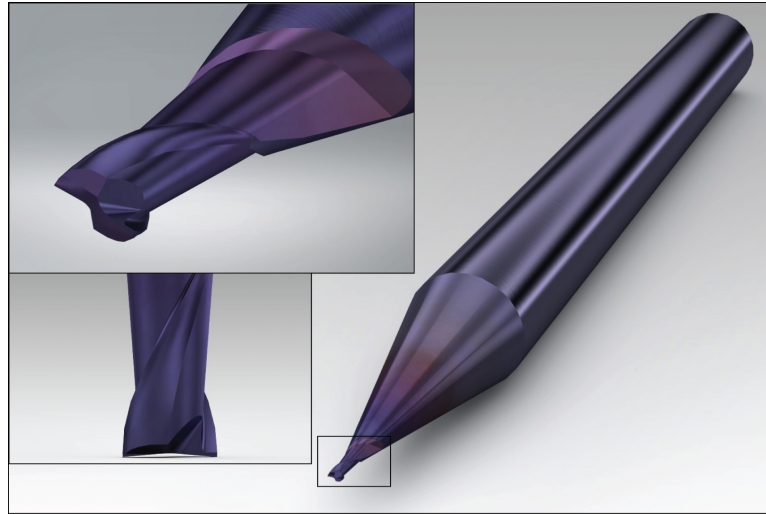


Figure 3.1: CAD model of the tool (MXH230 0.4x0.8, NS Tools, Japan).

3.2 Simulation Setup and Boundary Conditions

Tool deflection will depend on the modulus of elasticity of the defined material in the simulation. Since the modulus of elasticity of the tool material is unknown, a series of nano-indentation tests were carried out on the tool shank (see Section 2.3). The modulus of elasticity of the tool material was found as 615.5 GPa. A quasi-static analysis was used, and a linear elastic material was applied to the tool geometry using the identified modulus of elasticity and a poison's ratio of 0.22.

A tetrahedral mesh (Figure 3.2a) was applied to the geometry with a minimum and maximum element sizes of $10\text{ }\mu\text{m}$ and $500\text{ }\mu\text{m}$, respectively, with a maximum element growth rate of 1.35 and a curvature factor of 0.3. The mesh was optimized to produce consistent results with acceptable computational speed. To emulate the spindle clamping, a fixed boundary condition was applied at 15 mm of the tool tip as depicted in Figure 3.2a, which was the overhang value used during the experimental cutting tests. The boundary load was distributed on the rounded cutting edge of the tool, from the tool tip up to a height that is equal to the axial depth of cut that was used in the experiments (Figure 3.2b). The parametric sweep feature was used to vary the load in steps of 0:0.1:1 N.

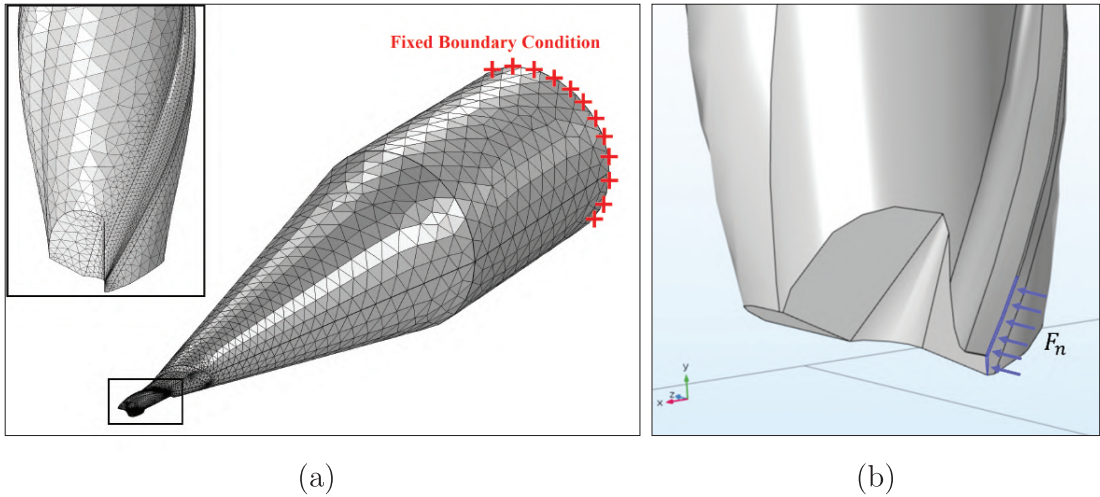


Figure 3.2: Finite element simulation setup. (a) Tetrahedral mesh and fixed boundary condition. (b) Boundary load.

3.3 Simulation Results

Two loading configurations were applied as shown in Figure 3.3. The force was applied in the normal direction in case I, and at an angle of $\phi = 45^\circ$ in case II. The purpose of using two configurations is to look at the deflection behavior of the tool tip in the case of loading in a direction other than normal, which can be the case in experimental loading tests. The deflection of the tool center was recorded at every step during the parametric sweep, and the results are presented in Figure 3.4. A linear regression was applied to the data points to produce a value of the tool tip stiffness in the normal direction k_n , which was found to be $0.47 \text{ N}/\mu\text{m}$ (case I). The value of the stiffness in case II was found to be $0.50 \text{ N}/\mu\text{m}$, which is 6% larger than the value of the stiffness in case I. Figure 3.5 shows the deflection field at 1 N of normal loading.

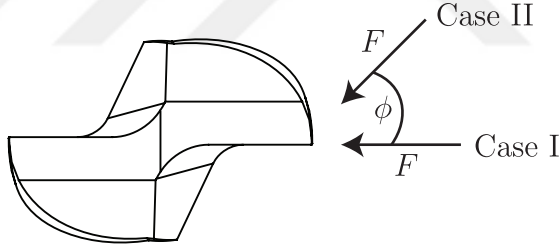


Figure 3.3: Loading configurations.

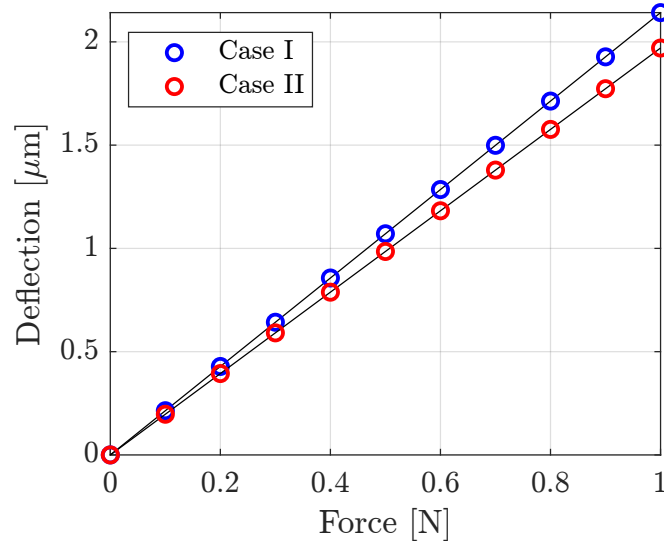


Figure 3.4: Finite element simulation results.

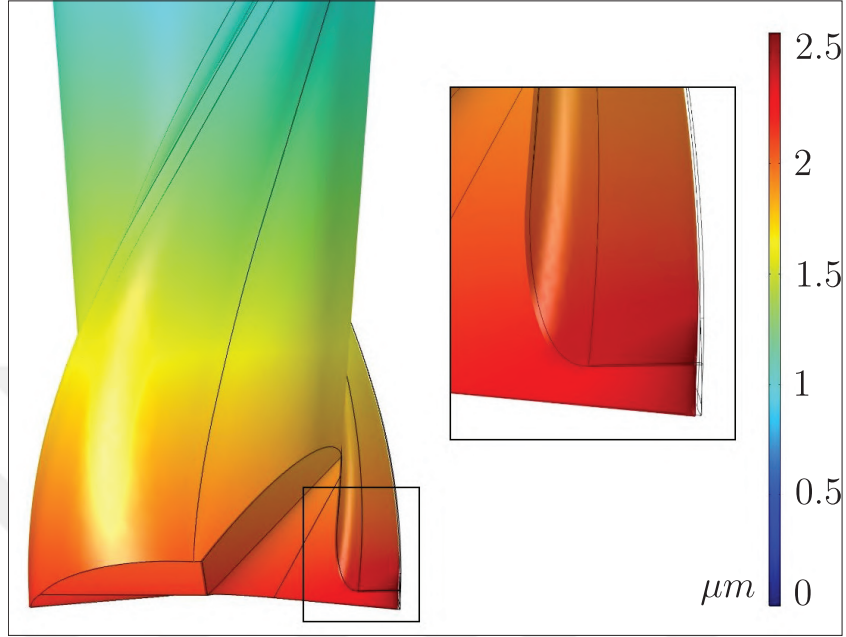


Figure 3.5: Deflection field at $F_n = 1$ N.

The simulation time averaged at 40 seconds using a computer with Intel Core i7-7700HQ CPU with 16GB of RAM, running Windows 10 operating system. This simulation time is considered very fast. The integration between Solidworks CAD package and COMSOL Multiphysics FE package allows fast updates of the simulation results in the case of any change in the micro-milling conditions such as the axial depth of cut or tool overhang, or the tool geometry such as the diameter, helix angle or length of cut. This simulation eliminates the need for experimental testing of tool tip deflection, which is proven to be very meticulous and challenging. The simulation can also be further expanded to study the frequency response of the tool using modal analysis which can help study chatter.

Chapter 4

A Hybrid Cutting Force Model for Micro Milling Processes

The hybrid cutting force model presented in this section combines numerical and experimental approaches to formulate an algorithm for the calculation of the uncut chip thickness which will be incorporated into a mechanistic force model to predict cutting forces. The runout model used by Aksin and Karpas in [43] which is based on the trochoidal trajectory of the cutting teeth of the micro-end-mill with consideration of helix angle effect is utilized to calculate an initial value of the uncut chip thickness. The finite element analysis which was established in chapter 3 is then utilized to update the uncut chip thickness value and accommodate tool deflection based on a hookean spring model. The effect of chip thickness accumulation is then incorporated based on the minimum uncut chip thickness, and an optimization algorithm is applied to identify model parameters using the experimental cutting force signal.

4.1 Uncut Chip Thickness

The uncut chip thickness is first calculated from the trochoidal trajectory of the cutting teeth with consideration of runout [22]. The immersed depth of the tool is assumed to consist of a number of disc elements, at which the chip thickness is different due to the helix angle. Tool immersion angle is described in terms of time t_i as:

$$t_i = t_s - \frac{i \cos^{-1} \left(\frac{2R^2 - a_p^2 \tan^2 \lambda}{2R^2} \right)}{\omega K} \quad (4.1)$$

where t_s is the start time, i is the disc element index, R is the tool radius, a_p is the axial depth of cut, λ is the helix angle, ω is the angular speed and K is the total number of disc elements.

By considering the tool rotation and feed direction (Figure 4.1), the locations of the tool center and the j^{th} cutting edge at the time t_i (points O and P) can be found using simple kinematics of the tooth trajectories. At some point in time t_i' where the previous flute intersects the line OP , the locations of points O', Q can be found in a similar manner. Given that points P, Q are on the same line, the uncut chip thickness considering runout h_r^i can be found from the geometric relation [44]:

$$h_r^i = (y_P - y_Q) \sqrt{\tan^2 \theta_i + 1} \quad (4.2)$$

In order to find point Q , the value of t_i' shall be known. Newton-Raphson method [45] can be used to solve the following equation numerically to find t_i' [23]:

$$F(t_i') = (x_P - q_Q) - (y_P - y_Q) \tan \theta_i = 0 \quad (4.3)$$

The normal and tangential forces considering tool runout are calculated based on the mechanistic model as:

$$dF_n(\theta_i) = K_n h_r(\theta_i)^{a_n} dz \quad (4.4a)$$

$$dF_t(\theta_i) = K_t h_r(\theta_i)^{a_t} dz \quad (4.4b)$$

where K_n, K_t, a_n, a_t are cutting coefficients identified experimentally, and dz is the disc element thickness.

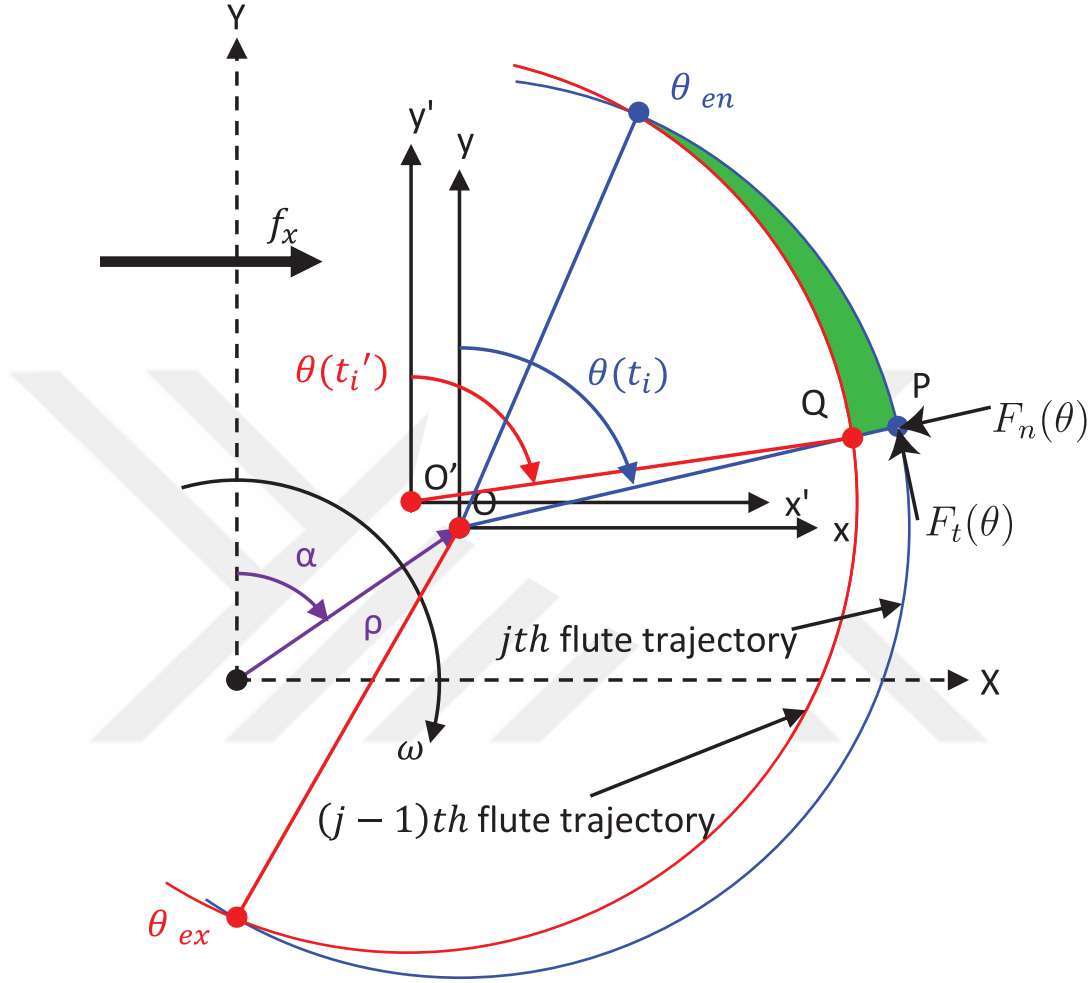


Figure 4.1: Geometric conditions governing flute trochoidal trajectory [43].

The normal force can be considered responsible for the tool deflection during micro-milling. After the normal force is evaluated from Equation 4.4a, it is then used to calculate an estimate of the tool deflection from:

$$\delta h^i = S_n C_n dF_n \quad (4.5)$$

here, S_n is the tool compliance in the normal direction (mm/N) which was evaluated from the finite element analysis (see chapter 3), dF_n is the normal force, and C_n is a correction factor defined as a constant. The purpose of this constant is to determine the portion of the normal force that is responsible for the tool deflection, and it will be identified using an optimization algorithm. The new value of the uncut chip thickness considering tool runout and deflection is then

calculated as:

$$h_{rd}^i = h_r^i - \delta h^i \quad (4.6)$$

To accommodate the effect of chip thickness accumulation, the value of the uncut chip thickness considering runout and deflection h_{rd}^i is compared with the minimum uncut chip thickness value h_{min} . At a certain immersion angle θ_i where h_{rd}^i is lower than the minimum uncut chip thickness value h_{min} , the workpiece material is assumed to undergo ploughing and the uncut chip thickness value is added to the value at the next tooth pass $h_{rda}^i(\theta_i + \frac{2\pi}{N_z})$. It has been shown in previous studies that the minimum uncut chip thickness can be related to the cutting edge radius [2, 35]. In this model, the value of h_{min} was assumed to be $0.3 \mu\text{m}$. The elemental normal and tangential forces are then calculated by substituting h_r^i with h_{rda}^i in Equation 4.4. The cutting forces in the workpiece reference plane are then calculated from:

$$\begin{bmatrix} dF_x \\ dF_y \end{bmatrix} = \begin{bmatrix} -\cos \theta & -\sin \theta \\ \sin \theta & -\cos \theta \end{bmatrix} \begin{bmatrix} dF_t \\ dF_n \end{bmatrix} \quad (4.7)$$

A numerical integration algorithm can then be used to calculate the total cutting forces during the process [46]. The computer code detects the entry and exit angles automatically and calculates the cutting forces only when the cutting teeth are engaged with the workpiece material.

4.2 Model Validation

Five slot micro-milling tests were conducted on commercially pure titanium (cpTi) using the experimental setup presented in chapter 2. The slots were 5 mm in length. Spindle speed and axial depth of cut were held constant at 25000 rpm and $40 \mu\text{m}$, respectively, throughout all the cutting tests. The feed rate and the corresponding feed per tooth values that were used are summarize in Table 4.1. Prior to every cutting test, a cleaning cut was first performed with $20 \mu\text{m}$ axial depth of cut to level the surface. An additional cut was performed at the end of the experiment to observe any change in the cutting force signal due to

wear, which was not present. The tool was inspected under the microscope after the cutting tests and no significant wear was visual.

Table 4.1 Cutting conditions in slot milling.

Test No.	Feed Rate (mm/min)	Feed f_t ($\mu m/tooth$)
1	25	0.5
2	50	1
3	100	2
4	200	4
5	300	6

4.2.1 Cutting force signal processing and identification of specific force coefficients

An initial set of cutting coefficients is first identified by analyzing the cutting force signal. The collected force data was first offset by the mean value of the first 10000 samples where no cutting action was recorded, to correct any drift induced by the data acquisition system. A low pass filter was then applied at a cutting frequency of 3.3 kHz to filter out higher order harmonics that may be present in the signal. The actual spindle speed was identified by investigating the frequency content of the measured signal using a Fast Fourier Transformation (Figure 4.2). The actual spindle speed was found to be 25260 rpm. The frequency content of the signal was also investigated for chatter, which was not present. The resultant force signal was calculated, and peak analysis was carried out to identify the signal valleys. The signal was cropped at a valley point as shown in Figure 4.3, and that point was chosen as the starting time. The cutting force signal was then transformed to the rotating reference plane of the tool (F_t, F_n) using an inverse of the transformation presented in Equation 4.7, and the sampling size and frequency of the measured force signal.

The identification of the cutting force coefficients was then carried out using curve fitting. The cutting force signal in the rotating reference plane of the tool was split into equal segments representing one tooth pass each, with consideration of the two cutting teeth of the tool separately. The resultant force signal valleys

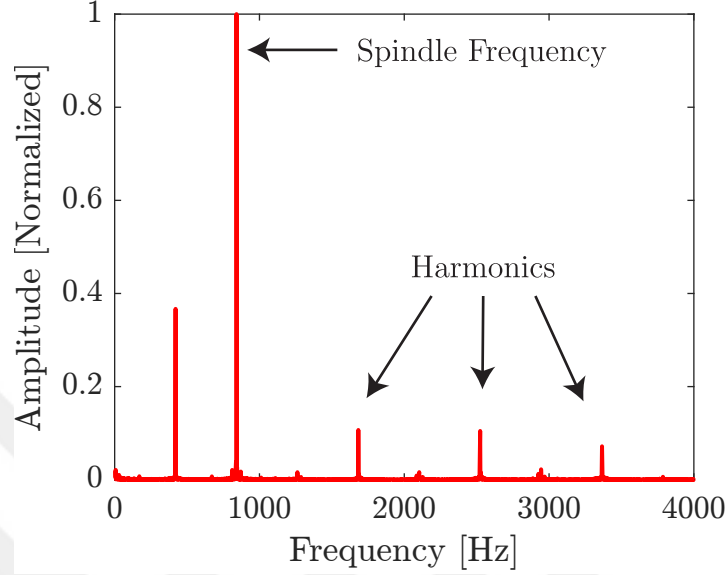


Figure 4.2: Fast Fourier Transformation of the cutting force signal to identify the actual spindle speed.

were used to quantify the segments. The signal segments for the second cutting tooth were flipped, and all the segments are plotted on top of each other and averaged as shown in Figure 4.4. The effect of runout is obvious on the averaged signals as the averaged curves representing the first and second cutting teeth alternate in magnitude (black dashed curves in Figure 4.4). A final average was taken for both dotted curves (solid black curve in Figure 4.4). It was assumed that the chip thickness reaches a maximum value at $\theta = \pi/2$, and since the curves were averaged for both cutting teeth of the tool, this value should correspond to the feed per tooth value f_t . Using this assumption, the up-millinging and down-milling segments of the final curve are averaged and normalized by the axial depth of cut a_p , and then a power function was fit to the data by minimization of the least squared error (Figure 4.5), thus identifying the initial values of the specific cutting coefficients $K_{no}, a_{no}, K_{to}, a_{to}$ at all the feed rates.

