

To the Graduate Council:

I am submitting herewith a dissertation written by Ryan Garcia entitled "Time domain simulation of modulated tool path turning for surface finish prediction." I have examined the final paper copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Mechanical Engineering.

Tony Schmitz, Major Professor

We have read this dissertation
and recommend its acceptance:

Tony Schmitz

Bradley Jared

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Ryan Copenhaver

Accepted for the Council:

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(Original signatures are on file with official student records.)

Time domain simulation of modulated tool path turning for surface finish prediction

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Ryan Garcia
December 2024

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*I dedicate this body of work to my family for their enduring support through all of
my academic studies.*

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"In theory, theory and practice are the same. In practice, they are not." - Albert Einstein

Abstract

Understanding surfaces created during finish machining operations is critical to the proper function of components. Methods for predicting surfaces in traditional turning are insufficient for surfaces generated by modulated tool path (MTP) turning. This project predicts MTP turning surface finish using a time domain simulation that solves the second order time delayed differential equations which describe the process. The time domain simulation incorporates the modulated tool path motion, workpiece and tool dynamics, material side flow effects, and spindle speed changes for constant surface speed turning of non-constant diameter parts. A new modeling approach for side flow and its influence on surface finish is described. The effect of coolant on side flow is also investigated. This work builds on prior MTP modeling efforts by including an extended side flow model and two axes of motion for tapered and curvilinear part geometries. Finally, a method for implementing the new time domain simulation capabilities into the current MTP workflow is described. This work advances surface finish prediction for MTP finishing operations. The outcome is improved productivity and reduced testing for optimum parameter selection when using MTP tool paths for finishing operations.

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Chapter 1

Introduction

1.1 Surface finish prediction

Understanding the surfaces that are created during manufacturing processes is critical to the proper function of components. Surface metrology can be traced back to the early 1940s to research work performed at the Rank Taylor Hobson Company (15). The scope of this work is not to analyze different measurement technologies but to provide a method for the prediction of surfaces that are generated during modulated tool path (MTP) turning operations, where sinusoidal motion is superimposed on the nominal tool motion to intentionally break chips using short intervals where the tool temporarily disengages with the workpiece.

Surface roughness is one component of the total profile. The total surface profile is comprised of waviness, surface roughness, and measurement noise, depending on the measuring instrument. To isolate the surface roughness from the waviness, filtering techniques are applied. A graphical illustration of this process is shown in figure 1.1.

The surface finish for machined components can be estimated analytically based on tool geometry and tool feedrates. This can be done for standard turning and milling operations (16). For MTP turning, however, the complexity of the tool motion and process dynamics must be considered to provide accurate surface profile predictions.

For example, the side flow of material around the cutting edge must be considered at the small feedrates selected for finishing operations. This is further described in chapter 2.

1.2 Modulated tool path (MTP) originality

In turning operations, one challenge is chip breaking. It is an issue for both manual and computer numerical control (CNC) lathe operations. The difficulty is that traditional turning, facing, threading, parting, and boring operations provide continuous cutting, where continuous contact between the cutting edge and part is present. Unlike milling operations, where the cutting tool edges move in and out of contact with the part during rotation of the cutting tool, in turning, once the cutting edge contacts the part, it typically stays in contact until it has finished the cutting operation. This continuous contact tends to create long continuous chips that are difficult to manage and can cause several issues, including machinist injury during removal, damage to the machine tool, damage to the part from the rubbing of the chip, poor coolant flow, and increased cycle time due to the manual chip removal intermittently during the machining process.

Figure 1.2 shows a long continuous chip wrapped around the workpiece and the chuck during a turning operation. This phenomenon is commonly referred to as a “bird’s nest.” MTP machining strategies enable discontinuous chips to be created during turning. Discontinuous chips are made possible by superimposing a low frequency and amplitude oscillation on the nominal feed motion. In general, this requires sinusoidal motion in both the z and x axes for CNC lathes. MTP machining strategies provide a method of chip breaking that is unique to CNC machines and leverages the ability to control the motion of each axis simultaneously, together with spindle speed, to break chips along curvilinear tool paths, which may not be possible with other chip-breaking strategies (17).

The ability to predict the performance of machining operations is critical for cost-effective manufacturing. Factors such as material availability, cost, and time make numerous cutting tests expensive or infeasible. Because of these factors, it is important to be able to accurately predict the surface finish of machined components based on simulations for high-value components and materials. The additional tool motions superimposed by the MTP feed oscillations make a guess-and-check approach infeasible due to the added variables (frequency and amplitude of the sinusoidal motion). Therefore, a simulation approach is required to replace current trial and error practices.

MTP provides a novel chip-breaking approach that does not rely on specialized rake face geometry, custom high-pressure coolant setups, or tool modulation devices. This method of creating discontinuous chips leverages the ability of the CNC turning center to superimpose low-frequency oscillations on the nominal feed motions. This enables the cutting tool to come in and out of the cut, which causes the continuous chip to be broken into discontinuous sections as the tool moves out of the cut. However, not all oscillation parameters will cause discontinuous chips to be formed. The key parameters that control successful chip breaking are 1. OPR: oscillations per revolution; the oscillation frequency (f) relative to the spindle speed (Ω); and 2. RAF: ratio of amplitude to feed, the oscillation amplitude (A) relative to the feed per revolution (f_r). See equations 1.1 and 1.2. Figure 1.3 shows how these discontinuous chips are created during a tube-turning operation. The OPR and RAF combinations that will result in discontinuous chips are mapped in figure 1.4.

$$OPR = \frac{(60 \cdot f)}{\Omega} \quad (1.1)$$

$$RAF = \frac{A}{f_r} \quad (1.2)$$

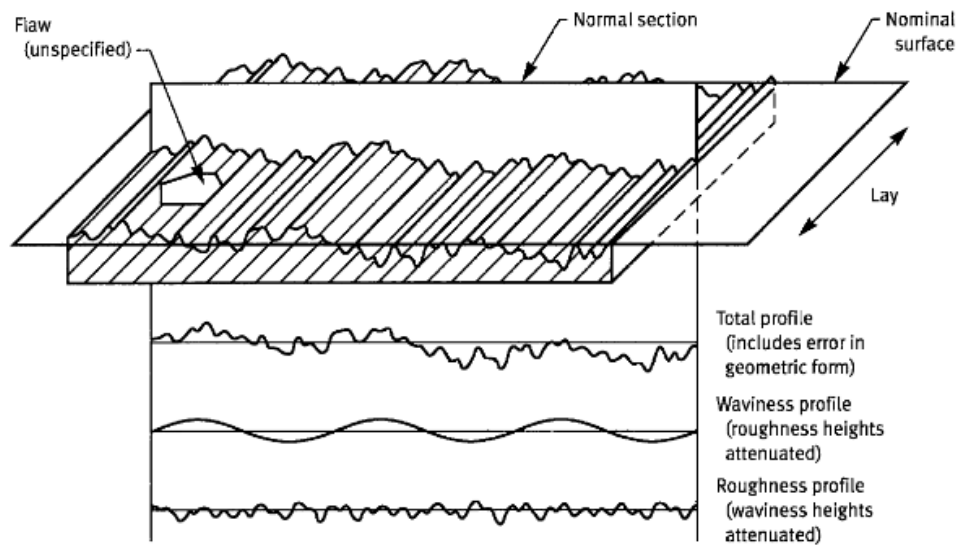


Figure 1.1: Surface roughness and waviness. Reprinted from ASME B46.1-2002 (1).



Figure 1.2: Birds nest created during boring operation on CNC lathe

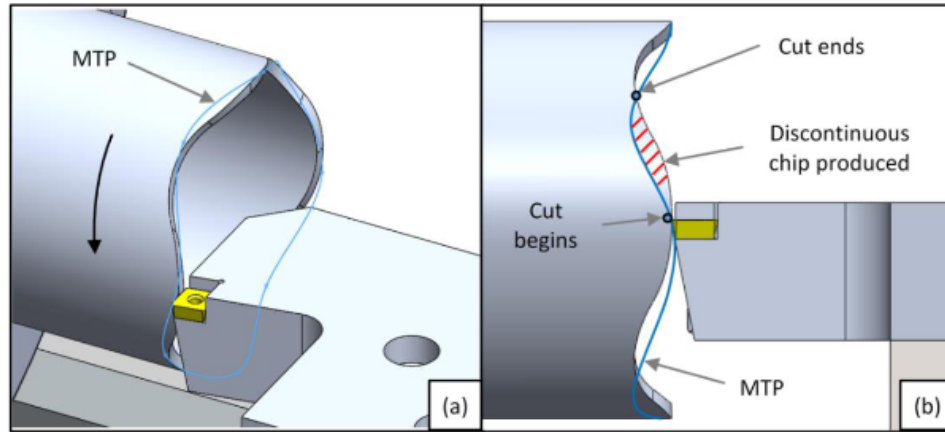


Figure 1.3: Example of MTP tube turning operation (2).

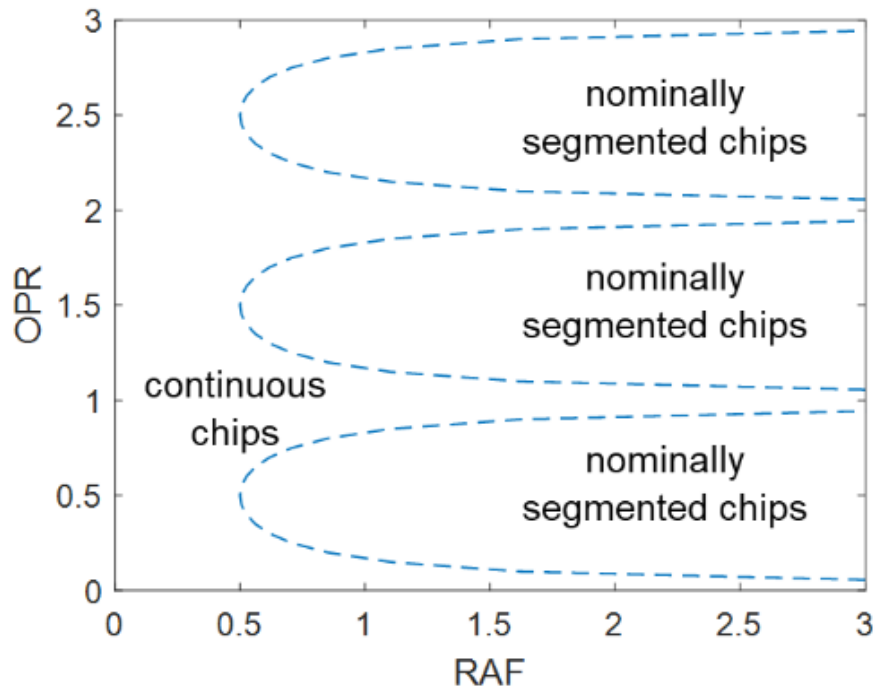


Figure 1.4: MTP parameter map with analytical chip breaking boundaries represented by dashed lines (3).

Chapter 2

Literature review

2.1 Alternative chip breaking technologies

Significant research has been done on chip breaking for CNC turning operations. The most common approach is to use specialized rake face geometries, commonly known as chip breakers, to cause chips to curl on themselves and break (18), (19). However, it is difficult to design chip breakers because the performance depends on the depth of cut, feedrate, and part material. Therefore, trial and error is required to obtain a functional design (20). Chip breakers are also less effective at the small depths of cut and low feed rates which are typically selected in finishing operations (21). Several studies have reported chip breaker designs and chip formation predictions (22), (23), (24), (25), (26), (27). Example chip breaker geometries are displayed in figure 2.1.

Another method for chip breaking is the use of high-pressure coolant directed at the back of the chip just behind the cutting edge (28). Challenges associated with the use of high-pressure coolant include environmental and safety concerns and directing the coolant at the proper location on the chip backside, which varies during contouring operations where the chip location is changing on the cutting tool edge throughout the duration of the cut (28). The schematic in figure 2.2 shows the ideal location for the high-pressure jet on the chip.



Figure 2.1: Example of chip breaking insert geometry.

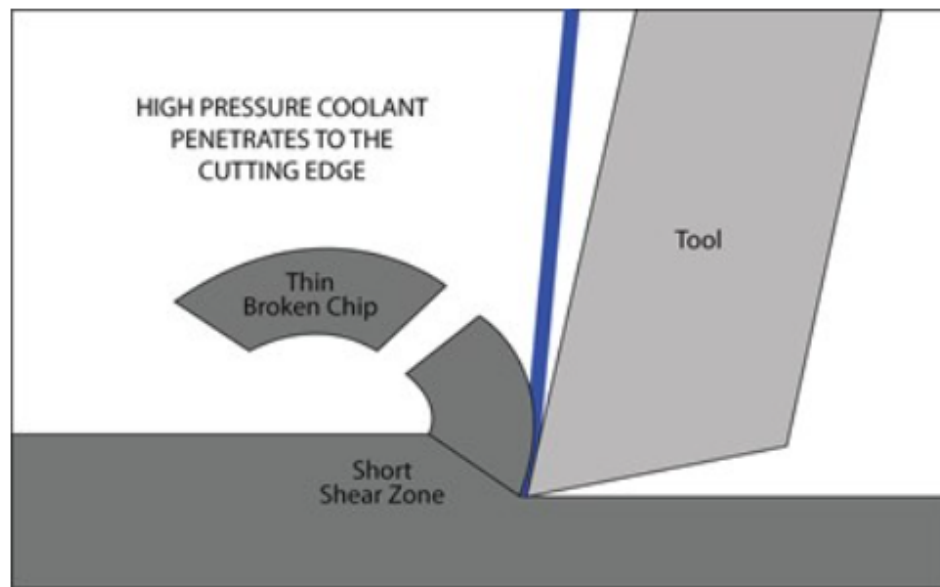


Figure 2.2: Example of high pressure coolant chip breaking setup (4).

The use of cryogenic coolants such as liquid nitrogen has been shown to increase chip breaking during turning operations (29). The use of cryogenic coolants presents similar issues to those of high-pressure coolants. One of these issues is the need for custom-designed tooling for implementation, as is shown in figure 2.3. There are also safety concerns with the use of liquid nitrogen, such as cold exposure injuries and asphyxiation concerns (30).

The use of modulation-assisted machining mechanisms has been researched previously (6), (31). Chip breaking is made possible using an external mechanism to provide tool oscillation that causes the cutting edge to come in and out of the cut. This method of creating discontinuous chips does not rely on physical chip breakers or high-pressure coolant being directed at the cutting edge. Rather, because the cutting tool moves in and out of the cut, it is impossible for a continuous chip to form. One challenge associated with modulation-assisted machining is synchronizing the tool oscillations with the spindle (and, therefore, part) rotation. MTP overcomes this limitation because the CNC controller, which commands the tool oscillations using the machine axes, can synchronize axis motion with the rotation of the spindle. Both modulation-assisted machining and MTP use a sinusoidal tool motion. A fundamental limitation associated with modulation-assisted machining, however, is that it is not possible for the modulation direction to be modified. This is required when machining contours where the modulation direction must be changed based on the feed direction. One of the early modulation-assisted machining devices is displayed in figure 2.4.

2.2 Prior MTP research

MTP chip-breaking strategies and modulation-assisted machining chip-breaking strategies are related because they both impose tool motion in and out of the cut to segment chips. However, the oscillation frequencies used in MTP are commonly

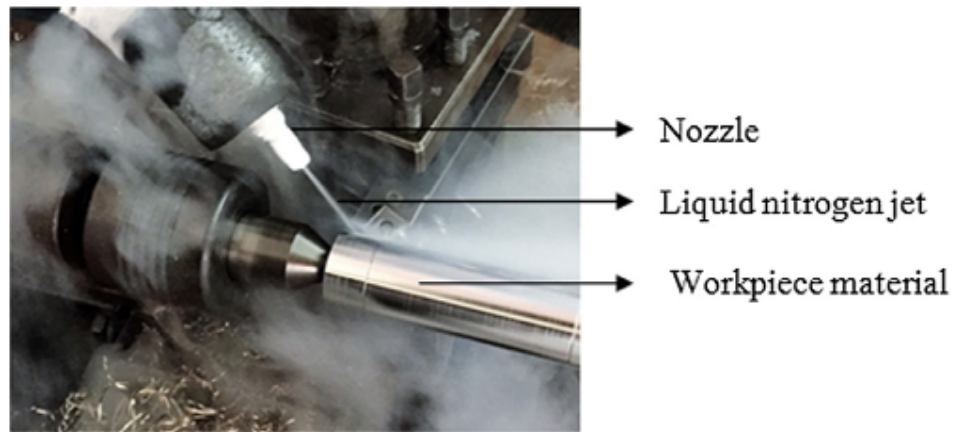


Figure 2.3: Example of cryogenic machining setup on lathe (5).

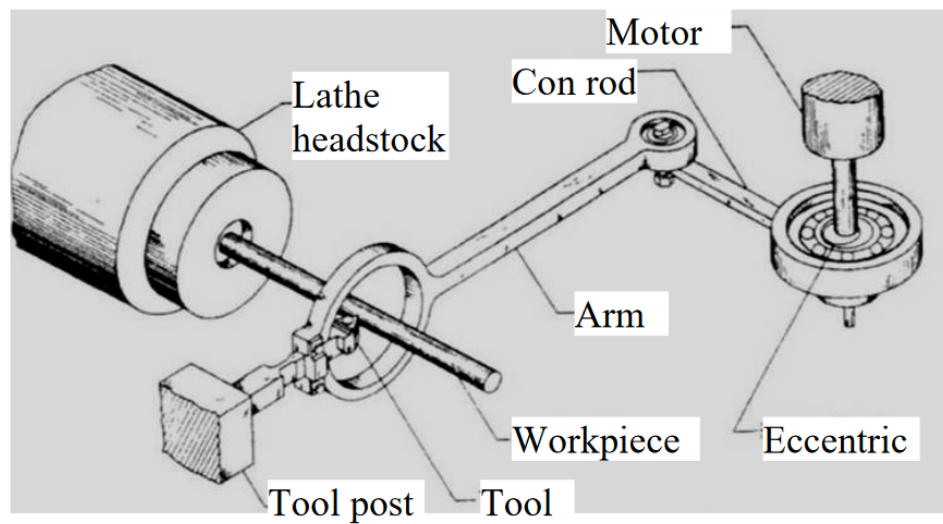


Figure 2.4: Oscillation device for chip breaking (6).

10 Hz or less, depending on the machine tool controller performance. Modulation-assisted machining, on the other hand, applies tool oscillation frequencies up to 1 kHz using piezoelectric transducers.

Multiple researchers have studied MTP. Adams (32) investigated the selection of MTP parameters. He developed initial methods for predicting which combination of MTP parameters would result in discontinuous chips. Adams also investigated the effect that MTP chip-breaking tool paths had on the surface finish of machined parts and the temperature during cutting.

Assaid (33) investigated methods for MTP tool path generation, as well as characterizing machine tool performance for the selection of optimized MTP parameters that are within the machine tool's physical limits. Assaid developed MTP programming capabilities through the use of an updated graphical user interface (GUI). This improved the interface developed by Adams, which had limited programming capabilities for multiple geometric inputs. Assaid also developed methods to apply MTP oscillations throughout an entire part contour by introducing methods for trimming MTP tool oscillations to limit overshoot of part geometry which would result in gouging the finished part surface. Assaid also considered machine characterization measurements using different instruments, including laser interferometers, capacitance probes, and a Heidenhain grid plate. A brief investigation into surface finish simulation was also completed with follow-on surface finish work performed by Mcfarland (34).

Mcfarland (34) predicted surface finish produced by MTP turning operations by combining tool motions produced by MTP turning and tool geometry to produce a numerical simulation. The testing that was performed found that there was generally reasonable agreement between the predicted and measured surface finish values, but the physical surface profiles were not accurate. The need to investigate the contribution of tool vibrations into the surface finish prediction was mentioned but was not investigated further.

Tursky (35) studied the effect of MTP cutting on temperature and tool wear. Methods for characterizing machine tool error were also evaluated, expanding upon the work done by Assaid (33) by measuring machine motions based on sinusoidal motion commands. Methods for recording the tool motion using several methods were proposed and tested. A six-point linear interpolation was used to approximate the desired sine wave motion for MTP turning operations. Tursky found that the MTP turning operations experienced lower tool wear rates than traditional constant feed turning operations. This was attributed to the lower temperatures that the cutting edge experiences during the intermittent MTP when compared to constant feedrate turning operations.

Woody (36) conducted further experiments on the chip-breaking capabilities of MTP, as well as tool wear testing for MTP. Based on the reduced tool temperature during MTP, it was theorized that the intermittent cutting resulted in a lower average cutting temperature, which caused an increase in the tool life by decreasing the wear rate on the cutting tool. A patent for the MTP process using synchronized machine tool axis motion to break chips was granted in 2012 (17).

Love (37) characterized machine tool motion and studied how the corresponding response could be used to select optimal MTP parameters to advance the work by Tursky and Assaid (35), (33). This was a critical step forward in MTP turning research because providing the ability to select MTP parameters that the machine is able to perform is critical to ensure proper chip breaking and surface finish. The method for characterizing the machine tool performance was based on a dynamic sine wave test that was performed on the machine. Love developed methods for performing machine characterization testing and analyzing the corresponding recorded tool motions to develop a metric by which the machine's ability to perform MTP tool motions could be quantified. This provided the ability to limit the selection of MTP parameters to only values that a machine tool could perform successfully.

DiMarco (38) investigated the use of an alternative controller for the use of MTP tool paths. The new controller was proposed because the method by which MTP

turning creates discontinuous chips is to superimpose a sine wave on the nominal feed direction. Traditional controllers are not designed for sinusoidal motion. Instead, they are tuned for linear, circular, and spline interpolation.

Copenhaver (7) described the cutting force and tool vibration using a second order time delay differential equation of motion that included MTP oscillation. The numerical solution of the equation enabled the prediction of cutting force and process stability. Inputs were the MTP oscillation parameters, tool tip dynamics, and workpiece dynamics. Copenhaver also began initial work on surface finish prediction with the inclusion of tool and workpiece vibrations in addition to the MTP tool motions. This approach improved the accuracy over previous attempts that did not incorporate vibrations. The work that is proposed in this research expands on Copenhaver’s surface finish prediction by incorporating curvilinear geometry and changing spindle speeds during constant surface speed turning.

2.3 Surface finish measurement techniques

Surface finish measurements are conducted using contact or non-contact techniques. A contact instrument is the stylus profilometer, such as a Mitutoyo Surftest SJ210, which is a hand-held surface finish tester that can be used on the manufacturing floor to inspect parts. See figure 2.5.

Another contact instrument is the Mitutoyo Contracer, which can be used to record longer surface traces on a part as well as remove the mechanical filtering that is typically done by the hand-held surface finish measurement devices, such as the Surftest SJ210, due to the mechanical sled that the sharp stylus rides on. Setup elements are shown in figure 2.6 for a typical Mitutoyo Contracer setup.

Non-contact methods of recording surface texture can also be used. One common measurement method that is used is a confocal microscope. Figure 2.7 shows a graphical depiction of how a confocal microscope operation. The laser excitation source emits a laser beam into the system to focus onto the sample. The fluorescence

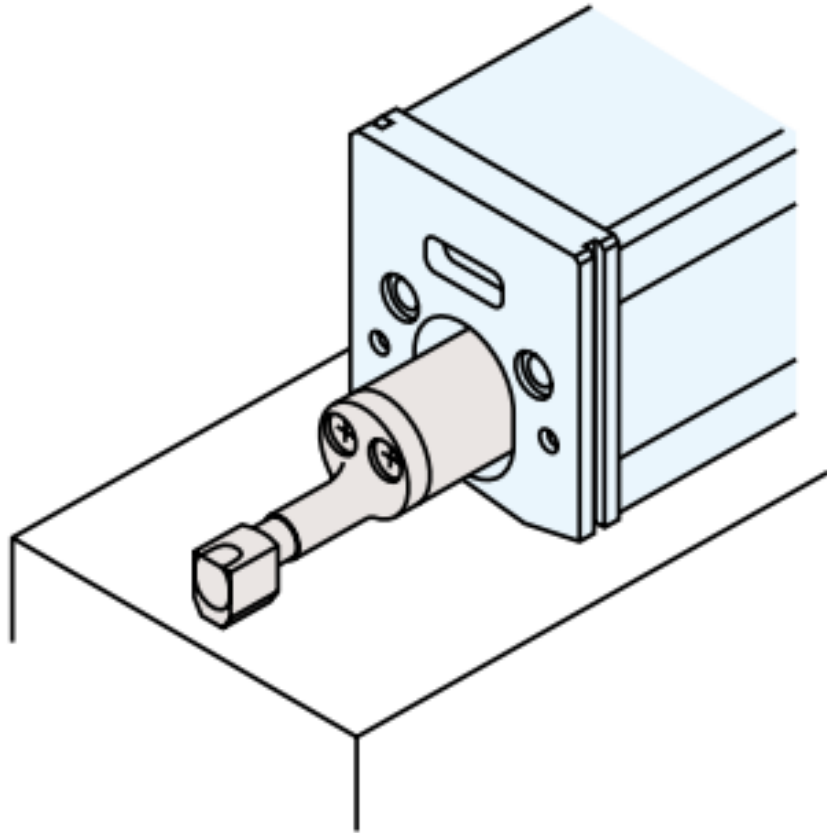


Figure 2.5: Detector on Mitutoyo SJ-210 Surftest

dichroic mirror reflects the excitation light onto the specimen, and the light is reflected back towards the pinhole aperture. The pinhole is an essential component of confocal microscope and acts as a spatial filter. It prevents any light that is not confocal to the objective focal plane from interfering with the image. Stepper motors allow the laser beam to travel incrementally across the sample, obtaining x and y scans performed in the z-direction. This automates three-dimensional data collection and enables a 3D image, or topograph, to be created (8),(39),(40). A high numerical aperture objective is used to achieve high resolutions. For surface finish measurement, a 50x objective lens is typically used with the Alicona InfiniteFocusSL system applied in this research.

White light interferometry is also used as a non-contact method to measure surface texture on a part (41). In this case, a low coherence white light source replaces the confocal laser and the objective is scanned in the z direction to measure topographs.

2.4 Side flow

The phenomenon of side flow in turning operations has been studied since the mid-20th century. Early experiments were completed by Isaev (42), Brammertz (43), Sata and Shaw (44), Pekelharing and Gieszen (9), and Selvam and Radhakrishnan (45). They observed that side flow serves to negatively affect surface finish and causes the measured value to exceed the theoretical (kinematic) value. Based on this early work, side flow has been defined as displacement of workpiece material toward the trailing edge of the cutting tool (i.e., on the opposite side of the nose radius from the feed direction) such that burrs form on the feed mark cusps (or ridges). Material adhesion on the machined surface between the cusps has also been reported. Both reduce the surface quality. Figure 2.8 displays an image obtained in 1971 from Pekelharing (9) to show the effect of side flow on the turned surface. The uneven cusps are clearly seen.

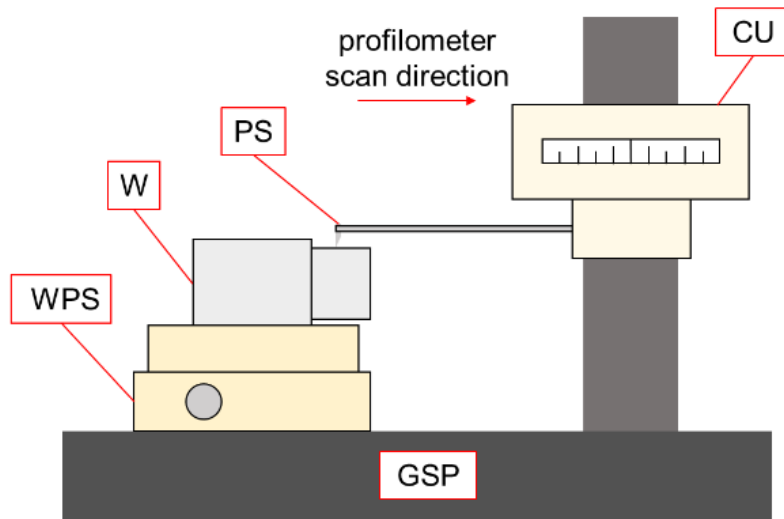


Figure 2.6: Mitutoyo Contracer profilometer measurement setup including granite surface plate (GSP), workpiece (W), controller unit (CU), profilometer stylus (PS), and workpiece positioning stage (WPS) (7).