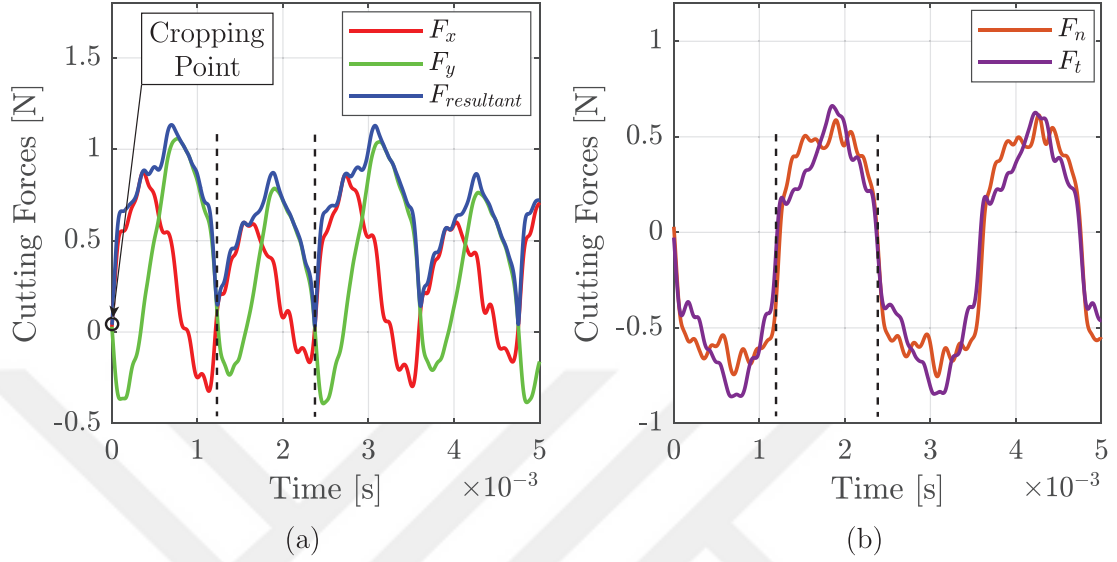


Figure 4.3: Experimental cutting force signal transformation and cropping. (a) Signal in the workpiece reference plane. (b) Signal in the tool rotating reference plane.

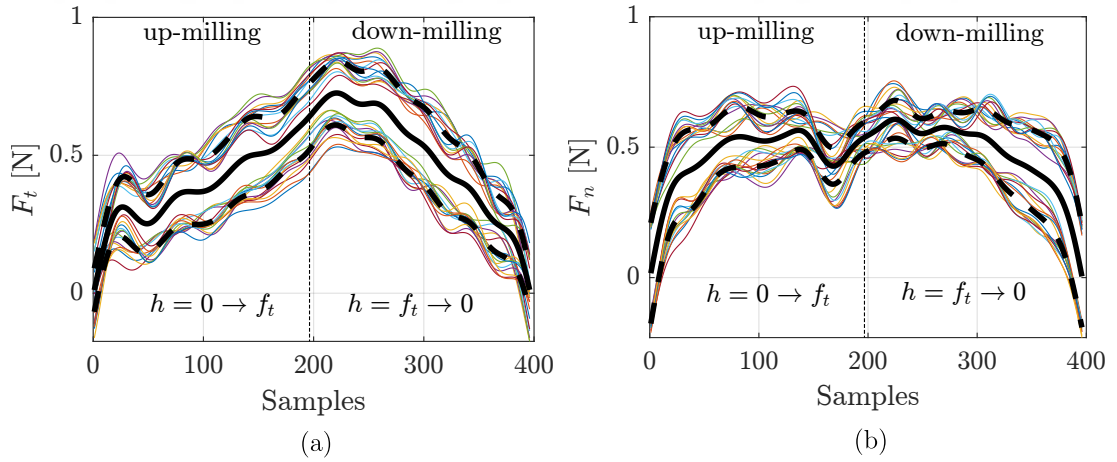


Figure 4.4: Splitting and averaging the force signal. (a) Tangential force. (b) Normal force.

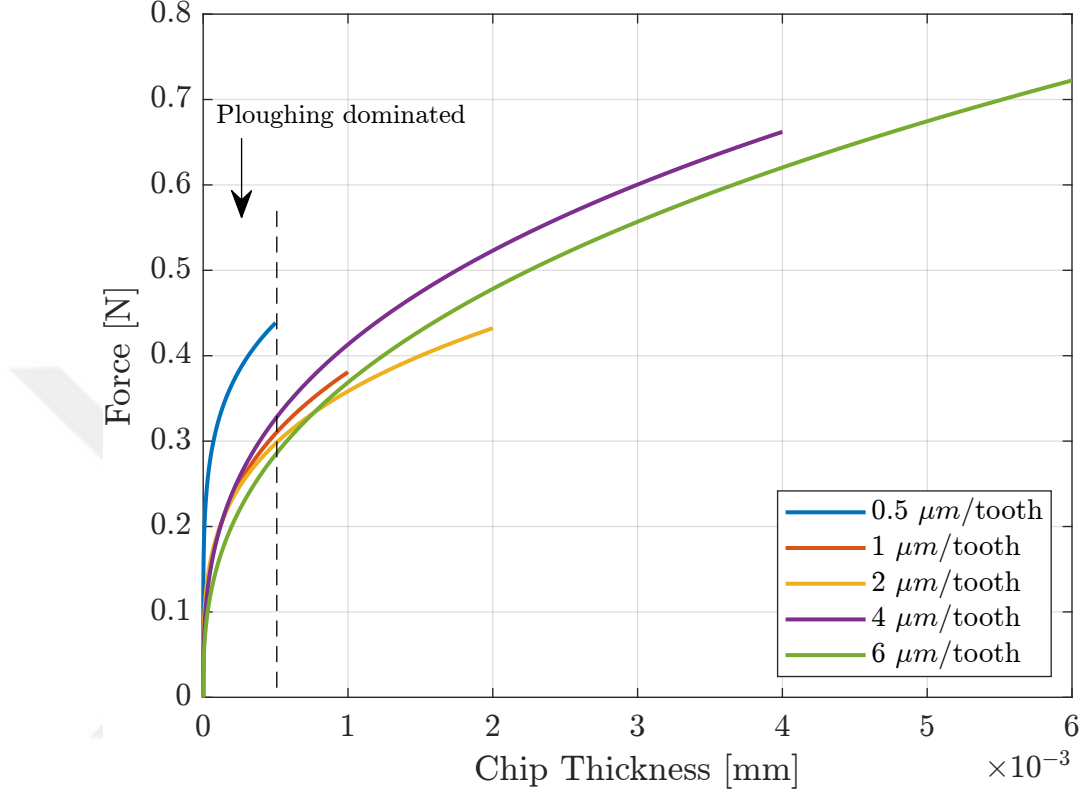


Figure 4.5: Variation of the mechanistic force model at different feed values

4.2.2 Identification of runout parameters from the cutting force signal

Tool runout effects can be observed from the periodic changes on the peaks and valleys of the cutting force signal. In the case of a 2-flute micro-end-mill, a runout angle valued between $0 - \pi$ will result in a higher peak in the chip thickness, as well as a wider phase angle ($\theta_{exit} - \theta_{entry} > \pi$) for the first tooth pass (Figure 4.6). Using this observation, runout parameters can be estimated using peak analysis of the force signal and optimization.

A range of the signal was cropped starting from a point at a valley of the resultant force signal as depicted in Figure 4.7. Peak analysis was performed to locate the peaks and valleys of the signal, and numerical optimization was used to minimize the following error function to identify the runout parameters ρ, α :

$$\varepsilon_r = (\delta P_{experimental} - \delta P_{simulated})^2 + (\delta V_{experimental} - \delta V_{simulated})^2 \quad (4.8)$$

where $\delta P, \delta V$ are defined as:

$$\delta P = \frac{\sum_{i=1}^{n_p} (y_{p2i-1} - y_{p2i})}{n_p} \quad (4.9a)$$

$$\delta V = \frac{\sum_{j=1}^{n_v} \left[\frac{x_{v3j} - x_{v3j-1}}{x_{v3j-1} - x_{v3j-2}} \right]}{n_v} \quad (4.9b)$$

Here, i, j are peak and valley indices respectively, y_p is the peak magnitude, x_v is the valley location on the x-axis, n_p is equal to the total number of peaks in the signal divided by 2, and n_v is equal to the total number of valleys divided by 3. The simulated signal is calculated with consideration of runout only in this step.

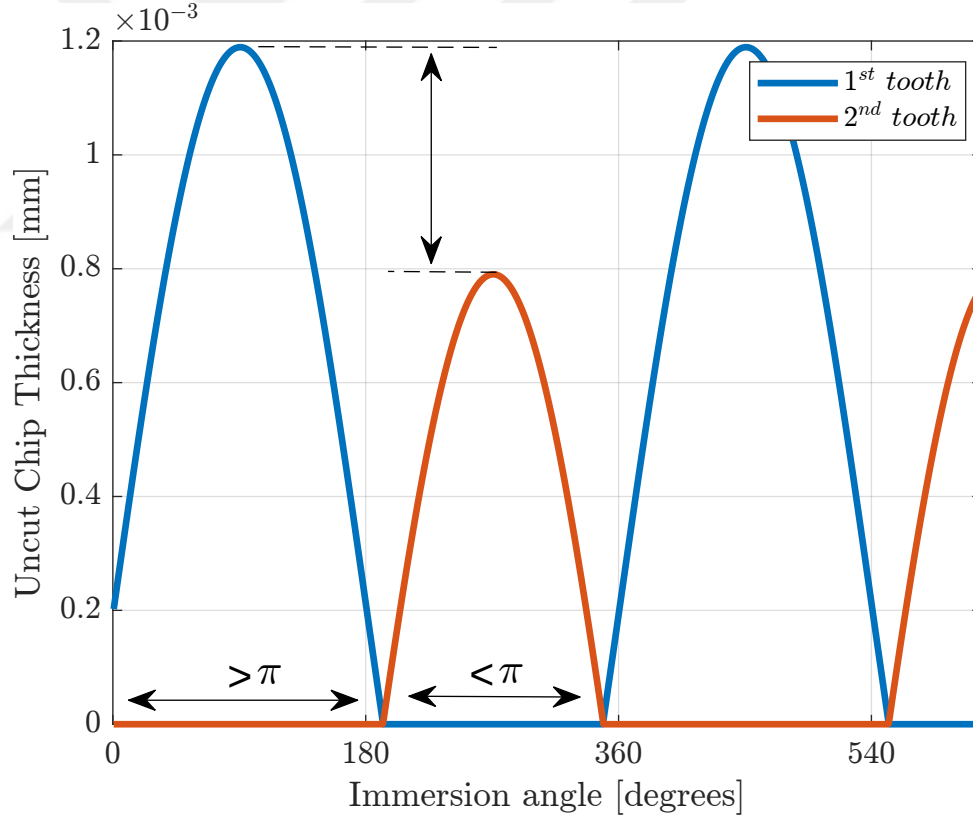


Figure 4.6: Runout effect on the chip thickness.

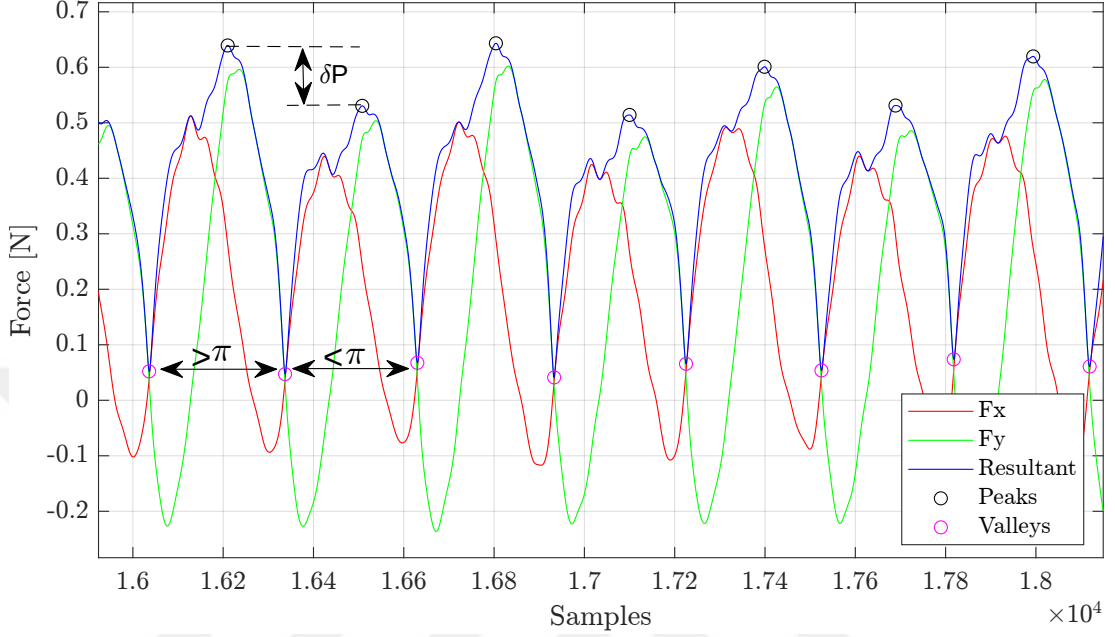


Figure 4.7: Peak analysis of experimental force signal.

4.2.3 Optimization of the specific force coefficients and identification of tool deflection correction factor

The model uses a unique set of cutting coefficients for every feed value that was used during the experimental cutting tests. Since the tool was never unclamped during the cutting tests, runout parameters were held constant, and the cutting coefficients (K_n, K_t, a_n, a_t, C_n) were optimized by minimization of the error function:

$$\varepsilon = \sum_{i=1}^n (F_{x,exp}^i - F_{x,sim}^i)^2 + (F_{y,exp}^i - F_{y,sim}^i)^2 \quad (4.10)$$

where, i is the sample index and n is the total number of samples in the force signal. Figure 4.8 shows the general workflow of the cutting force model presented in this chapter. An initial set of specific cutting conditions is first identified using Fast Fourier Transformation and curve fitting of the experimental cutting force signal. This set is then used in the runout model to facilitate the identification of the runout parameters from the experimental signal using peak analysis and optimization. The runout parameters, combined with the tool compliance which is identified from the finite element analysis of tool deflection are then integrated

into the mechanistic force model. An optimization algorithm is then used to optimize the specific cutting coefficients and identify the tool deflection correction factor, to ultimately produce the predicted cutting force signal.

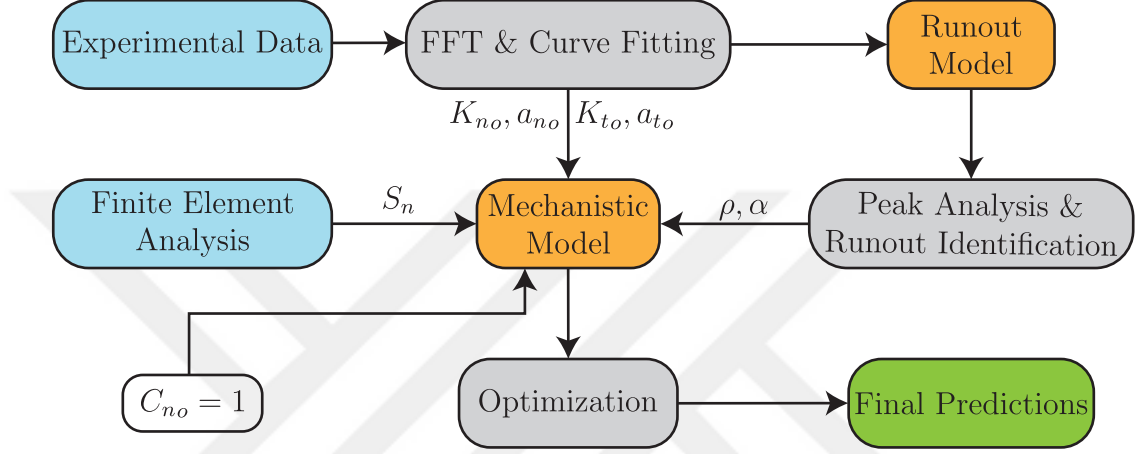


Figure 4.8: General workflow of the hybrid cutting force model.

4.3 Results and Discussion

Tool runout parameters ρ, α identified from Section 4.2.2 were $0.15 \mu\text{m}$ and 1.08 radians, respectively. Table 4.2 lists the calibrated model parameters, as well as the root mean squared error at the different feeds. Figure 4.9 shows the simulated uncut chip thickness at $1 \mu\text{m}/\text{tooth}$ feed. The predicted and measured force signals at $1, 2$ and $4 \mu\text{m}/\text{tooth}$ feeds are presented in Figures 4.10–4.12.

Table 4.2 Calibrated model parameters and RMS error at different feeds ($\mu\text{m}/\text{tooth}$).

Feed:	0.5	1	2	4	6
K_n	48.167	77.264	58.053	60.431	47.094
K_t	174.72	274.82	343.10	361.10	485.02
a_n	0.2074	0.3104	0.2679	0.2516	0.2110
a_t	0.3927	0.4852	0.4880	0.5157	0.5615
C_n	0.2144	0.2074	0.3998	0.3975	0.5664
$RMSE_{F_x}$	0.1725	0.0609	0.0842	0.0689	0.0978
$RMSE_{F_y}$	0.2356	0.1033	0.0803	0.1351	0.1521

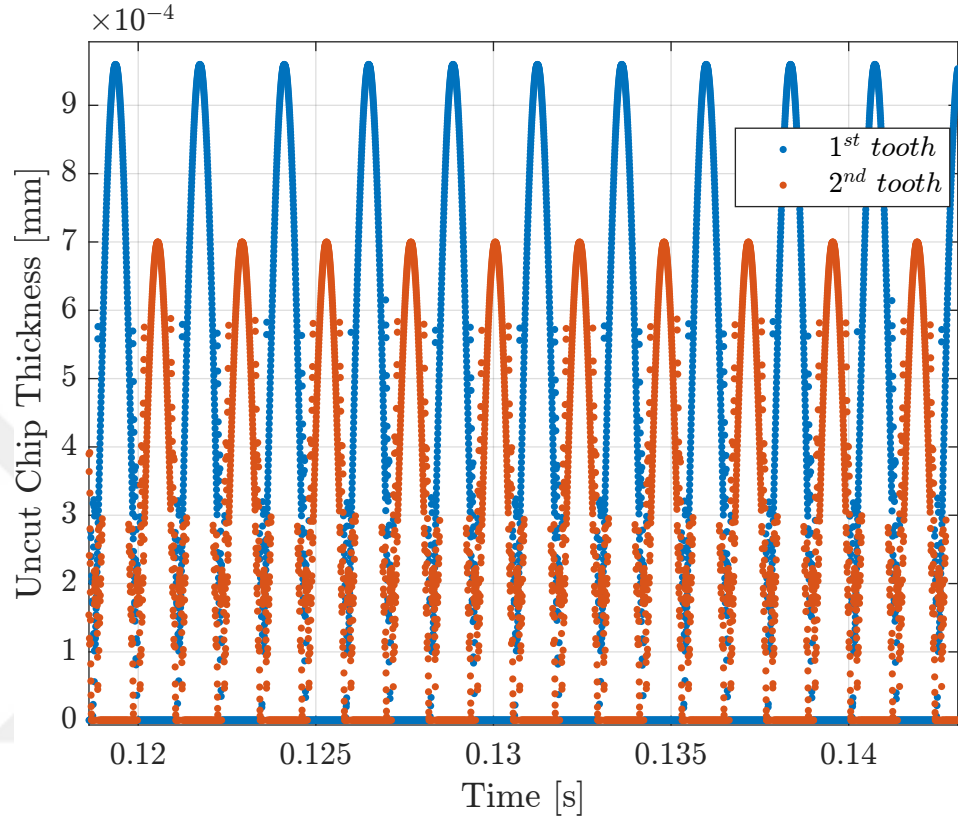


Figure 4.9: Simulated uncut chip thickness at 50 mm/min feed rate.

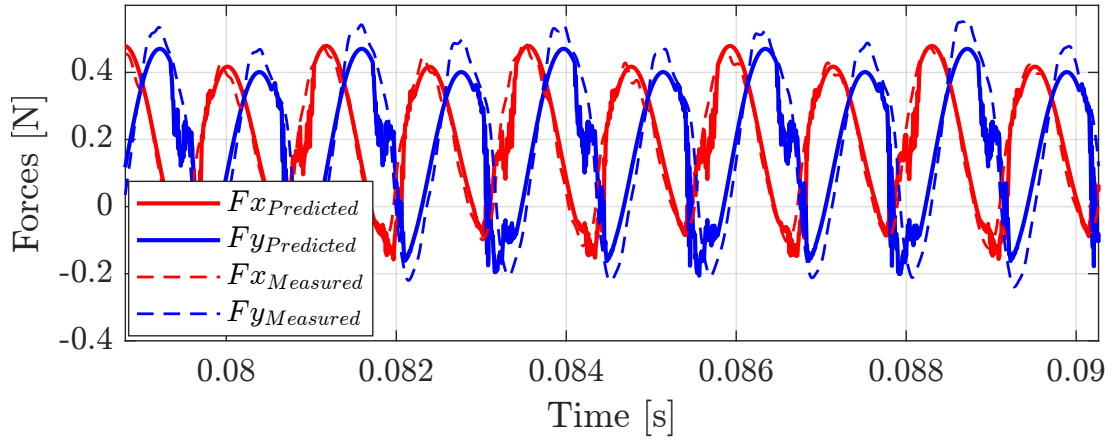


Figure 4.10: Simulated cutting force signal at 50 mm/min feed rate.