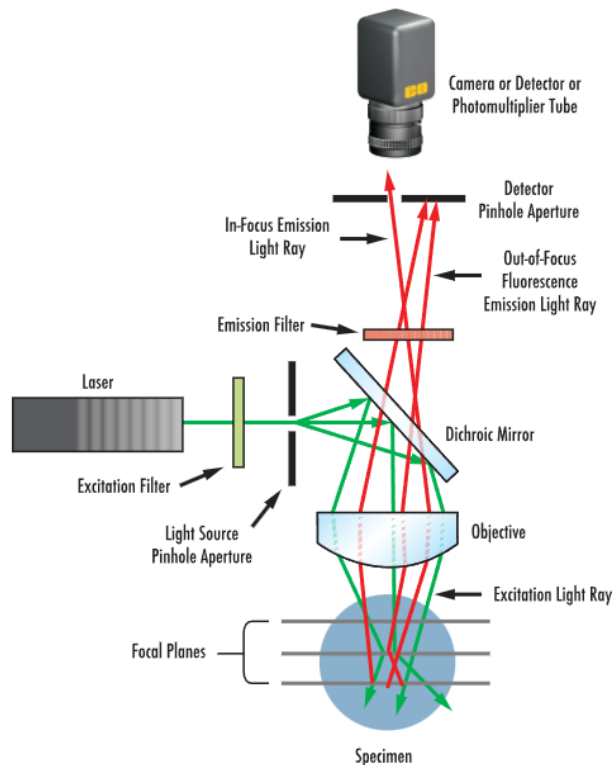


Figure 2.7: Confocal microscope graphical depiction. (8)

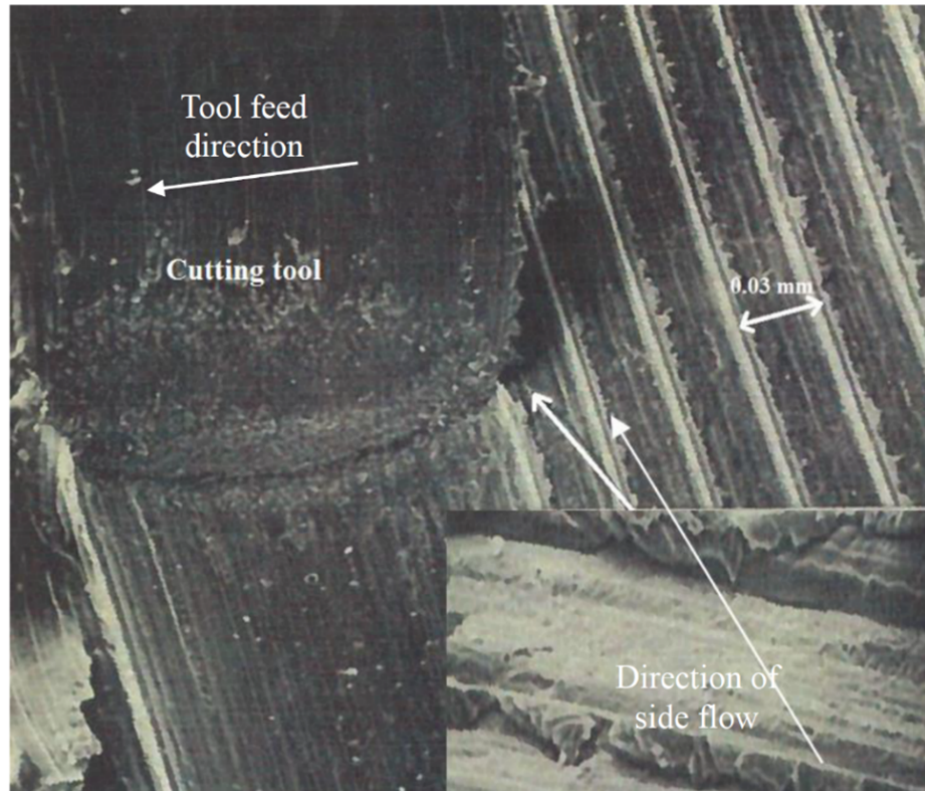


Figure 2.8: Image of side flow from reference (9). The additional material on top of the feed mark cusps is seen.

Table 2.1: Side flow literature review

Topic	Reference
Described side flow as a disturbance in the cutting zone for finish turning.	Isaev, A.I., 1950 (42)
Modeled turning surface finish using the process kinematics and effect of "Spanzipfel", or material left behind on the machined surface.	Brammertz, P.H., 1961 (43)
Showed that side flow negatively affects surface finish.	Sata, T. and Shaw, M.C., 1964 (44)
Side flow was identified and studied. Its detrimental effect on surface finish was examined.	Pekelharing, A. and Gieszen, C., 1971 (9)
Determined that built-up edge and side flow increase surface finish and hardness of machined surfaces.	Selvam, M.S. and Radhakrishnan, V., 1973 (45)
Revised the Brammertz surface finish model to include the effects of a feed-dependent minimum uncut chip thickness.	Grzesik, W., 1996 (46)
Considered the effects of tool nose radius, tool wear, feed, and minimum chip thickness on side flow in hard turning.	El-Wardany, T.I. and Elbestawi, M.A., 1998 (47)
Side flow in hard turning was studied, including the effects of edge preparation, nose radius, feed, and tool wear.	Kishawy, H.A. and Elbestawi, M.A., 1999 (10)
A model was presented to predict surface finish during turning of 5083 aluminum. The model included contributions by the process kinematics, tool edge geometry, and side flow.	Liu, K. and Melkote, S.N., 2006 (11)
A finite element was presented to predict material side flow during hard turning.	Kishawy, H.A., Haglund, A. and Balazinski, M., 2006 (48)
Surface finish for diamond turning was evaluated. The effects of material swelling and recovery were considered.	Kong, M.C., Lee, W.B., Cheung, C.F. and To, S., 2006 (49)
Surface finish for hard turning was studied, including the effects of feed, thermal softening, and side flow.	Chen, G.J., Liu, X.L. and Yue, C.X., 2010 (50)
Dry hard turning using polycrystalline cubic boron nitride inserts was completed and the surface finish was measured. Side flow was considered.	Zawada-Tomkiewicz, A., 2011 (51)
The effects of tool geometry on wear and surface finish were reported.	Dogra, M., Sharma, V.S. and Dureja, J., 2011 (52)
The effects of workpiece microstructure, feed, and tool geometry on surface finish in diamond turning were evaluated. The cutting edge geometry was shown to affect side flow.	Tauhiduzzaman, M. and Veldhuis, S.C., 2014 (53)
Dry hard turning was completed using polycrystalline cubic boron nitride inserts. The effects of cutting speed, depth of cut, tool nose radius, and workpiece hardness on surface finish were evaluated. Side flow was observed.	Tang, L., Gao, C., Huang, J., Shen, H. and Lin, X., 2015 (54)
The surface defect machining approach was implemented for hard turning to improve surface finish. Side flow was observed.	Rashid, W.B. and Goel, S., 2016 (55)
A diamond turning surface finish model was presented that included the process kinematics, side flow, spring back, tool edge waviness, and Gaussian noise.	He, C.L., Zong, W.J. and Sun, T., 2016 (56)
The effect of tool geometry and crystallographic orientation on side flow and surface finish in nano-scale cutting was studied.	Xu, F., Fang, F. and Zhang, X., 2017 (57)
Hard turning was completed using chamfered cubic boron nitride inserts. The effect of tool nose radius on side flow and surface finish was tested.	Žak, K., 2017 (58)
Hard turning was completed using liquid nitrogen, minimum quantity lubrication, flood coolant, and dry conditions. Surface finish was characterized and the effect on side flow was evaluated.	Sivaiah, P. and Chakradhar, D., 2018 (59)
Molecular dynamics simulation was used to study side flow, material recovery, and surface finish for cutting single crystal silicon.	Xu, F., Fang, F. and Zhang, X., 2018 (60)
Surface finish when turning with and without coolant was compared. Side flow was considered.	Hadzley, A.B., Anis, A.A., Farizan, M.N., Osman, M.H., Norfaizi, T. and Noorazizi, S., 2018 (61)
Side flow during finish turning of hardened steel using polycrystalline cubic boron nitride inserts was evaluated. Inserts with and without coatings were tested.	Ociepa, M., Jenek, M., Feldshtein, E. and Leksycki, K., 2019 (62)
A geometric model was described to predict the surface profile for finish turning considering feed, nose radius, error motions, and material.	Brown, I. and Schoop, J., 2020 (12)
A time domain simulation for surface finish prediction in modulated tool path (MTP) turning was presented. Side flow was incorporated using an effective tool nose radius.	Copenhaver, R., Smith, S. and Schmitz, T., 2021 (13)
The effect of side flow during dry finish turning of stainless steel on surface finish was tested.	Leksycki, K., Feldshtein, E. and Ociepa, M., 2021 (63)

Papers that build on the pioneering efforts in (42), (43), (44), (9), (45) are listed in Table 2.1. Based on these studies, several observations about side flow are provided here.

- Side flow causes the surface finish to exceed the theoretical value, which is based on the turning kinematics only (i.e., feed and tool nose radius).
- Side flow has been primarily studied for hard turning and diamond turning because surface quality is critical for both processes. However, the phenomenon is relevant to all low feed (finish) turning operations of ductile materials.
- Side flow mechanisms have been identified as: 1) material that passes between the tool flank face and work surface for chip thickness values less than the minimum chip thickness; and 2) low flow stress material that extrudes through wear features, such as notch wear, on the side of the cutting edge (10). A schematic is provided in Figure 2.9 (10) to explain the surface shown in Figure 2.8 (9).
- Side flow can be significant when turning with high cutting speeds and low feeds. At high cutting speeds, the increased temperatures at the tool-workpiece interface can cause reduced flow stress (thermal softening) and increased side flow. At low feeds, the size of the side flow features is significant relative to the cusp height.
- Side flow depends on the tool nose radius, edge preparation (e.g., hone or chamfer), feed, tool wear, and minimum chip thickness. The minimum chip thickness is a complex function of the cutting edge radius, feed, cutting speed, cutting tool geometry, and hardness and microstructure of workpiece material.

Several authors have used this understanding of side flow to propose surface finish models with improved accuracy over the kinematic description alone. Brammertz (43) modeled the surface finish in turning using the process kinematics and effect

of “Spanzipfel”, or chip tip/material left behind on the machined surface. Grzesik updated the Brammertz model to include the minimum chip thickness (46). See Eq. 2.1, where f is the feed, r_n is the tool nose radius, and h_{min} is the minimum chip thickness. The first term represents the contribution by the turning kinematics alone.

$$R_t = \frac{f^2}{8r_n} + \frac{h_{min}}{2} \left(1 + \frac{h_{min}r_n}{f^2} \right) \quad (2.1)$$

Liu and Melkote (11) presented a surface finish model for low feed turning with three components. See Eq. 2.2, where R_{th} is the kinematic contribution, R_p incorporates the side flow effects, and R_{edge} includes the cutting edge roughness. They explained side flow using figure 2.10.

$$R_{total} = R_{th} + R_p + R_{edge} \quad (2.2)$$

He et al. (56) considered the process kinematics, spring back, side flow, and other effects in their surface finish model. See Eq. 2.3, where R_{tew} is the kinematic contribution, s describes material spring back, w incorporates side flow, and ϵ_t represents other factors, such as material inclusions, built-up edge, and vibration.

$$R_{th} = R_{tew} - s + w + \epsilon_t \quad (2.3)$$

Brown and Schoop (12) described a geometric model for surface finish prediction in low feed turning. The model included feed, tool nose radius, tool edge radius, error motions, and material-dependent parameters. The surface simulation is depicted in figure 2.11, where the effect of side flow is clearly seen on the cusp shapes.

Copenhaver et al. (13) incorporated the effect of side flow in a time domain simulation by modifying the tool nose radius for small chip thickness (feed) values. Specifically, the effective nose radius was taken to be less than the actual nose radius; this matches the bottom portion of figure 2.10, where the dashed line that corresponds to the surface profile with side flow has a smaller radius than the nominal profile

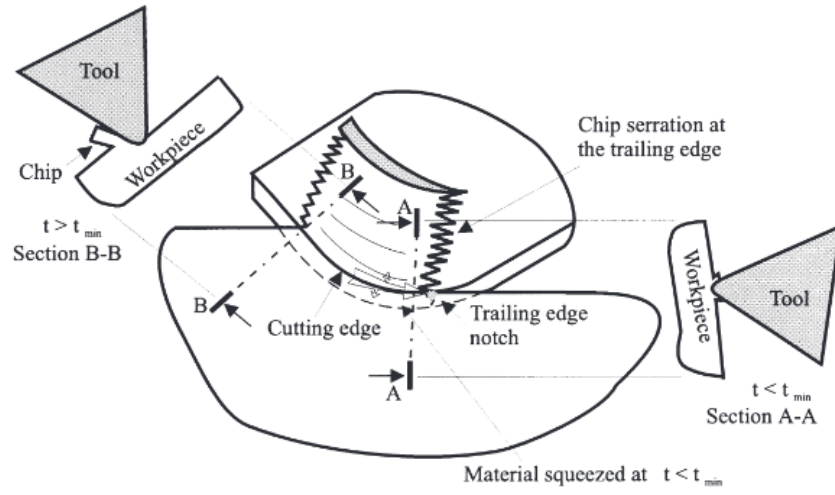


Figure 2.9: Side flow description from reference (10), where t_{min} is the minimum chip thickness.

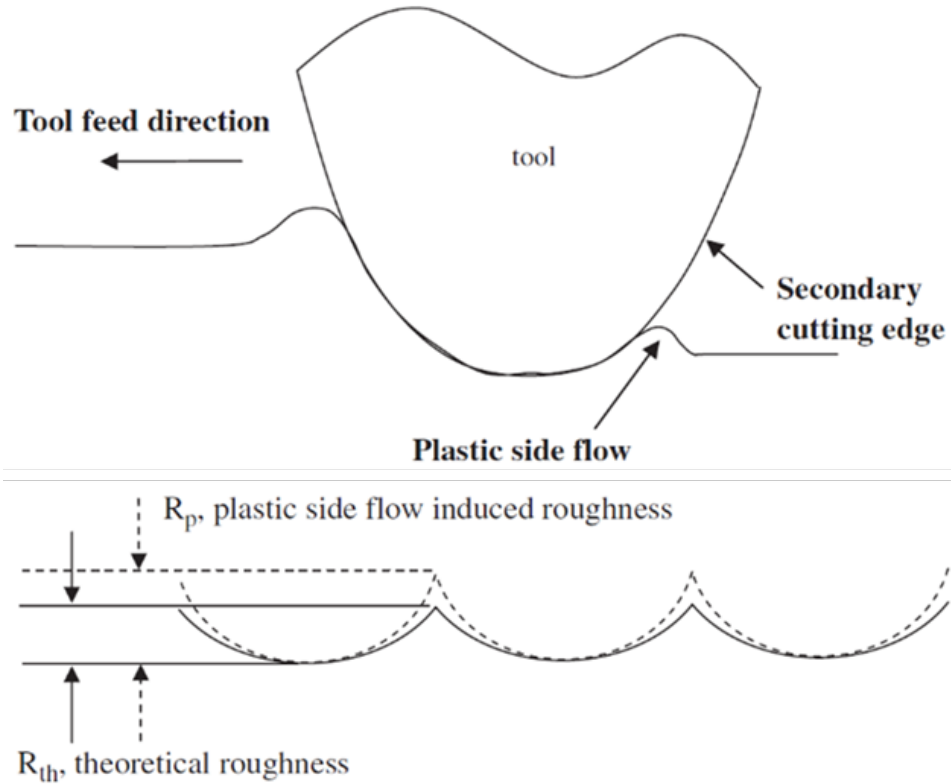


Figure 2.10: Depiction of side flow (top) and the associated increase in cusp height (bottom) (11)

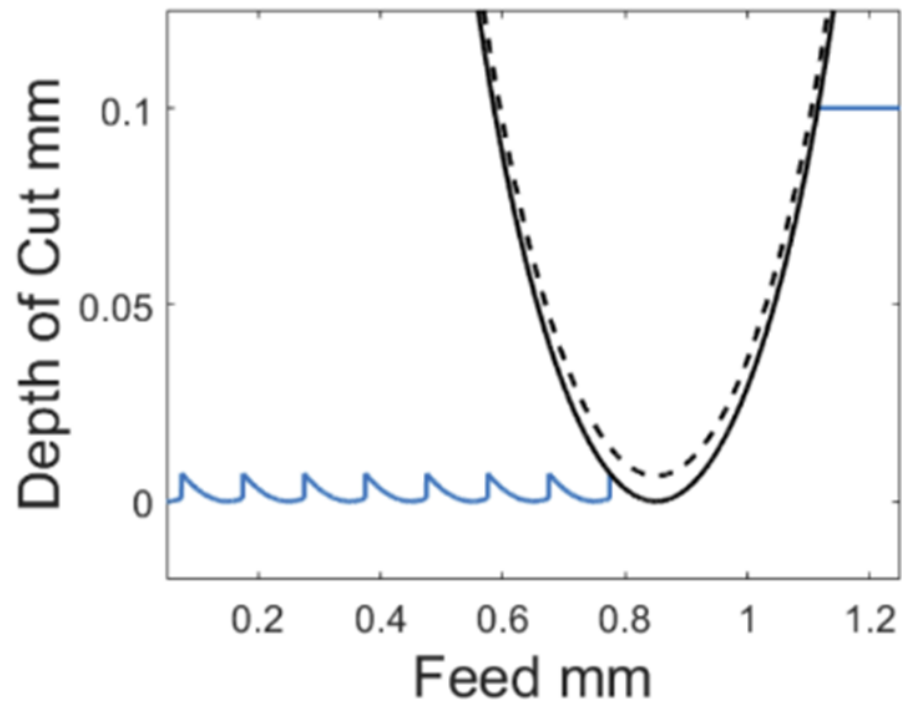


Figure 2.11: Surface simulation from reference ([12](#))

represented by the solid line. An example of the approach from (13) is provided in figure 2.12.

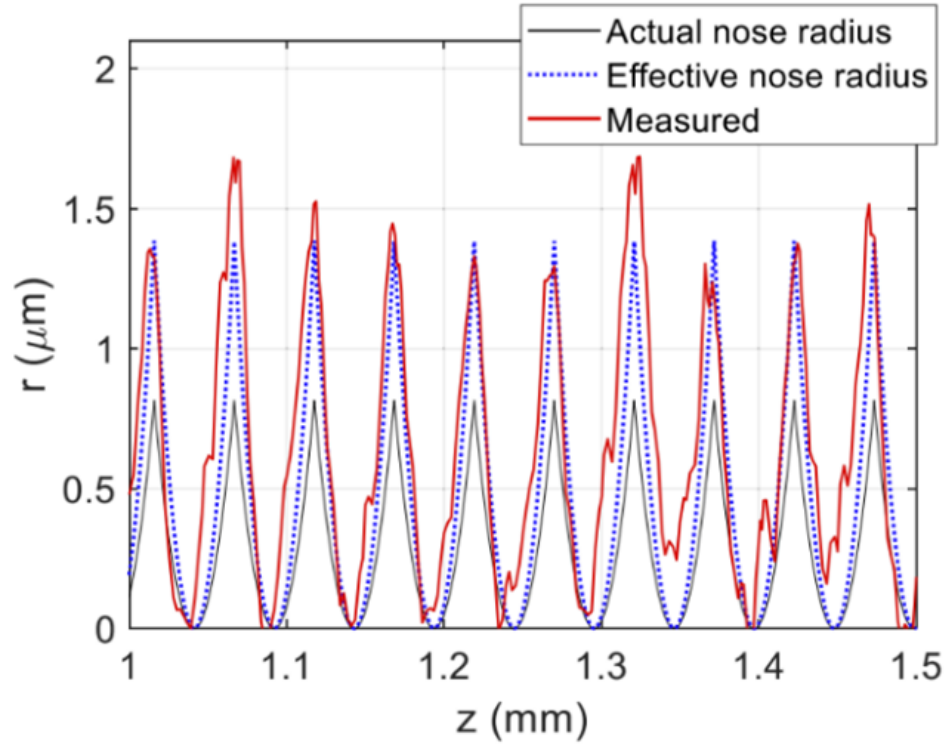


Figure 2.12: Effective tool nose radius example from reference (13). The effective nose radius is less than the actual nose radius, so the cusp heights are larger for the effective nose radius.

Chapter 3

Materials and methods: MTP surface simulation

3.1 Research objective

The research objective of this project is to provide a time domain simulation that predicts the surface profiles of parts machined using MTP turning. First, background information for the time domain simulation is provided. Second, modeling efforts for side flow are described and implemented in the time domain simulation. Third, single axis test cuts are reported to evaluate the effectiveness of the time domain simulation. Fourth, two axis taper test cuts are used to evaluate the time domain simulation additions to allow for changing spindle speeds and combined axis motions. Fifth, a curvilinear geometry defined by the machine tool test part (MTTP) is used to evaluate the prediction capabilities.

3.2 MTP simulation

3.2.1 MTP kinematics

MTP tool motion is created by imposing sinusoidal motion on the nominal feed motion of the cutting tool. Equation 3.1 shows how the tool's z_f position is calculated based on the commanded feed per revolution, f_r [mm/rev], the time, t [sec] and the OPR and RAF values that were selected such that discontinuous chips were produced. This approach is also applied to the x (cross feed) direction as well to generate two-axis MTP tool paths.

$$z_f = \left(\frac{\Omega}{60} f_r \right) t + RAF \cdot f_r \sin \left(\frac{\Omega}{60} \cdot 2\pi \cdot OPR \cdot t \right) \quad (3.1)$$

For parts with non-constant diameter, such as a taper, constant cutting speed machining requires that the spindle speed changes with part diameter. The spindle speed [rev/sec], Ω , is calculated using equation 3.2, where V is the cutting speed [m/min] and d is the part diameter [m]. As the x axis position changes (and therefore the part diameter), the spindle speed must also change to maintain a constant cutting speed. This becomes a challenge for the controller to maintain this constantly changing spindle speed for MTP tool paths because the CNC machine's x and z motions must respect the spindle speed changes throughout the tool path. This is not a challenge in traditional (constant feed) tool paths because the motion of the machine's axis is not oscillating as with MTP tool motion. The x -axis of the machine, which controls the spindle speed when constant surface speed is turned on, is always gradually increasing or decreasing, which allows the spindle speed to either ramp up or down depending on the direction of motion. To address this issue, the MTP tool path updates the spindle speed only at pre-selected increments for changing workpiece diameters. The typical increment is 10 revolutions per minute [rpm] as the diameter changes.

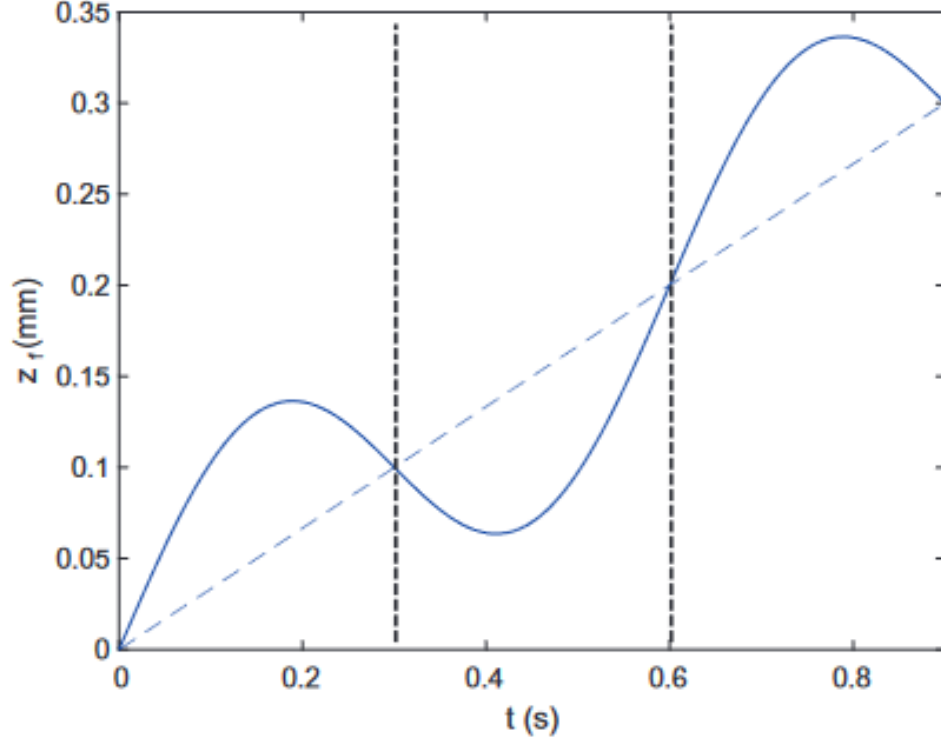


Figure 3.1: MTP feed motion for three spindle revolutions. The spindle speed is 200 rpm, the feed per revolution is 0.1 mm/rev, and the RAF and OPR values are 0.8 and 0.5. The dashed positive slope line identifies the constant feed contribution to the motion (first term in Eq. 3.1), while the solid line shows its sum with the sinusoidal MTP contribution (second term). The vertical dotted lines denote each revolution (2).

$$\Omega = \frac{V \cdot 60}{d \cdot \pi} \quad (3.2)$$

The instantaneous chip thickness is calculated using the MTP tool motion from one revolution to the next. The instantaneous chip thickness is required for the prediction of cutting forces and tool vibrations in the time domain simulation. The chip thickness calculation is depicted in figures 3.2 and 3.3. It can be seen that the chip thickness during part of the second revolution goes to zero (figure 8), as the tool motion overlaps a previously cut portion of tool motion. The nominal chip thickness is calculated by taking the current tool position and subtracting it from maximum of all the previous tool locations at a single location (angular orientation).

The instantaneous chip thickness, h , calculation is shown in equation 3.3, where n represents the current revolution number. For a non-rigid cutting tool, equation 3.3 is modified to include tool displacements in the surface normal direction (z_t). See equation 3.4 (7). Figure 3.4 shows the resulting chip thickness using equations 3.3 and 3.4. When the instantaneous chip thickness is less than zero ($h < 0$), it is set to zero. This indicates that no cutting is occurring.

$$h = z_{f,n} - \max\{z_{f,n-1}, z_{f,n-2}, \dots\} \quad (3.3)$$

$$h = (z_{f,n} - z_{t,n}) - \max\{(z_{f,n-1} - z_{t,n-1}), (z_{f,n-2} - z_{t,n-2}), \dots\} \quad (3.4)$$

3.2.2 Cutting force modeling

Cutting force modeling for MTP turning is completed in this study using a time domain simulation that solves the second order time delay differential equation of motion. MTP differs from traditional turning operations because the chip thickness varies due to the MTP tool motions. This resembles milling forces. Equation 3.5

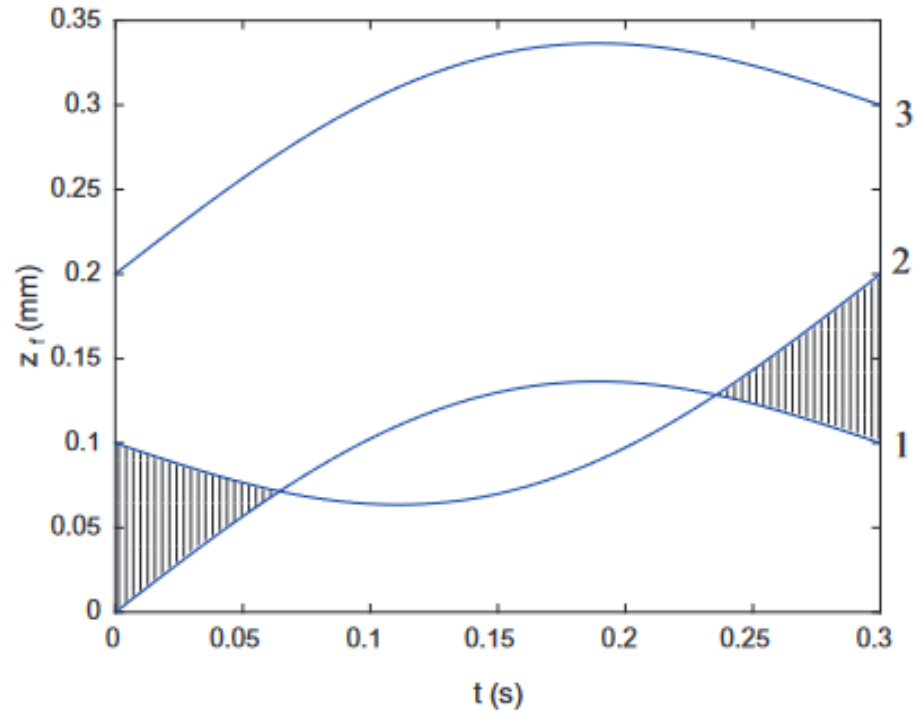


Figure 3.2: Chip thickness calculation for revolution 2. The nonzero chip thickness zones are denoted by the hatched areas (2).

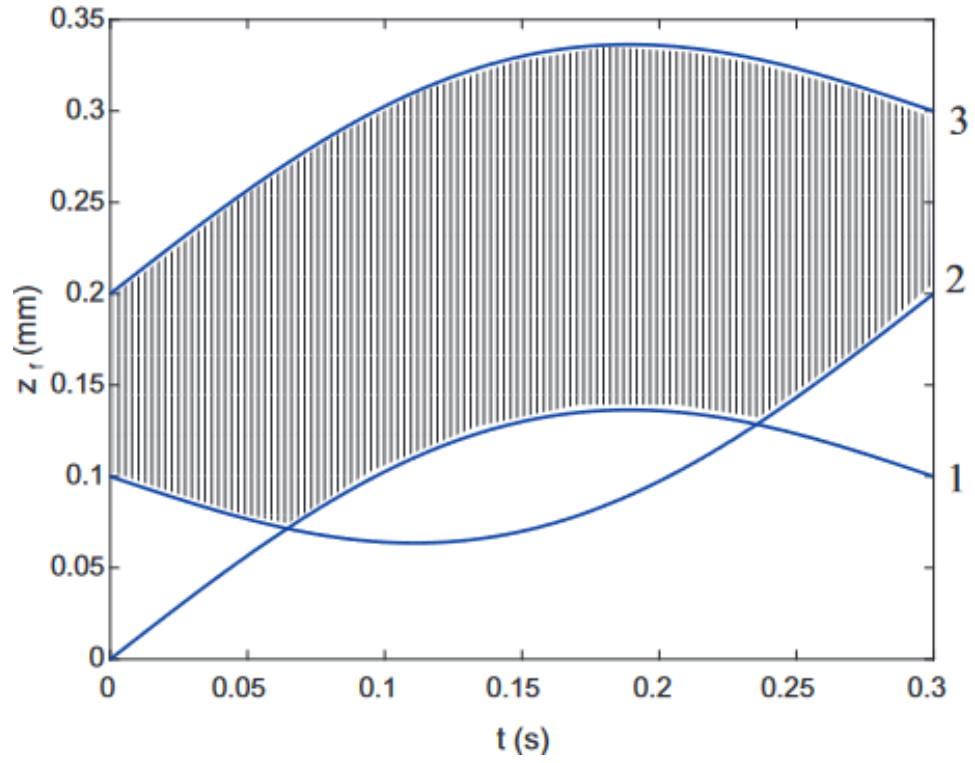


Figure 3.3: Chip thickness calculation for revolution 3. The nonzero chip thickness zones are denoted by the hatched areas (2).

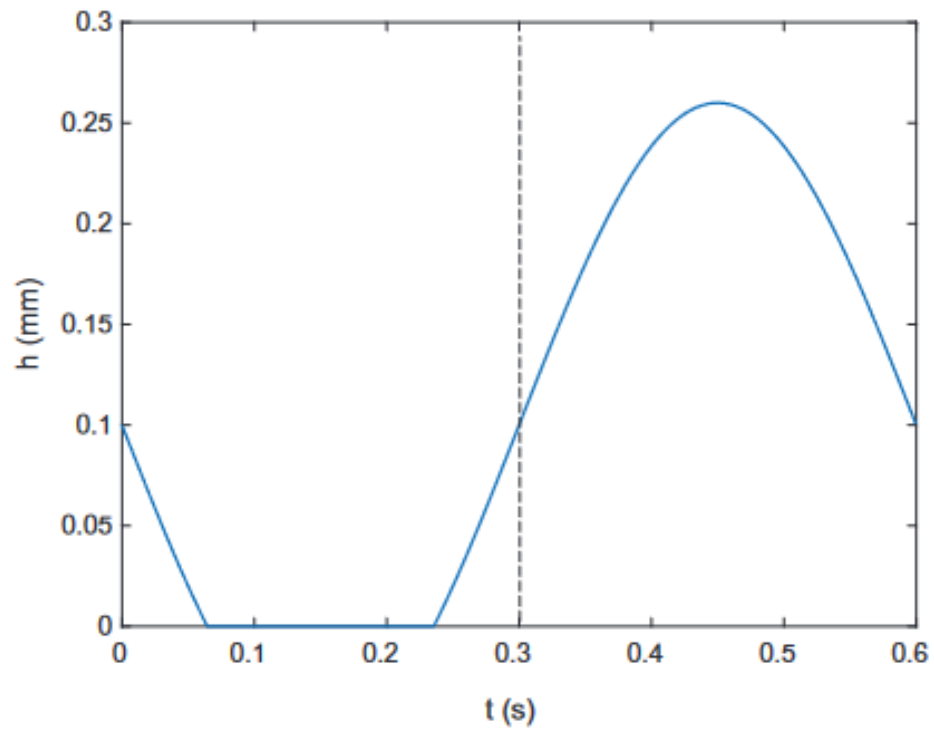


Figure 3.4: Instantaneous chip thickness for revolutions 2 and 3. The dashed line represents the end of revolution 2 and the start of revolution 3 (7).

shows the cutting force (F) calculation using chip thickness (h), chip width (b), and the cutting force coefficient (K_s).

$$F = K_s b h \quad (3.5)$$

The cutting force can be represented by its components in the normal and tangential directions. The resultant force is related to the normal and tangential cutting forces through the cutting force angle (β); see equations 3.6 and 3.8 which include the tangential and normal cutting force coefficients k_t and k_n , respectively. See equations 3.7 and 3.9, where the a, b, and c values represent power law fitting parameters. These values are found experimentally from fitting cutting force values that are collected during constant feed test cuts at varying chip thickness values.

$$F_t = F \sin(\beta) = (K_s \sin(\beta)) b h = k_t b h \quad (3.6)$$

$$k_t = a_t h^{b_t} + c_t \quad (3.7)$$

$$F_n = F \cos(\beta) = (K_s \cos(\beta)) b h = k_n b h \quad (3.8)$$

$$k_n = a_n h^{b_n} + c_n \quad (3.9)$$

The cutting force in the radial direction is calculated using equation 3.10. A power law is again used to define k_r .

$$F_r = k_r b h \quad (3.10)$$

$$k_r = a_r h^{b_r} + c_r \quad (3.11)$$

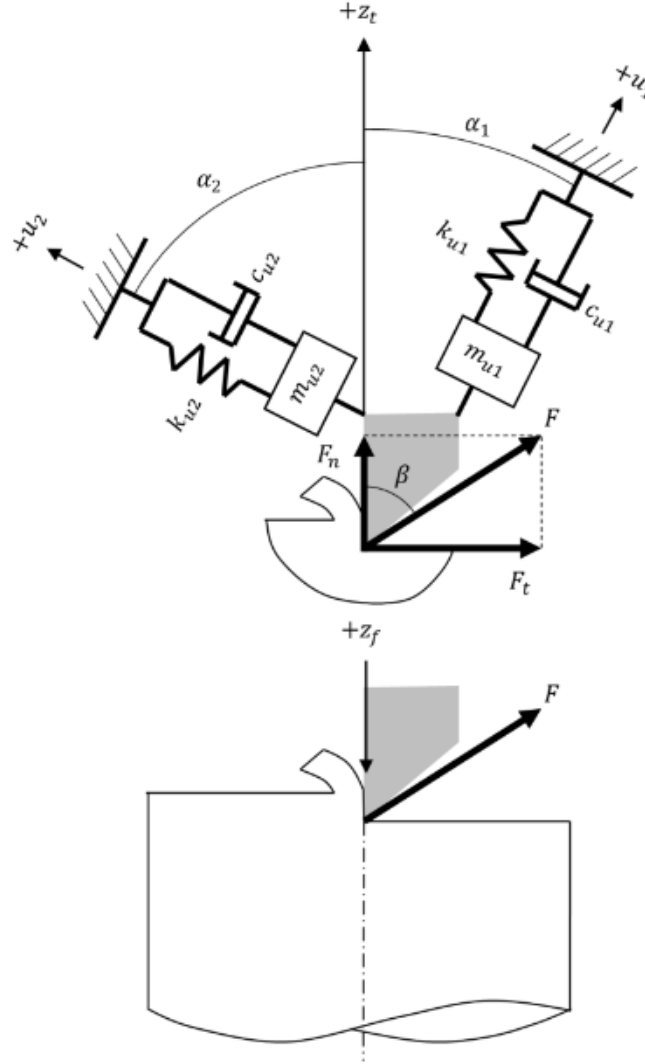


Figure 3.5: (Top) Flexible tool MTP turning dynamics model. The tangential, F_t normal, F_n , and resultant force, F , components are identified, as well as the modal parameters that represent the structural dynamics in two orthogonal directions, u_1 and u_2 . The MTP feed motion, z_f , and tool vibration, z_t , are also identified. (Bottom) Model orientation for turning. (7)

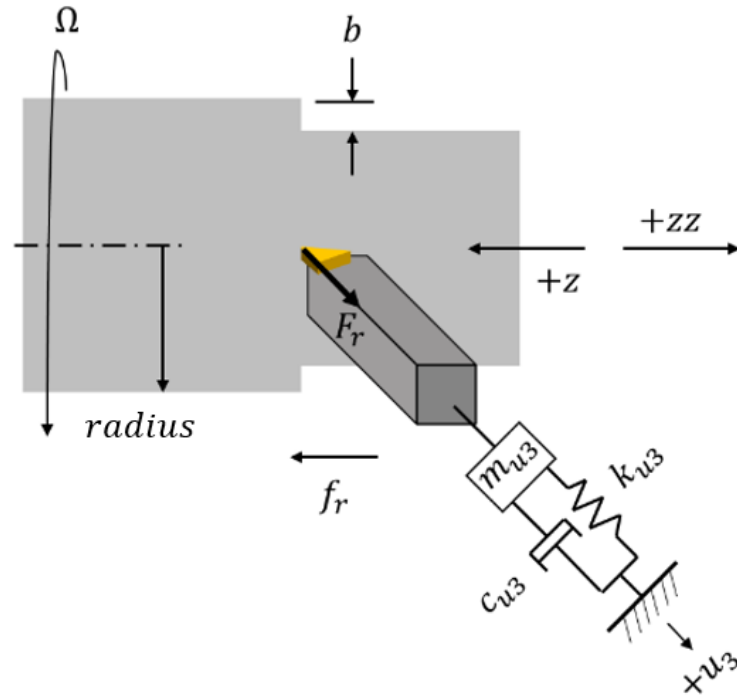


Figure 3.6: Flexible tool MTP turning surface finish model. The radial force, F_r , component is shown, as well as the structural dynamics in the radial direction u_3 . The MTP motion is denoted by $+z$ and the total motion is denoted by $+zz$ (7).

The resulting cutting forces are projected in the u_1 , u_2 , and u_3 directions to determine the cutting tool displacements for constant outside diameter (OD) turning. For taper turning and curvilinear geometry, the resulting forces depend on the tool's position on the part's surface.

$$F_{u1} = F \cos(\beta - \alpha_1) \quad (3.12)$$

$$F_{u2} = F \cos(\beta + \alpha_2) \quad (3.13)$$

$$F_{u3} = F_r \quad (3.14)$$

3.2.3 Vibration modeling

Accounting for the tool (and potentially workpiece) vibrations during machining is essential to model the resulting MTP surface accurately rather than considering only the kinematic MTP tool motion. To predict the tool and workpiece vibrations, the frequency response function (FRF) of the tool and the workpiece are required (2). The most common method that is used to measure the FRF is modal (tap) testing. This involves the use of an impact hammer and a low mass accelerometer that is fixed to the workpiece or cutting tool (64). The tool or workpiece is tapped with the impact hammer and the accelerometer records the acceleration of the tool or workpiece. The data is collected by a signal analyzer and the measured force and acceleration are converted into a displacement to force FRF. The measured FRF is then fit using modal fitting techniques to identify the natural frequency, stiffness values, and damping ratio for each vibration mode of interest. These modal parameters are used in the time domain simulation to model tool (and workpiece) flexibility during turning operations. Photographs of tap testing for the cutting tool and workpiece are shown in figure 3.7. Tap tests are performed in all three directions (x, y, and z). See figure 3.8.

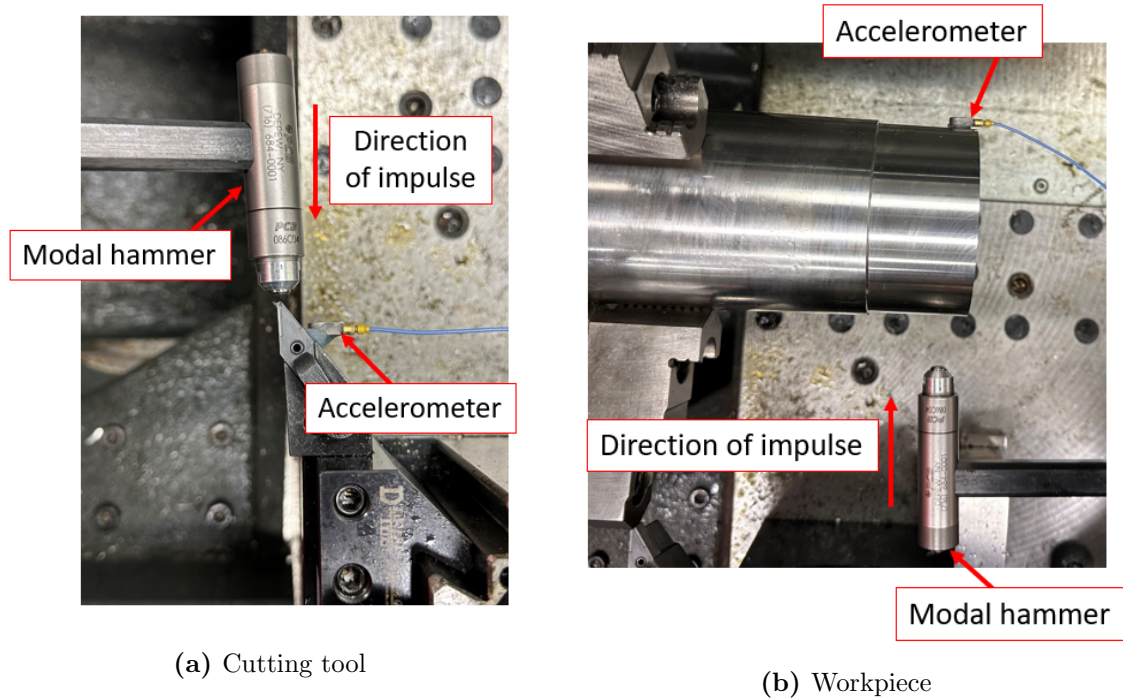


Figure 3.7: Tap testing setup for HAAS TL-1.

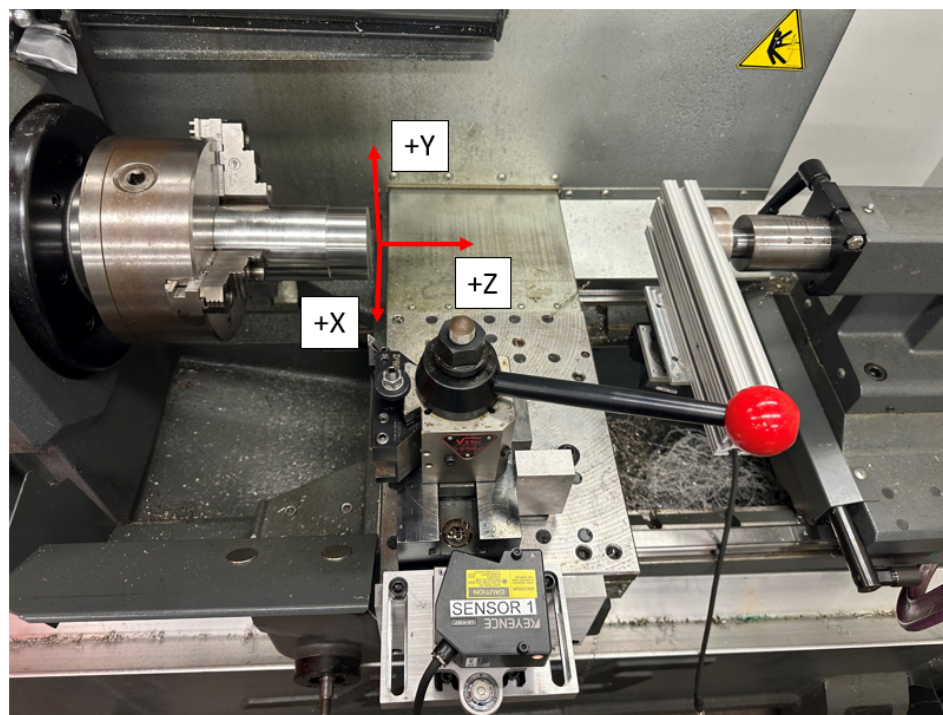


Figure 3.8: Work coordinate system definition for modal tap testing.

3.2.4 Combined cutting force and vibrations modeling

The chip thickness, chip width, and the cutting force model is used to calculate the cutting force. After the cutting force is found, a second order time delay differential equation of motion can be used to determine cutting tool displacements. The MTP tool motion, in combination with the cutting tool displacements, is used to calculate the resulting surface, which is then used for the next chip thickness calculation, as well as the resulting surface prediction.

The chip thickness, chip width, and the cutting force model are used to calculate the cutting force. After the cutting force is calculated, the second order time delay differential equation of motion is solved by numerical integration to determine the cutting tool displacement. The MTP tool motion is combined with the cutting tool displacement to calculate the resulting surface, which is then used for the next chip thickness calculation and the resulting surface prediction. The numerical integration is performed in small time steps (dt), where the time step is selected to be N times smaller than the smallest vibration period (i.e., the inverse of the largest natural frequency, $f_{n,max}$).

$$dt = \frac{1}{N \cdot f_{n,max}} \quad (3.15)$$

Equations 3.16, 3.17, and 3.18 represent the numerical integration using the modified Euler method (2).

$$\begin{aligned} \ddot{u}_1 &= \frac{F_{u1} - c_{u1}\dot{u}_1 - k_{u1}u_1}{m_{u1}} \\ \dot{u}_1 &= \dot{u}_1 + \ddot{u}_1 dt \\ u_1 &= u_1 + \dot{u}_1 dt \end{aligned} \quad (3.16)$$

$$\begin{aligned}
\ddot{u}_2 &= \frac{F_{u2} - c_{u2}\dot{u}_2 - k_{u2}u_2}{m_{u2}} \\
\dot{u}_2 &= \dot{u}_2 + \ddot{u}_2 dt \\
u_2 &= u_2 + \dot{u}_2 dt
\end{aligned} \tag{3.17}$$

$$\begin{aligned}
\ddot{u}_3 &= \frac{F_{u3} - c_{u3}\dot{u}_3 - k_{u3}u_3}{m_{u3}} \\
\dot{u}_3 &= \dot{u}_3 + \ddot{u}_3 dt \\
u_3 &= u_3 + \dot{u}_3 dt
\end{aligned} \tag{3.18}$$

The m , c , and k values are the modal mass, damping, and stiffness for the corresponding direction. These are obtained using the measured FRFs and modal fitting. The over-dots on the u terms represent the time derivatives. The first time derivative (velocity) is represented by a single dot, and the second time derivative (acceleration) is represented by a double dot. The current acceleration is calculated first, using the current force component. The acceleration is used to update the current velocity. The current velocity is found by summing the previous velocity and the product of the new acceleration and the time step. The current displacement is found by summing the previous displacement and the product of the new velocity and the time step. For the constant OD turning example the resulting displacement is calculated using equation 3.19.

$$z_t = u_1 \cos \alpha_1 + u_2 \cos \alpha_2 \tag{3.19}$$

3.2.5 Surface finish modeling

The surface profile that is produced by the MTP and tool motion is predicted by selecting a circumferential location on the (cylindrical) machined surface and recorded

motion. These values are stored in a vector z_{parsed} . The locations that are saved from four revolutions are shown in figure 3.9 as an example, where d is the circumferential location. The radial values for these corresponding z locations are also saved to a vector n_{parsed} .

Points along the tool nose radius (n) are modeled using equation 3.20, where n_r is the specified tool nose radius of the tool and z is the axial position along the feed direction. Using the z_{parsed} and n_{parsed} values the points are plotted at each of the corresponding locations. The overlapping sections of the individual tool nose radius plots can then be trimmed to yield the simulated surface profile as shown in figure 3.10.

$$n = -(n_r^2 - (z - z_o)^2)^{1/2} + n_o \quad (3.20)$$

An effective tool nose radius is also modeled to account for the effects of side flow at low chip thicknesses (7). This model applies a power law that depends on the chip thickness. The equation for points along the tool nose radius is updated as shown in equation 3.21 to include the power law for the effective tool nose radius. The coefficients a , b , and c represent the power law fit. These are found by performing constant feed test cuts at decreasing chip thicknesses and changing the nose radius to match the measured surface profile.

$$n = -((ah^b + c)^2 - (z - z_o)^2)^{1/2} + n_o \quad (3.21)$$

3.3 Roughness calculation

The arithmetic mean (R_a) can be calculated for a recorded surface profile of length (l_e) using equation 3.22 as stated in ISO standard 21920-2. This is calculated for the surface profile predicted by simulation as well as the filtered surface roughness profile from the cutting test to validate model predictions.

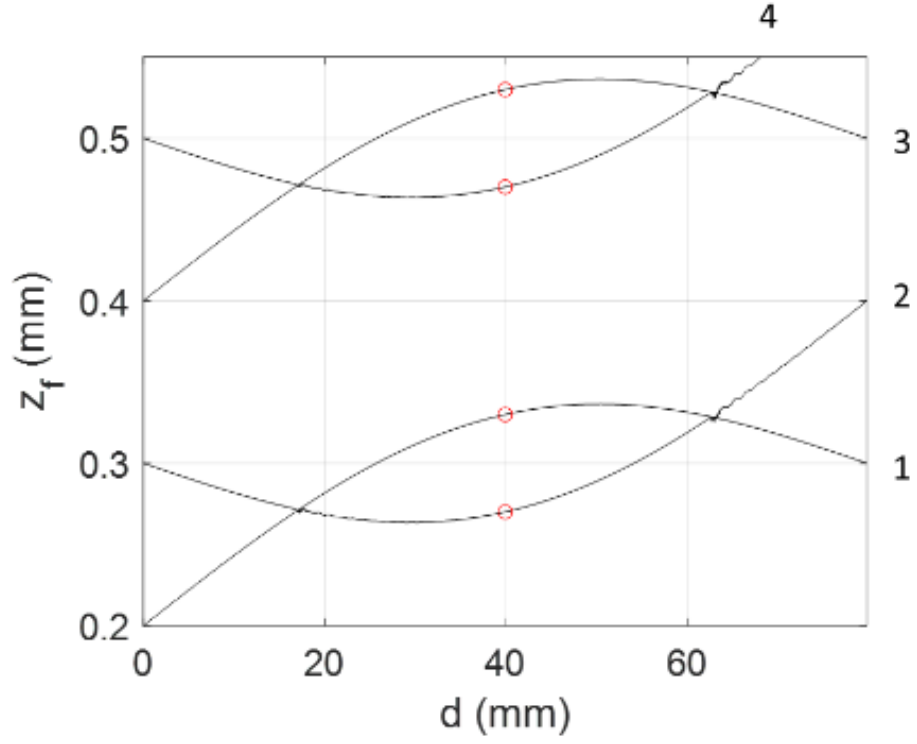


Figure 3.9: MTP feed motion for four spindle revolutions. The spindle speed is 200 rpm, the feed per revolution is 0.1 mm/rev, and the *OPR* and *RAF* values are 0.5 and 0.8. The circles indicate the tool nose radius test locations (7).

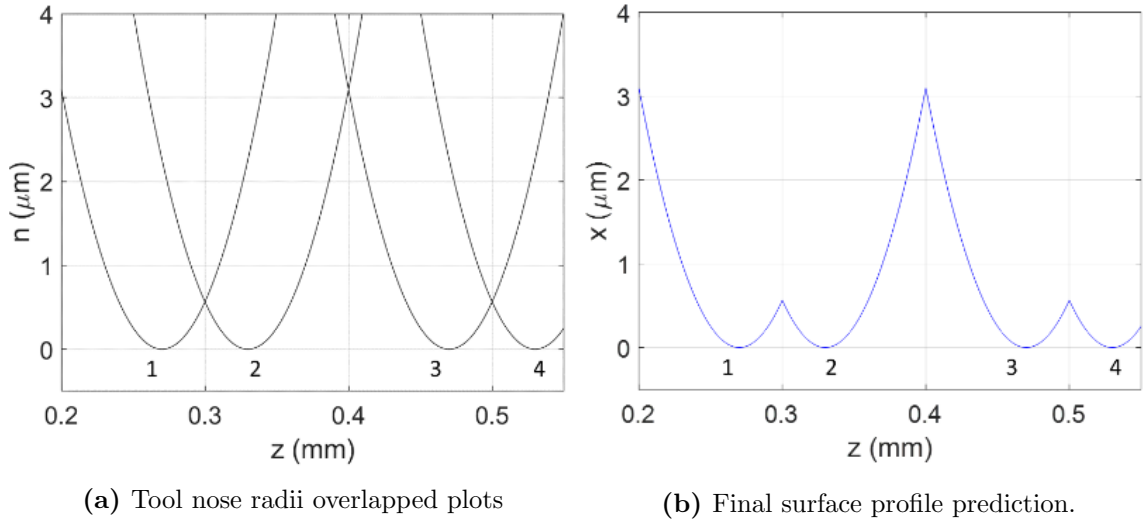


Figure 3.10: Time domain simulation generated surface profile (7).

$$R_a = \frac{1}{l_e} \int |z(x)| dx \tag{3.22}$$

Chapter 4

Surface finish filtering

4.1 Background

Filtering the surface profile is an important step in the analysis of the surface roughness. The filtering is based on wavelengths of specific interest. Profile filters are used to separate roughness, waviness, and form from the primary profile. Figure 4.1 shows the overlap between the roughness and waviness profile that is present within the primary profile. The λ_s profile filter defines the intersection between roughness and shorter wavelength components. The λ_c profile filter defines the intersection between the roughness and waviness profiles. The λ_f profile filter defines the intersection between the waviness and longer wavelength components of the primary profile such as form (14).

The first types of filters that were used for surface roughness analysis were electrical filters used prior to modern computers and analysis software. These used a two-resistor-capacitor (2RC) network. The filters worked by computing a running average of the current and previous voltages and assigned reduced weights to the voltages earlier in time. However, due to the filter design, there was a phase error introduced into the recorded data (15). To better understand this phase error that is introduced by the 2RC filter, it was simulated digitally by Whitehouse (14). The

filter was created using a weighting function that applied a cutoff to separate short-wavelength components from long wavelength components.

With the creation of modern computing systems and analysis, software-based digital filtering is now the primary choice for surface finish analysis (15). One of the most common digital filters is the Gaussian filter. The Gaussian filter eliminates the non-linear phase of the 2RC filter. There are three main issues with the application of the traditional Gaussian filter to a primary profile. The first is the waviness profile will have distortions at the edges of an open profile. To address this issue, a length equal to one-half or one cutoff wavelength is removed from the ends of the waviness profile. In situations where short traces are used, this is not an acceptable approach. The second is the waviness profile does not follow the texture in the presence of large form, such as cylindrical or spherical geometries. The third is that the filter is not robust against outliers (15).

4.2 Filtering techniques

Two main digital filters were evaluated and compared. The differences between a Gaussian regression filter and a spline filter are shown.

The Gaussian regression filter is a traditional Gaussian filter combined with either a zero-order or second-order polynomial fit to reduce the edge distortion at the start and end of profiles and to help mitigate issues with large form. When the zero-order Gaussian regression filter and the traditional Gaussian filter are compared, as shown in figure 4.2, the edge distortion is significantly reduced with the use of the zero-order Gaussian regression filter.

If a second-order Gaussian regression filter is used instead of the zero-order Gaussian regression filter, then it is possible to further minimize the edge distortion effects of the Gaussian filter as seen in figure 4.3. The second-order Gaussian regression filter is more computationally intensive than the zero-order Gaussian

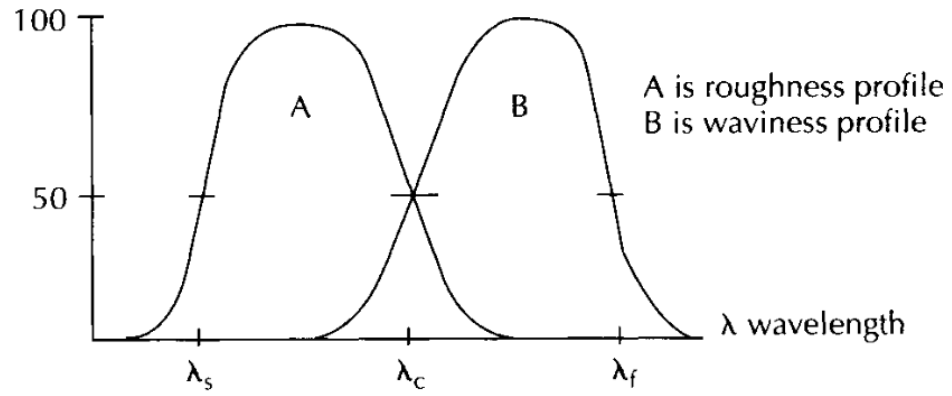


Figure 4.1: Profile filters (14).

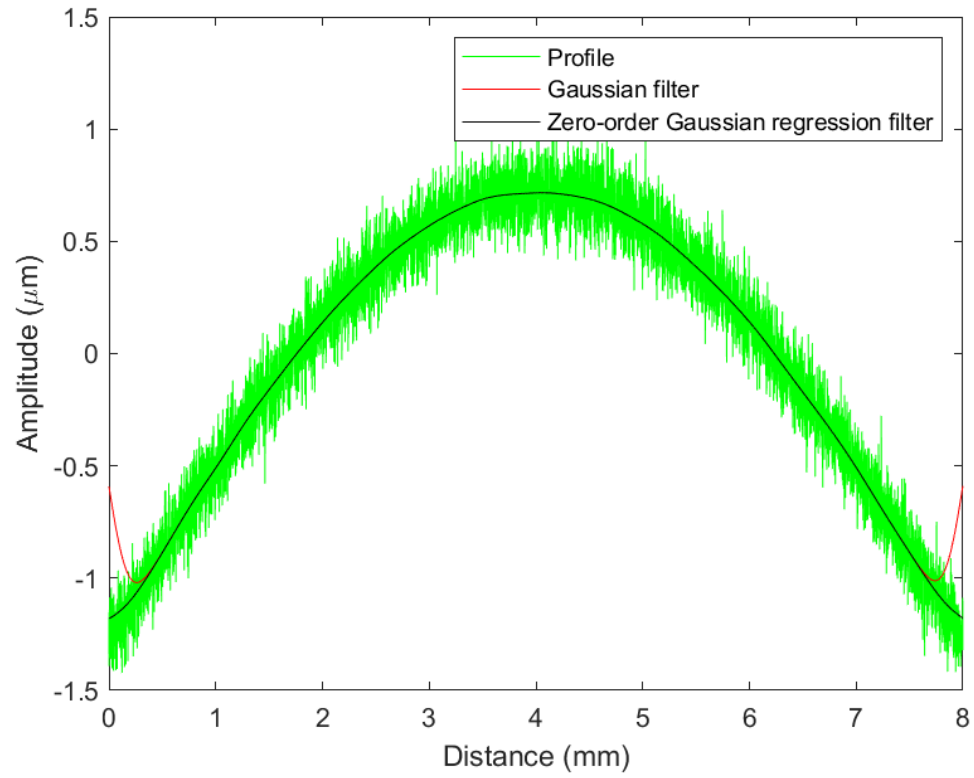


Figure 4.2: Traditional Gaussian filter compared with zero-order Gaussian regression filter with a 0.8 mm cutoff (15).

regression filter, but improves performance in the presence of large form. The zero-order Gaussian filter and second-order Gaussian filter are not robust against outliers in the data set. The spline filter can handle the edge distortion effects and is robust against outliers.