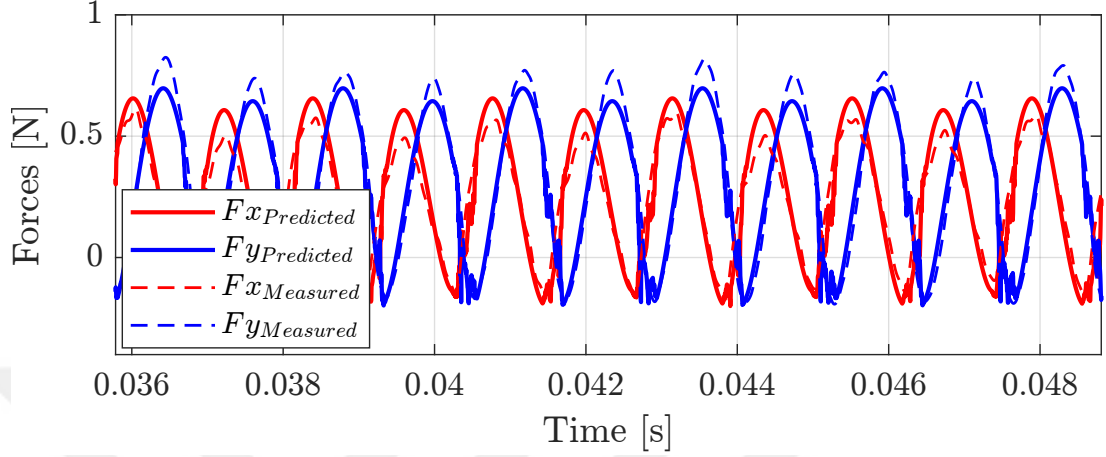


Figure 4.11: Simulated cutting force signal at 100 mm/min feed rate.

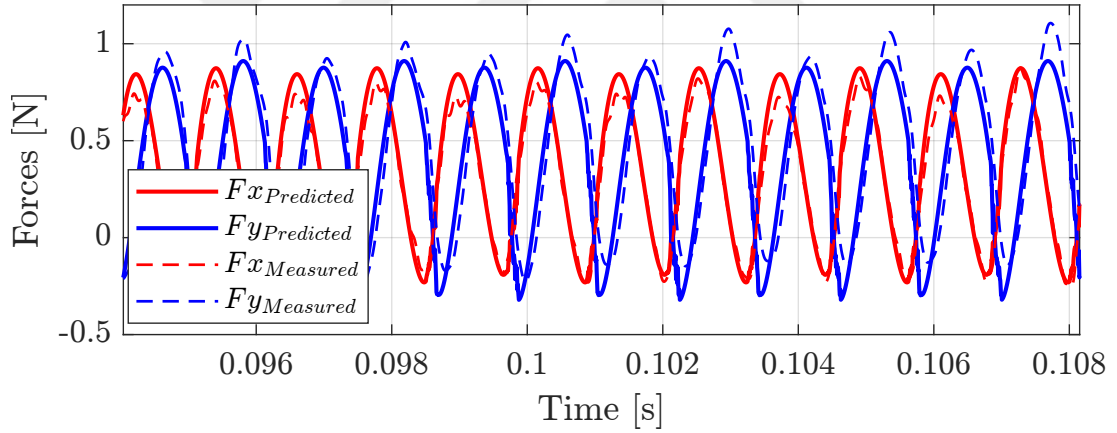


Figure 4.12: Simulated cutting force signal at 200 mm/min feed rate.

The model is able to produce accurate predictions of the uncut chip thickness and cutting forces as seen from Figures 4.10–4.12. Cutting at low feed rates is associated with the domination of ploughing action, and the predicted forces are often underestimated in this region. The ability of the proposed model to optimize and use a unique set of parameters at different feed rates allows it to capture the increase in the cutting forces at the ploughing dominated region (Figure 4.5). This increase can be related to friction, tool wear, and plastic deformation and hardening of the workpiece material due to the ploughing action, all of which is not included in this model. Tool deflection becomes less significant in this zone. This can be noted from the reduced values of C_n (Table 4.2).

Chapter 5

Force Model Parameter Identification Using Machined Surface Topography

Machined surface topography is a subject of great interest in micro-milling process modeling [36–41]. Since the overall objective of any machining process is to maximize topographic accuracy and surface quality, prediction of machined surface is essential for reliable machining. While enormous research has been conducted to predict and optimize cutting forces and surface quality, to the best knowledge of the author, no research is reported on using the machined surface to extract model parameters such as tool runout during micro-milling. The study presented in this chapter provides a surface investigation for the identification of force model parameters in micro-milling. The traces left by the cutting teeth on the floor surface are investigated and incorporated with an extended uncut chip thickness model in an optimization algorithm to identify runout parameters directly from the machined surface.

5.1 Micro-milling Force Model

In order to accurately quantify the micro-milling force model parameters, a reliable cutting force model that considers as much of the phenomena associated with micro-milling processes as possible shall be used. While the model proposed in chapter 4 produces accurate force predictions, it relies heavily on numerical optimization. The uncut chip thickness model proposed by Afazov et al. [25] is extended in this chapter to consider multiple previous trochoidal passes of the micro-end-mill teeth, which has proven to enhance the accuracy of the uncut chip thickness estimation near the entry and exit of the cut. Tool deflection and chip thickness accumulation are also incorporated in an analytical and systematic manner, and the effect of the helix angle is maintained. A nomenclature is given to assist the mathematical deliberations presented in this section.

Nomenclature

i	axial element index
j	tooth index
t_i	time at i^{th} axial element of the current tooth
t_i'	time at i^{th} axial element of the previous tooth
t_{i,n_j}	time at i^{th} axial element of the n_j^{th} previous tooth
t_o	simulation starting time
t_f	simulation ending time
$\theta_{i,j}$	immersion angle of the j^{th} tooth at the i^{th} axial element
R	tool radius
N_z	number of cutting teeth
λ	helix angle
a_p	axial depth of cut
ω	spindle speed in rad/s
K	total number of axial elements
dz	axial element thickness
f_x	feed rate in mm/min in x-direction
f_y	feed rate in mm/min in y-direction

f_t	feed per tooth in $\mu\text{m}/\text{tooth}$
ρ	runout radius in mm
α	runout angle in radians
h_r	simulated uncut chip thickness considering runout and trajectories of the current and previous cutting teeth
h_{r,n_j}	simulated uncut chip thickness considering runout and trajectories of the current and n_j^{th} previous cutting teeth
h_{rd}	simulated uncut chip thickness considering runout and deflection
h_{rda}	simulated uncut chip thickness considering runout, deflection, and chip thickness accumulation
h_{min}	minimum uncut chip thickness
F_n	cutting force component in the normal direction
F_t	cutting force component in the tangential direction
F_x	cutting force component in the x-direction
F_y	cutting force component in the y-direction
k_n	tool tip stiffness in the normal direction
K_{tc}	cutting coefficient of the tangential force
K_{tp}	ploughing coefficient of the tangential force
K_{nc}	cutting coefficient of the normal force
K_{np}	ploughing coefficient of the normal force
a_{tc}, a_{tp}	model constants of the tangential force
a_{nc}, a_{np}	model constants of the normal force
$\delta x_p, \delta x_v$	horizontal distances between surface profile peaks and valleys
x_o, y_o	origin offset parameters
dt	time sample size in seconds
n_s	number of samples of the cutting force signal

5.1.1 Modified runout model

The presented uncut chip thickness model considering runout is extended from [25]. The immersed depth of the micro end mill is first discretized into K axial disc elements of equal thickness dz to accommodate helix lag as depicted in Figure 5.1.

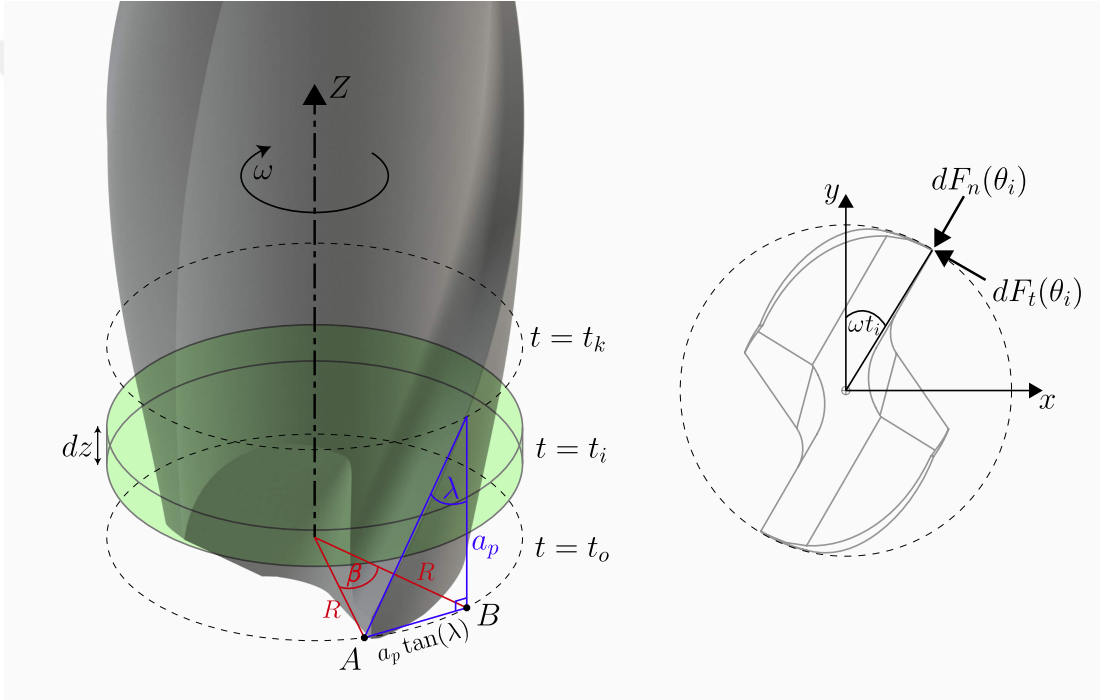


Figure 5.1: Discretization of the engaged axial depth of the two-flute micro-end-mill.

For a micro end mill with a number of cutting teeth of N_z , a radius of R , and a helix angle of λ , cutting at an axial depth of cut of a_p , the immersion angle of the j^{th} cutting tooth at the i^{th} disc element during the tool rotation $\theta_{i,j}$ is described in terms of time as:

$$\theta_{i,j} = \omega t_i - \frac{2\pi j}{N_z} \quad (5.1)$$

where ω is the spindle speed in rad/s, $j = 0, 1 \dots N_z - 1$, $i = 1 \dots K$, and t_i is the time at the first cutting tooth at the i^{th} disc element which is described as:

$$t_i = t_B - \frac{i(t_A - t_B)}{K} \quad (5.2)$$

where t_A, t_B are the time values at nodes A, B respectively. Taking t_A as a known starting time t_o , t_B can be calculated from:

$$t_B = t_A - \frac{\beta}{\omega} \quad (5.3)$$

The angle β can be calculated from:

$$\beta = \arccos\left(\frac{2R^2 - a_p^2 \tan^2 \lambda}{2R^2}\right) \quad (5.4)$$

A reference plane xoy is constructed on the workpiece as depicted in Figure 5.2, such that the origin coincides with the tool center considering zero runout at the starting time t_o . For a micro-end-mill cutting at feed rates in the x, y directions as f_x, f_y (mm/min), having a runout of ρ (mm) and a runout angle of α radians, the trajectory of the center of the tool (denoted as C in Figure 5.2) can be located as:

$$x_C(t_i) = \frac{f_x t_i}{60} + \rho \sin(\omega t_i + \alpha) \quad (5.5a)$$

$$y_C(t_i) = \frac{f_y t_i}{60} + \rho \cos(\omega t_i + \alpha) \quad (5.5b)$$

The trajectory of the j^{th} cutting tooth at the i^{th} disc element at a specific instant in time t_i (point P) can be described as:

$$x_P(t_i) = x_C(t_i) + R \sin\left(\omega t_i - \frac{2\pi j}{N_z}\right) \quad (5.6a)$$

$$y_P(t_i) = y_C(t_i) + R \cos\left(\omega t_i - \frac{2\pi j}{N_z}\right) \quad (5.6b)$$

In a similar manner, points C', Q which correspond to the tool center and the previous cutting tooth trajectories, respectively, at a previous instant in time t'_i when the previous cutting tooth trajectory intersects the line CP can be located by substituting t_i with t'_i and j with $j - 1$ in Equations 5.5 and 5.6 as follows:

$$x_{C'}(t'_i) = \frac{f_x t'_i}{60} + \rho \sin(\omega t'_i + \alpha) \quad (5.7a)$$

$$y_{C'}(t'_i) = \frac{f_y t'_i}{60} + \rho \cos(\omega t'_i + \alpha) \quad (5.7b)$$

$$x_Q(t'_i) = x_{C'}(t'_i) + R \sin\left(\omega t'_i - \frac{2\pi(j-1)}{N_z}\right) \quad (5.8a)$$

$$y_Q(t'_i) = y_{C'}(t'_i) + R \cos\left(\omega t'_i - \frac{2\pi(j-1)}{N_z}\right) \quad (5.8b)$$

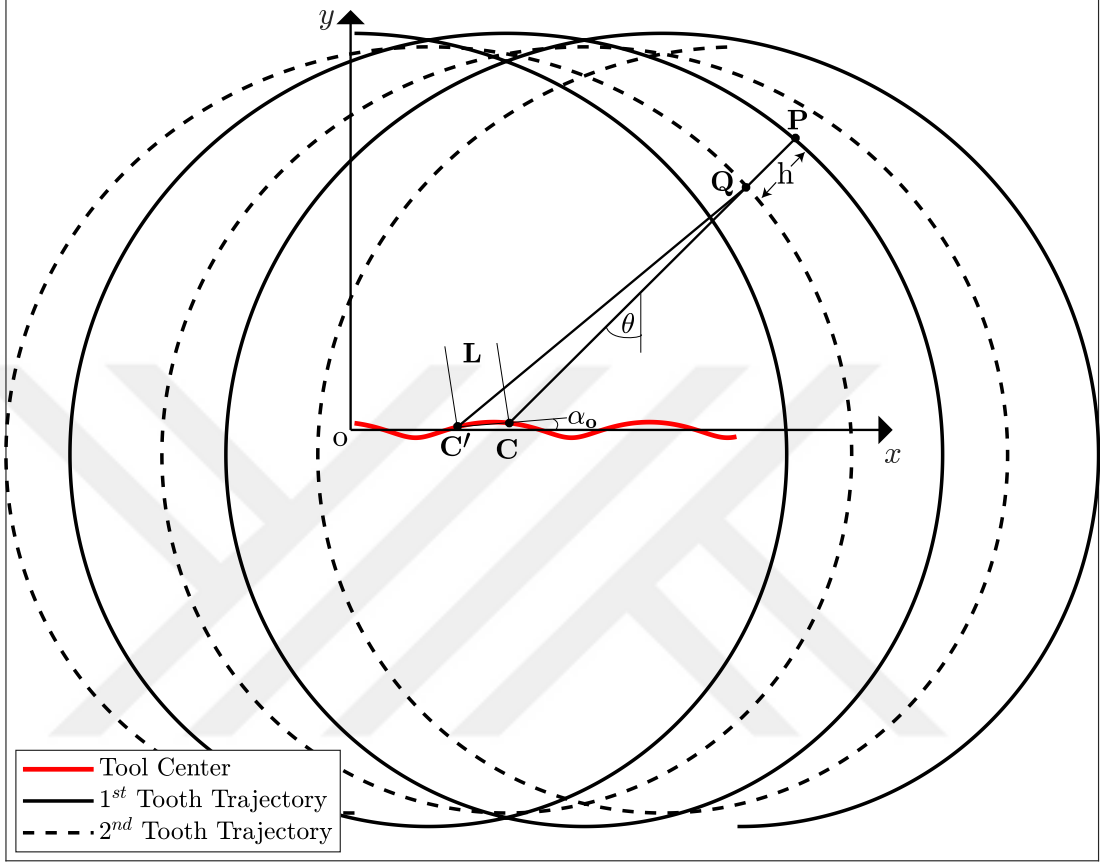


Figure 5.2: Simulated trajectory of the cutting teeth of a two-flute ($N_z = 2$) micro-end-mill.

The time t'_i can be determined from the following geometric relation:

$$[x_P(t_i) - x_Q(t'_i)] - [y_P(t_i) - y_Q(t'_i)] \tan(\omega t_i) = 0 \quad (5.9)$$

Equation 5.10 can be written by substituting Equations 5.6 and 5.8 in Equation 5.9 as following:

$$\begin{aligned} & \left\{ \left[\frac{f_x t_i}{60} + \rho \sin(\omega t_i + \alpha) + R \sin\left(\omega t_i - \frac{2\pi j}{N_z}\right) \right] \right. \\ & - \left[\frac{f_x t'_i}{60} + \rho \sin(\omega t'_i + \alpha) + R \sin\left(\omega t'_i - \frac{2\pi(j-1)}{N_z}\right) \right] \Bigg\} \\ & - \left\{ \left[\frac{f_y t_i}{60} + \rho \cos(\omega t_i + \alpha) + R \cos\left(\omega t_i - \frac{2\pi j}{N_z}\right) \right] \right. \\ & - \left[\frac{f_y t'_i}{60} + \rho \cos(\omega t'_i + \alpha) + R \cos\left(\omega t'_i - \frac{2\pi(j-1)}{N_z}\right) \right] \Bigg\} \tan(\omega t_i) = 0 \end{aligned} \quad (5.10)$$

Equation 5.10 can be solved for t'_i numerically using Newton-Raphson's method [45]. The initial guess can be written as:

$$t'_{io} = t_i - \frac{2\pi}{\omega N_z} \quad (5.11)$$

After the value of t'_i is found, the uncut chip thickness considering runout and a rigid tool can be found from the geometric relation:

$$h_r(\theta_{i,j}) = R + L \sin(\theta_{i,j} + \alpha_o) - \sqrt{R^2 - L^2 \cos^2(\theta_{i,j} + \alpha_o)} \quad (5.12)$$

The length L and the angle α_o can be calculated as:

$$L = \sqrt{[x_C(t_i) - x_{C'}(t'_i)]^2 + [y_C(t_i) - y_{C'}(t'_i)]^2} \quad (5.13)$$

$$\alpha_o = \arctan \left(\frac{y_C(t_i) - y_{C'}(t'_i)}{x_C(t_i) - x_{C'}(t'_i)} \right) \quad (5.14)$$

When the feed per tooth f_t is small in presence of a relatively large runout, a j^{th} cutting tooth can cut material that is left from not only the $(j-1)^{th}$ tooth pass, but from several previous tooth passes. To illustrate, Figures 5.3–5.5 show the simulated cutting tooth trajectories at the first disc element $i = 1$ for a 2-flute micro-end-mill. The figures present three cases where the runout angle is held constant at 30 degrees, and the runout radius and the feed per tooth values are changed.

It can be observed that as the feed decreases, the effect of runout becomes more prominent, and the chip load varies significantly from one cutting tooth to another. In the case of slot milling with a 2-flute micro-end-mill, this can be visible at immersion angles that are closer to the entry and exit of the cut (the areas highlighted in yellow in Figures 5.3–5.4). When the value f_t/ρ is in the vicinity of the number of teeth N_z , the second cutting tooth might not engage in the cut (Figure 5.5). This is especially true when the runout angle α is equal to zero and $f_t/\rho \leq N_z$, under the assumption of a rigid cutter. Therefore, to produce an accurate estimate of the uncut chip thickness at low feed rates in presence of a large runout, it is necessary to consider not only one previous tooth pass, but N_z number of previous tooth passes.

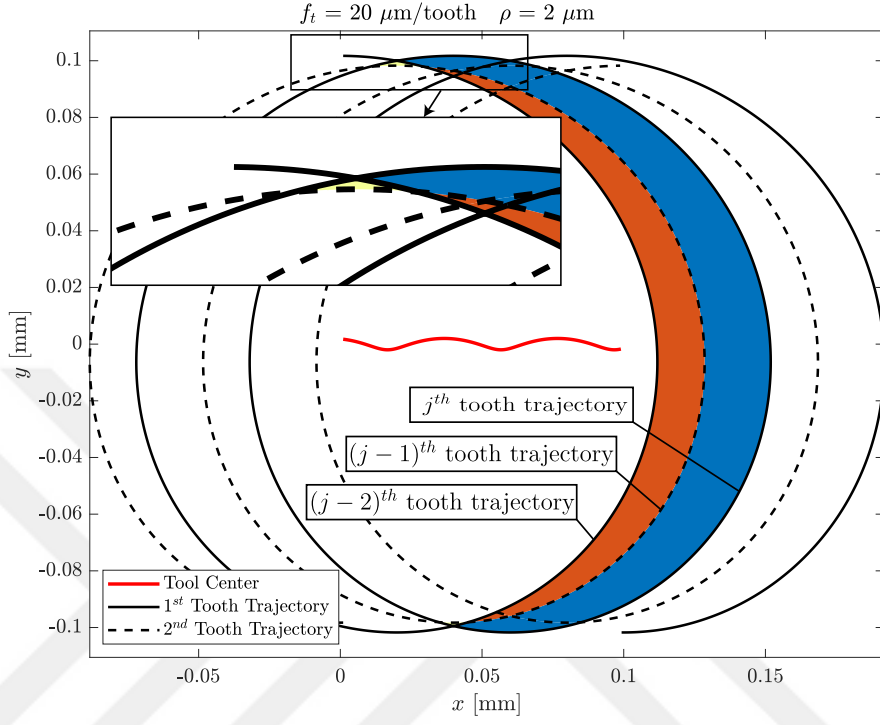


Figure 5.3: Simulated cutting tooth trajectories: Case I.

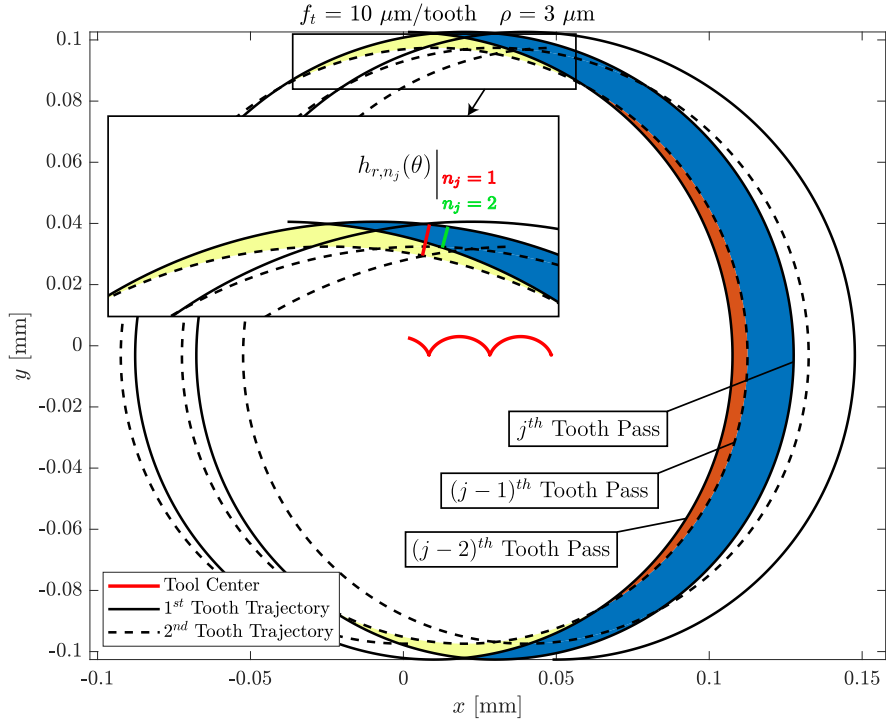


Figure 5.4: Simulated cutting tooth trajectories: Case II.

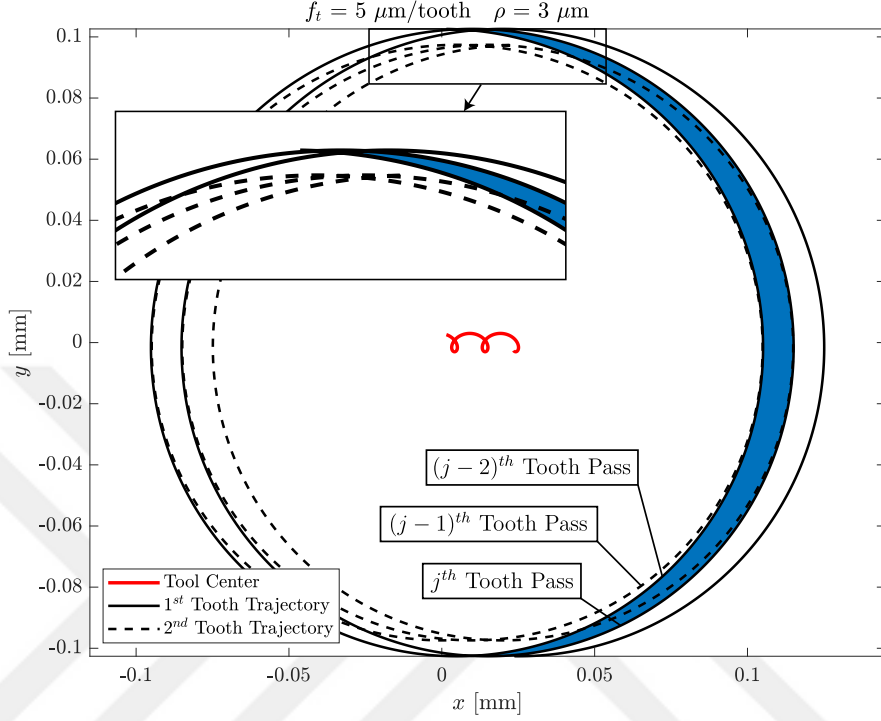


Figure 5.5: Simulated cutting tooth trajectories: Case III.

Equations 5.7–5.14 can be modified to produce a number of solutions for the uncut chip thickness $h_{r,n_j}(\theta_{i,j})$ that is equal to the number of flutes N_z of the micro-end-mill, essentially by substituting t'_i with t_{i,n_j} (denoting the time at the $(j - n_j)^{th}$ tooth pass), and $(j - 1)$ with $(j - n_j)$, for $n_j = 1 \dots N_z$. The initial guess for the Newton-Raphson method can then be modified to:

$$t_{i,n_j o} = t_i - \frac{2\pi n_j}{\omega N_z} \quad (5.15)$$

And the final estimate of the uncut chip thickness considering runout can be taken as the minimum of all the solutions as:

$$h_r(\theta_{i,j}) = \min_{n_j=1 \dots N_z} (h_{r,n_j}(\theta_{i,j})) \quad (5.16)$$

5.1.2 Tool deflection

In micro-milling, tool deflection can have significant effects on the tool-workpiece engagement and chip load which can lead to geometric errors on the machined component. When the tool diameter is very small, deflections resulting from cutting forces cannot be omitted from the modeling process. While both the normal and tangential components of the cutting force contribute to the total deflection of the cutter during machining, deflection in the tangential direction has little to no effect on the uncut chip thickness and therefore, static cutter deflection resulting from the normal force component is considered in this model. Figure 5.6 shows the effect of cutter deflection on the formulation of the uncut chip thickness. A Hookean spring model can be applied to incorporate the effect of cutter deflection on the uncut chip thickness.

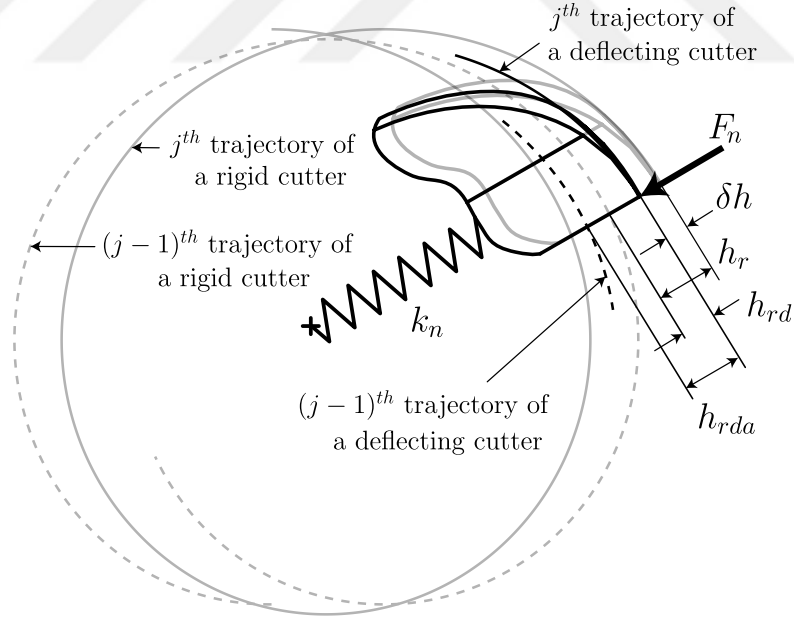


Figure 5.6: Illustration of the influence of micro-end-mill deflection on the uncut chip thickness.

Knowing the tool tip stiffness k_n (N/mm) from the finite element analysis (see chapter 3), the following force balance equation can be written:

$$F_n(\theta) = k_n \cdot \delta h(\theta) \quad (5.17)$$

where $\delta h(\theta)$ is the cutter deflection in (mm). Equation 5.17 can be rewritten to

describe the elemental normal force and deflection at the disc element level as:

$$K_n \cdot h_{rd}(\theta_{i,j})^{a_n} \cdot dz = \frac{k_n}{K} [h_r(\theta_{i,j}) - h_{rd}(\theta_{i,j})] \quad (5.18)$$

Equation 5.18 is solved for $h_{rd}(\theta_i)$; which is the value of the uncut chip thickness with consideration of runout and deflection. The value of the cutter deflection δh is then calculated and added to the uncut chip thickness value in the $(j+1)^{th}$ tooth pass as:

$$\delta h(\theta_{i,j}) = h_r(\theta_{i,j}) - h_{rd}(\theta_{i,j}) \quad (5.19)$$

$$h_{rd}(\theta_{i,j+1}) = h_{rd}(\theta_{i,j}) + \delta h(\theta_{i,j}) \quad (5.20)$$

5.1.3 Chip thickness accumulation

To accommodate chip thickness accumulation in the force model, the uncut chip thickness value from the previous tooth pass is compared with the minimum uncut chip thickness. In the case that the uncut chip thickness from the previous tooth pass $(j-1)$ is lower than the minimum uncut chip thickness h_{min} , accumulation occurs and the value of the uncut chip thickness at the current tooth pass $h_{rd}(\theta_{i,j})$ is updated to $h_{rda}(\theta_{i,j})$; which is the value of the uncut chip thickness with consideration of runout, deflection and chip thickness accumulation, according to the following equation:

$$h_{rda}(\theta_{i,j}) = \begin{cases} h_{rd}(\theta_{i,j}) & h_{rd}(\theta_{i,j-1}) \geq h_{min} \\ h_{rd}(\theta_{i,j}) + h_{rd}(\theta_{i,j-1}) & h_{rd}(\theta_{i,j-1}) < h_{min} \end{cases} \quad (5.21)$$

The uncut chip thickness will continue to accumulate in the subsequent tooth passes until exceeding the minimum uncut chip thickness value. The identification of the minimum uncut chip thickness is discussed in Section 5.3.1.2.

5.1.4 Mechanistic force model

The cutting force model presented in chapter 4 uses a different set of cutting coefficients for different feed rates. While this was shown to improve the accuracy

of force predictions, it hinders the versatility of the model. In the model presented in this chapter, only two sets of cutting coefficients are used, namely ploughing $(K_{tp}, a_{tp}, K_{np}, a_{np})$, and cutting $(K_{tc}, a_{tc}, K_{nc}, a_{nc})$ coefficients. This approach can provide better predictions in the ploughing dominated region on the chip thickness (i.e. $h_{rda}(\theta_{i,j}) < h_{min}$), while maintaining versatility. The cutting forces are calculated in the rotating reference plane of the tool based on the power function mechanistic model as:

$$dF_t(\theta_{i,j}) = \begin{cases} K_{tc} \cdot h_{rda}(\theta_{i,j})^{a_{tc}} \cdot dz & h_{rda}(\theta_{i,j}) \geq h_{min} \\ K_{tp} \cdot h_{rda}(\theta_{i,j})^{a_{tp}} \cdot dz & h_{rda}(\theta_{i,j}) < h_{min} \end{cases} \quad (5.22a)$$

$$dF_n(\theta_{i,j}) = \begin{cases} K_{nc} \cdot h_{rda}(\theta_{i,j})^{a_{nc}} \cdot dz & h_{rda}(\theta_{i,j}) \geq h_{min} \\ K_{np} \cdot h_{rda}(\theta_{i,j})^{a_{np}} \cdot dz & h_{rda}(\theta_{i,j}) < h_{min} \end{cases} \quad (5.22b)$$

where $dF_n(\theta_{i,j}), dF_t(\theta_{i,j})$ are the elemental normal and tangential components of the cutting force acting on the tool, $K_{tc}, a_{tc}, K_{nc}, a_{nc}$ are the specific force coefficients in the cutting dominated region ($h_{rda}(\theta_{i,j}) \geq h_{min}$), $K_{tp}, a_{tp}, K_{np}, a_{np}$ are the specific force coefficients in the ploughing dominated region ($h_{rda}(\theta_{i,j}) < h_{min}$) and dz is the disc element thickness in mm which is equal to:

$$dz = \frac{a_p}{K} \quad (5.23)$$

where a_p is the axial depth of cut in mm. After calculating the cutting forces in the tool reference plane from Equation 5.22, the forces are then transformed into the reference plane of the workpiece using the following equation:

$$\begin{bmatrix} dF_x(\theta_{i,j}) \\ dF_y(\theta_{i,j}) \end{bmatrix} = \begin{bmatrix} -\cos(\theta_{i,j}) & -\sin(\theta_{i,j}) \\ \sin(\theta_{i,j}) & -\cos(\theta_{i,j}) \end{bmatrix} \begin{bmatrix} dF_t(\theta_{i,j}) \\ dF_n(\theta_{i,j}) \end{bmatrix} \quad (5.24)$$

The elemental cutting forces are then summed along the axial height of the tool to produce the final cutting force signal using the following equation:

$$F_{x,y}(t) = \sum_{i=1}^K \sum_{j=0}^{N_z-1} dF_{x,y}(\theta_{i,j}) \quad (5.25)$$

The uncut chip thickness model detects entry and exit angles based on the trochoidal trajectory of the cutting teeth and calculates positive uncut chip thickness values only when the tool is engaged with the workpiece. It is worth mentioning

that since the axial forces acting on the tool during micro-milling processes are very low compared to tangential and normal forces [20], only forces in the feed and cross-feed direction, namely F_x, F_y are modeled in this study. A flow chart summarizing the force model is presented in Figure 5.7.

5.2 Micro-milling Tests

Micro slot-milling and side-milling tests were carried out on a commercially pure titanium workpiece using a coated carbide two-flute micro end mill with $400\ \mu\text{m}$ diameter, $800\ \mu\text{m}$ length of cut, and 30-degree helix angle (MXH230 0.4×0.8, NS Tools, Japan). The experimental setup was presented in chapter 2. Spindle speed was held constant at 25000 rpm during all the cutting tests. Six slots 10 mm in length were cut while holding the axial depth of cut constant at $40\ \mu\text{m}$. The rest of the cutting conditions during slot milling are presented in Table 5.1. Five side milling cuts 2 mm in length were conducted at a constant feed of $4\ \mu\text{m/tooth}$. The rest of the cutting conditions during the side milling tests are presented in Table 5.2.

Table 5.1 Slot milling conditions.

Test No.	Feed Rate (mm/min)	Feed ($\mu\text{m/tooth}$)
1	50	1
2	100	2
3	200	4
4	300	6
5	400	8
6	500	10

Table 5.2 Side milling conditions.

Test No.	Axial Depth of Cut	Radial Depth of Cut	Radial Immersion %
1	$100\ \mu\text{m}$	$100\ \mu\text{m}$	25%
2	$100\ \mu\text{m}$	$150\ \mu\text{m}$	37.5%
3	$100\ \mu\text{m}$	$180\ \mu\text{m}$	45%
4	$150\ \mu\text{m}$	$180\ \mu\text{m}$	45%
5	$150\ \mu\text{m}$	$150\ \mu\text{m}$	37.5%

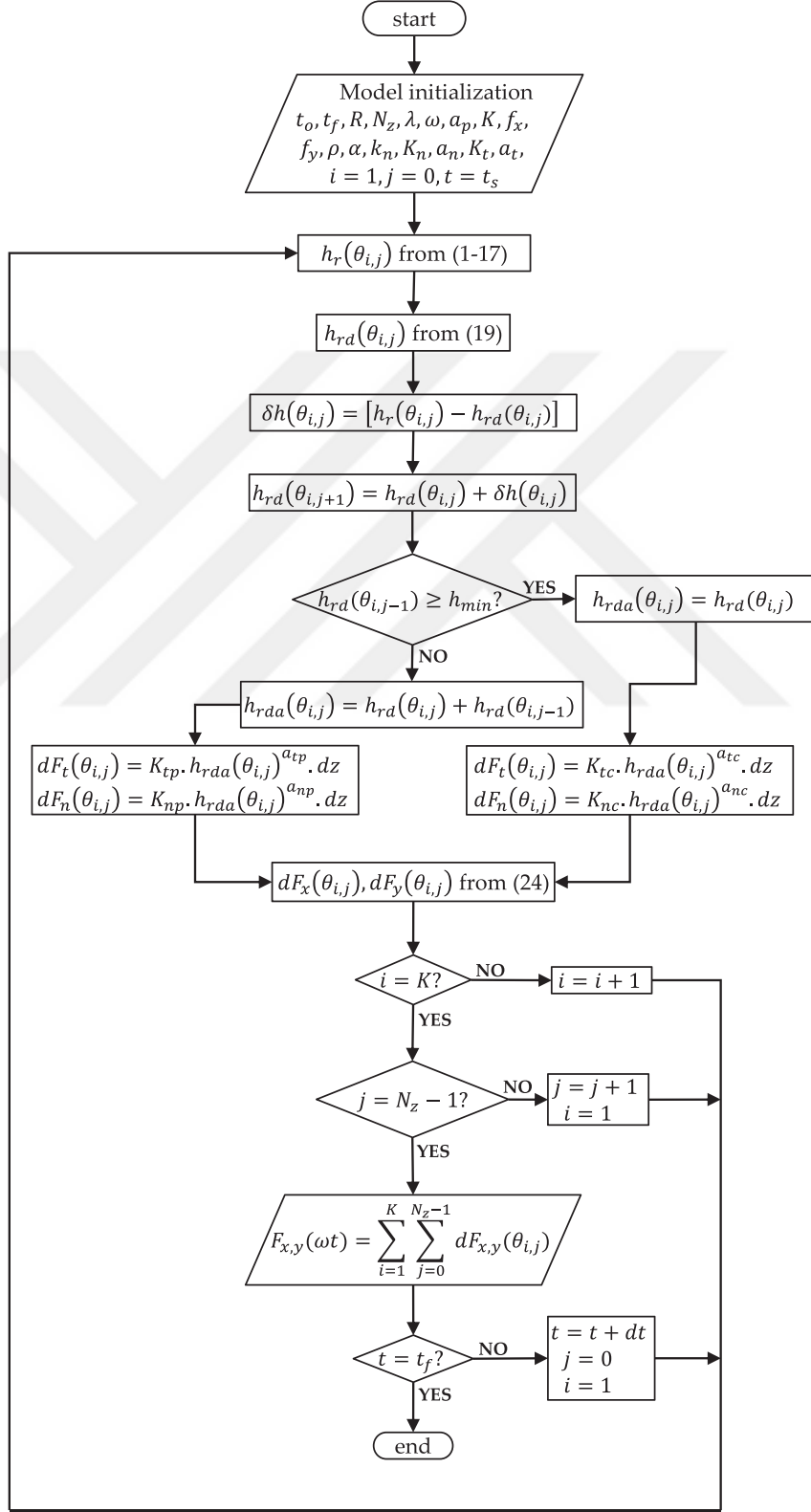


Figure 5.7: Flow chart of the cutting force model.

5.3 Investigation of Experimental Data

5.3.1 Identification of the model parameters using machined surface topography

The machined surfaces are investigated under the laser scanning microscope in order to analyze the machining marks of the cutting teeth on the workpiece. Surface data from the floors of the slot milling experiments and the side walls of side milling experiments is analyzed to identify the runout parameters and the value of the minimum uncut chip thickness as shown in Figure 5.8. This figure is rendered using actual laser scans of the surfaces as texture maps in a professional rendering software (Solidworks Visualize Professional).

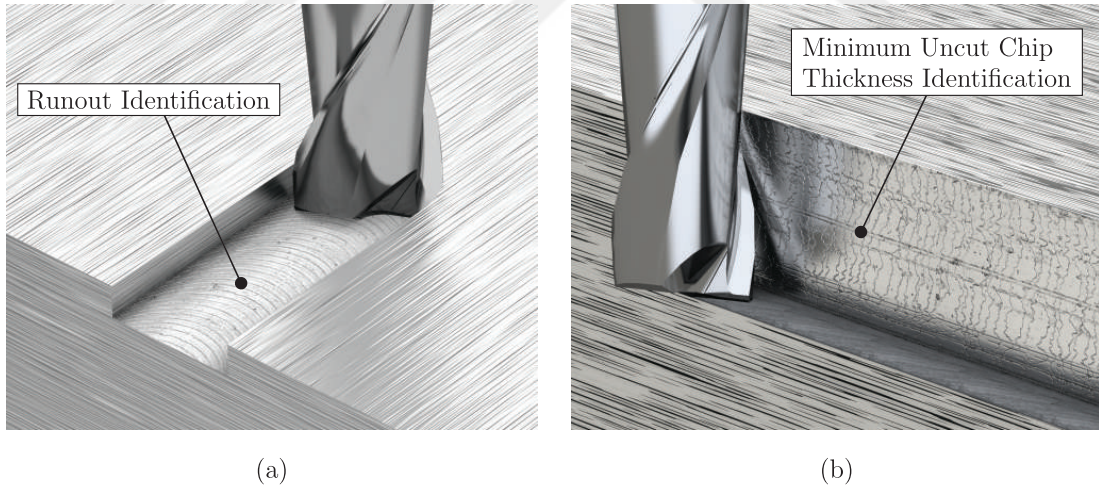


Figure 5.8: Machined surface investigation to identify (a) Runout parameters, (b) Minimum uncut chip thickness.