There are two types of spline filters. Non-periodic spline filters are used for filtering open profiles (flat surfaces). Periodic spline filters are used for filtering closed profiles (roundness). When comparing a spline filter's transmission characteristics to a Gaussian filter, the spline filter has a steeper transmission characteristic than the Gaussian filter. See figure 4.4. The spline filter also does not suffer from the edge distortion that is seen with a traditional Gaussian filter, as seen in figure 4.5. The spline filter is also less influenced by form than the Gaussian filter.

The spline filter is incorporated in the latest ISO standard that specifies filtering (ISO 16610-22:2015). The main disadvantage of the spline filter is that there is no expression for the weighting function and it is therefore cumbersome to implement (15).

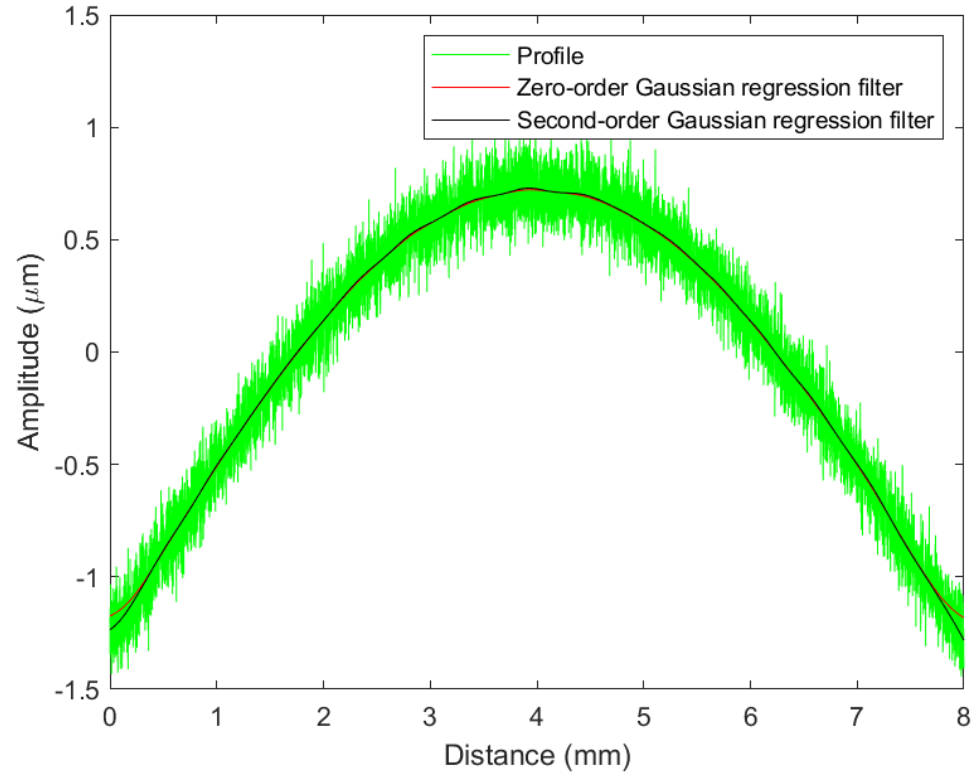


Figure 4.3: Zero-order Gaussian regression filter compared with second-order Gaussian regression filter with a 0.8 mm cutoff (15).

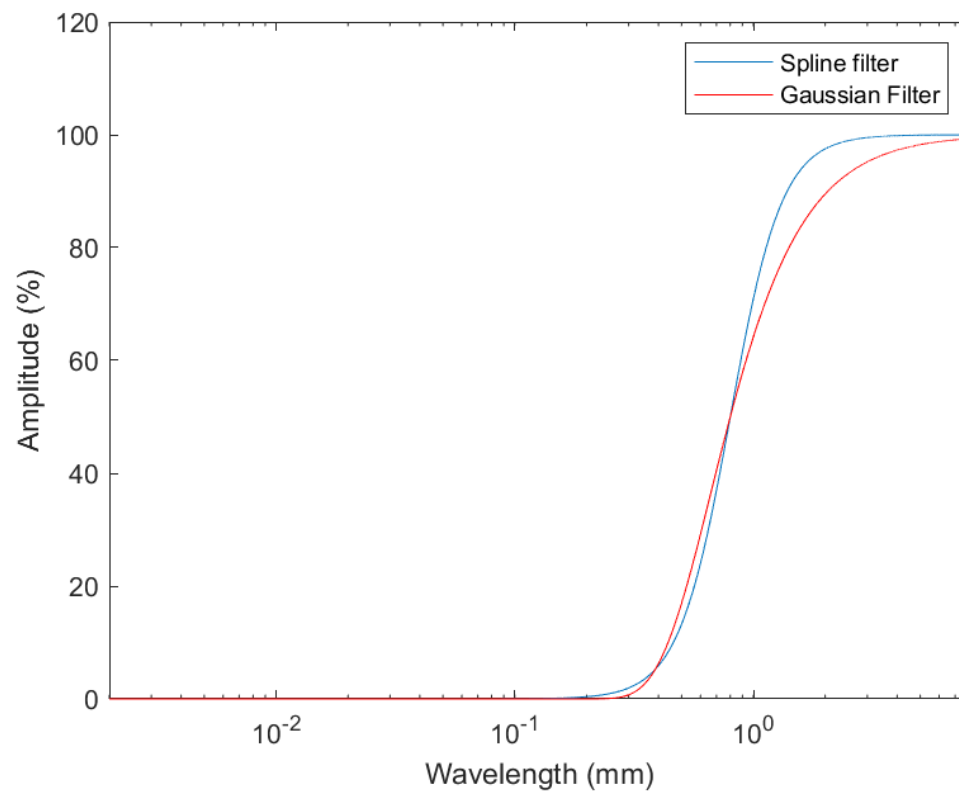


Figure 4.4: Spline filter transmission characteristics vs Gaussian filter transmission characteristics (15).

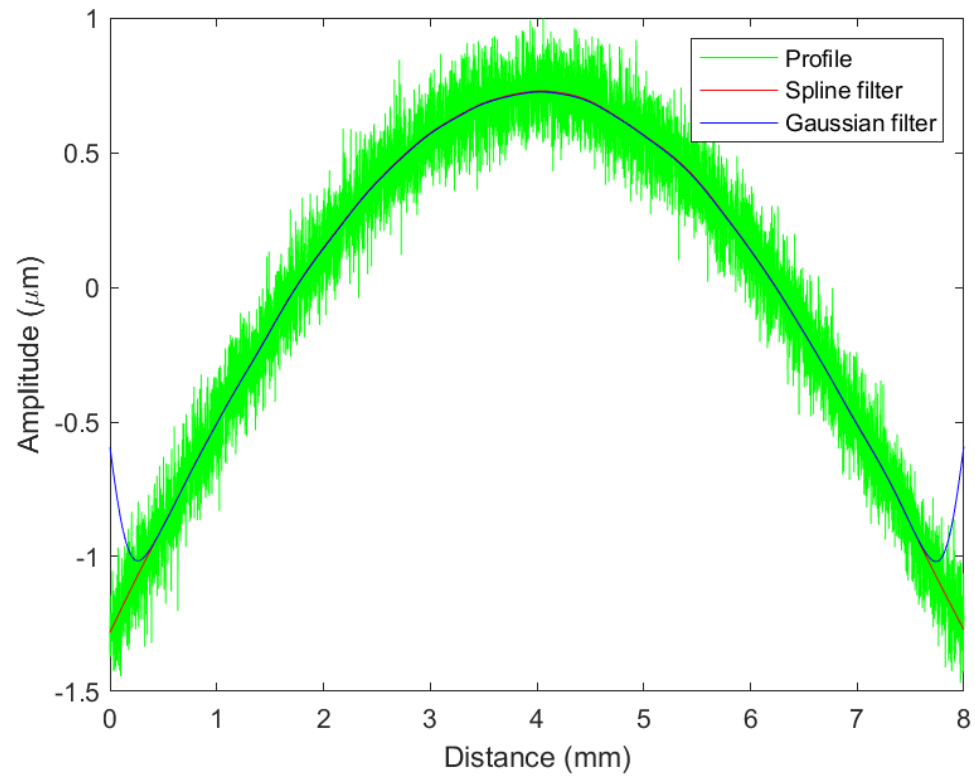


Figure 4.5: Spline filter waviness vs Gaussian filter waviness (15).

Chapter 5

Laser displacement sensor calibration

5.0.1 Calibration of laser displacement sensors

Two LK-H157 laser displacement sensors were used to record tool motion during test cuts. This recorded tool motion was then used in combination with the recorded spindle speed to extract the MTP parameters the machine achieved during the test cuts. It was necessary to find sensitivity coefficients that relate the measured voltage to displacement for these sensors. Step tests were completed using a linear air bearing stage. The air bearing stage was programmed to move in small increments, and the laser displacement sensor was used to measure the known stage displacement. The setup is shown in figure 5.1. A laser Doppler vibrometer from Polytech was used to confirm the air bearing stage displacement. The stage motion was plotted versus the laser displacement sensor voltage and then a least square fit was used to determine the sensitivity coefficient for each sensor.

The error between the calibrated and commanded displacement is shown in figure 5.2. It is seen that sensor 1 exhibits a larger error. Therefore, a range of 35 mm to 55 mm was chosen as the working range for sensor 1. The least squares fit was then performed again using this limited range. The error between the measured values

and the corresponding commanded distance values using the limited range and new sensitivity coefficients are displayed in figure 5.3.

5.0.2 Laser displacement sensor mount testing

Aluminum mounts were manufactured to hold the laser displacement sensors in the Haas ST-15 CNC lathe for the cutting test. The z-axis sensor mount was mounted to the sliding tailstock. The design of this fixture was an aluminum plate construction as shown in figure 5.4. A rotational stage was mounted to the aluminum fixture that enabled alignment of the laser displacement sensor parallel to the machine's z-axis.

For the x-axis sensor mount, an aluminum fixture plate was mounted to a Morse taper adapter, which was then clamped in the machine's tailstock as shown in figure 5.5. Similar to the z-axis sensor mount, the laser displacement sensor was mounted to a rotational stage that enabled alignment of the laser displacement sensor parallel to the machine's x-axis.

Because nonfunctional surfaces of the machine casting were poor roughness, laser targets were added so that a flat parallel surface could be used for the laser displacement sensors to record the motion of each axis. As shown in figure 5.6 a goniometer stage enabled the targets to be aligned parallel to the x-axis for the z-axis laser target and the z-axis for the x-axis laser target. The laser targets were ground gage blocks that were epoxied to the goniometer stages and these assemblies were attached to the machine casting using neodymium magnets.

To verify that the laser displacement mounts were sufficiently stiff, modal tap testing was used to find the natural frequencies and ensure they were sufficiently high to not be near typical MTP oscillation frequencies (0.5 Hz to 9 Hz). Figures 5.7 through 5.14 show the setup for the tap test as well as the corresponding frequency response functions (FRFs). Based on the results from the tap testing, it was determined that the mounts had natural frequencies that were sufficiently higher

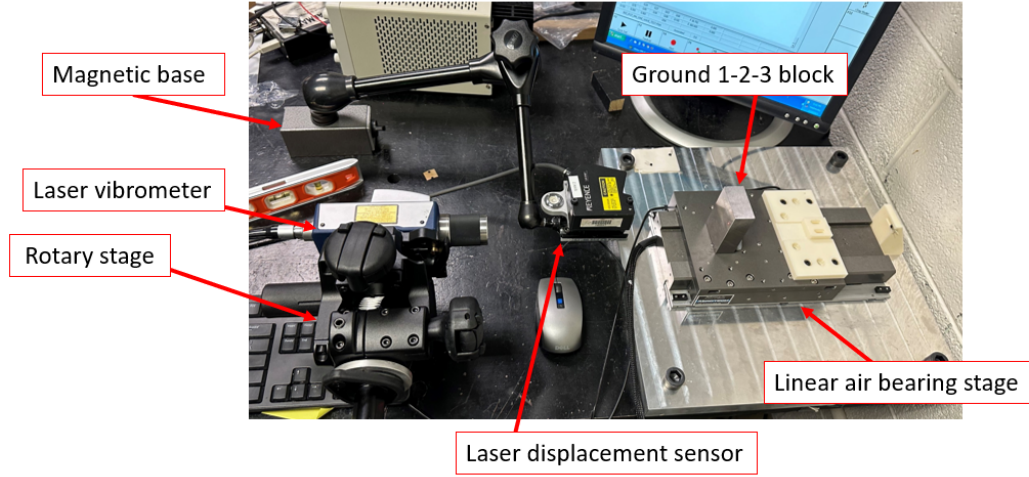


Figure 5.1: Setup for laser displacement sensor calibration.

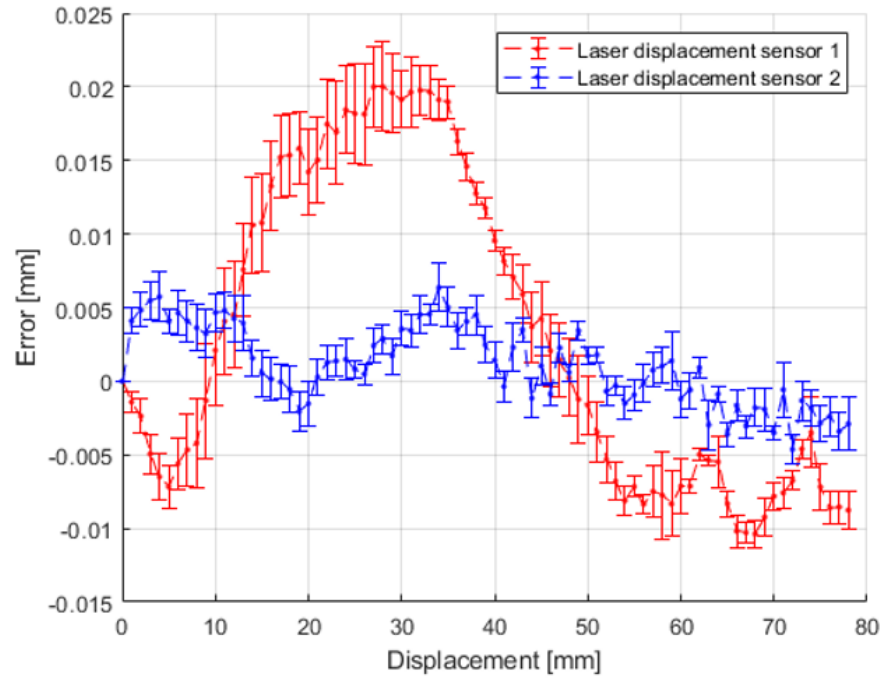


Figure 5.2: Error between the measured laser displacement values and the commanded values for the linear air bearing stage. The error bars represent the standard deviation from three repeats.

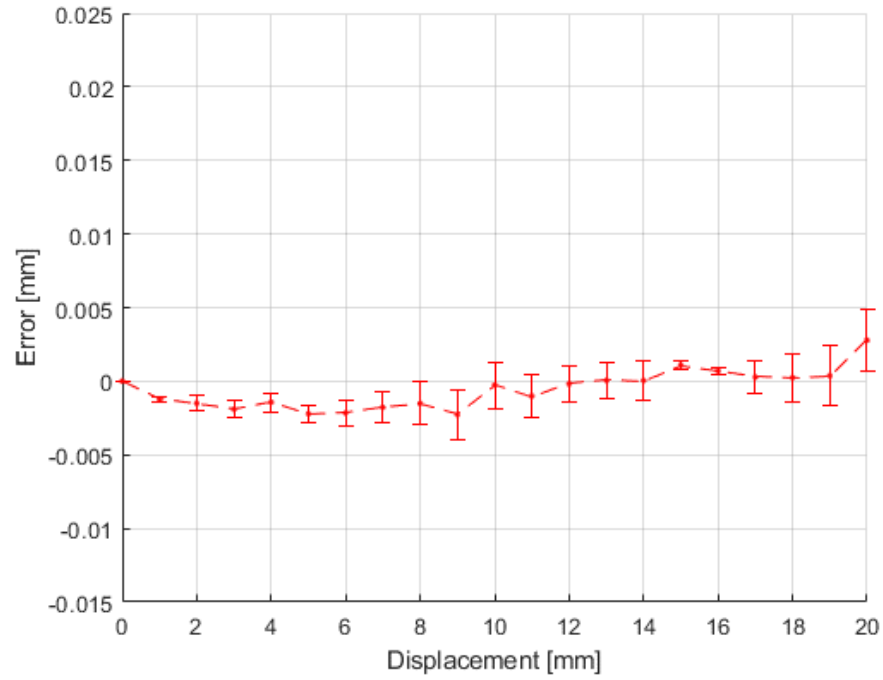


Figure 5.3: Error between the measured laser displacement values and the commanded values for the Aerotech air bearing stage for limited sensor 1 range. The error bars represent the standard deviation for three repeats.

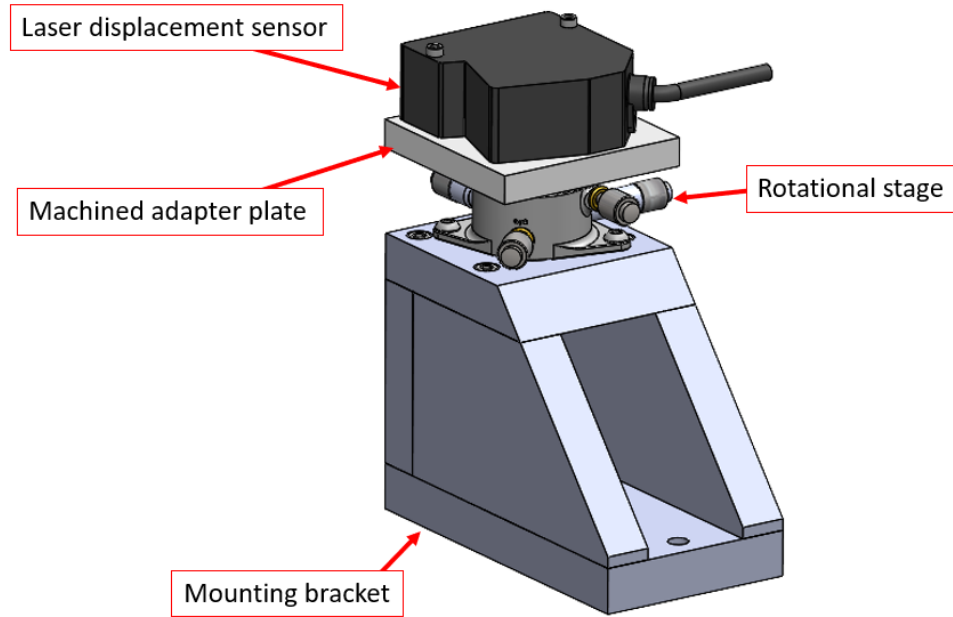


Figure 5.4: Laser displacement sensor mount design for z-axis measurements.

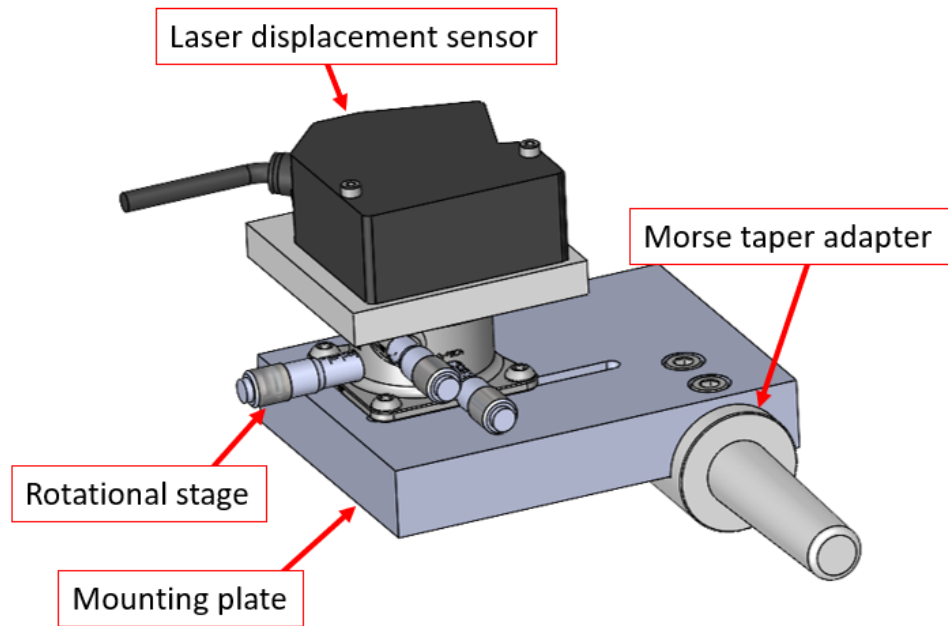


Figure 5.5: Laser displacement sensor mount design for x-axis measurements.

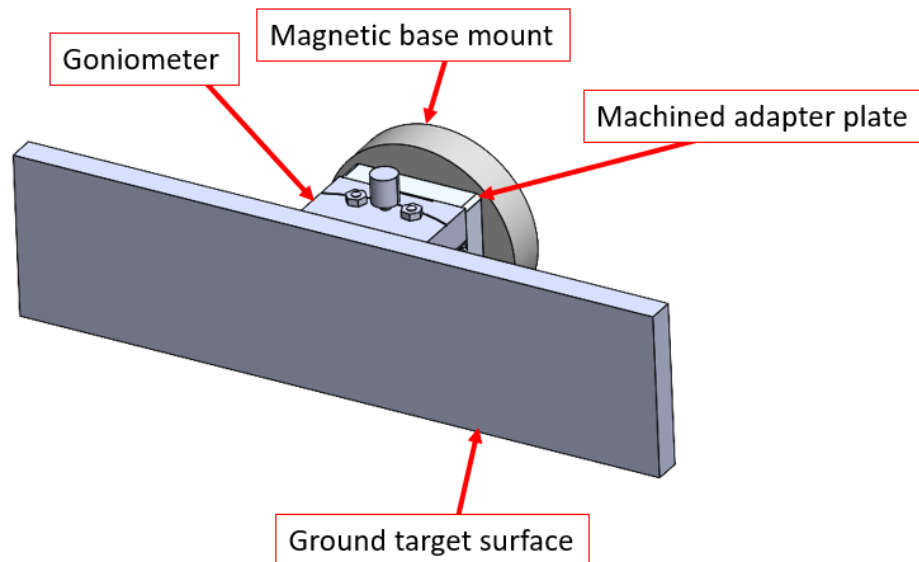


Figure 5.6: Alignment target for laser displacement sensors.

than the expected oscillation frequencies from the machine during MTP motions to avoid measurement errors.

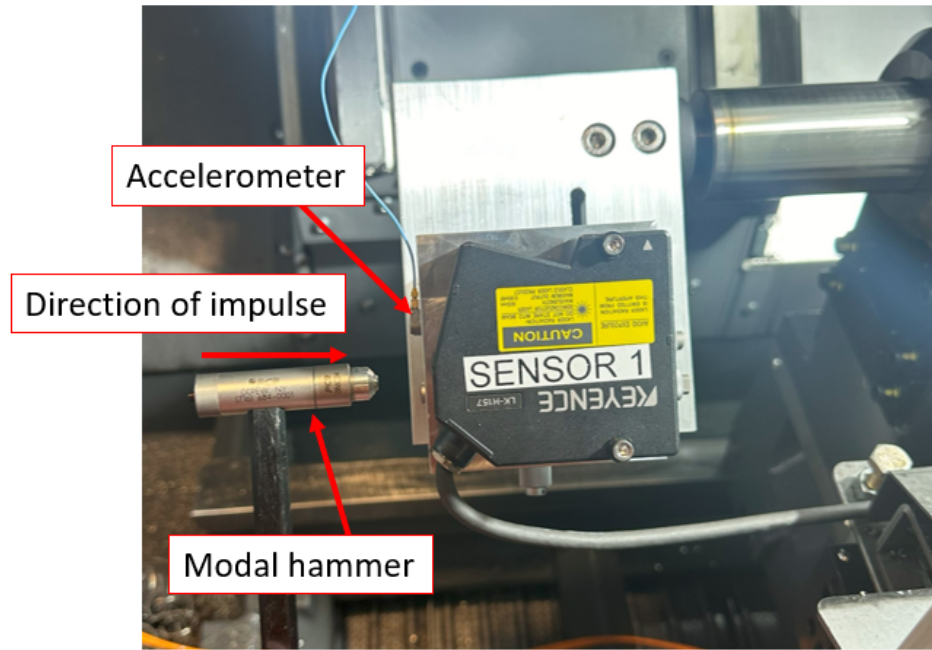


Figure 5.7: Modal tap test setup for x-axis laser displacement sensors mount z-axis direction.

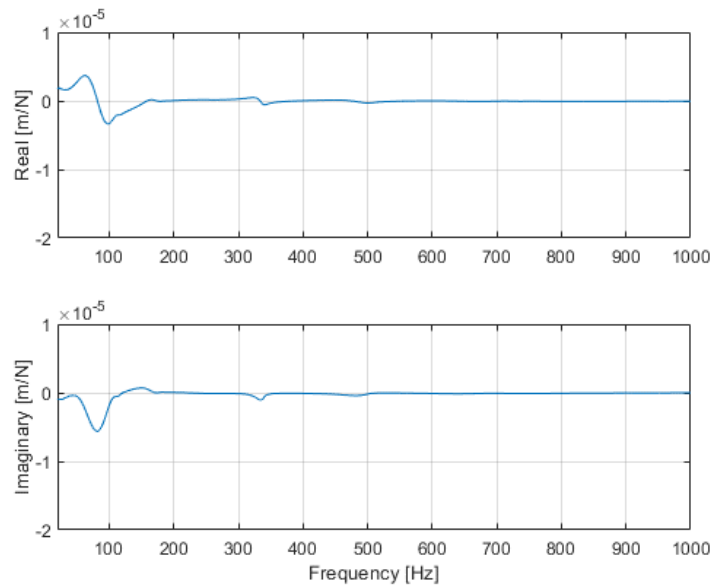


Figure 5.8: FRF from tap test first natural frequency 82.4 Hz, stiffness 6.55×10^5 N/m, damping ratio 0.139.

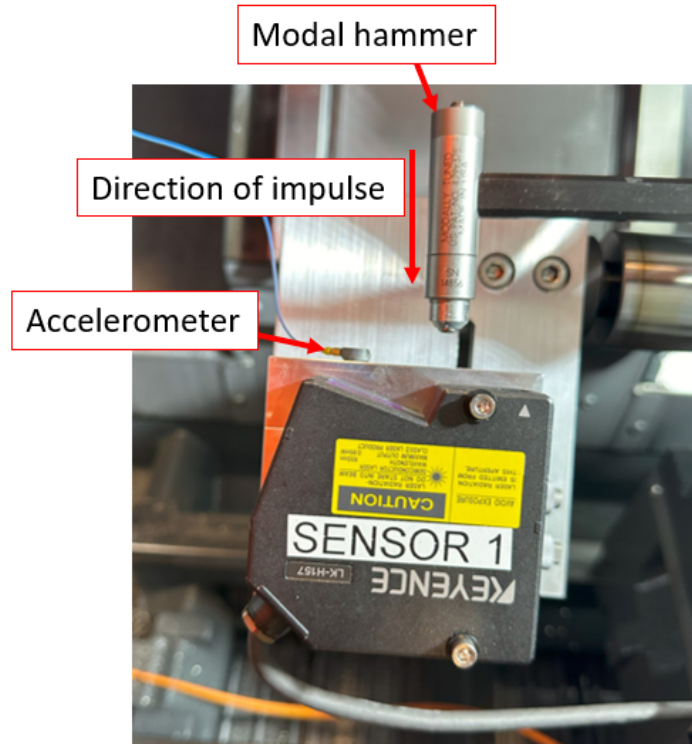


Figure 5.9: Modal tap test setup for x-axis laser displacement sensors mount x-axis direction.

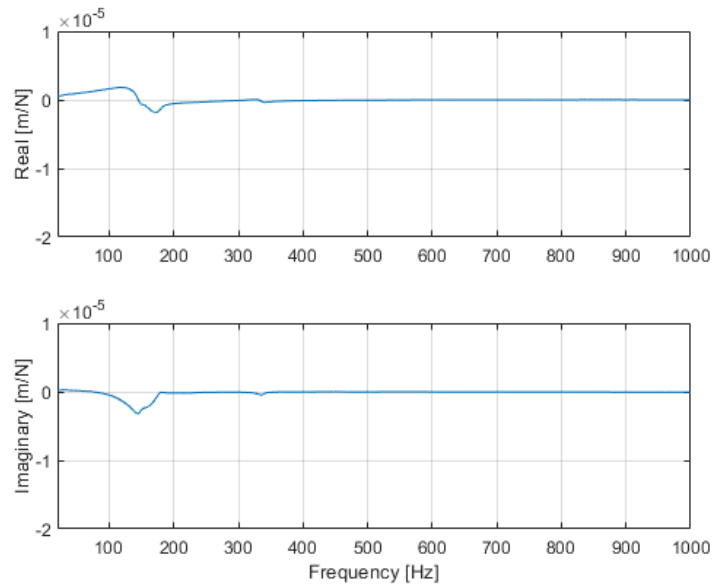


Figure 5.10: FRF from tap test first natural frequency 145 Hz, stiffness 1.51×10^6 N/m, damping ratio 0.105.

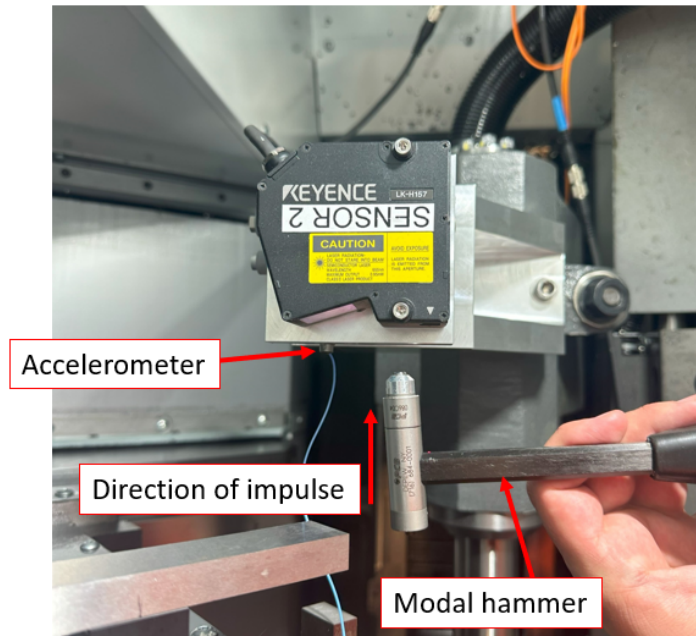


Figure 5.11: Modal tap test setup for z-axis laser displacement sensors mount z-axis direction.

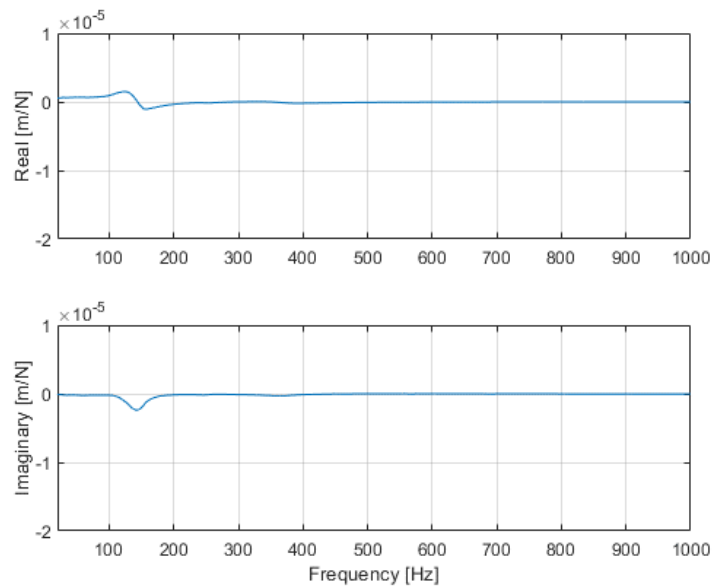


Figure 5.12: FRF from tap test first natural frequency 144 Hz, stiffness 1.86×10^6 N/m, damping ratio 0.115.

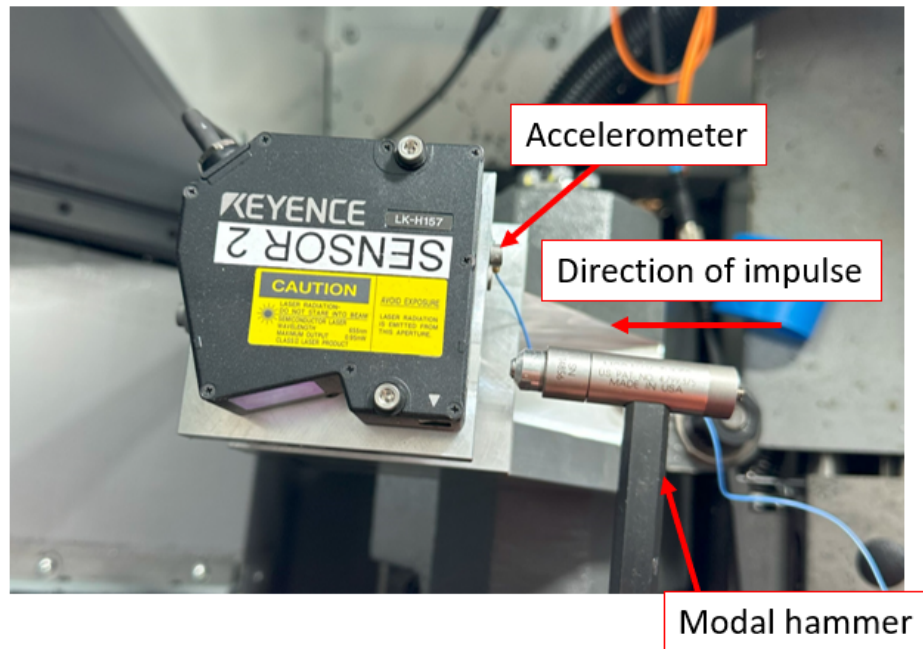


Figure 5.13: Modal tap test setup for z-axis laser displacement sensors mount x-axis direction.

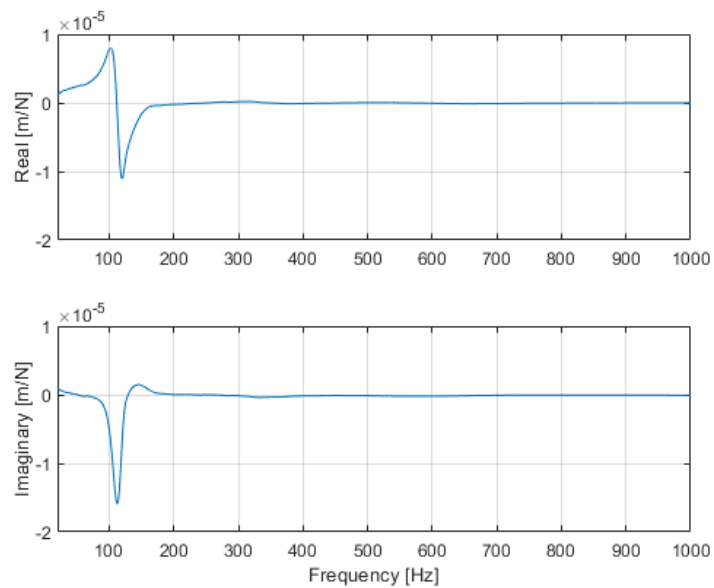


Figure 5.14: FRF from tap test first natural frequency 112 Hz, stiffness 4.02×10^5 N/m, damping ratio 0.0785.

Chapter 6

Effective tool nose radius testing

6.1 Experimental setup

The experimental setup that was used to conduct the effective tool nose radius testing is shown in figures 6.1 and 6.2. A Haas ST-15 slant bed CNC lathe was used for the testing. Steel soft jaws were machined to hold the workpiece and provide repeatable locating of multiple workpieces for testing. The laser displacement sensors were attached to the machine using the mounts described in chapter 5. Additionally, a Terahertz LT-880-T laser tachometer was used to record spindle speed during test cuts, where retro-reflective tape was affixed to the spindle to record once-per-revolution spindle speed data; see figure 6.2. Figure 6.3 shows the geometry of the test workpiece that was used to determine the effective tool nose radius model for the simulation. Table 6.2 shows the cutting speeds, chip width, feedrates, and taper angles for the experiments. Three different conditions were tested to investigate material side flow behavior under various conditions: dry (no coolant), flood coolant, and minimum quantity lubrication (MQL). The insert that was used for testing was a VNMG332-MR4 883 Seco insert, part number 74009615. The tool tip FRFs were measured by impact testing in the tangential, radial, and axial directions. The modal parameters are shown in table 6.1

An Alicona InfiniteFocusSL with a 50x objective lens was used to measure the surfaces generated during the test cuts. Figure 6.4 shows the setup used to measure the surface profiles from the test cuts. 3-D-printed fixtures were used to hold the different taper angle workpieces at different angles so the surface being measured was normal to the microscope lens.

6.2 Effective tool nose radius fitting procedure

The following procedure was used to determine the effective tool nose radius as a function of chip thicknesses. These effective tool nose radii were then used to define a piecewise linear function that was used to describe the effective tool nose radius for any chip thickness.

For each machined surface, a virtual line trace was created from the 3D height map using the Alicona InfiniteFocusSL software. Figure 6.5 shows the unfiltered profile shown in blue (top panel), the waviness that was isolated using the spline filter shown in black (middle panel), and the surface roughness profile shown in red (bottom panel) that was isolated by subtracting the waviness from the unfiltered profile.

The simulated surface profile was then compared to the measured surface profile. The tool nose radius for the simulation was adjusted until agreement between the peaks and valleys was achieved. This tool nose radius was the effective tool nose radius for the specific combination of chip thickness, cutting speed, material, and depth of cut. For a 0.1016 mm/rev test cut with dry conditions, the results are shown in figure 6.6.

The process of fitting the effective tool nose radius was automated by using an optimization function within MATLAB, where the objective was for the simulated average roughness, R_a , to be equal to the measured R_a .

The surface profiles that were recorded by the Alicona InfinitefocusSL were longer than what is required by ISO 21920-3:2021 (65). This ISO standard specifies an evaluation length for the R_a calculated based on the λ_c (wavelength) value used for

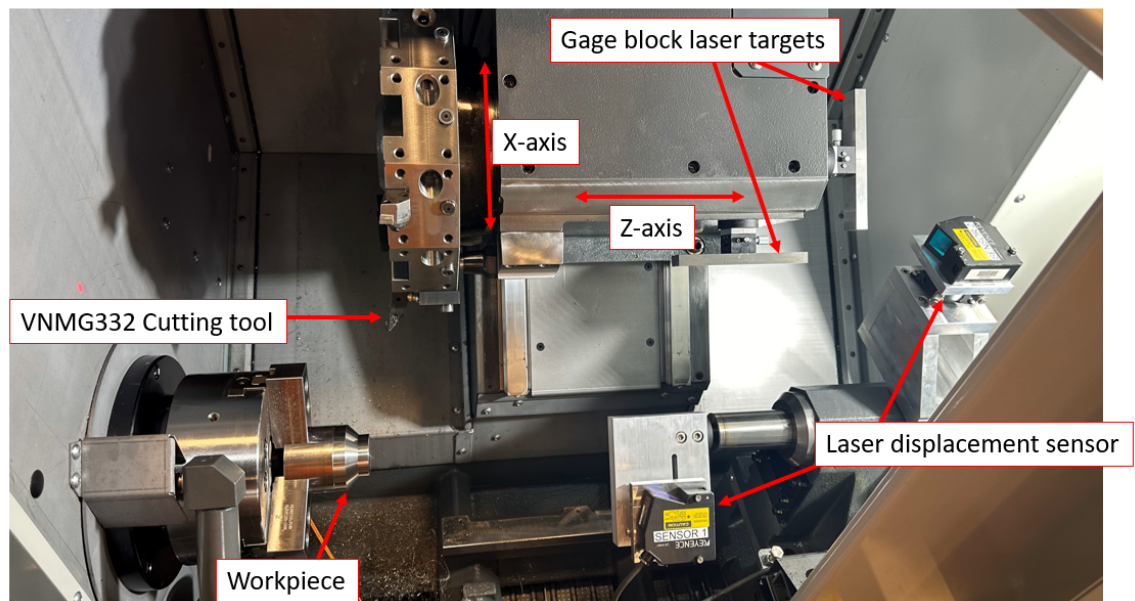


Figure 6.1: Experimental setup on Haas ST-15.

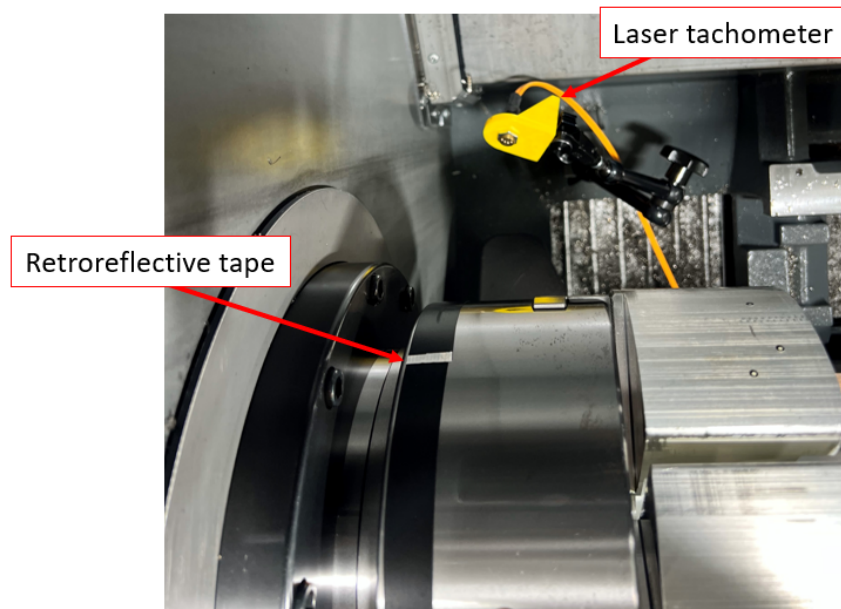


Figure 6.2: Laser tachometer setup on Haas ST-15.

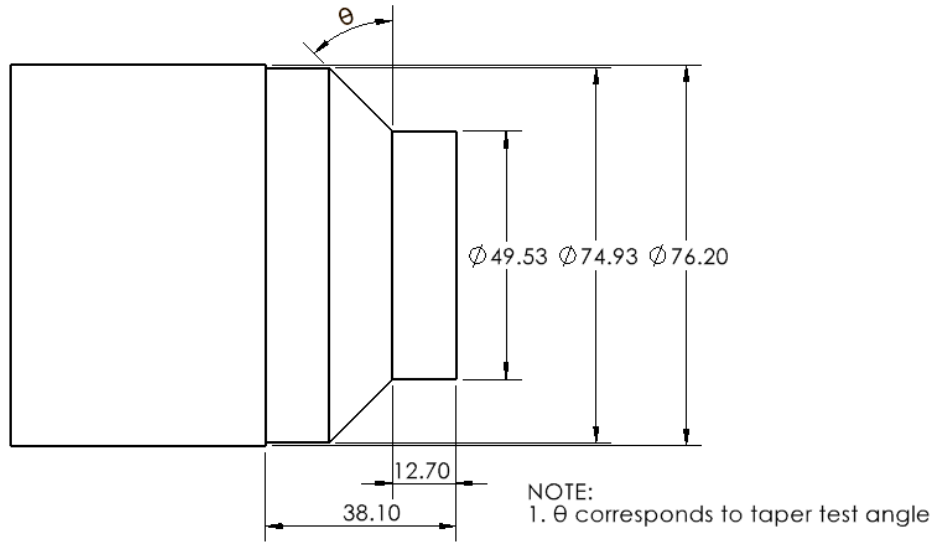


Figure 6.3: Part drawing for taper workpiece.

Table 6.1: Modal parameters for tool tip in the tangential, radial, and axial directions for Haas St-15.

Tangential direction			Radial direction			Axial direction		
m (kg)	c (N-s/m)	k (N/m)	m (kg)	c (N-s/m)	k (N/m)	m (kg)	c (N-s/m)	k (N/m)
6.48×10^1	9.73×10^3	1.51×10^8	1.54×10^2	9.07×10^3	5.13×10^7	2.21×10^1	5.37×10^3	6.39×10^8
1.32×10^1	2.32×10^4	6.01×10^8	1.05×10^3	4.32×10^4	8.00×10^8	3.04	6.14×10^3	1.98×10^8
1.19	9.43×10^3	6.08×10^8	1.20×10^3	5.67×10^4	1.48×10^9	3.13	1.31×10^3	3.34×10^8
5.76×10^{-2}	6.49×10^1	4.35×10^7	9.34×10^2	1.28×10^5	2.25×10^9	3.85×10^{-1}	4.50×10^2	1.68×10^8
			2.80×10^3	1.96×10^5	1.14×10^{10}	1.21×10^{-1}	2.25×10^2	7.77×10^7
			1.63×10^3	1.36×10^5	1.36×10^{10}	7.09×10^{-1}	6.72×10^2	4.97×10^8
			1.38×10^2	3.51×10^4	3.98×10^9	3.92×10^{-1}	5.81×10^2	3.09×10^8
			1.13×10^2	3.60×10^4	1.22×10^{10}	1.40	1.51×10^3	1.43×10^9
			9.97×10^1	7.78×10^4	2.23×10^{10}			
			5.70×10^1	3.93×10^4	2.58×10^{10}			
			1.51×10^2	5.41×10^5	1.00×10^{11}			
			4.88×10^{-1}	7.86×10^2	3.59×10^8			
			1.09×10^1	1.69×10^4	8.81×10^9			
			1.64×10^1	3.24×10^4	1.62×10^{10}			
			6.66×10^{-1}	8.07×10^3	1.12×10^9			
			8.80	2.13×10^4	1.92×10^{10}			

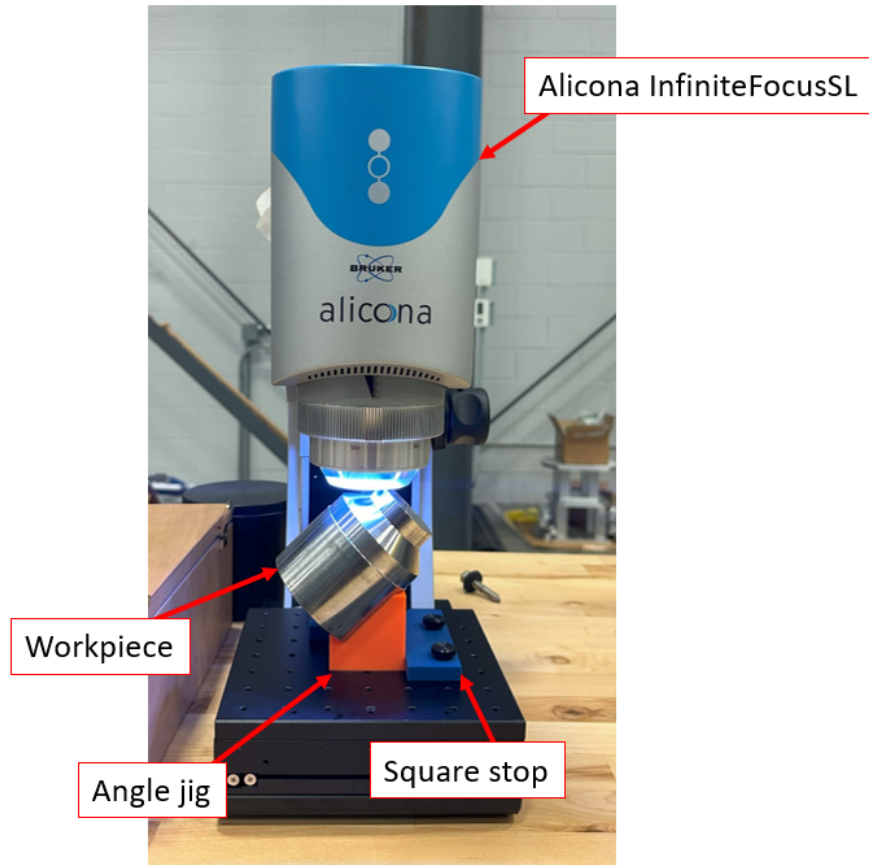


Figure 6.4: Alicona InfiniteFocusSL measurement setup with taper workpiece, angle jig, and square stop.

Table 6.2: Effective tool nose radius testing parameters.

Cutting speed (m/min)	Chip width (mm)	Commanded feedrate (mm/rev)	Taper angle (deg)
91.4	0.127	0.0254	35, 45, 55
91.4	0.127	0.0381	35, 45, 55
91.4	0.127	0.0508	35, 45, 55
91.4	0.127	0.0635	35, 45, 55
91.4	0.127	0.0762	35, 45, 55
91.4	0.127	0.0889	35, 45, 55
91.4	0.127	0.102	35, 45, 55
91.4	0.127	0.114	35, 45, 55
91.4	0.127	0.127	35, 45, 55
91.4	0.127	0.140	35, 45, 55
91.4	0.127	0.152	35, 45, 55
91.4	0.127	0.165	35, 45, 55

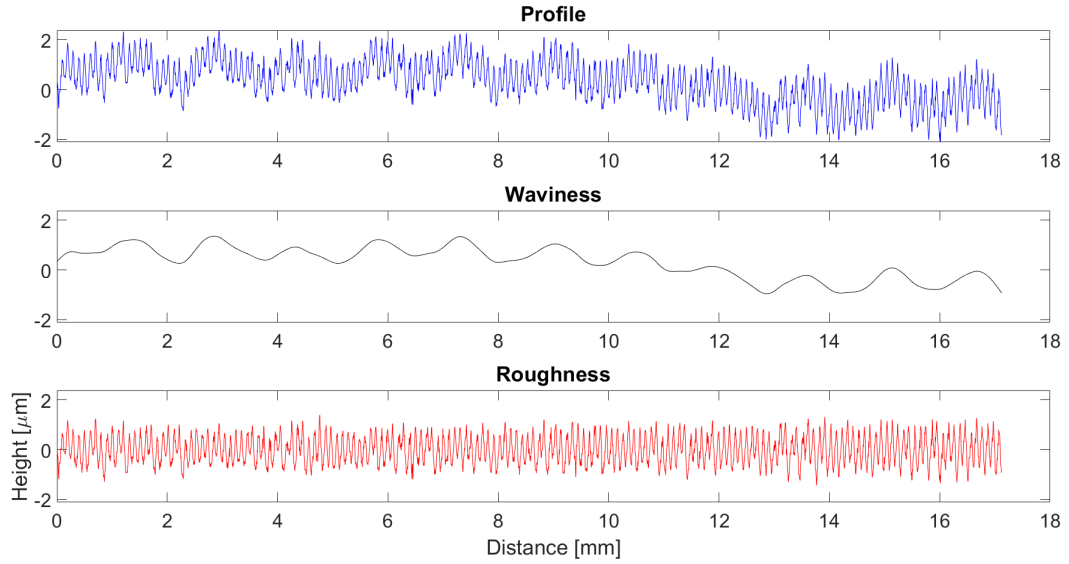


Figure 6.5: Recorded surface profile for 0.1016 mm/rev test.

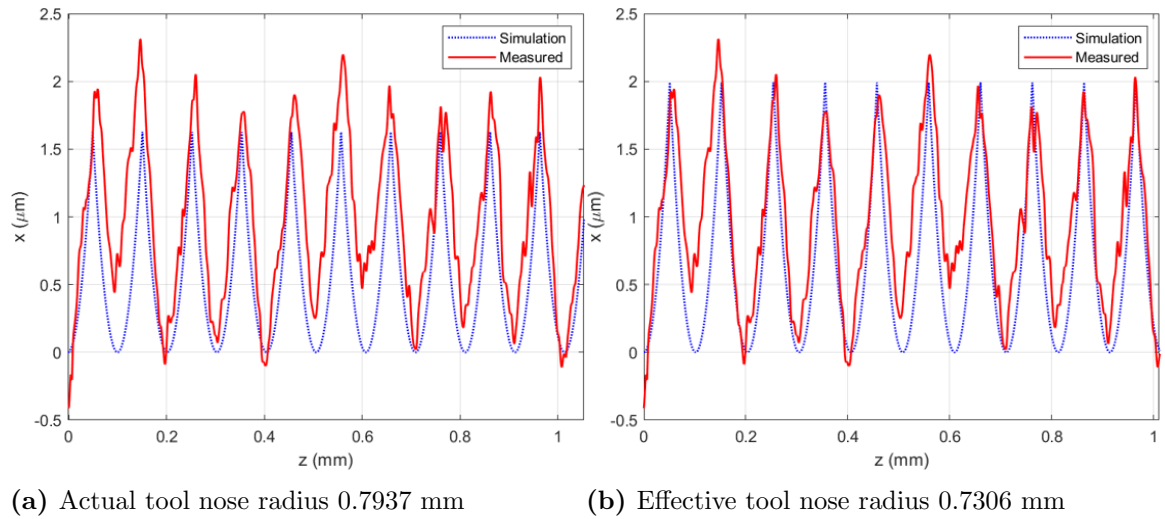


Figure 6.6: Measured surface profiles compared to simulation using a) actual and b) effective tool nose radius for 45 degree workpiece.

the spline filter. In this study, a λ_c value of 0.8 mm was used. Based on this λ_c value, an evaluation length of 4 mm was used to calculate the Ra. In order to quantify the uncertainty for the effective tool nose radius model, a Monte Carlo approach was used.

Figure 6.7 shows the entire trace length and 4 mm sections from the 0.1016 mm/rev test case for the 45 degree taper. The Ra values from the four sections were each used to find the effective tool nose radius. Table 6.3 shows the results. The mean effective tool nose radius is 0.7306 mm and the standard deviation is 0.0418 mm. These values were then used to define the distribution for each selected feed rate within a Monte Carlo simulation.

6.3 Monte Carlo Simulation

The Monte Carlo simulation used the mean and standard deviation of the effective tool nose radius for each chip thickness. For the case of the dry testing, these values are provided in table 6.5. In each iteration of the Monte Carlo simulation, an effective tool nose radius was randomly sampled from a normal distribution defined by the mean and standard deviation for each chip thickness shown in table 6.5. The set of effective tool nose radius values for all chip thicknesses were used to create a linear fit using the form of equation 6.1. The slope m and intercept b were recorded. This process was repeated 1×10^4 times to generate a distribution of slope and intercept values. For each combination of slope and intercept the effective tool nose radius values for the tested chip thicknesses was calculated. These values are used to create a mean, and standard deviation at each desired chip thickness. Table 6.4 shows these results for the three iterations. Figure 6.8 shows the results from three iterations of the Monte Carlo simulation. The upper limit for the piecewise function was set to the actual tool nose radius of the insert used for testing. The lower limit of the piecewise function was set to the mean minimum calculated effective tool nose radius. Equation 6.2 shows the resulting piecewise function. Figure 6.9 shows the piecewise

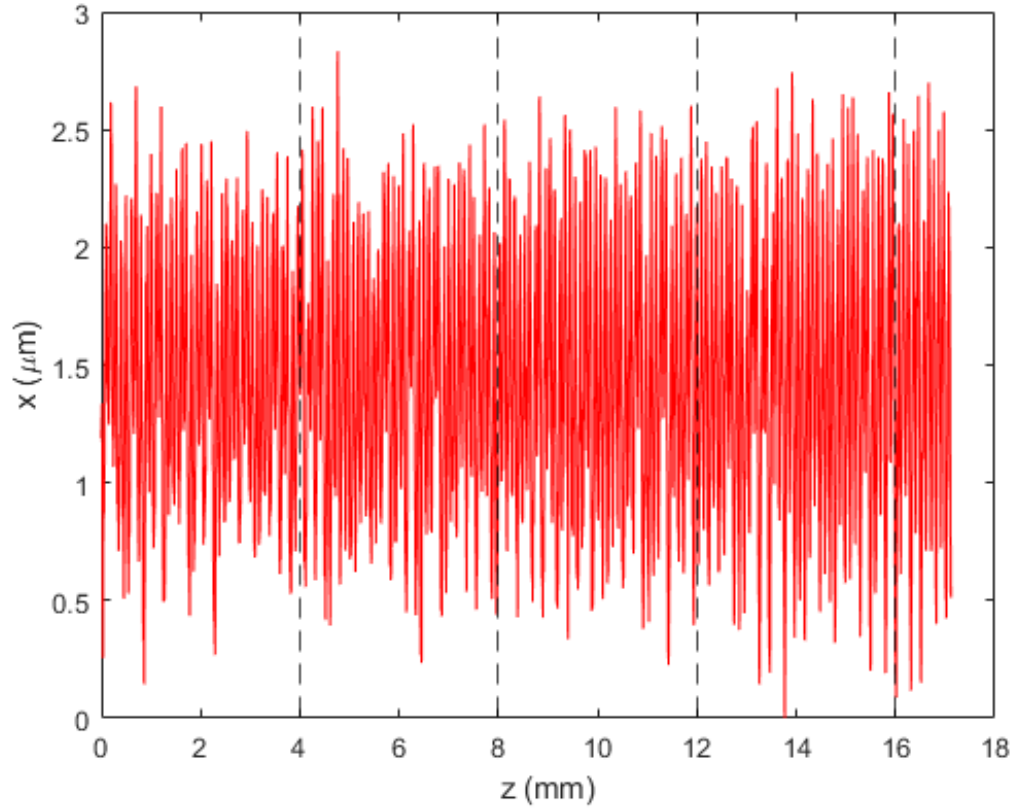


Figure 6.7: Recorded surface profile for 0.1016 mm/rev test with vertical dashed lines representing sections used to calculate Ra.

Table 6.3: Summary of values for 0.1016 mm/rev 45 degree taper dry test.