5.3.1.1 Runout parameters

A line profile was taken at the centerline of the slot where the maximum chip thickness throughout the single tooth pass is expected, and a peak detection algorithm was used to identify the peaks and the valleys of the surface profile as shown in Figure 5.9. It can be noted from Figure 5.9b–c that the depth of

valleys is alternating in magnitude. This can be related to the tool deflection in presence of runout. Tool runout results in a variation in the chip load between the two consequent tooth passes. As a result, the normal force and tool deflection would also vary. The deeper scratches on the surface are a clear observation of the larger bending of the tool tip towards the surface due to deflection, and the depth of these scratches alternates as the first and second teeth of the tool are engaged in the cut.

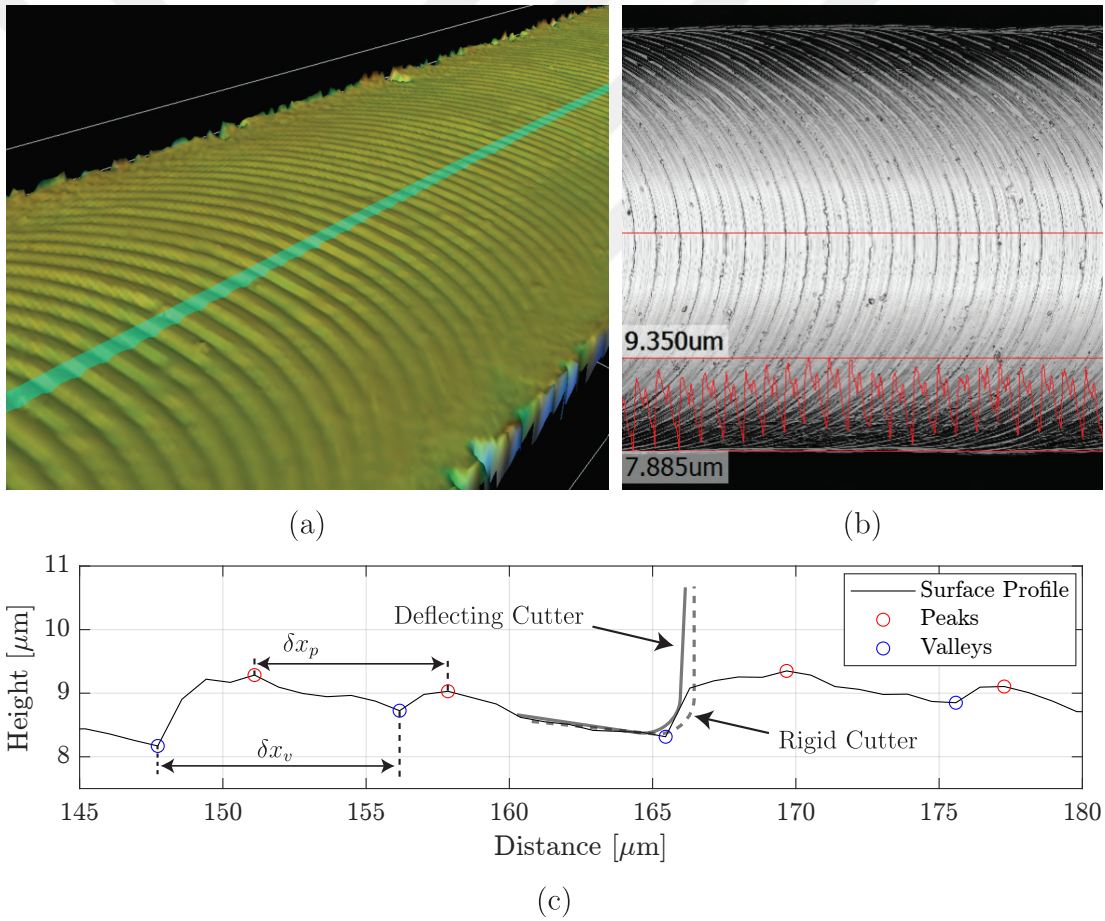


Figure 5.9: Peak analysis of the surface profile measurement.

The horizontal distances between the peaks δx_p and the valleys δx_v are calculated using a computer code, and they are represented in histogram distributions in Figure 5.10. The histogram in Figure 5.10a shows two values averaging near 8 and 12 μm . It can be visible that this alternation is the effect of runout on the actual chip thickness at the centerline of the slot, as the commanded feed was 10

$\mu\text{m}/\text{tooth}$ in this case. The histogram in Figure 5.10b shows a normal distribution around $10 \mu\text{m}$. The fact that the alternation is visible on the histogram of the valleys but not the peaks can be explained by the likelihood of consequent tooth passes altering the top of the surface but not the bottom. Therefore, it can be assumed that the valleys of this profile represent the actual intersection of the tooth trajectories with the centerline of the slot, and the horizontal distance between these valleys (δx_v) represents the actual chip thickness at that location.

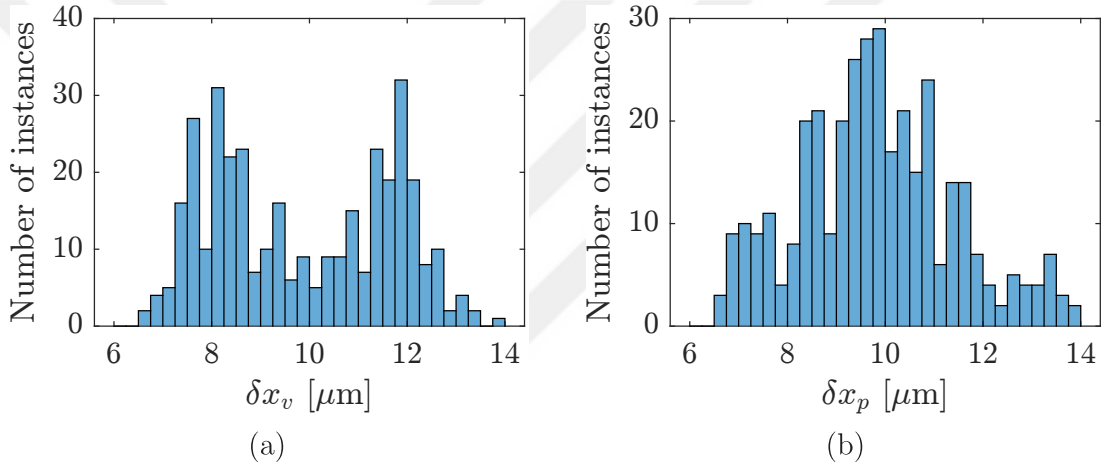


Figure 5.10: Histogram distributions of the peak analysis results at $10 \mu\text{m}/\text{tooth}$ feed. (a) Horizontal distance between valleys (δx_v). (b) Horizontal distance between peaks (δx_p).

Runout parameters cannot be calculated using these values alone. To calculate the runout parameters, it is necessary to utilize the uncut chip thickness model that was developed in Section 5.1. First, the absolute error between the averages of experimental and simulated maximum uncut chip thickness resulting from the two different cutting teeth of the micro end mill at 6, 8, and $10 \mu\text{m}/\text{tooth}$ feeds is minimized by minimization of the following fitness function using the genetic algorithm:

$$\varepsilon = \sum_{f_t=6,8,10} \sum_{j=0,1} \left| \overline{h_{rd}}|_{max} \left(\theta_{\frac{K}{2},j} \right)_{exp} - \overline{h_{rd}}|_{max} \left(\theta_{\frac{K}{2},j} \right)_{sim} \right| \quad (5.26)$$

The algorithm is set to halt when the average change in the fitness function value throughout 100 stall generations is less than a predefined tolerance of 10^{-6} .

Since a single location on the surface was used in this analysis (the maximum

chip thickness at the slot centerline), multiple solutions that satisfied the error criterion were found. To identify a single solution, point coordinates belonging to three consecutive tooth passes on the surface were located with consideration of the surface topography and profile valleys as depicted in Figure 5.11. The surface marks were picked carefully such that the resulting values of δx_v at the centerline correspond to the most occurring values indicated from the histogram distributions. Genetic algorithm was used again to minimize the summation of the shortest distances from each data point to the corresponding simulated tooth trajectories that are calculated using a modified expression of Equation 5.6 as:

$$x_P(t_1) = x_o + x_C(t_1) + R \sin \left(\omega t_1 - \frac{2\pi j}{N_z} \right) \quad (5.27a)$$

$$y_P(t_1) = y_o + y_C(t_1) + R \cos \left(\omega t_1 - \frac{2\pi j}{N_z} \right) \quad (5.27b)$$

where x_o, y_o are offset parameters that are included in the optimization algorithm in order to find the location of the origin of the reference plane in which the tooth trajectories are simulated.

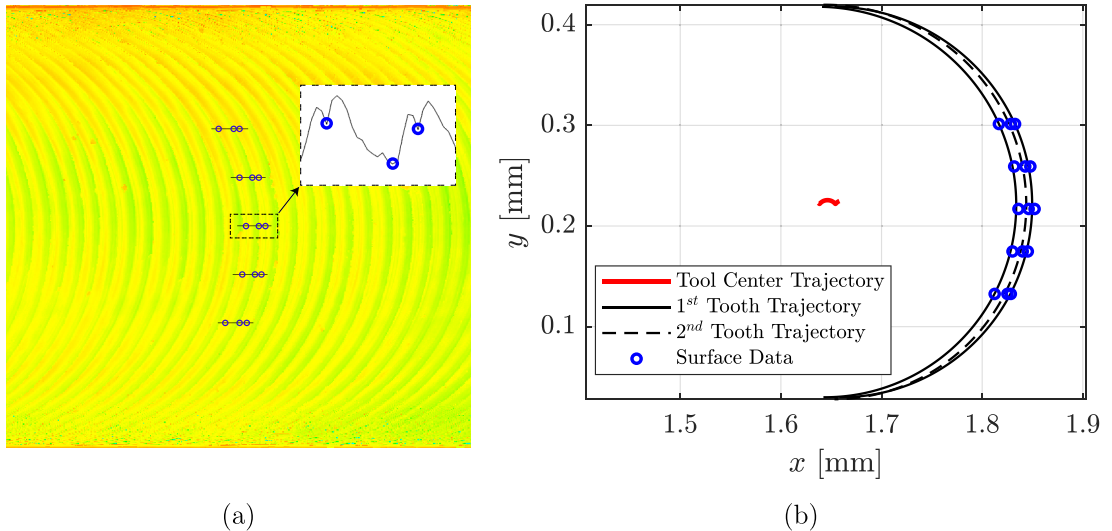


Figure 5.11: (a) Selection of surface data points for optimization at 8 $\mu\text{m}/\text{tooth}$ feed. (b) Optimized tooth trajectories at 8 $\mu\text{m}/\text{tooth}$ feed.

The solutions yielded from the optimization algorithm using a single location were plotted against each other as shown in Figure 5.12. It was observed from the figure that the runout parameters are co-dependent. The fitness function values

ranged from 3.04×10^{-3} to 3.06×10^{-3} , which gives a difference of only 25×10^{-5} ($\sim 0.8\%$) between the best and worst solutions. The single solution yielded from the optimization algorithm using the surface marks of three consecutive tooth passes is marked with an 'x' in Figure 5.12. It can be noted that the identified runout parameters using this analysis agree with the values resulting from the investigation of the surface profile at the centerline of the slot.

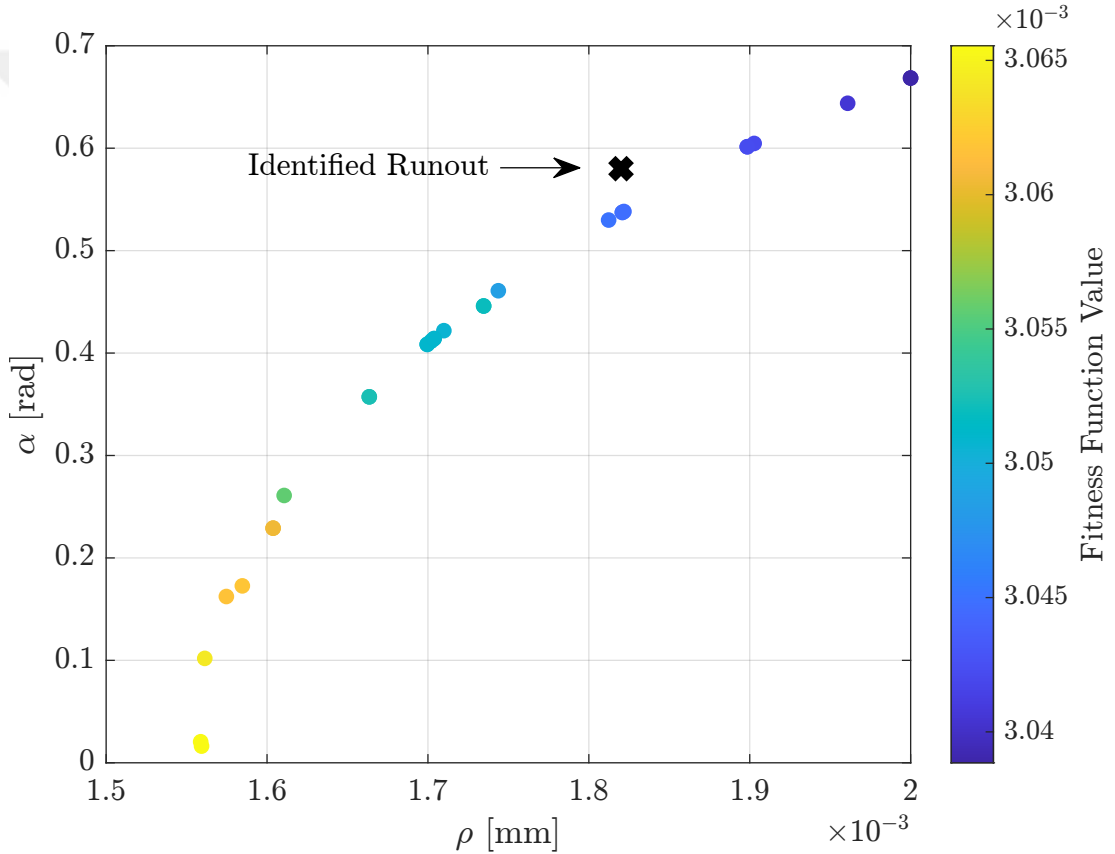


Figure 5.12: Runout parameters optimization results.

The values of the identified runout and offset parameters are reported in Table 5.3. It's worth mentioning that the scanned surfaces are the elastically recovered surfaces after machining. Therefore, the effect of elastic recovery can be included in the identified runout parameters. Isolating the effect of elastic recovery will introduce another unknown in the process, which is the elastic recovery rate. Additionally, it has been shown in a previous study that the effect of elastic recovery becomes significant at lower feed rates [41]. Therefore, the surface investigation was carried out at relatively high feed rates in this study (i.e. 6,8,10 $\mu\text{m}/\text{tooth}$).

5.3.1.2 Minimum uncut chip thickness

Liu et al. [34] presented an analytical model for the prediction of the minimum uncut chip thickness in micro-milling processes. The minimum uncut chip thickness was validated experimentally by investigation of the side walls of the milled surface and measurement of the ridges that were left on the surface, which indicate sudden transitions between ploughing and cutting action. A similar approach was followed to measure the minimum uncut chip thickness using side milling tests (Figure 5.13). The side milling conditions are discussed in Section 5.2.

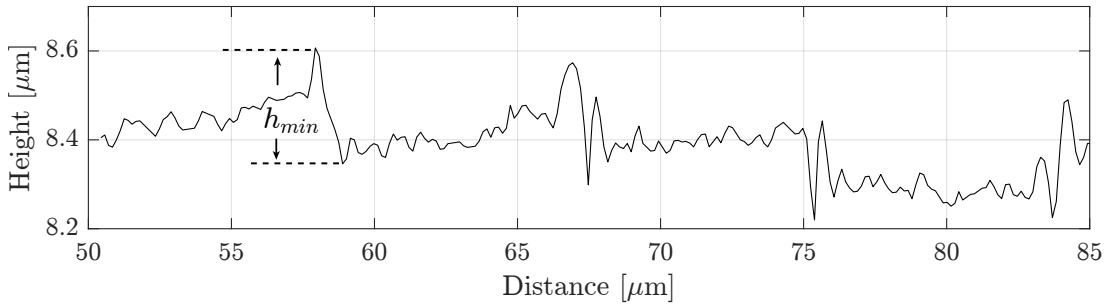
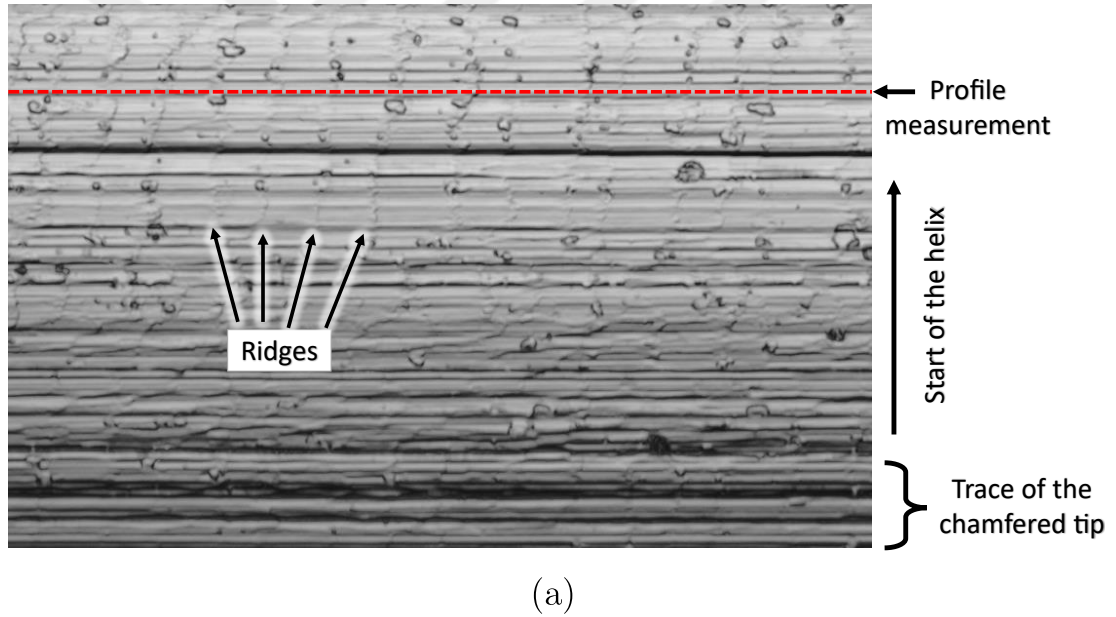


Figure 5.13: Investigation of the side walls. (a) Surface topography. (b) Surface profile measurement and identification of the minimum uncut chip thickness.

The side wall surfaces were scanned with the laser scanning microscope using a 50x objective lens, and horizontal profile measurements were taken at 3 different heights at 25 μm increments on the side walls. The average value considering all the profile measurement for the five cutting tests was calculated as 0.2 μm , which was assumed as the minimum uncut chip thickness value. The edge radius of the tool r_e was measured as 1.78 μm , which gives a h_{min}/r_e ratio of 0.11 (11%).

5.3.2 Cutting force signal processing and identification of the cutting coefficients

The cutting force signal was processed in the same manner as presented in Section 4.2.1. The same curve fitting technique was applied again to identify the specific force coefficients. Upon splitting and fitting the experimental force signal (see Figure 4.4), the resulting power functions are presented in Figure 5.14. The effect of the minimum chip thickness can be observed on the tangential force in Figure 5.14, where a sudden change in the slope of the up-milling force signal implies a transition from ploughing to cutting action. The value of the assumed chip thickness in this region agrees with the value of the minimum uncut chip thickness identified in Section 5.3.1.2.

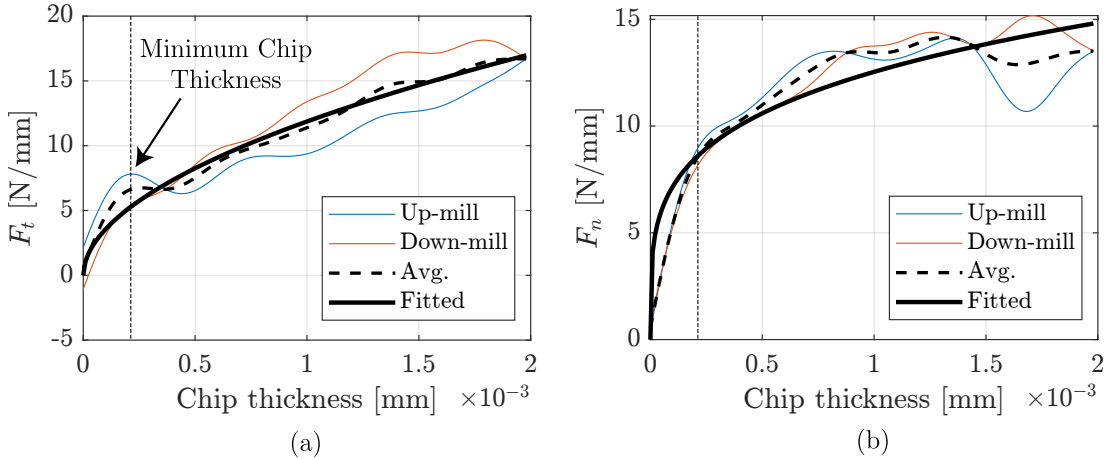


Figure 5.14: Curve fitting the force signal. (a) Tangential force. (b) Normal force.

Figure 5.15 shows the identified mechanistic normal force functions at all the feed rates. These model functions are identified in the same manner as presented in Section 4.2.1. It can be noted from Figure 5.15 that the identified coefficients at $1 \mu\text{m}$ feed per tooth produce a slightly larger force at lower chip thickness values. This increase is ought to the dominance of ploughing in this region as the feed per tooth value is decreased. The coefficients identified for this feed, namely $K_{tp}, a_{tp}, K_{np}, a_{np}$, are used in the mechanistic model when ploughing is dominant i.e. when $h_{rda}(\theta_{i,j}) < h_{min}$. The rest of the coefficient sets (i.e. for feeds 2-10 $\mu\text{m}/\text{tooth}$) are averaged into one set of coefficients, namely $K_{tc}, a_{tc}, K_{nc}, a_{nc}$ to be used when cutting is dominant i.e. when $h_{rda}(\theta_{i,j}) \geq h_{min}$. The values of the identified cutting coefficients are reported in Table 5.3. This approach enhances the versatility of the model over feed rates where cutting action is dominant, while still producing accurate predictions of the cutting forces at lower feeds where ploughing action is dominant.

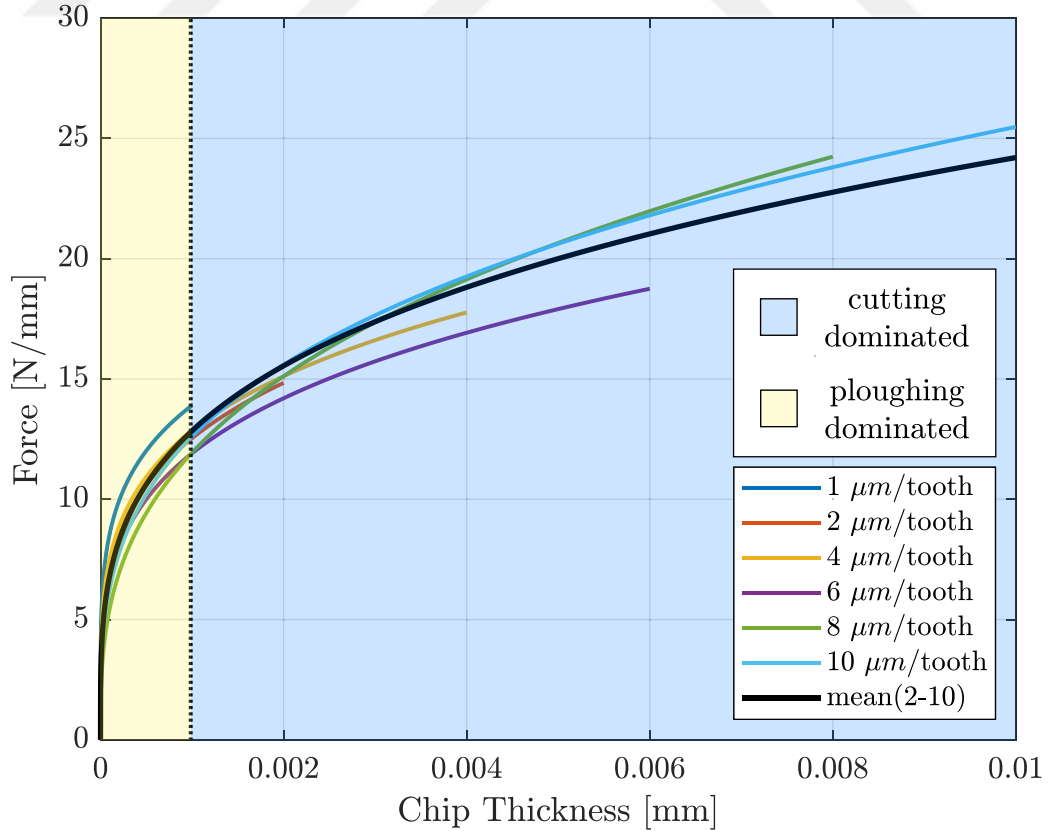


Figure 5.15: Mechanistic force model functions identified at different feed values and the identification of cutting and ploughing dominant regions.

5.4 Results and Discussion

The identified model parameters are presented in Table 5.3. Figures 5.16–5.18 show the simulated uncut chip thickness at three different feed per tooth values, namely 1, 4 and 8 $\mu\text{m}/\text{tooth}$. Figures 5.19–5.21 show the predicted cutting force signal compared to the measured data, at the said feed values. The root mean squared error between the predicted and measured cutting force signal is reported in Table 5.4.

The cutting force model produces accurate predictions of the signal over a wide range of feed values, as seen from Figures 5.19–5.21 and Table 5.4. A slight deviation in the peak forces of the predicted signal from the experimental data can be observed which can be related to the averaging of the curves used to identify the cutting coefficients. Using a separate set of cutting coefficients at different feeds can increase the accuracy of peak force predictions.

Table 5.3 Identified model parameters.

	Ploughing		Cutting	
	K_{np} [N/mm^2]	a_{np}	K_{nc} [N/mm^2]	a_{nc}
Force Coefficients	59.65	0.2108	85.934	0.2751
	K_{tp} [N/mm^2]	a_{tp}	K_{tc} [N/mm^2]	a_{tc}
	266.6	0.4570	618.34	0.5877
Runout Parameters	ρ		α	
	1.82 μm		0.58 rad	

Table 5.4 RMS error in the cutting force signal.

Feed	RMSE in F_x	RMSE in F_y
1 $\mu\text{m}/\text{tooth}$	0.0264	0.0629
4 $\mu\text{m}/\text{tooth}$	0.0941	0.0685
8 $\mu\text{m}/\text{tooth}$	0.1524	0.0130

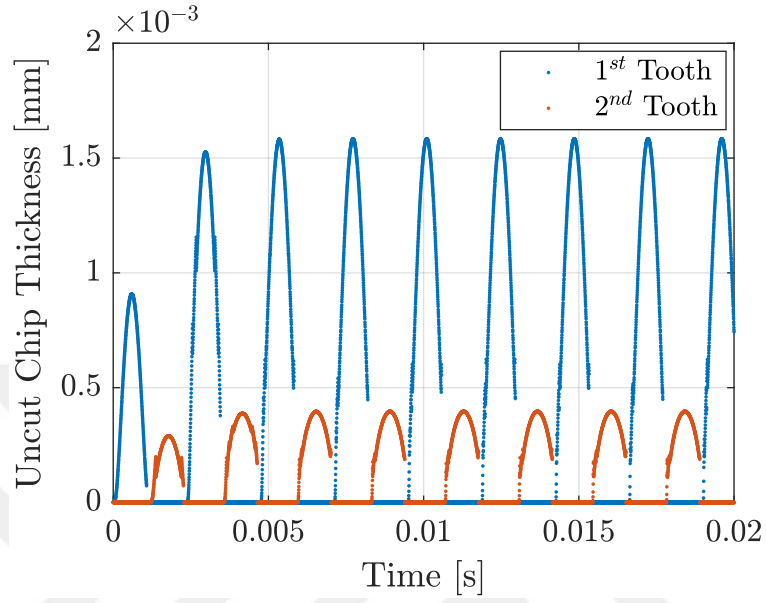


Figure 5.16: Simulated uncut chip thickness at $1 \mu\text{m}/\text{tooth}$.

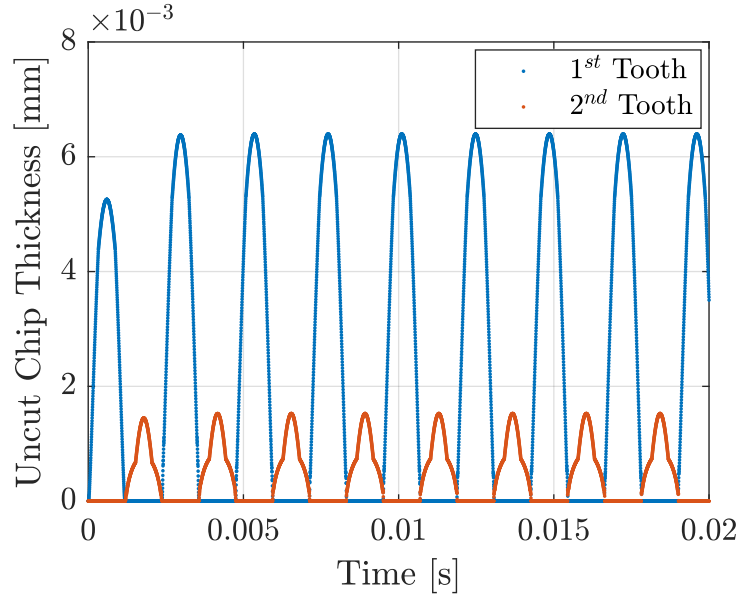


Figure 5.17: Simulated uncut chip thickness at $4 \mu\text{m}/\text{tooth}$.

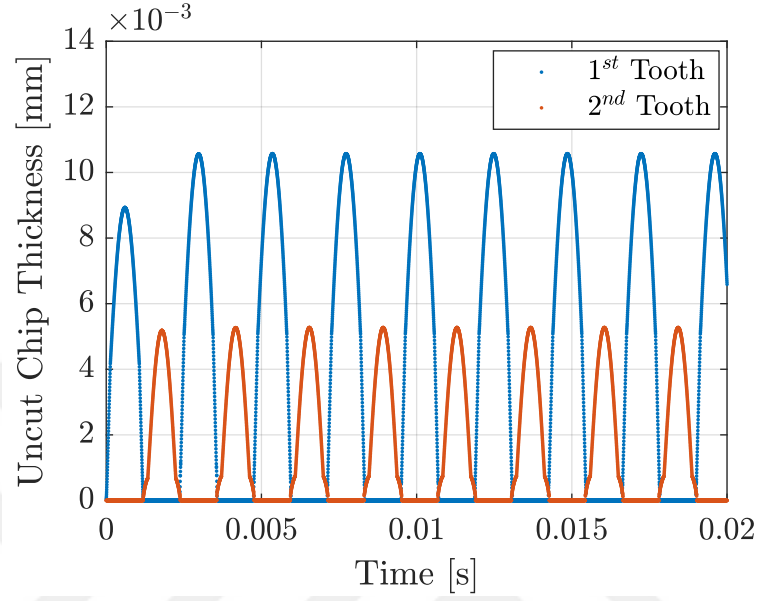


Figure 5.18: Simulated uncut chip thickness at $8 \mu\text{m}/\text{tooth}$.

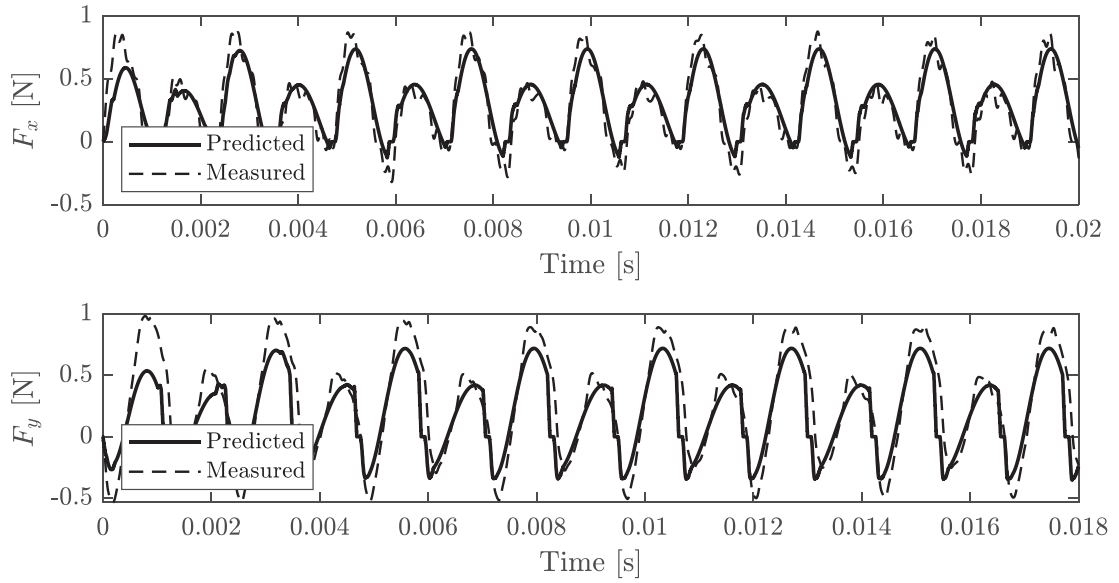


Figure 5.19: Simulated and measured cutting force signals at $1 \mu\text{m}/\text{tooth}$.

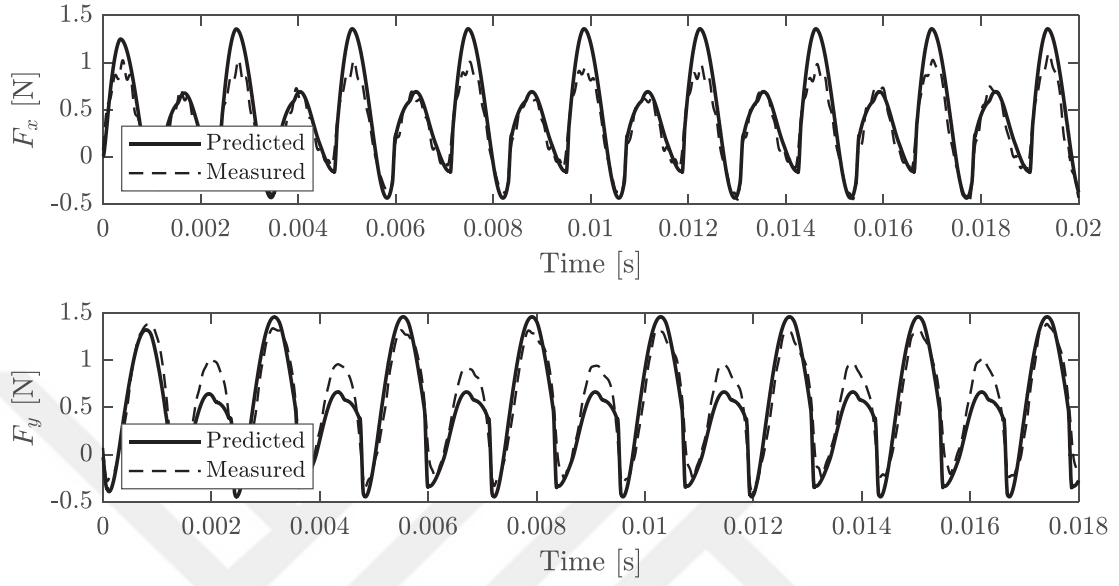


Figure 5.20: Simulated and measured cutting force signals at at $4 \mu\text{m}/\text{tooth}$.

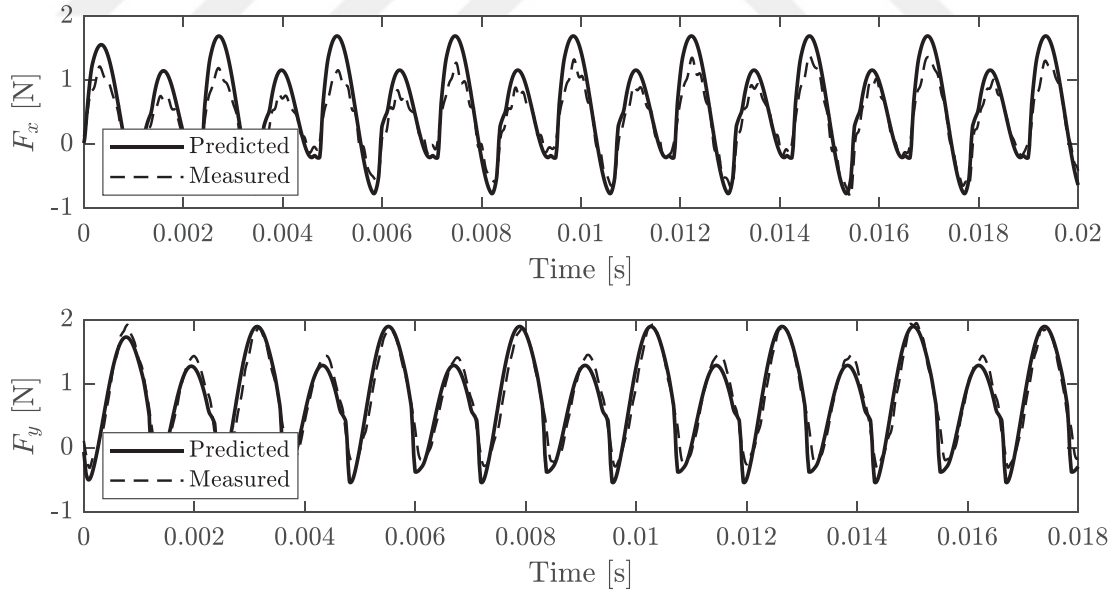


Figure 5.21: Simulated and measured cutting force signals at at $8 \mu\text{m}/\text{tooth}$.

To examine the proposed improvement to the runout model, the uncut chip thickness produced by the model presented in [25] is compared with the uncut chip thickness produced by the model presented in this work. Figures 5.22–5.24 show a comparison between the runout model presented by [25], and the runout model proposed in Section 5.1.1. The figures show the simulated uncut chip thickness at the first disc element $i = 1$ for a 2-flute micro-end-mill slot milling at 25,000 rpm with consideration of runout only for three different cases. The runout angle was held constant at 30 degrees, and the runout and the feed per tooth values are changed. The effect of low feed rate in presence of large runout for very small micro-end-mills is very pronounced in the presented cases. The model presented in [25] provides an inaccurate estimation of the uncut chip thickness by overestimating the value of the uncut chip thickness around the entry and exit angles, as well as the phase angle of the dominant cutting tooth (i.e. the first tooth in the case of positive runout radius and a runout angle between $(0 - \pi/2)$) as shown in Figure 5.23. At the very extreme cases (Figure 5.24), the second cutting edge of a rigid tool is not engaged with the workpiece and the model presented in [25] fails to describe that. Additionally, the model overestimates the maximum value of uncut chip thickness, which should not exceed $N_z \times f_t$ in any case.

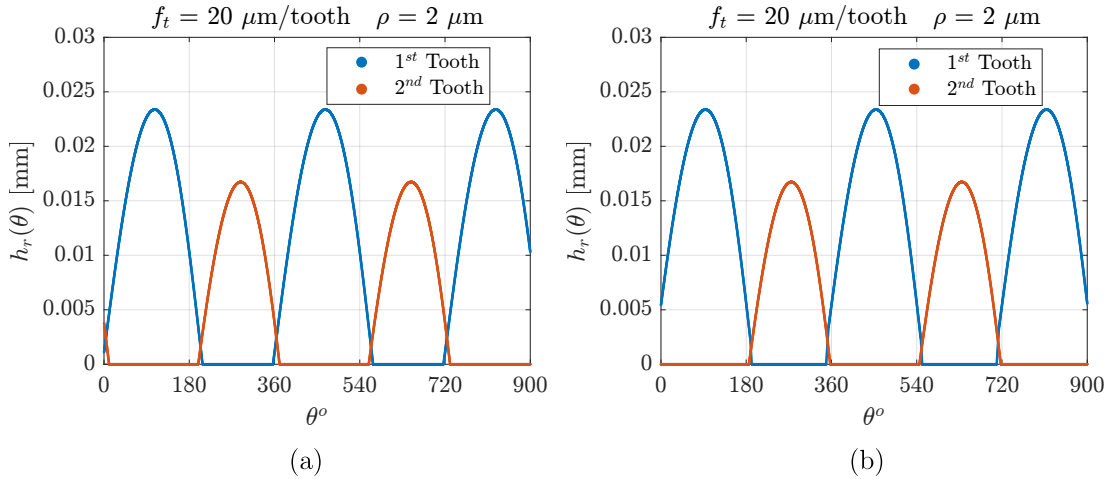


Figure 5.22: Case I: Comparison between the uncut chip thickness predicted by (a) Runout model proposed by [25]. (b) Proposed runout model.

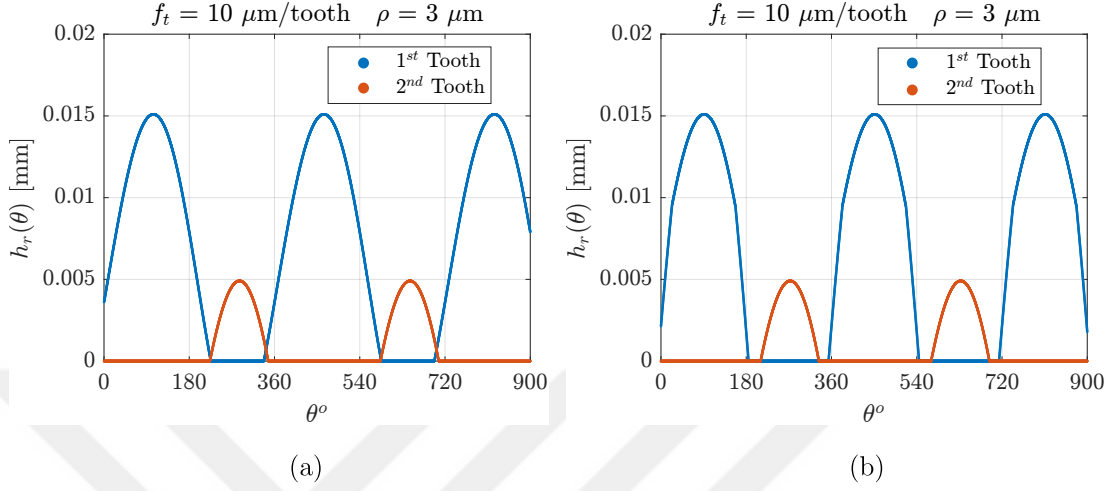


Figure 5.23: Case II: Comparison between the uncut chip thickness predicted by (a) Runout model proposed by [25]. (b) Proposed runout model.