Section	Calculated Ra (μm)	Effective tool nose radius (mm)
1	0.4267	0.7775
2	0.4452	0.7453
3	0.4599	0.7215
4	0.4893	0.6782

function with the upper and lower limits included. The error bars are created using two standard deviations for each chip thickness tested using the described procedure.

$$nr = m \cdot h_m + b \quad (6.1)$$

$$nr = \begin{cases} 0.2378 & h_m \leq 0.0254 \\ 7.0725 \cdot h_m - 0.0582 & 0.0254 < h_m < 0.104 \\ 0.7937 & h_m \geq 0.104 \end{cases} \quad (6.2)$$

6.4 Effective tool nose radius comparison

The effective tool nose radius calibration was repeated for MQL and flood coolant conditions. For the MQL testing, all three taper angles reported in table 6.2 were tested, while the flood coolant was tested with the 45 degree taper angle only. For the MQL testing, MSA-AME 507 was used as the coolant. For the flood coolant testing, TRIM MicroSol 585XT at a concentration of 10% was used. The MQL and flood coolant piecewise functions are shown in equations 6.3 and 6.4. Figure 6.11 shows the results for the MQL testing with the error bars created using the Monte Carlo simulation, and the results for the flood coolant testing are shown in figures 6.10 and 6.12.

$$nr = \begin{cases} 0.1181 & h_m \leq 0.0254 \\ 12.8383 \cdot h_m - 0.2080 & 0.0254 < h_m < 0.078 \\ 0.7937 & h_m \geq 0.078 \end{cases} \quad (6.3)$$

$$nr = \begin{cases} 0.0654 & h_m \leq 0.0254 \\ 12.8508 \cdot h_m - 0.2611 & 0.0254 < h_m < 0.0821 \\ 0.7937 & h_m \geq 0.0821 \end{cases} \quad (6.4)$$

Table 6.4: Values for 45 degree taper dry test for three iterations of the Monte Carlo simulation.

Chip thickness [mm]	Simulation iteration calculated effective tool nose radius [mm]				
	1	2	3	Mean	Standard Deviation
0.0254	0.2196	0.2405	0.2491	0.2364	0.0152
0.0381	0.2967	0.2665	0.3205	0.2946	0.0271
0.0508	0.5237	0.4854	0.4348	0.4813	0.0446
0.0635	0.6106	0.6155	0.5860	0.6040	0.0158
0.0762	0.6620	0.5779	0.4623	0.5674	0.1003

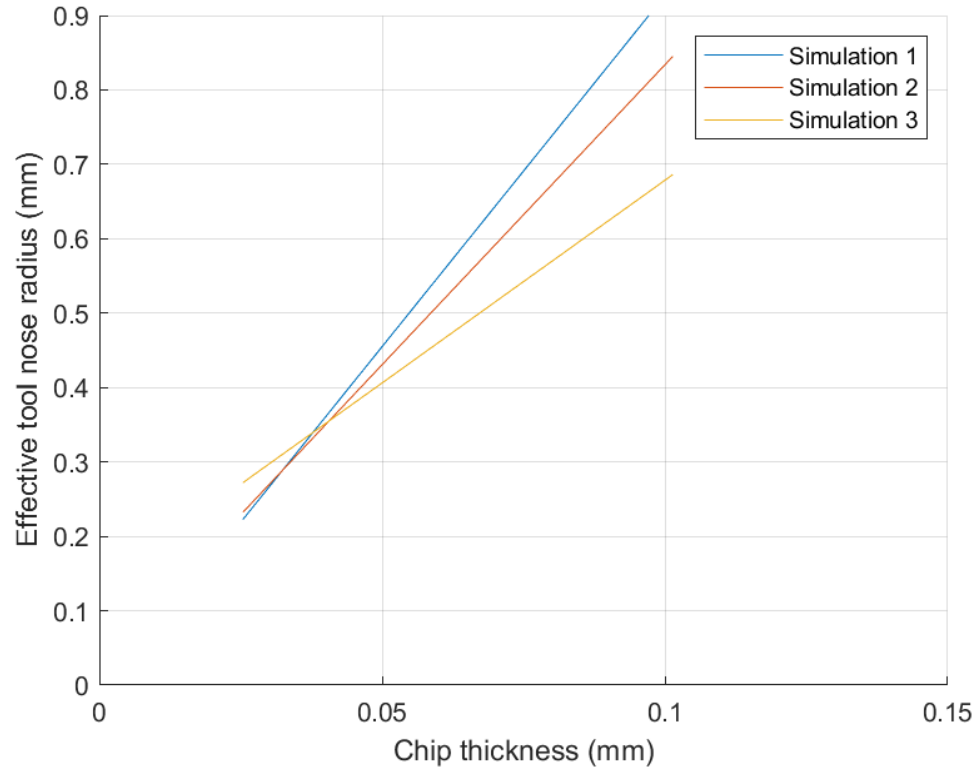


Figure 6.8: Results from three Monte Carlo simulation iterations.

Table 6.5: Summary of values for 45 degree taper dry test for Monte Carlo simulation.

Chip thickness (mm)	Effective tool nose radius mean (mm)	Effective tool nose radius standard deviation (mm)
0.0254	0.2245	0.0238
0.0381	0.3002	0.0279
0.0508	0.4499	0.0496
0.0635	0.5795	0.0221
0.0762	0.5336	0.0906

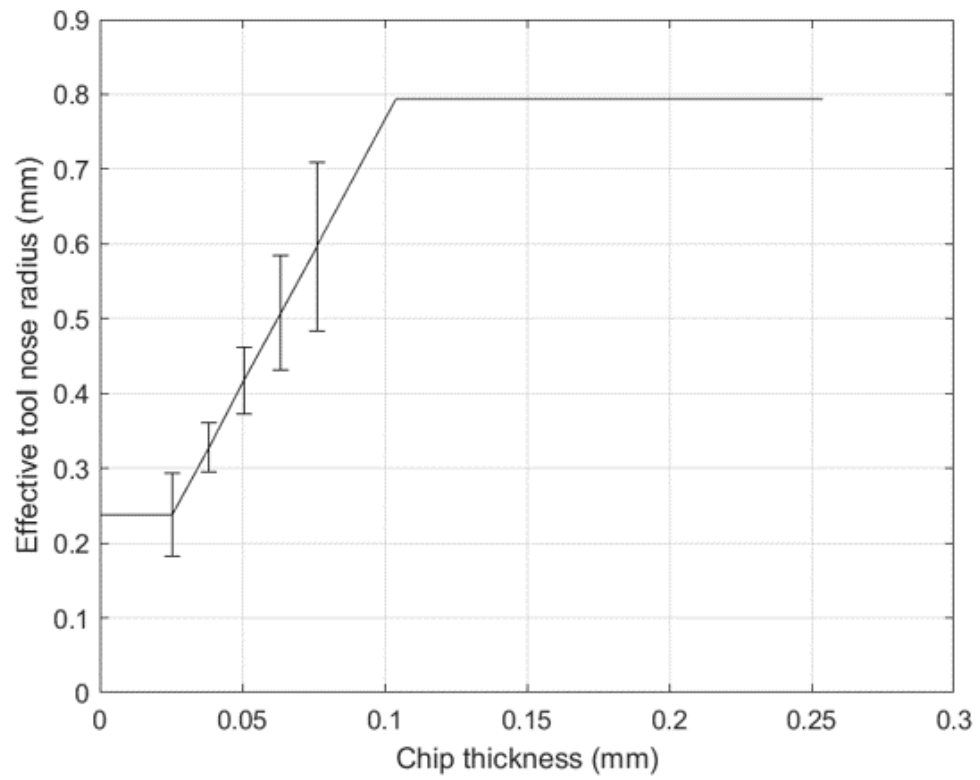


Figure 6.9: Effective tool nose radius model plot for dry cutting conditions for 45 degree taper angle.

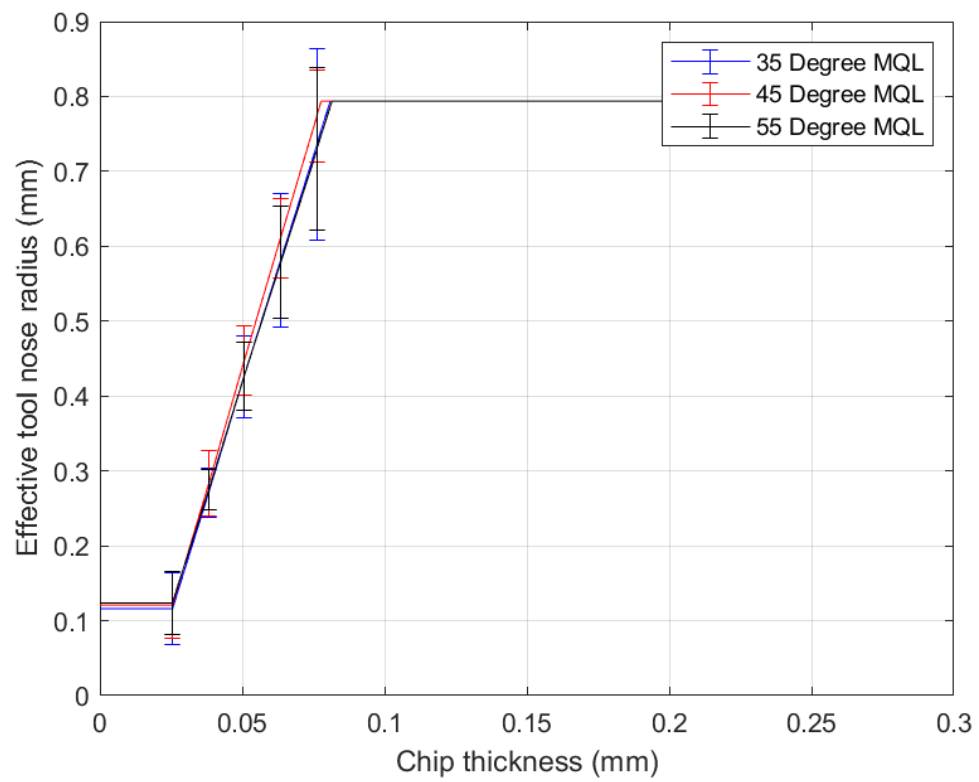


Figure 6.10: Effective tool nose radius model plot for MQL cutting conditions.

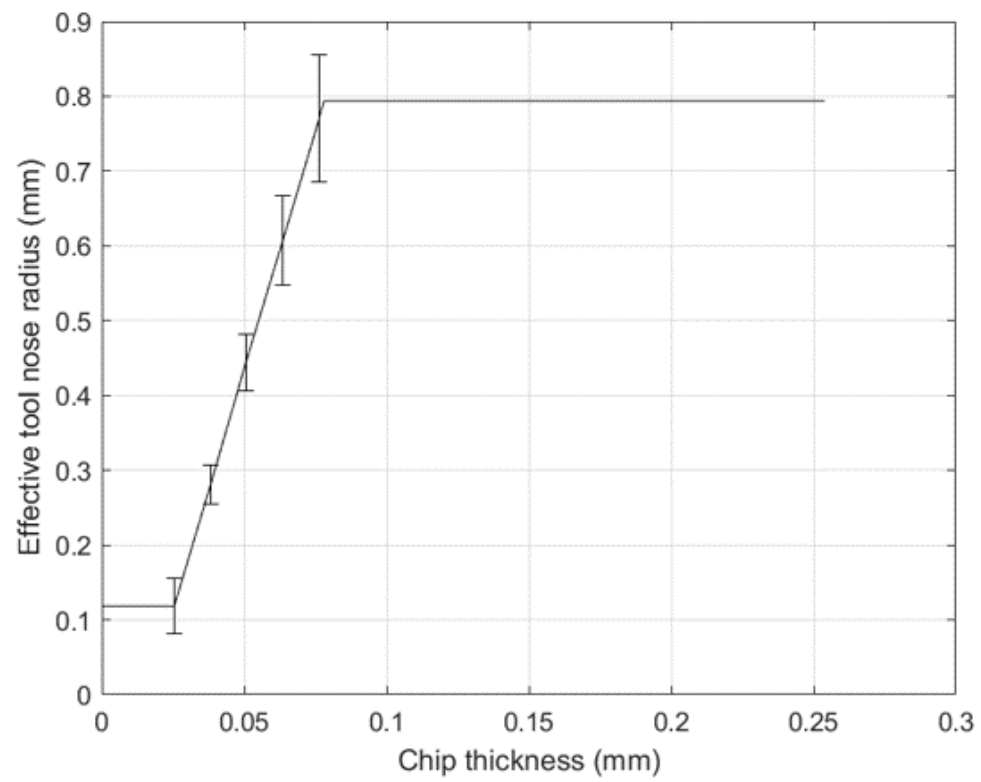


Figure 6.11: Effective tool nose radius model plot for MQL cutting conditions average.

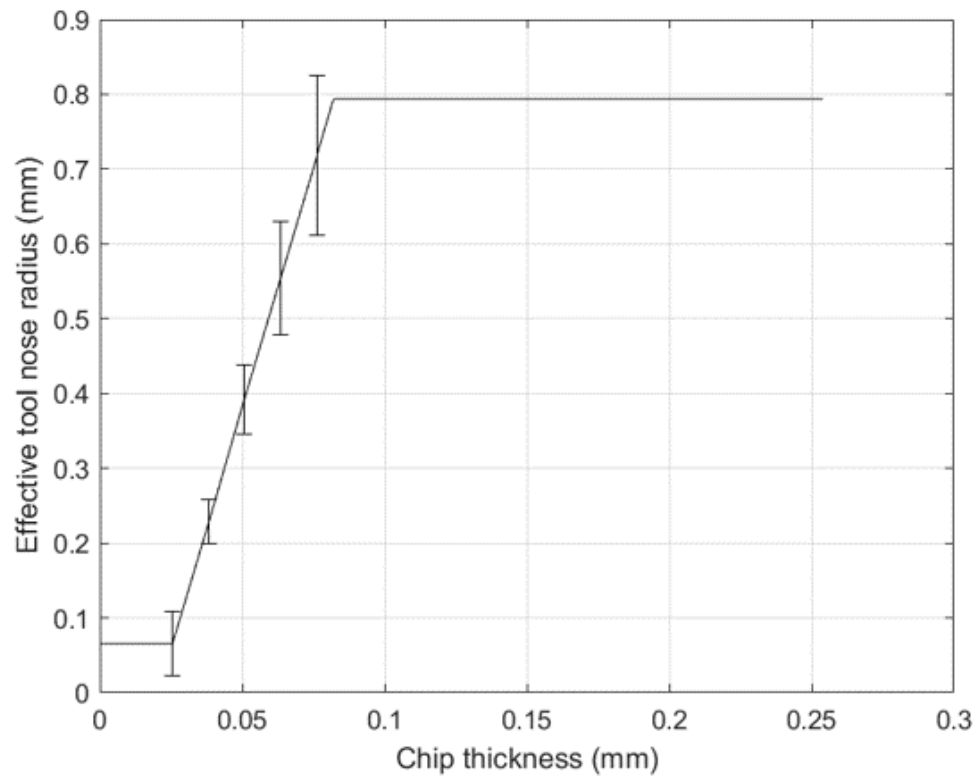


Figure 6.12: Effective tool nose radius model plot for flood cutting conditions for 45 degree taper angles.

When comparing the MQL and flood coolant test results, the slopes are similar and there is generally good overlap between the error bars between the two different tests. The dry cutting test has a different slope and larger minimum effective tool nose radius than the two test cases with lubrication. This indicates that lubrication has a significant effect on material side flow and should be considered when predicting surface finish. Figure 6.13 shows the MQL effective tool nose radius model compared to the flood coolant and dry cutting conditions models. For further MTP testing, MQL was applied in all cases.

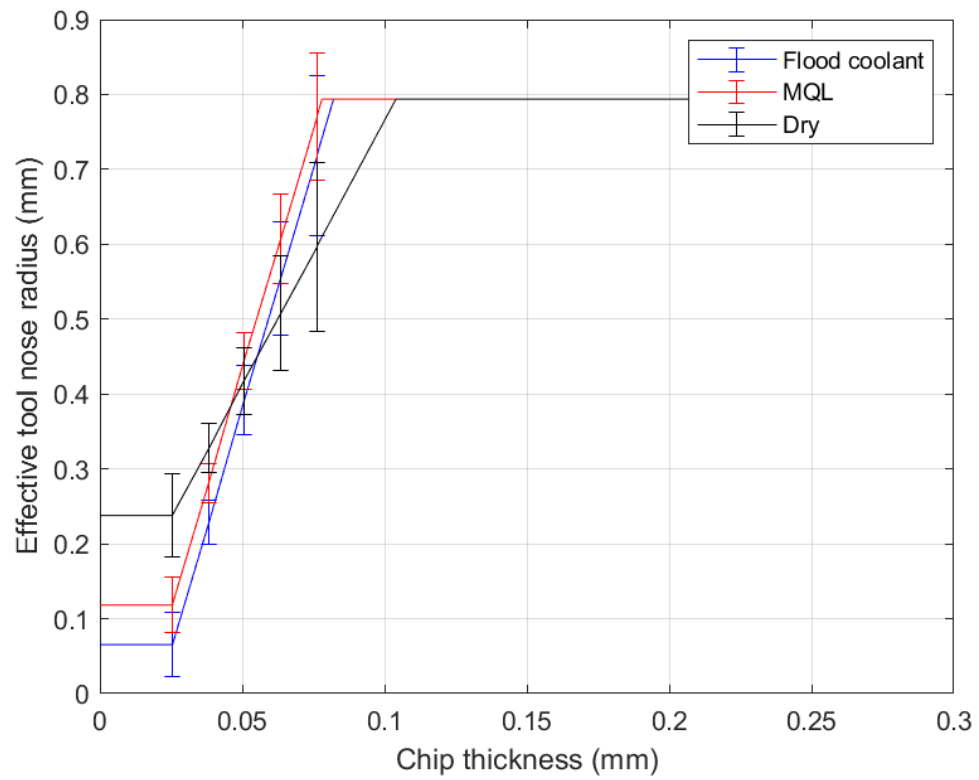


Figure 6.13: Effective tool nose radius model plot comparing MQL, flood coolant, and dry cutting conditions.

Chapter 7

Constant outside diameter turning testing

7.1 Experimental setup

To model the cutting forces during MTP turning, cutting force coefficient testing was completed on a Haas TL-1 CNC lathe. The insert that was used for testing was a VNMG332-MR4 883 Seco insert, part number 74009615. The setup is shown in figure 7.1. A Kistler 9257B cutting force dynamometer was mounted to the carriage to measure in-process cutting force components in the radial F_r , normal F_n , and tangential F_t directions. A laser displacement sensor was used to measure the tool motion during the testing. The laser displacement sensor was used to confirm that the machine tool achieved the commanded feed rate to have an accurate cutting force coefficient model. The test parameters that were used for the cutting force coefficient testing are reported in table 7.1. The modal tap test results for the tool are shown in table 7.2.

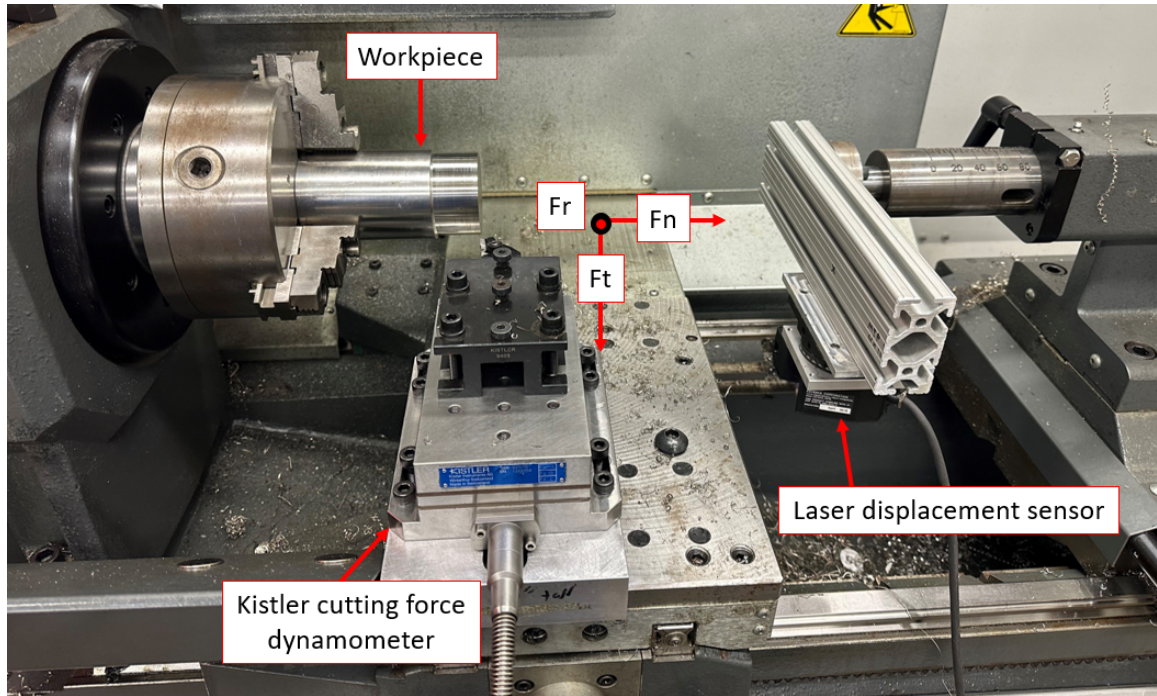


Figure 7.1: Cutting force testing setup on Haas TL-1 lathe.

Table 7.1: Cutting force coefficient test parameters.

Cutting speed (m/min)	Chip width (mm)	Commanded feedrate (mm/rev)
91.4	0.127	0.0254
91.4	0.127	0.0508
91.4	0.127	0.0762
91.4	0.127	0.102
91.4	0.127	0.127
91.4	0.127	0.153
91.4	0.127	0.178
91.4	0.127	0.203
91.4	0.127	0.229
91.4	0.127	0.254
91.4	0.127	0.279
91.4	0.127	0.305

7.2 Cutting force coefficient testing results

Cutting force coefficients were measured by completing cutting testing at known conditions and measuring the force. The workpiece material was 304 stainless steel, which will also be used for the surface finish prediction and testing. The cutting force coefficient testing was done using Rapid Tap, which was initially applied to the part and cutting insert. This was done to limit the effects of built-up edge on the testing. The resulting k_r , k_n , and k_t cutting force coefficients are provided in equations 7.1 through 7.3 shown in units of N/mm^2 . The cutting force coefficients that were found through testing were used for the remaining MTP surface finish testing.

$$k_r = 193 \cdot h^{-0.719} + 148 \quad (7.1)$$

$$k_n = 405 \cdot h^{-0.7459} + 1350 \quad (7.2)$$

$$k_t = 180 \cdot h^{-0.963} + 2400 \quad (7.3)$$

7.3 Constant outside diameter cylinders

Constant outside diameter cylinders were turned using different combinations of feedrates while holding all other machining variables constant to determine an effective tool nose radius model. The surface profiles were measured using a Mitutoyo Contracer using the setup that was shown in figure 2.6. The tool nose radius used to generate the simulation profile is adjusted until a good agreement between the peaks and valleys is achieved, as seen in figure 7.3.

The results of the cutting tests are summarized in table 7.3. The effective tool nose radius and chip thickness combinations are represented using the piecewise function

Table 7.2: Modal parameters for tool tip in the tangential, radial, and axial directions for Haas TL-1.

Tangential direction			Radial direction			Axial direction		
m (kg)	c (N-s/m)	k (N/m)	m (kg)	c (N-s/m)	k (N/m)	m (kg)	c (N-s/m)	k (N/m)
8.75×10^1	6.51×10^6	1.48×10^8	4.51×10^1	4.46×10^3	1.25×10^8	7.24×10^4	2.40×10^6	1.00×10^{11}
4.32	4.80×10^5	1.87×10^7	8.39	8.52×10^2	3.35×10^7	1.10×10^1	2.18×10^3	6.09×10^7
1.22×10^1	1.50×10^6	7.76×10^7	2.24×10^1	2.12×10^3	1.14×10^8	1.31	1.05×10^4	3.94×10^7
1.51×10^1	4.37×10^6	1.97×10^8	2.51×10^1	3.10×10^3	1.92×10^8	3.22	7.34×10^3	3.81×10^8
4.25×10^1	4.98×10^6	7.89×10^8	1.68×10^1	1.40×10^3	2.48×10^8	9.90×10^{-1}	1.95×10^3	1.62×10^8
2.08	8.23×10^5	6.72×10^7	1.62×10^1	1.88×10^3	2.67×10^8	2.25×10^{-4}	6.34×10^3	8.11×10^8
3.00	1.42×10^6	1.19×10^8	1.64×10^1	3.16×10^3	4.23×10^8	2.31×10^{-1}	1.32×10^3	1.89×10^8
2.15	7.91×10^5	1.49×10^8	1.49	6.41×10^2	5.80×10^7	1.36×10^{-1}	8.39×10^2	1.72×10^8
6.42×10^{-1}	1.65×10^5	4.71×10^7	4.88×10^{-1}	2.00×10^2	3.52×10^7	4.26×10^{-2}	3.99×10^2	8.35×10^7
3.57	1.29×10^6	5.26×10^8	4.02	1.01×10^3	5.93×10^8	9.22×10^{-2}	8.81×10^2	2.84×10^8

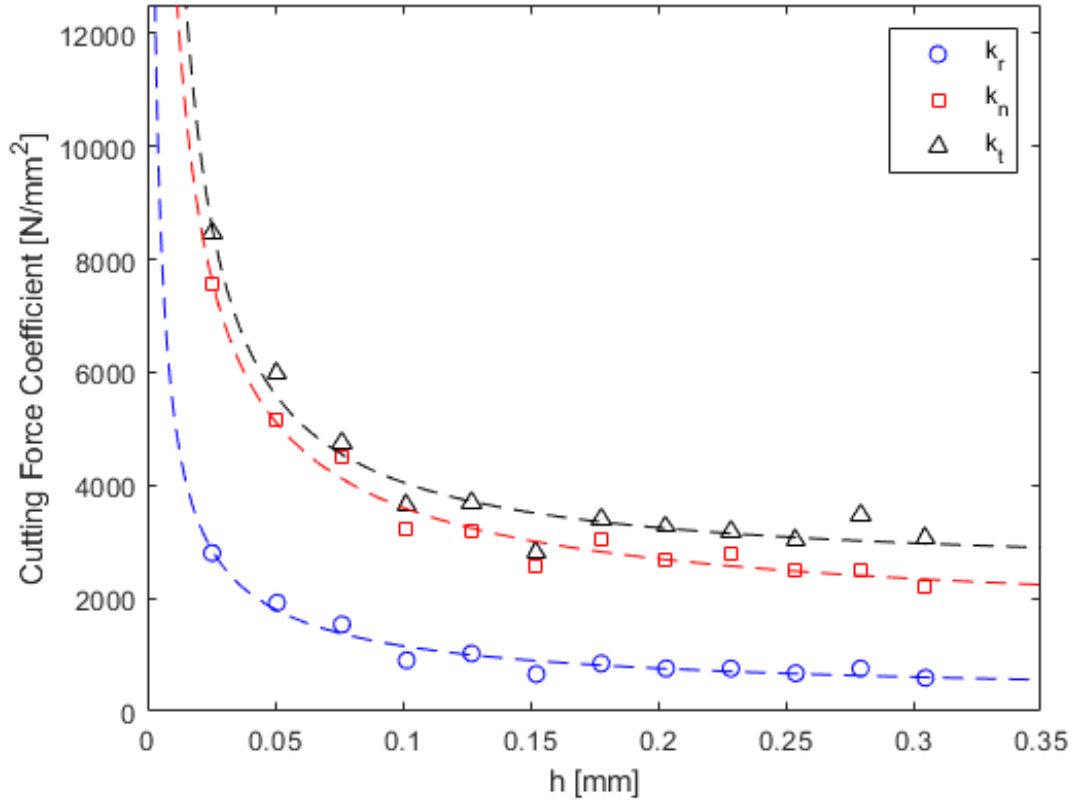


Figure 7.2: Cutting force coefficient power law fits. The cutting speed was 91.4 m/min, the chip width was 0.127 mm, and the chip thickness ranged from 0.0254 mm to 0.305 mm in 0.0254 mm increments.