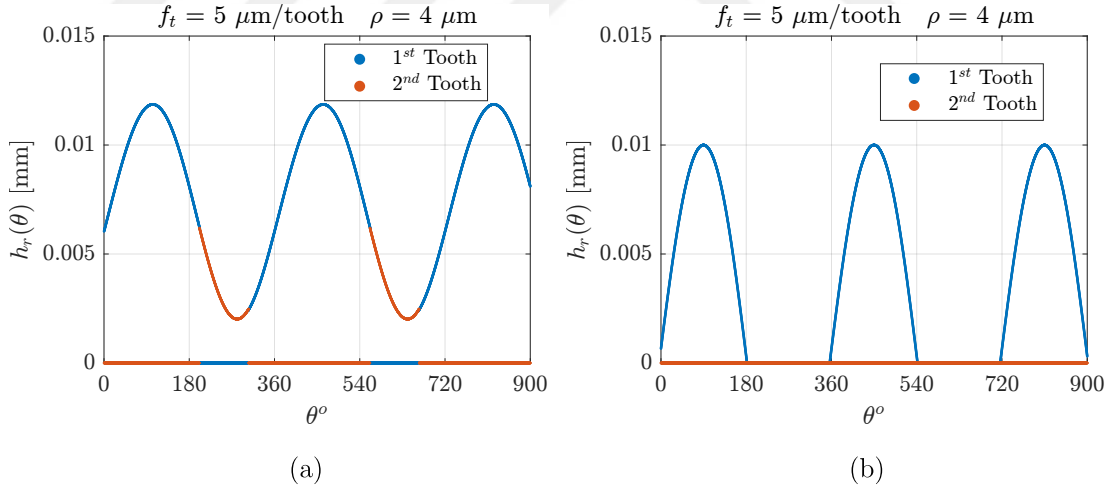


Figure 5.24: Case III: Comparison between the uncut chip thickness predicted by (a) Runout model proposed by [25]. (b) Proposed runout model.

Since both the tool and spindle runout contribute to the total runout in the process, the same tool was removed and clamped on the spindle in a different orientation to produce a different runout condition. All the experimental conditions were held constant, and the analysis presented in Section 5.3.1 was carried out again. The same trend was observed; however, the solutions were spread over a wider curve indicating a different runout condition. The solutions for the first

and second runout conditions are presented in Figure 5.25. In both cases, force predictions with similar order of accuracy were obtained for all the solutions per runout condition. This codependence between the runout radius and runout angle allows for the prediction of one of the parameters in the case that the other is known, which can ease the use of sensors in runout measurement and reduce the human error. This analysis can also be used to define upper and lower bounds of the runout parameters for a given process.

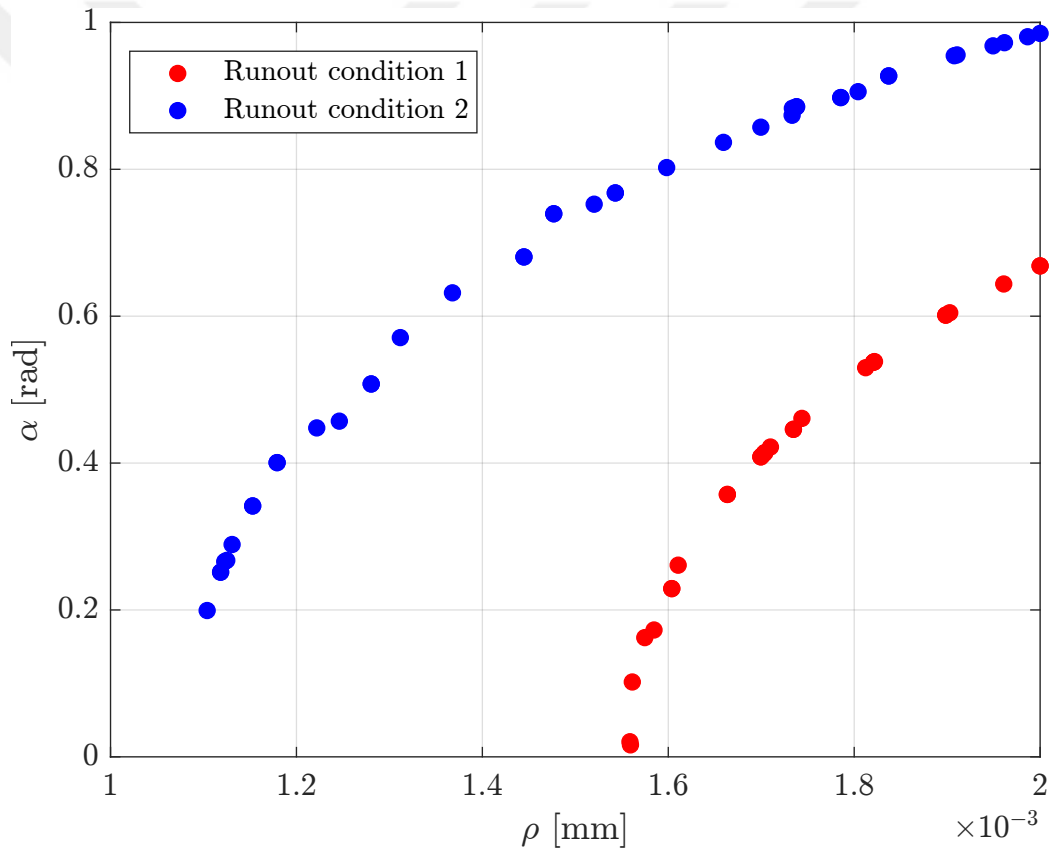


Figure 5.25: Runout parameters optimization results for both runout conditions.

Figure 5.26 shows the simulated forces in the second runout condition. Accurate predictions were also obtained in this case as seen from the figure. The runout solutions obtained from the centerline profile in Section 5.3.1 were used in the cutting force model to look at the error in the force predictions. The error was calculated as the summation of the RMS errors in the force signal in both

the x and y directions. The error ranged from 0.3775 to 0.381, which gives a difference of only 3.5×10^{-3} ($\sim 0.91\%$) in total RMS error between the best and worst solutions. This shows that multiple runout pairs can be used in force prediction of micro-milling as long as they lie on the curve represented by the points in Figures 5.12 and 5.25, while maintaining the same order of accuracy. Figure 5.27 shows the peak and RMS values of the resultant force signal for both runout conditions. The peak and RMS values appear similar.

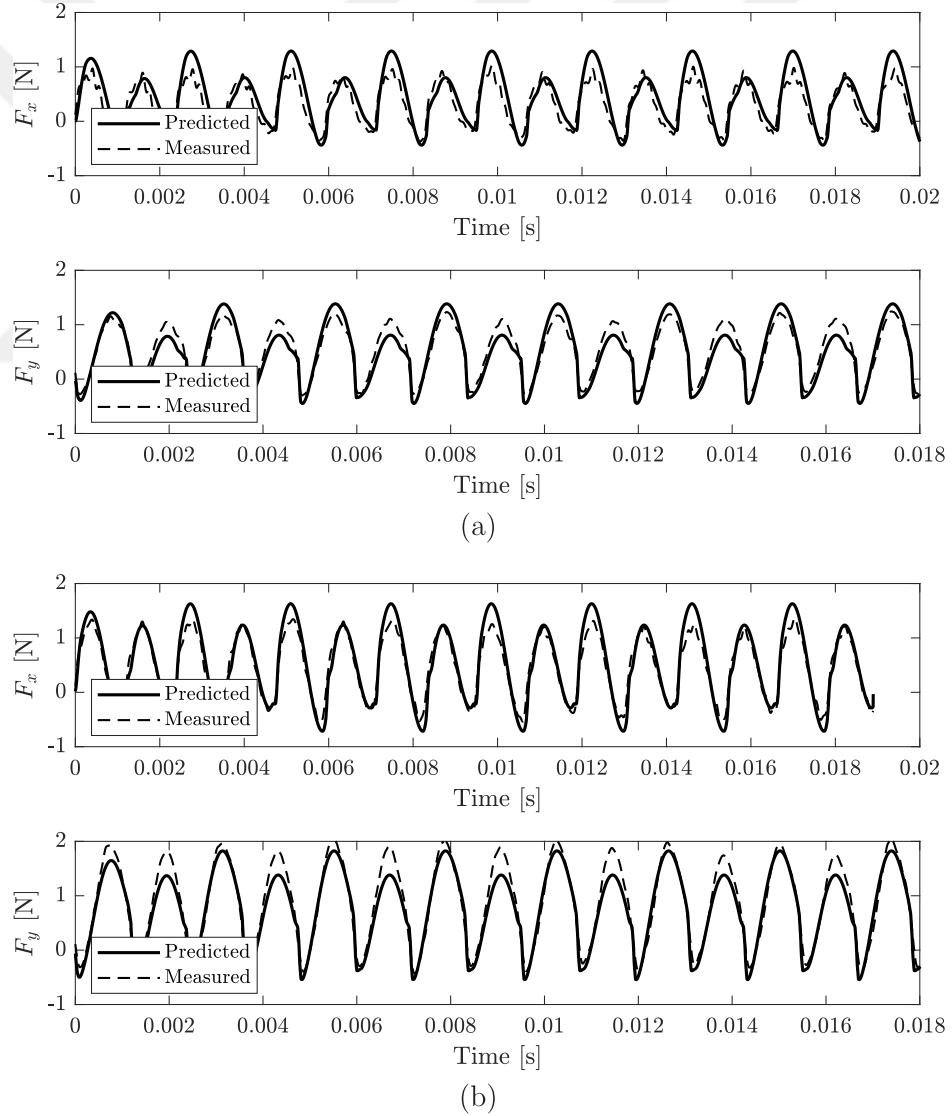


Figure 5.26: Simulated and measured cutting force signals in the second runout condition at (a) $4 \mu\text{m/tooth}$. (b) $8 \mu\text{m/tooth}$.

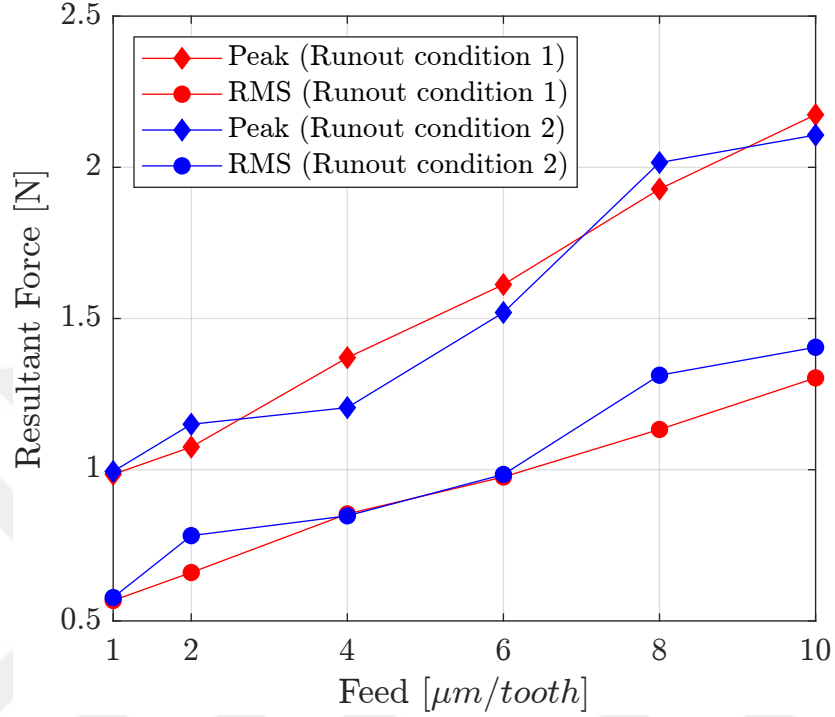


Figure 5.27: Peak and RMS values of the resultant force signal vs. feed for both runout conditions.

The machined surface roughness was investigated using the laser scanning microscope, and the roughness measurements are plotted against the feed per tooth values for both runout conditions as shown in Figure 5.28. It can be observed that the surface quality at the lower feed values is poor, which is expected due to the dominance of ploughing action. The surface quality improves as the feed per tooth is increased until best surface quality is achieved at $4 \mu\text{m}/\text{tooth}$ feed. The surface quality starts to worsen again as the feed per tooth is increased which can be related to higher cutting forces that are associated with severe tool deflection and higher cutting temperatures. The surface roughness trend in both runout conditions appears similar. However, surface quality appears to be worse at higher feeds in runout condition 1, as the runout was more severe in that case.

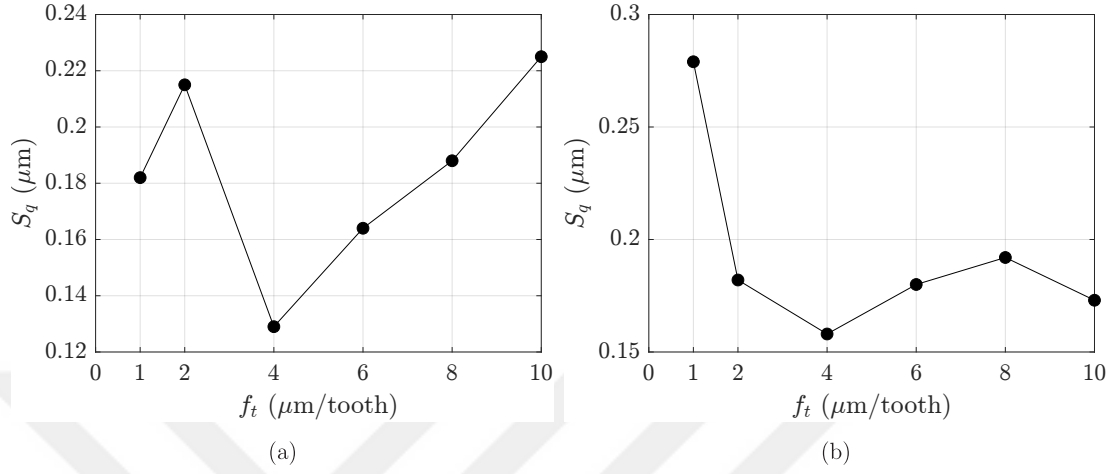


Figure 5.28: Surface roughness vs. feed values. (a) Runout condition 1. (b) Runout condition 2.

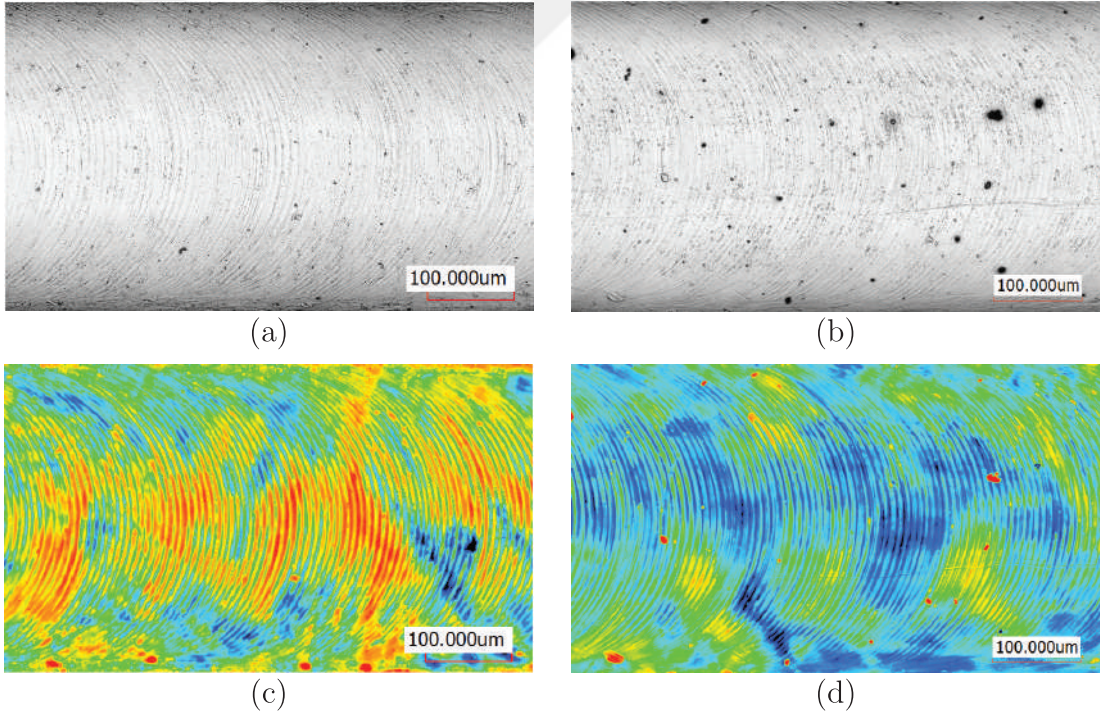


Figure 5.29: Topology of the best surface (at $4 \mu\text{m}/\text{tooth}$). (a,c) Runout condition 1. (b,d) Runout condition 2.

To further validate the cutting force model and the presented runout identification method, a smaller tool of 0.2 mm diameter was used to slot cpTi at

a spindle speed of 25000 rpm, an axial depth of cut of $40\text{ }\mu\text{m}$, and a feed of $5\text{ }\mu\text{m/tooth}$. The finite element simulation was updated with the new tool geometry, and the simulation was run to identify the tool tip stiffness which was found to be $0.132\text{ N}/\mu\text{m}$. The machined surface was investigated and the runout parameters were identified using the same approach presented in Section 5.3.1, and they were found to be $3.7\text{ }\mu\text{m}$ and 1.28 radians. The same force coefficients that were identified from the experimental tests using the 0.4 mm tool (Table 5.3) were used to simulate the uncut chip thickness and cutting force signal. The predictions are presented in Figures 5.30 and 5.31.

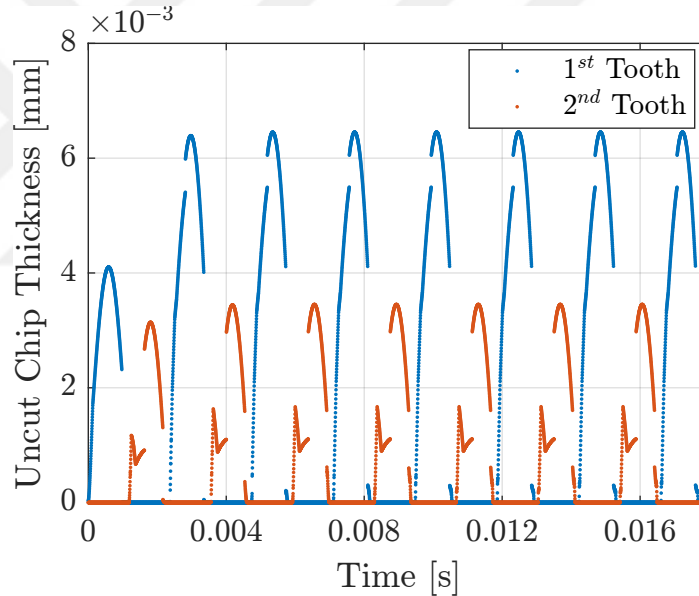


Figure 5.30: Simulated uncut chip thickness using 0.2 mm tool at $5\text{ }\mu\text{m/tooth}$.

Side milling simulations were carried out to evaluate the model performance in low radial immersion operations. As mentioned in Section 5.1, the model is able to identify the entry and exit angles and produce positive chip thickness values when the cutting teeth are engaged with the workpiece material in the case of slot milling. In the case of side milling, the entry and exit angles are calculated

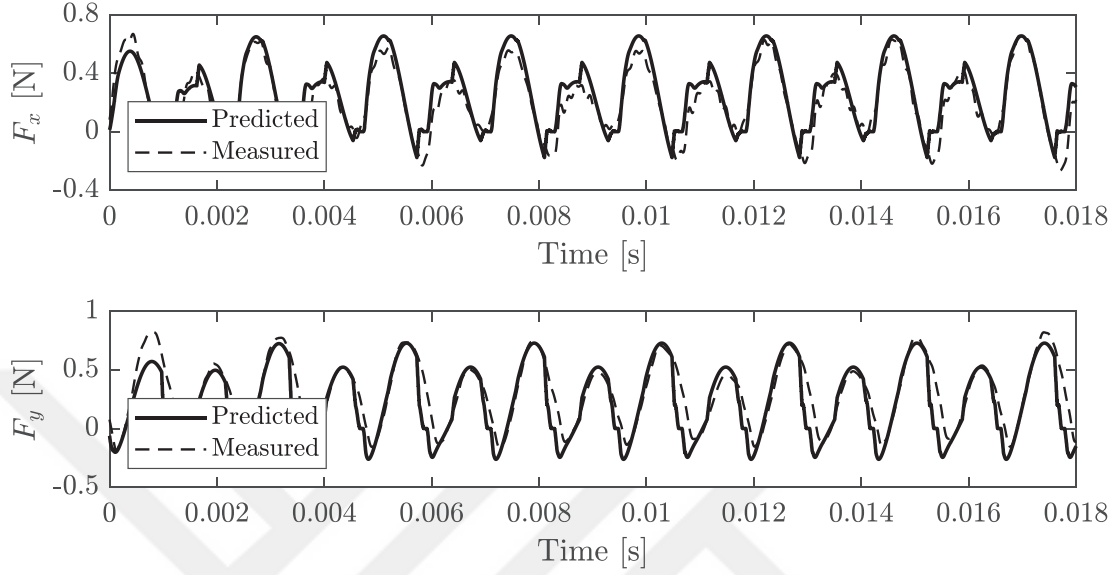


Figure 5.31: Simulated and measured cutting force signals using 0.2 mm tool at at 5 $\mu\text{m}/\text{tooth}$.

as following:

$$\theta_{en} = \begin{cases} 0 & \text{up-milling} \\ \pi - \cos^{-1} \left(\frac{R-a_e}{R} \right) & \text{down-milling} \end{cases} \quad (5.28a)$$

$$\theta_{ex} = \begin{cases} \cos^{-1} \left(\frac{R-a_e}{R} \right) & \text{up-milling} \\ \pi & \text{down-milling} \end{cases} \quad (5.28b)$$

here, θ_{en}, θ_{ex} are the entry and exit angles in radians, R is the tool radius in mm, and a_e is the radial depth of cut in mm. Figures 5.32–5.35 show the simulation results for the side milling tests no. 1 and 5 (see Table 5.2).