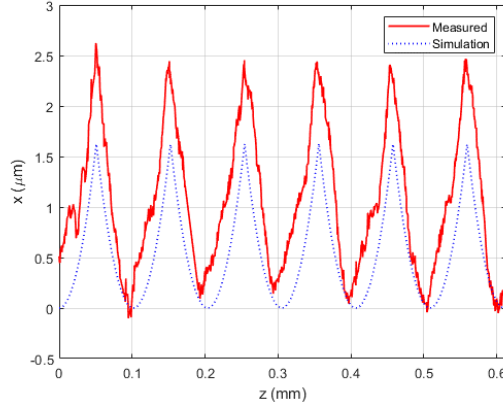
defined by equation 7.4. Figure 7.4 shows the results. Figure 7.5 shows the results for the time domain simulation compared to the measured surface profile.

$$n = \begin{cases} 0.2108 & h_m \leq 0.0410 \\ 6.6638 \cdot h_m - 0.0626 & 0.041 < h_m < 0.1285 \\ 0.7937 & 0.1285 \leq h_m \end{cases} \quad (7.4)$$

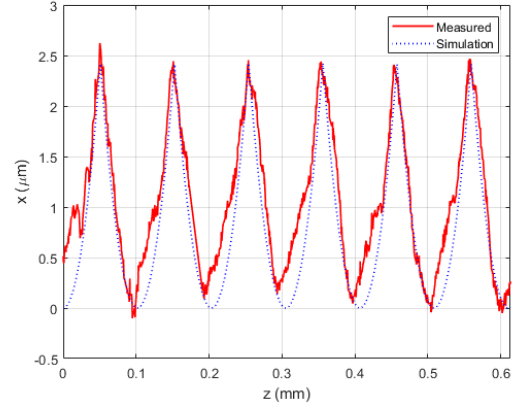
7.4 Effects of tool dynamics on surface finish

To better understand the effects of the cutting tool dynamics on surface finish, the time domain simulation was used to find the maximum stick out for a theoretical boring bar before tool displacements during cutting affect the resulting surface finish. For modeling the dynamics of the boring bar, the cantilever beam deflection formula shown in equation 7.5 was used, where F is the cutting force $[N]$, E is Young's modulus of the tool material $[N/m^2]$, I is the moment of inertia of the boring bar $[m^4]$, and L is the overhang length of the tool $[m]$. The moment of inertia is found by equation 7.6 where D is the diameter of the boring bar $[m]$. The model setup is shown in figures 7.6 and 7.7. The Young's modulus for steel is 210 GPa , and the density of steel is 7850 kg/m^3 (66). Equations 7.7 and 7.8 are used for calculating the stiffness for the k_x , k_y , and k_z of the boring bar. A damping ratio of 2.5 % was used for the time domain simulation. The cutting force coefficients found for 304 stainless steel were used for the simulation, and a diameter of 50.8 mm was used for the boring bar with a starting stick out length of 50 mm. The first natural frequency was calculated using equation 7.9 with a β value of 1.87510107 (64). Figure 7.8 shows the results from different stick out lengths tested with the time domain simulation. The resulting Ra of the surface profile begins to be affected after the stick out length is greater than 225 mm.

$$\delta = \frac{FL^3}{3EI} \quad (7.5)$$



(a) Tool nose radius 0.7937 mm



(b) Tool nose radius 0.5334 mm

Figure 7.3: Measured surface profiles compared to simulation using measured and effective tool nose radius for constant diameter workpiece.

Table 7.3: Summary of results from effective tool nose radius testing for constant outside diameter turning.

Chip thickness (mm)	Effective tool nose radius (mm)
0.0254	0.2108
0.0508	0.2108
0.0762	0.5842
0.102	0.5334
0.127	0.7937

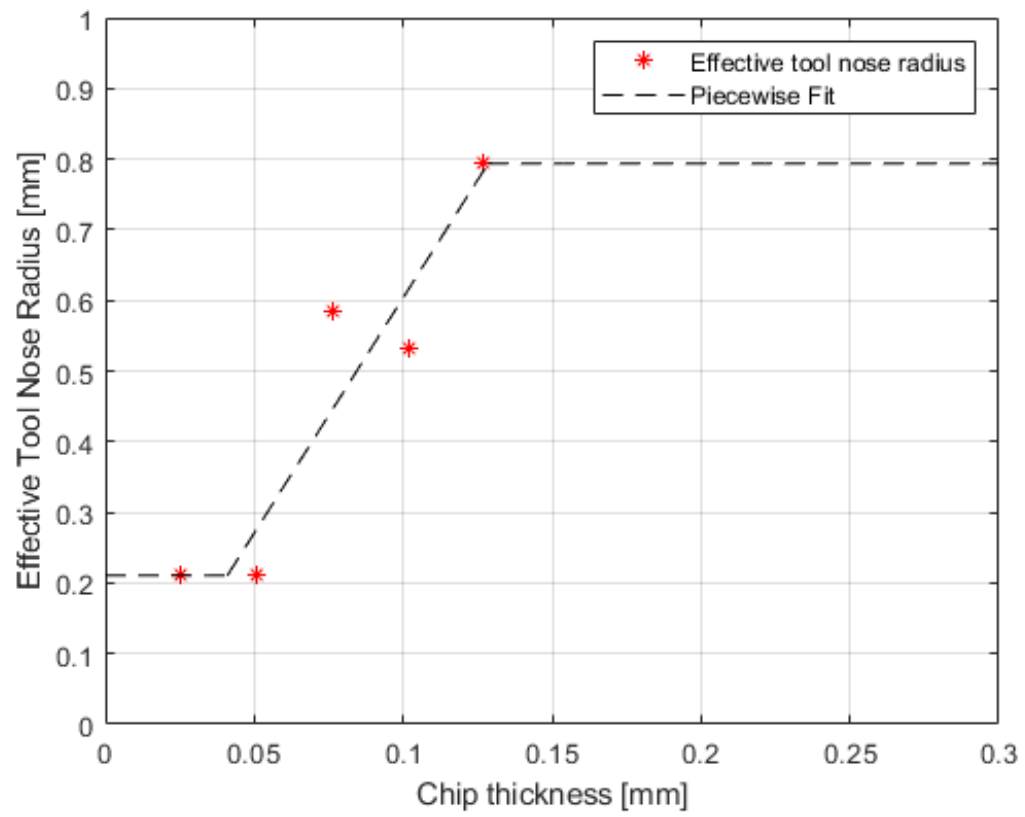


Figure 7.4: Effective tool nose radius and piecewise function.

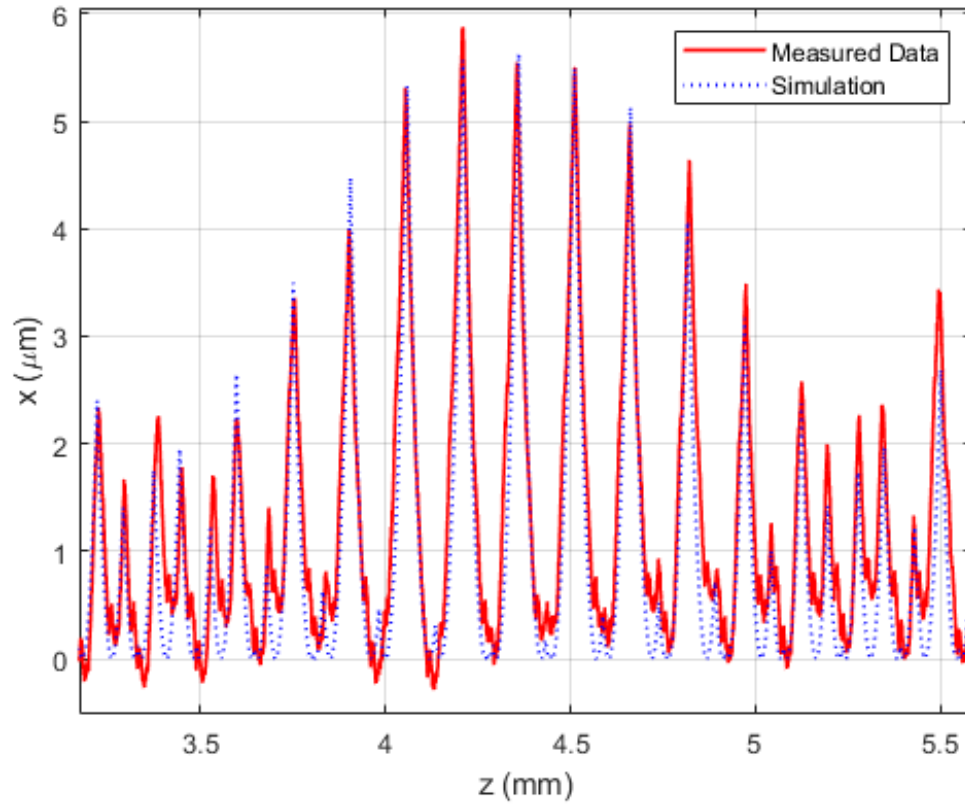


Figure 7.5: Measured MTP surface profile (OPR: 0.3243, RAF: 0.8, Cutting speed: 243.84 m/min, feedrate: 0.051 mm/rev) compared to simulation using effective tool nose radius piecewise function.

$$I = \frac{\pi 64 D^4}{64} \tag{7.6}$$

$$k_y = k_x = \frac{3EI}{L^3} \tag{7.7}$$

$$k_z = \frac{EA}{L} \tag{7.8}$$

$$f_n = \frac{\beta^2}{2\pi L^2} \sqrt{\frac{EI}{\rho A}} \tag{7.9}$$

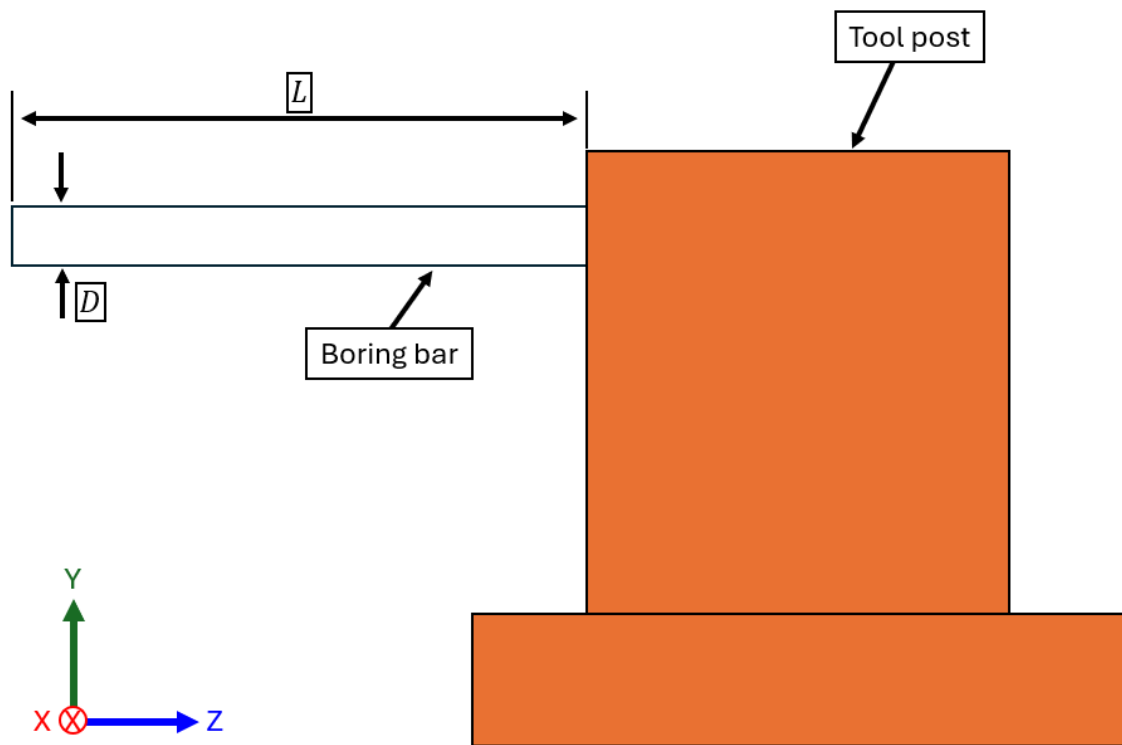


Figure 7.6: Boring bar and tool post setup used for time domain simulation. The cutting tool is not shown in the figure.

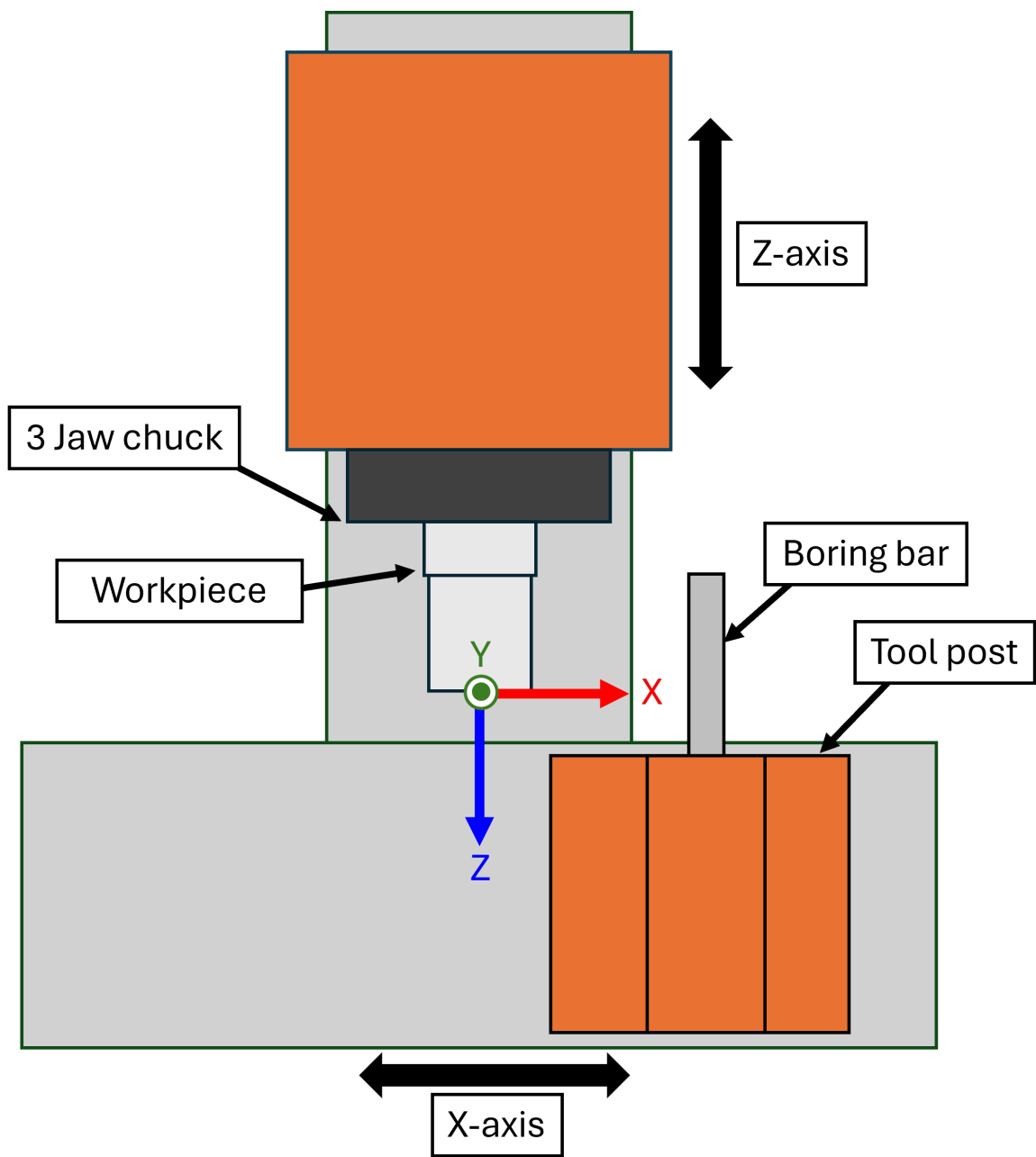


Figure 7.7: T-base lathe diagram.

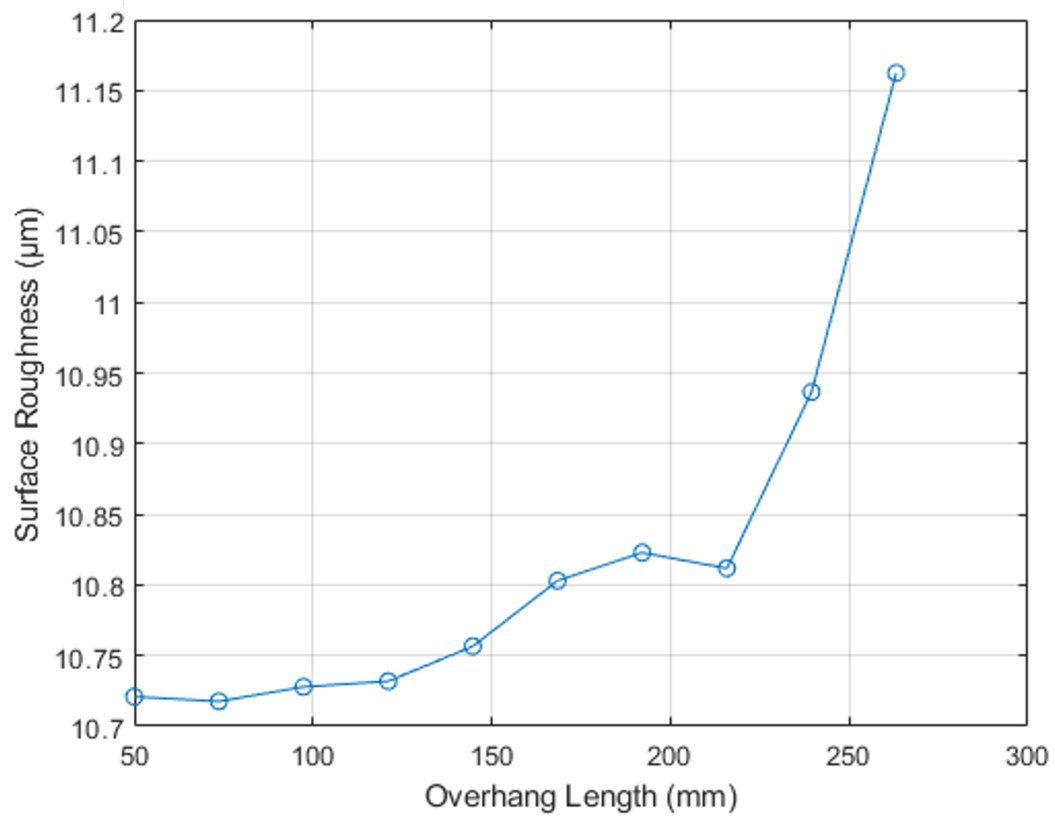


Figure 7.8: Calculated Ra plotted against boring bar stick out.

Chapter 8

Tapered workpiece testing

8.1 Experimental setup

The experimental setup that was used is the same setup as shown in figures 6.1 and 6.2 described in chapter 6. The laser displacement sensors were used to record tool motion measurements for both the x and z axes; these measurements with the laser tachometer spindle speed measurements are used to calculate the MTP parameters that the machine achieved during test cuts for use in the time domain simulation.

Table 8.1 shows the MTP parameters and feedrates that were tested for the three taper angles 35° , 45° , and 55° .

8.2 Calculating MTP parameters

The laser displacement sensors recorded tool motion, and the once per revolution spindle speed data from the laser tachometer can be used in combination to calculate the OPR and RAF values that the machine achieved during the test cut.

Figures 8.1 and 8.2 show the results from the laser displacement sensors for the 45 degree taper 0.127 mm/rev test with a commanded OPR of 0.6 and a commanded RAF of 1.0. The global motion of the x-axis and z-axis motion data has been removed so that only the MTP oscillations remain. Using equation 8.1, given that it is possible

to calculate the frequency from each sine wave peak and that the spindle speed in revolutions per minute (rpm) was recorded during the test cut, it is possible to calculate OPR values for each sine wave peak and plot them as a function of time. Figure 8.3 shows the results of these calculated OPR values for the duration of the test cut for both the x-axis and z-axis. Some drops in the OPR are shown in figure 8.3 that occur as the spindle speed decreases as the cutting tool moves further away from the centerline of the part to maintain the cutting speed of 91.4 m/min. These spindle speed jumps occur in 10 rpm jumps and cause a momentary drop in the calculated OPR value. These outliers are excluded when calculating a mean OPR for each axis. The mean OPR for the x-axis is 0.6669, and for the z-axis is 0.6670. Using equation 8.2, the mean OPR for this test cut was 0.6670. The standard deviation can also be calculated for these OPR values. Using equation 8.3 an uncertainty can be calculated for the OPR_{mean} .

$$OPR = \frac{(60 \cdot f)}{\Omega} \quad (8.1)$$

$$OPR_{mean} = \frac{(OPR_x + OPR_z)}{2} \quad (8.2)$$

$$\mu(OPR_{mean}) = \sqrt{\mu(OPR_x)^2 + \mu(OPR_z)^2} \quad (8.3)$$

A root-mean-square approach can be used to calculate the RAF values that the machine achieved during the test cuts. Using equation 8.4, the amplitude A can be calculated using equation 8.5 from the recorded tool motion data. This results in an RAF value of 0.9115 for the x-axis and an RAF value of 0.8775 for the z-axis. Using equation 8.6, the mean RAF can be calculated; the mean RAF for this test was 0.8945. The standard deviation between the x-axis RAF and z-axis RAF was calculated to be used as an uncertainty for the RAF_{mean} .

$$RAF = \frac{A}{f_r} \quad (8.4)$$

$$RMS = \frac{A}{\sqrt{2}} \quad (8.5)$$

$$RAF_{mean} = \frac{(RAF_x + RAF_z)}{2} \quad (8.6)$$

Table 8.2 shows the results of the calculated MTP parameters during the test cuts for all of the taper tests. These values are used for the time domain simulation to generate simulated surface profiles and calculate Ra values from the simulated profiles.

8.3 Time domain simulation

The time domain simulation has the ability to use a constant spindle speed ramp or a stepped spindle speed increase. The stepped spindle speed increase is done in jumps of 10 rpm; this functions identically to how the MTP GUI handles spindle speed changes to attempt to maintain a constant cutting speed. Taking, for example, a 45 degree taper and 0.127 mm/rev feedrate figure 8.4 shows the spindle speed as a function of time with a constant increase. Figure 8.5 shows the spindle speed as a function of time with a stepped increase. When looking at the constant versus the stepped spindle speed surface profiles, it becomes clear that the stepped spindle speed approach causes significant changes to the simulated surface profiles. Figure 8.6 shows the result for a constant spindle speed increase, while figure 8.7 shows the resulting surface for a stepped spindle speed approach. For the comparison between the time domain simulation and measured surface profiles, the stepped spindle speed approach was used.

Table 8.1: Cutting speed, chip width, feedrates, OPR, and RAF values for MTP testing.

Cutting speed [m/min]	Chip width [mm]	Commanded feedrate [mm/rev]	OPR	RAF
91.4	0.127	0.127	0.6	1.0
91.4	0.127	0.127	0.5	1.5
91.4	0.127	0.0762	0.6	1.0
91.4	0.127	0.0762	0.5	1.5
91.4	0.127	0.0254	0.6	1.0
91.4	0.127	0.0254	0.5	1.5

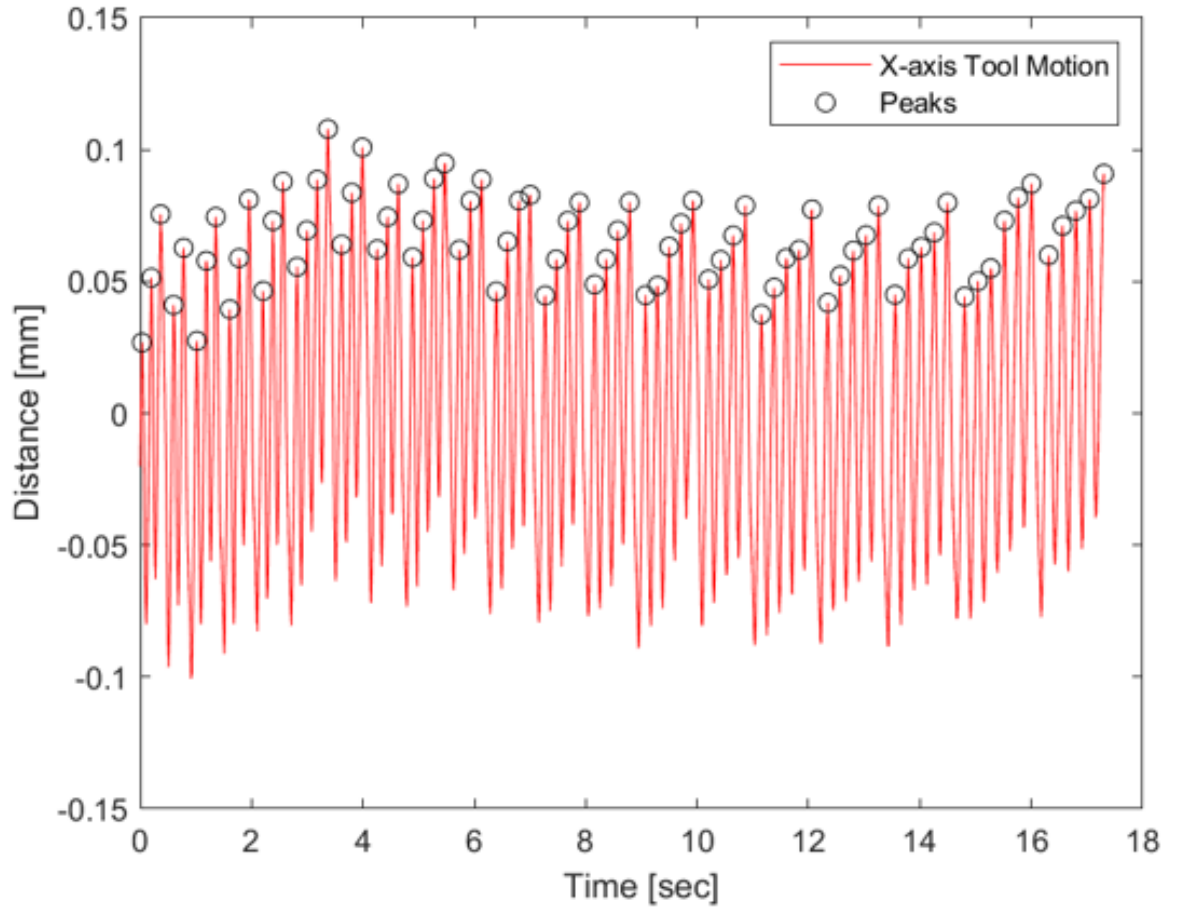


Figure 8.1: X-axis tool motion with peak locations selected for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

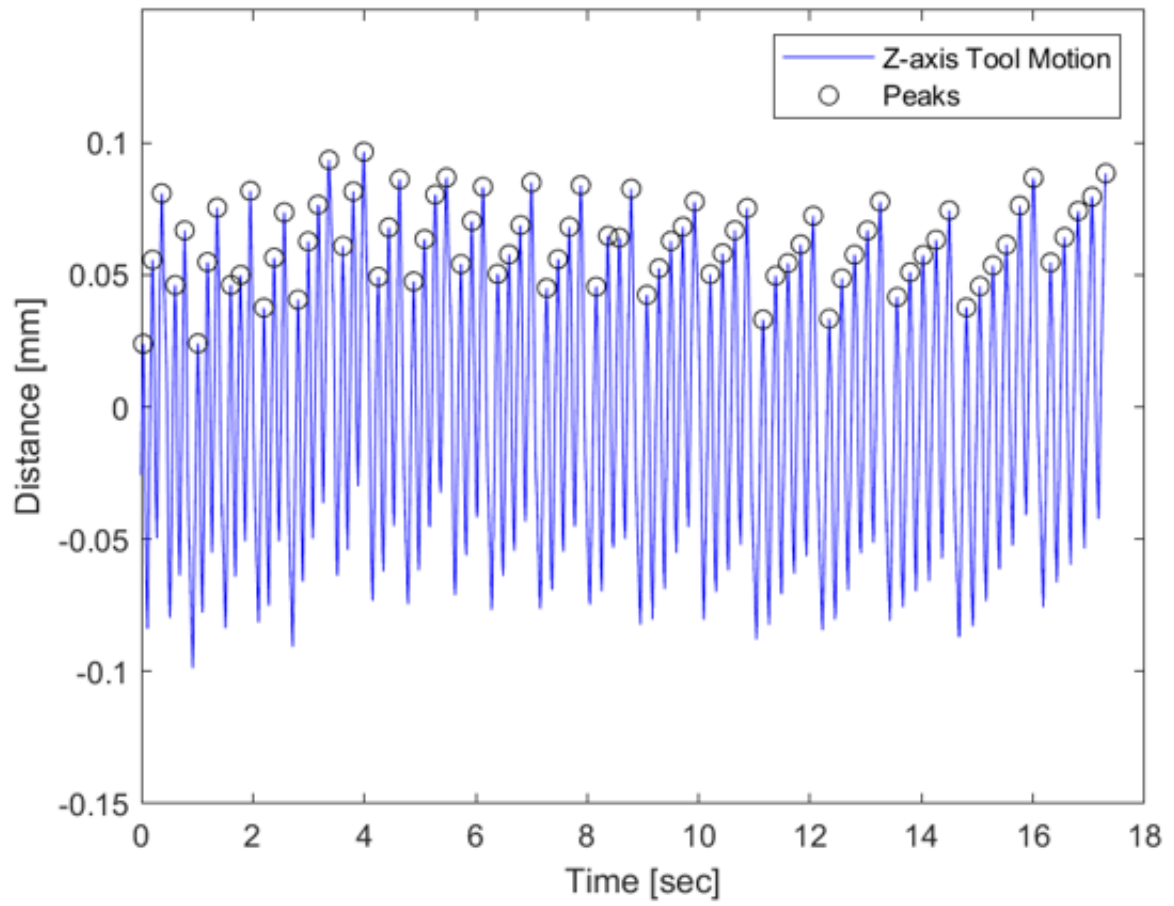


Figure 8.2: Z-axis tool motion with peak locations selected for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