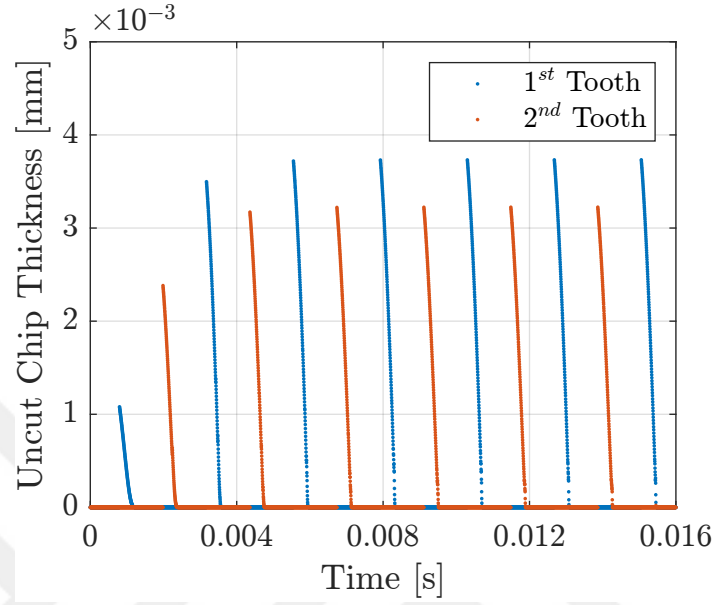


Figure 5.32: Simulated uncut chip thickness of side milling test no. 1.

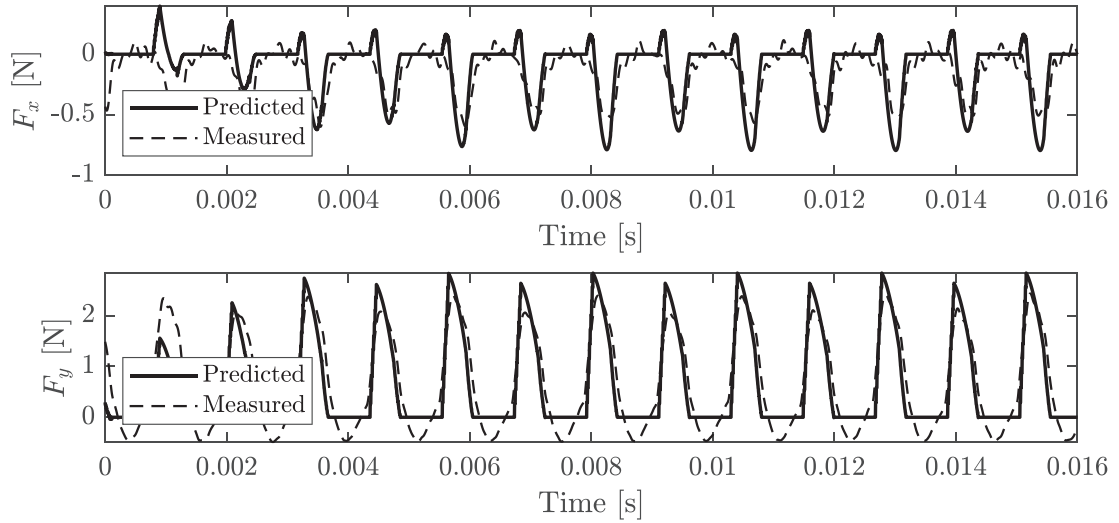


Figure 5.33: Simulated and measured cutting force signals of side milling test no. 1.

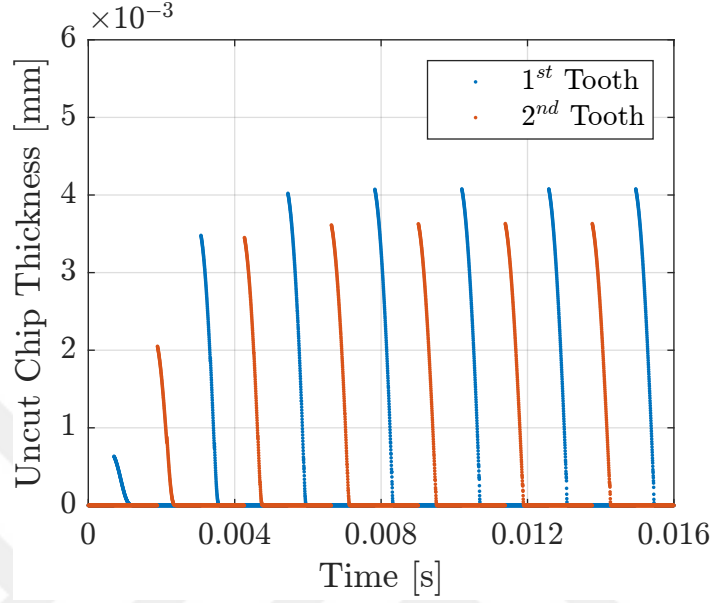


Figure 5.34: Simulated uncut chip thickness of side milling test no. 5.

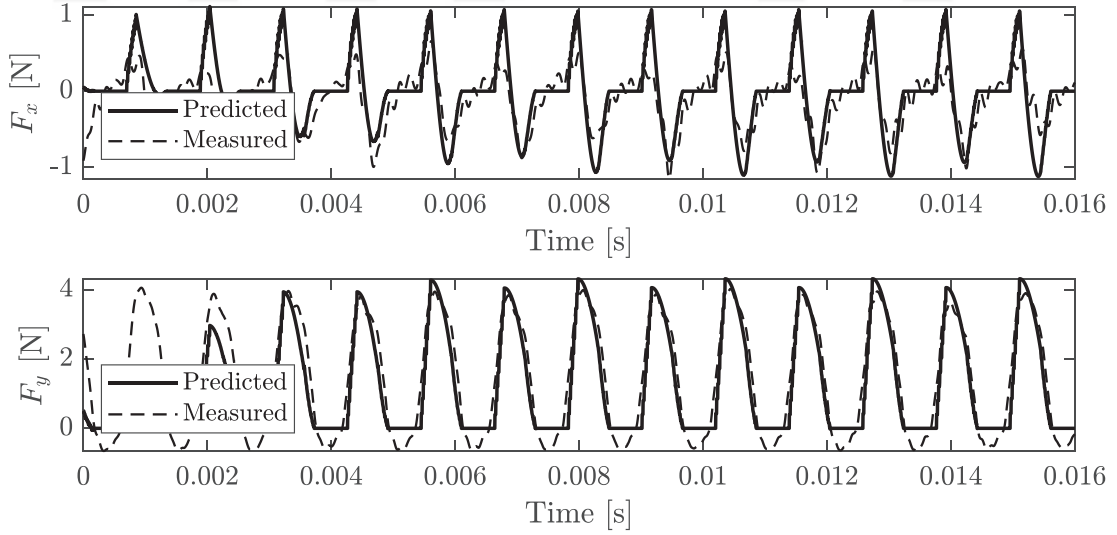


Figure 5.35: Simulated and measured cutting force signals of side milling test no. 5.

As seen from Figures 5.30 and 5.31, the presented model is able to capture the micro-milling process physics using smaller tools down to 0.2 mm with high accuracy. The presented runout identification method can also be applied systematically while using different tools and cutting conditions. Furthermore, Figures

5.32–5.35 show good agreement between the experimental and simulated cutting force signal in low immersion applications.

Cutting forces are considered a key output of the micro-milling process. However, the information which can be extracted from them can be limited due to noise and machining dynamics. The machined surface topography was shown to carry information that can be directly related to the actual trajectories of the micro-end-mill teeth, and it was successfully used to calibrate the runout parameters in a systematic manner. The proposed cutting force model and the runout parameter identification method are shown to be very effective in both full slot milling and side milling conditions. It was also shown that the methods can be scaled down even further and applied while using smaller tools down to 0.2 mm.

Chapter 6

Conclusion

This chapter provides a conclusive summary of the key research findings presented earlier in the thesis, as well as propose future research propositions and suggestions. The research presented in this thesis provides contributions to micro-milling process modeling and optimization, by establishing systematic approaches in force modeling and internal process parameter identification techniques. The aim of the research is to satisfy the industrial need for pre-machining simulations that can effectively help minimize trial and error tests, as well as monitor and optimize the overall micro-milling process outputs. Such simulations can be embedded in smart manufacturing and digital twin applications which can further expand the implementation of Industry 4.0 vision and goals in micro-milling applications. Furthermore, the model parameter identification techniques presented in this research can be used to isolate the uncertainties associated with micro-milling processes and reduce the need for advanced and expensive measurement systems. Analytical and numerical modeling methods are applied to study micro-milling associated phenomena such as runout of the tool and spindle system, tool deflection, and chip thickness accumulation due to ploughing action as a result of the minimum uncut chip thickness. Model parameter identification techniques using the experimental cutting force signal and surface topography were proposed and validated by slot and side micro-milling tests using tools of 200 and 400 μm diameters on commercially pure titanium.

Modeling of tool deflection is a crucial step in micro-milling process simulation. In chapter 3, a finite element analysis which studies the static tool tip deflection behavior during micro-milling is presented. Finite element analysis was shown to be fast and versatile while providing accurate results that can be integrated into analytical models in a systematic manner. A few key conclusions can be drawn from that study:

- The application of finite element analysis provided fast and easy estimation of the static tool tip stiffness under boundary conditions that emulate those in practice. Upon switching to a smaller tool of 200 μm diameter, the CAD model was updated with the new tool geometry and the finite element simulation was concluded in a very fast manner (<5 minutes).
- It was shown that the direction at which the normal force is applied can vary the resulting estimation of the tool tip stiffness. When the force was applied at 45° from the normal direction, the resulting tool tip stiffness was 6% larger. This shows that the use of finite element analysis can overcome the uncertainty in the direction over which the force is applied in the case of experimental evaluation of tool tip stiffness.

A hybrid micro-milling force model was presented in chapter 4. The model integrates the finite element analysis that was established in chapter 3 in mechanistic modeling of cutting forces with consideration of runout and minimum uncut chip thickness. The following conclusions can be drawn from that chapter:

- A novel approach to identify runout parameters based on peak analysis of the experimental cutting force signal during slot milling was proposed. Peak magnitudes and valley locations were related to chip thickness variation and the phase angle of the cutting teeth of the micro-end-mill.
- An optimization algorithm was used to optimize the specific cutting coefficients of the mechanistic force model using an initial guess that was identified using curve fitting of the experimental force signal at different feed rates. A constant related to tool deflection modeling was included

in the optimization and was found to increase with increasing feed rate. This shows that tool deflection effect on the cutting forces becomes more prominent at higher feed rates.

- The model was able to adapt to different cutting conditions by optimization of its internal parameters.
- The model was validated on commercially pure titanium by micro slot milling tests using a coated carbide micro-end-mill of 400 μm diameter, and accurate force predictions were obtained.

Chapter 5 presents a surface investigation for model based identification of runout parameters and minimum uncut chip thickness. A cutting force model was extended to consider multiple preceding tooth passes of the micro-end-mill by kinematic analysis of the trochoidal trajectory of the cutting teeth with consideration of tool deflection and chip thickness accumulation due to ploughing action, while maintaining the effect of helix lag. The model parameters were identified by investigating the machining marks on the workpiece surfaces. The following conclusions can be drawn from that study:

- A novel method for the calibration of runout parameters from the machined surface topography is presented, and it was successfully used to identify runout conditions during micro-milling of commercially pure titanium.
- The effect of runout was observed on the histogram distributions of the horizontal valley-to-valley distance of the surface profile at the centerline of the slot floor, which was assumed to be the actual chip thickness.
- It was shown that the runout radius and runout angle can be codependent in force modeling of micro-milling, and that multiple pairs of runout parameters can be used to produce force predictions in the same order of accuracy (0.91% error).
- The presented runout identification method can be used to define upper and lower bounds of the runout parameters for a given micro-milling process. It

can also be used to identify the runout angle in case the runout radius was known and conversely.

- The minimum uncut chip thickness during side milling of commercially pure titanium using a coated carbide micro-end-mill of 400 μm diameter was extracted from the side wall surfaces and was found to be 0.2 μm . The ratio of the minimum chip thickness to cutting edge radius h_{min}/r_e was found to be 11% in this study.
- A cutting force model is extended for micro-milling processes which utilizes finite element analysis of tool deflection. Micro-milling phenomena such as tool runout and trochoidal trajectory of the cutting teeth, helix lag, and chip thickness accumulation were studied in the model.
- The cutting force model was verified on commercially pure titanium during slot milling with 200 and 400 μm diameter tools, and side milling with a 400 μm diameter tool. The cutting force signal predicted using the model was in good agreement with the experimental signal in all of the studied cases.

Recommendations for future research

Micro-milling processes are associated with a wide range of uncertainties. While many of them are studied in this research, more can still be investigated. The presented methodology for internal parameter identification can be applied using expanded cutting force models that study more of the aforementioned uncertainties. The following suggestions can be recommended to further expand the research presented in this thesis:

- Software integration between Solidworks CAD package and COMSOL Multiphysics FE package was used in this research. Since the force models and optimization algorithms were written in MATLAB environment, further integration between MATLAB and COMSOL can be used to provide continuous communication and integration of the finite element analysis in the

cutting force models.

- The finite element analysis can be expanded using modal analysis to study the natural frequencies of the tool tip and chatter.
- Further investigation of the machining marks on the finished surface can be carried out and related to more cutting conditions and parameters.
- Elastic recovery is well known phenomenon in micro-scale machining. The cutting force models can be expanded to include the effect of elastic recovery on the surfaces.
- Dynamic tool deflection can be investigated by conducting side milling tests and investigating the vertical machined surface inclination and error, and relating that to the finite element analysis.
- Tool wear and friction during micro-milling can be investigated to provide better predictions of the cutting forces, as well as provide estimations on tool life expectancy and predict immature tool failure.

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Appendix A

Tool Geometry and CAD Model Configuration

The geometry of the micro-end-mill is inspected using optical and laser microscopes to facilitate the construction of the parametric CAD model to be used in the finite element analysis. Figures A.1 and A.2 show a few examples of the aforementioned measurements.

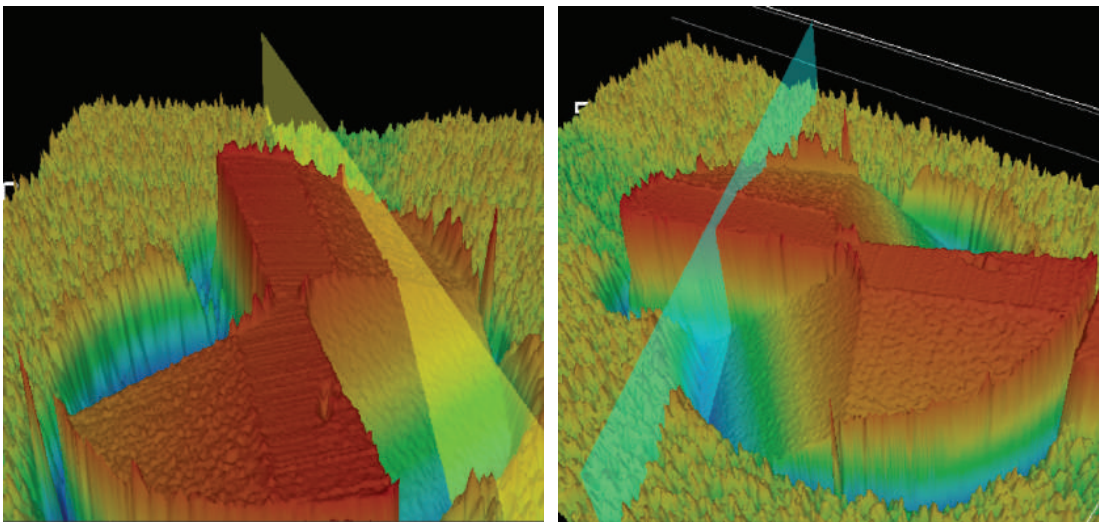


Figure A.1: Example measurements of tool geometry using laser microscopy.

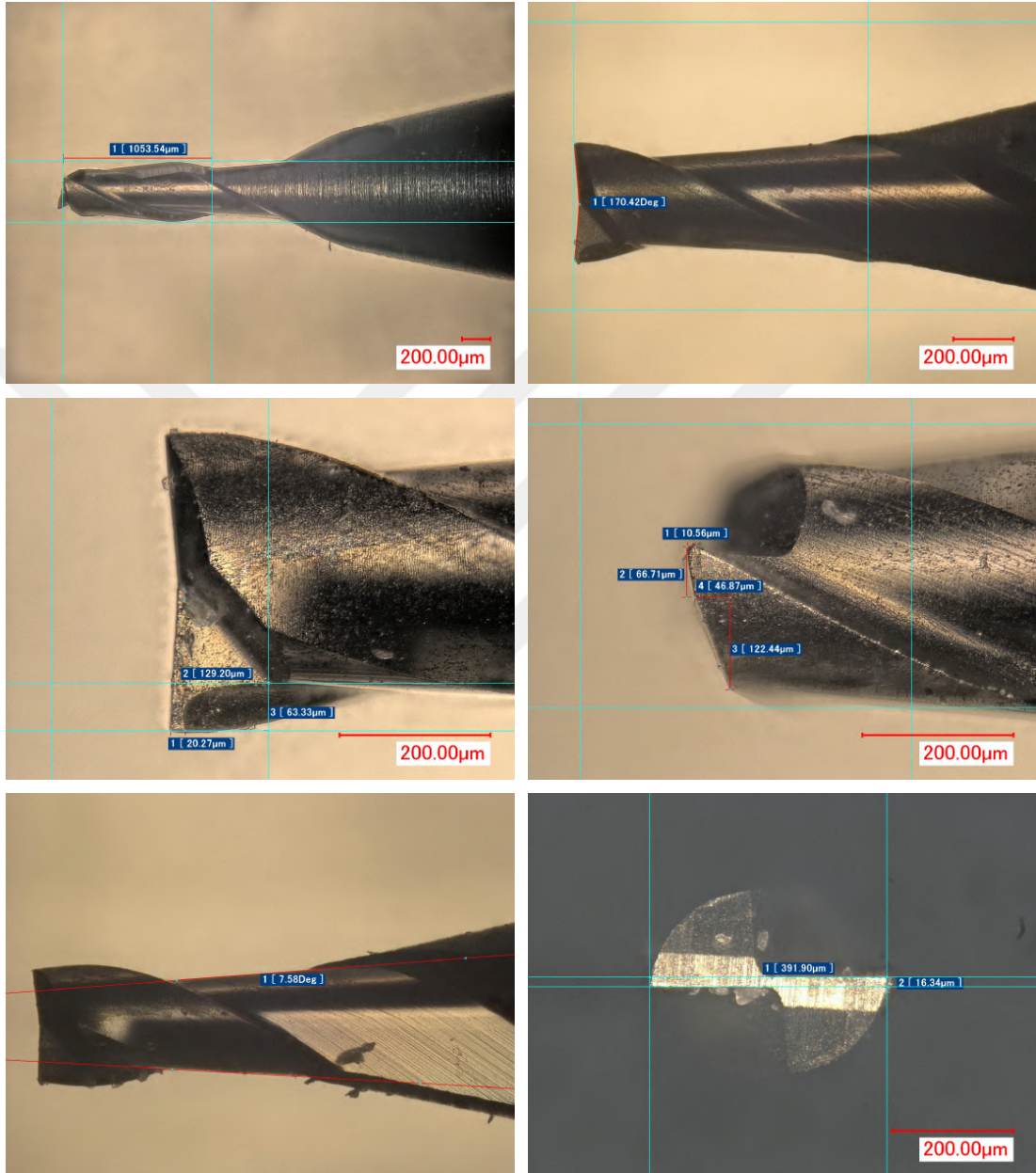


Figure A.2: Example measurements of tool geometry using optical microscopy.

The CAD model of the tool is created by dimensioning the geometry using global variables and equations. Figure A.3 shows a few of the parameters that can be adjusted to create new configurations of the cutting tool in a fast and accurate manner.

Name	Value / Equation	Evaluates to
Global Variables		
"Cutter Diameter"	= 0.39	0.39
"Shank Diameter"	= 4	4
"Helix Angle"	= 30deg	30deg
"Neck Taper Angle"	= 12deg	12deg
"Neck Diameter"	= 0.37	0.37
"Length of Cut"	= 0.8	0.8
"Overall Length"	= 45	45
"Under Neck Length"	= 0.2	0.2
"Number of Flutes"	= 2	2
"Flute Radius"	= 0.025	0.025
"Rake Angle"	= 5deg	5deg
"Core Diameter"	= 0.3	0.3
"Peripheral 1st Relief Angle"	= 5deg	5deg
"Peripheral 2nd Relief Angle"	= 20deg	20deg
"Edge Radius"	= 0.00178	0.00178
"Pitch"	= $\pi * \text{"Cutter Diameter"} / \tan (\text{"Helix Angle"})$	2.12215deg
"Helix Taper Angle"	= $\text{atan} ((\text{"Cutter Diameter"} - \text{"Neck Diameter"}) / \text{"Length of Cut"})$	0.71616
"Web Thickness"	= 0.02	0.02

Figure A.3: Examples of the configurable CAD model parameters.