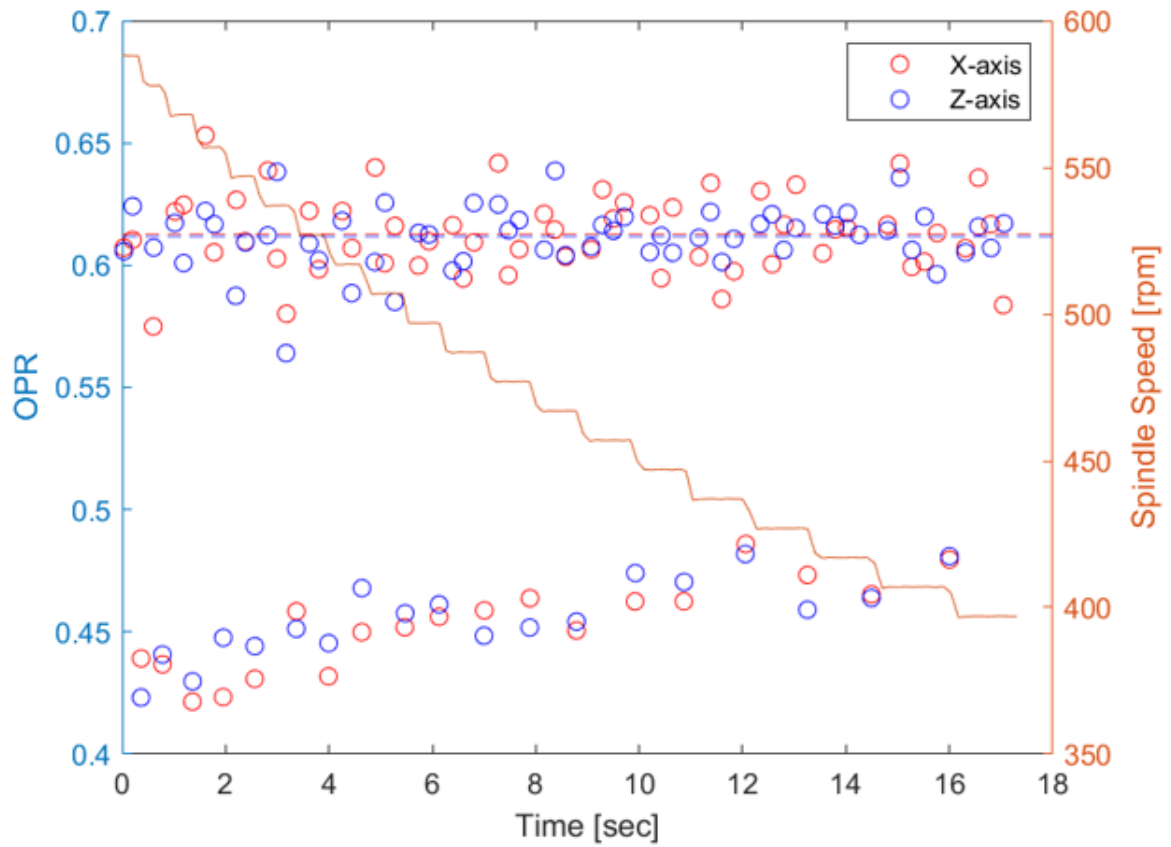


Figure 8.3: Calculated OPR values for test cuts with mean lines calculated for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

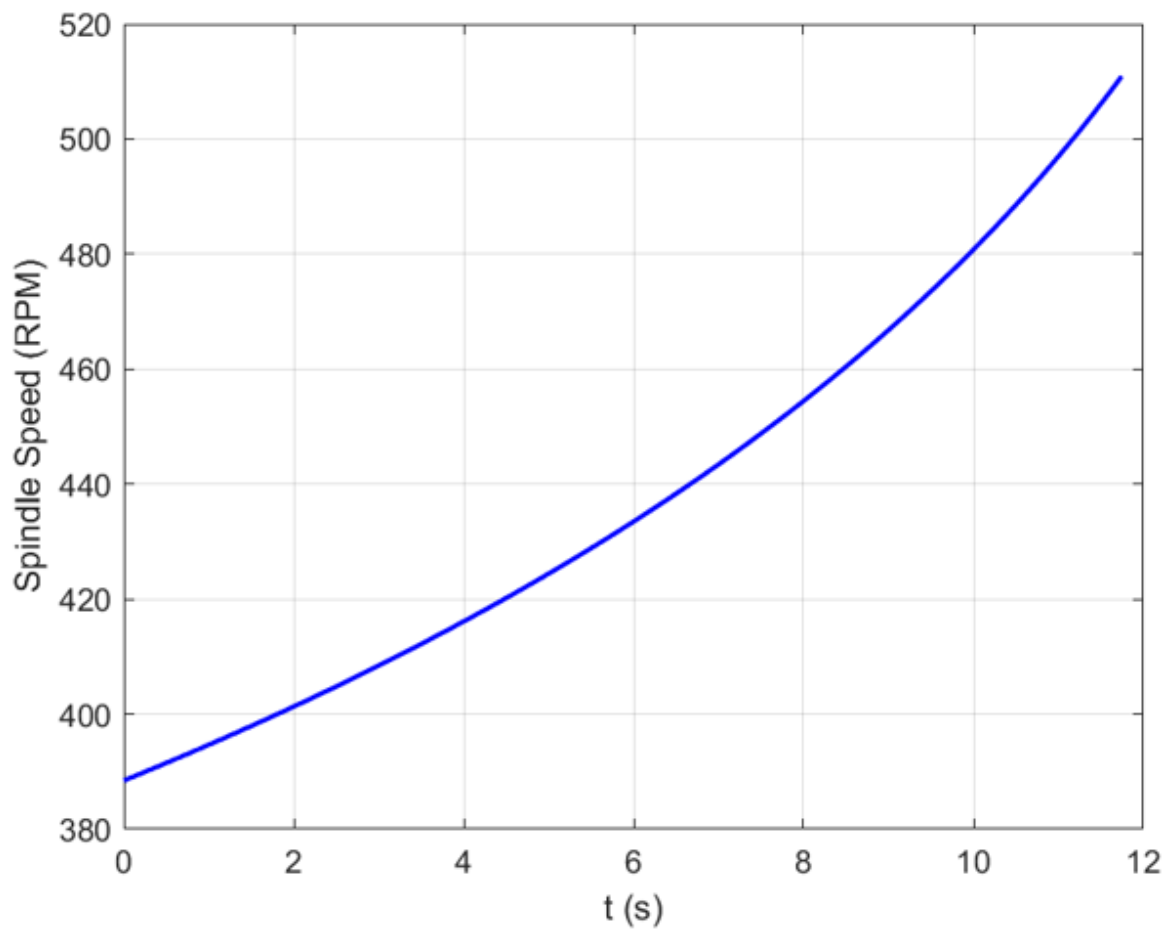


Figure 8.4: Constant ramp in spindle speed plotted over the duration of the time domain simulation.

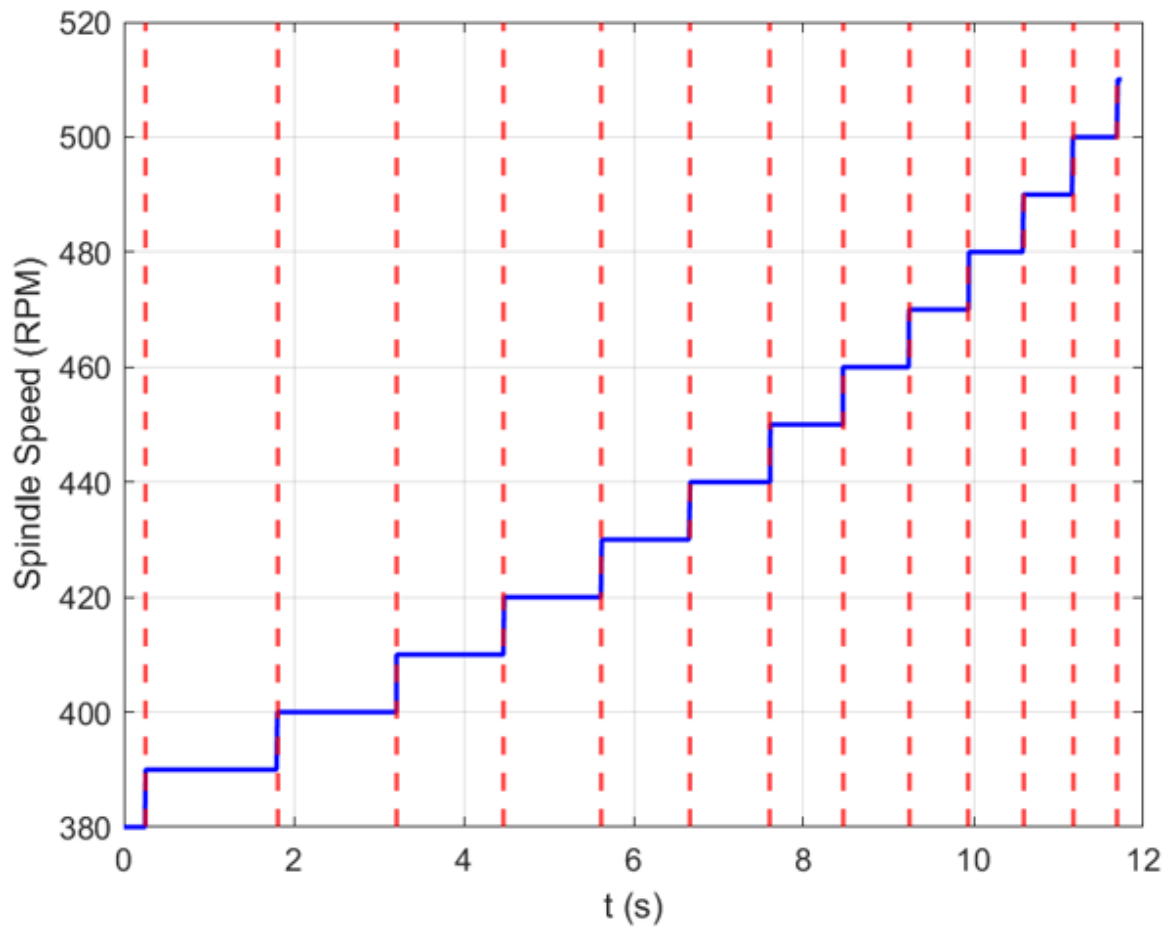


Figure 8.5: Stepped changes in spindle speed plotted over the duration of the time domain simulation vertical lines denote spindle speed changes.

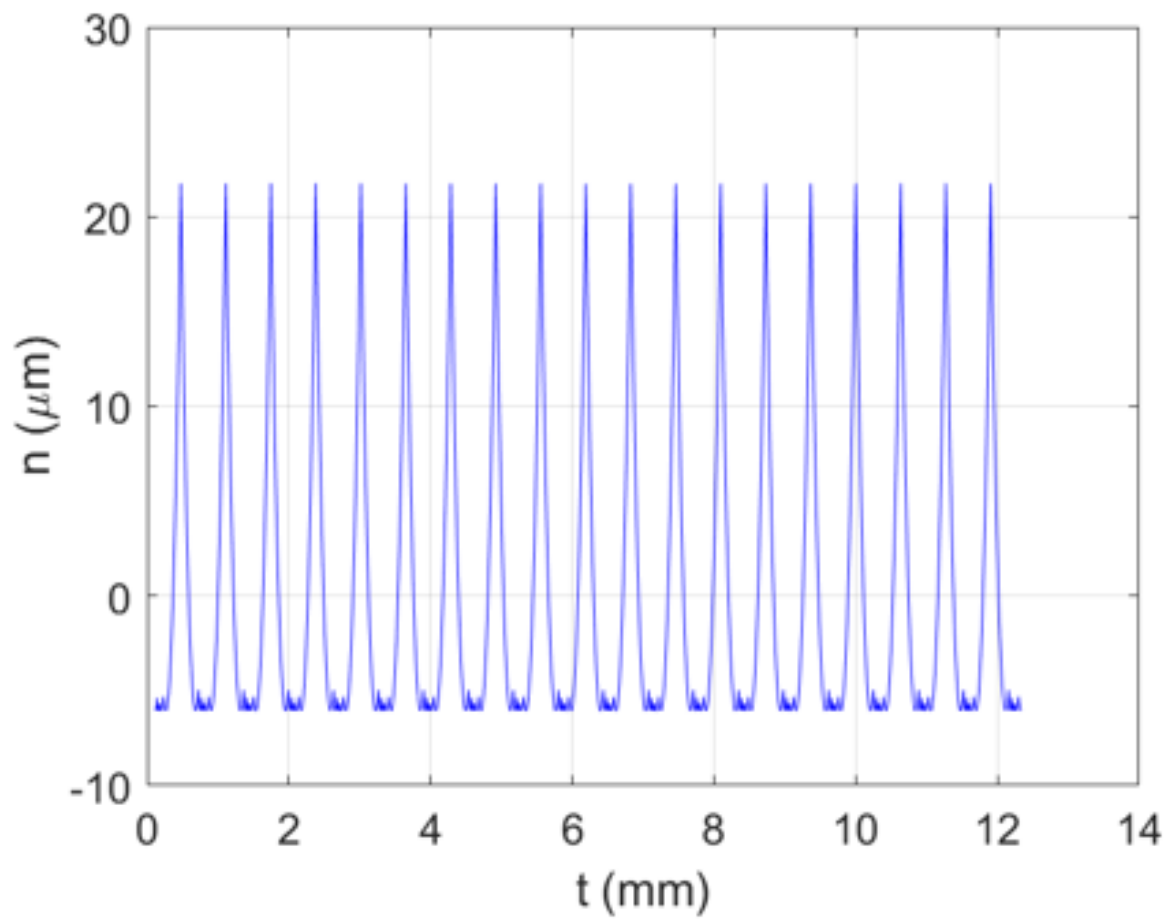


Figure 8.6: 45 degree 0.127 mm/rev OPR 0.4 RAF 2.25 simulation surface profile generated using constant spindle speed ramp.

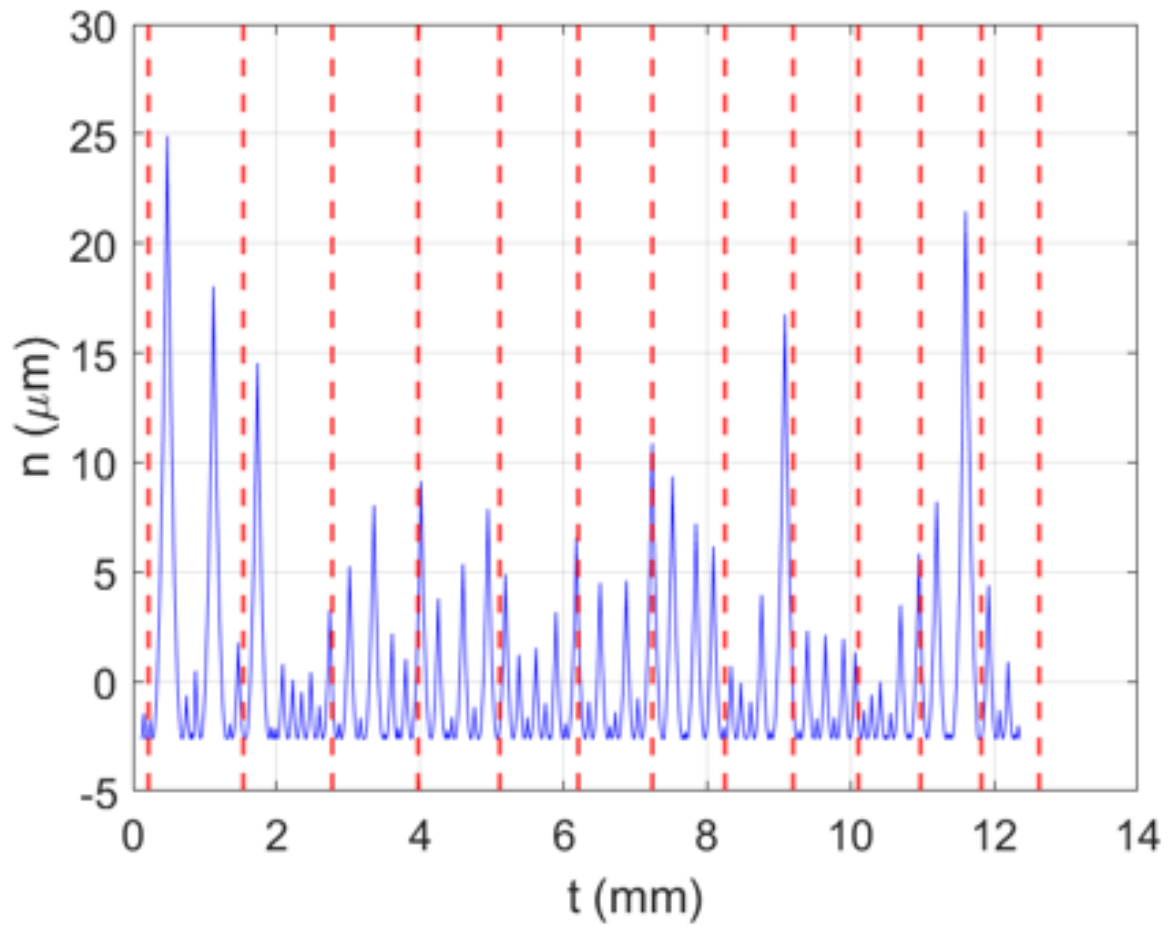


Figure 8.7: 45 degree 0.127 mm/rev OPR 0.4 RAF 2.25 simulation surface profile generated using stepped spindle speed increase with vertical lines representing changes in spindle speed.

8.4 MTP tapered workpiece results

The cutting tests were conducted with MSA-AME 507, which was used as the coolant in the MQL system. An approach similar approach previously described in chapter 6 where the Ra of the measured surface profile can be calculated for the evaluation length specified by ISO 21920-3:2021 (65). Figure 8.8 shows the entire trace length and the 4 mm sections for the Ra calculation. The Ra that was calculated for the measured surface was $2.2070 \mu m \pm 0.5102 \mu m$.

The time domain simulation incorporating the stepped changes in spindle speed was used to compare the simulation surface profile to the measured surface profile. The mean values for the OPR and RAF were used as inputs for the time domain simulation. The results of the simulation profile compared to the measured profile are shown in figure 8.9. It is possible to run the time domain simulation over the range of the the upper and lower limits for OPR and RAF to calculate an Ra value and uncertainty associated with the Ra value to compare it to the measure surface profiles. The results from these simulations are shown in figure 8.10 in the form of a heat map with RAF and OPR on the x-axis and y-axis of the plot and Ra represented by the different color gradients. The calculated Ra for the simulation is $2.1704 \mu m \pm 0.3087 \mu m$. Table 8.3 shows the results from all the taper MTP testing with the Ra of the simulation compared to the measured Ra values of the machined parts.

8.5 MTP tapered workpiece surface heat maps

Using the time domain simulation, all the possible combinations of OPR and RAF can be tested to create a heat map where the lowest Ra values can be chosen. Figure 8.11 shows the resulting heat map with darker blue sections, resulting in lower Ra values. Only combinations of OPR and RAF that result in broken chips are plotted on the heat map, as values that would not result in discontinuous chips would not

Table 8.2: Summary of values for recorded MTP parameters.

Taper angle [deg]	Commanded feedrate [mm/rev]	Commanded OPR	Commanded RAF	Recorded OPR	Recorded RAF
55	0.127	0.6	1.0	0.6653 ± 0.0441	0.8869 ± 0.0382
55	0.127	0.5	1.5	0.5482 ± 0.0323	1.3548 ± 0.0740
55	0.0762	0.6	1.0	0.6607 ± 0.0573	0.8778 ± 0.0735
55	0.0762	0.5	1.5	0.5602 ± 0.0353	1.3145 ± 0.0773
55	0.0254	0.6	1.0	0.7504 ± 0.1475	0.8303 ± 0.1065
55	0.0254	0.5	1.5	0.5592 ± 0.0917	1.3112 ± 0.1764
45	0.127	0.6	1.0	0.6663 ± 0.0483	0.9010 ± 0.0485
45	0.127	0.5	1.5	0.5506 ± 0.0349	1.3597 ± 0.0733
45	0.0762	0.6	1.0	0.6609 ± 0.050	0.8608 ± 0.050
45	0.0762	0.5	1.5	0.5587 ± 0.0371	1.3080 ± 0.0704
45	0.0254	0.6	1.0	0.7431 ± 0.1009	0.7739 ± 0.0440
45	0.0254	0.5	1.5	0.5477 ± 0.0859	1.3206 ± 0.1272
35	0.127	0.6	1.0	0.6679 ± 0.0462	0.8909 ± 0.0712
35	0.127	0.5	1.5	0.5483 ± 0.0296	1.3588 ± 0.0772
35	0.0762	0.6	1.0	0.6608 ± 0.0550	0.8884 ± 0.0237
35	0.0762	0.5	1.5	0.5592 ± 0.0378	1.3128 ± 0.0979
35	0.0254	0.6	1.0	0.7352 ± 0.1662	0.8244 ± 0.0221
35	0.0254	0.5	1.5	0.5405 ± 0.0624	1.3032 ± 0.1531

Table 8.3: Summary of values for simulation Ra values compared to measured Ra values.

Taper angle [deg]	Commanded feedrate [mm/rev]	Commanded OPR	Commanded RAF	Simulaton Ra [μm]	Measured Ra [μm]
55	0.127	0.6	1.0	2.3634 ± 0.6210	2.3368 ± 0.7876
55	0.127	0.5	1.5	2.1660 ± 0.3718	2.8835 ± 0.4339
55	0.0762	0.6	1.0	1.3839 ± 0.4848	1.2539 ± 0.6297
55	0.0762	0.5	1.5	0.9806 ± 0.4374	1.0784 ± 0.1974
55	0.0254	0.6	1.0	0.5210 ± 0.1605	0.4413 ± 0.1154
55	0.0254	0.5	1.5	0.3673 ± 0.1504	0.5807 ± 0.0527
45	0.127	0.6	1.0	2.1704 ± 0.3087	2.2070 ± 0.5102
45	0.127	0.5	1.5	2.1775 ± 0.3016	1.9854 ± 0.1870
45	0.0762	0.6	1.0	1.2708 ± 0.3433	1.0519 ± 0.3991
45	0.0762	0.5	1.5	0.9335 ± 0.2255	1.2563 ± 0.1293
45	0.0254	0.6	1.0	0.5435 ± 0.1320	0.5058 ± 0.0653
45	0.0254	0.5	1.5	0.3397 ± 0.1497	0.6440 ± 0.1450
35	0.127	0.6	1.0	2.1356 ± 0.5520	2.7035 ± 1.0001
35	0.127	0.5	1.5	2.0689 ± 0.2794	2.3422 ± 0.2298
35	0.0762	0.6	1.0	1.0353 ± 0.3761	1.2150 ± 0.3022
35	0.0762	0.5	1.5	0.8236 ± 0.1571	1.3856 ± 0.0888
35	0.0254	0.6	1.0	0.4411 ± 0.1510	0.5754 ± 0.2138
35	0.0254	0.5	1.5	0.2987 ± 0.1164	0.6790 ± 0.1099

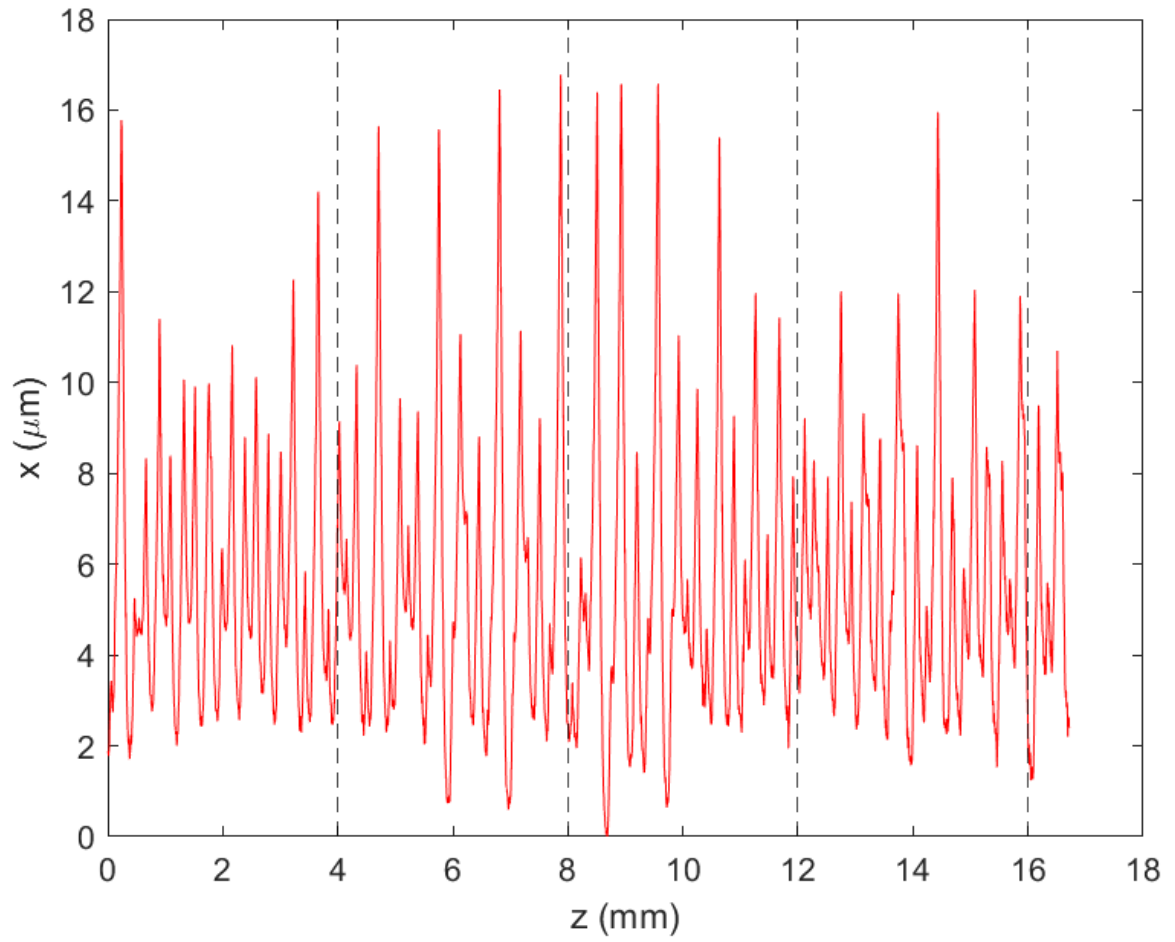


Figure 8.8: Measured surface profile for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF with vertical dashed lines representing sections for Ra calculation.

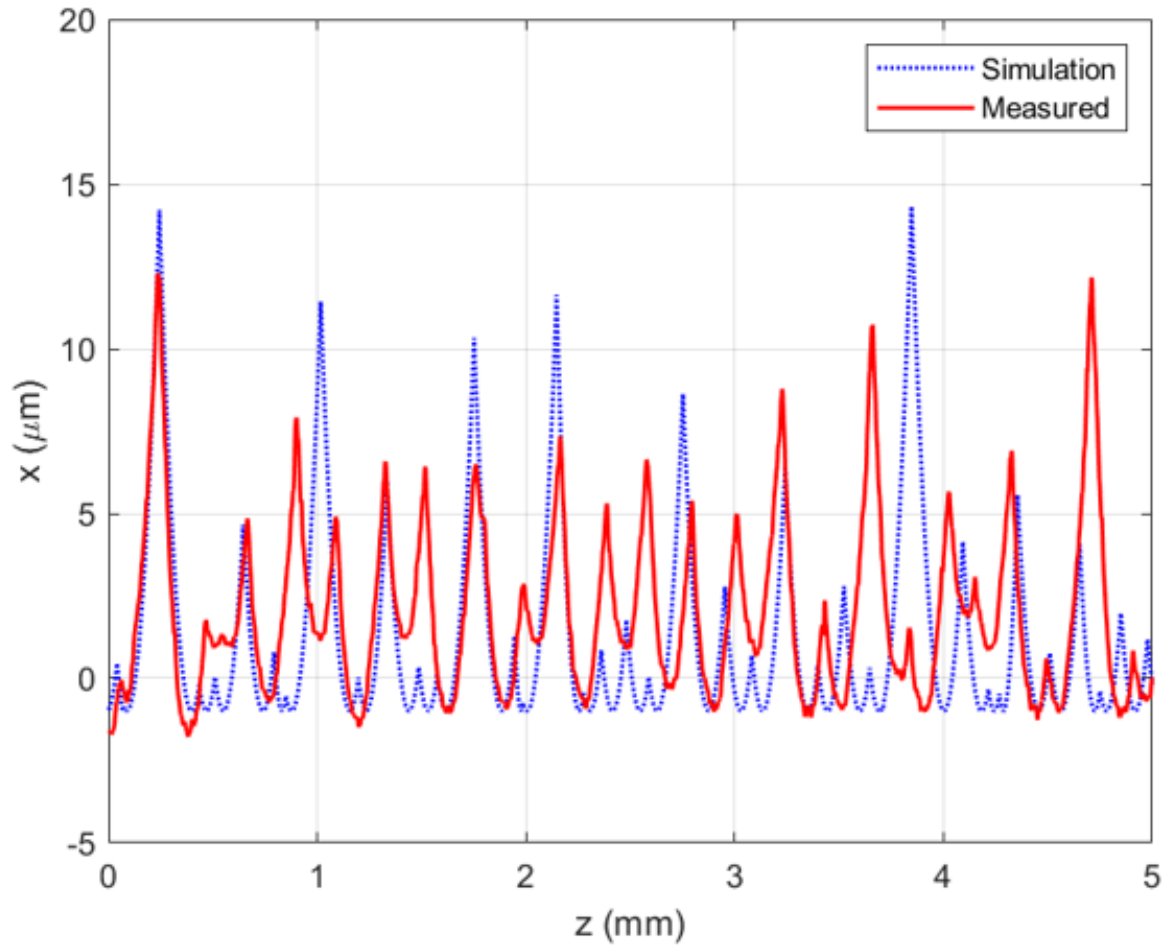


Figure 8.9: Simulation surface profile compared to measured profile for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

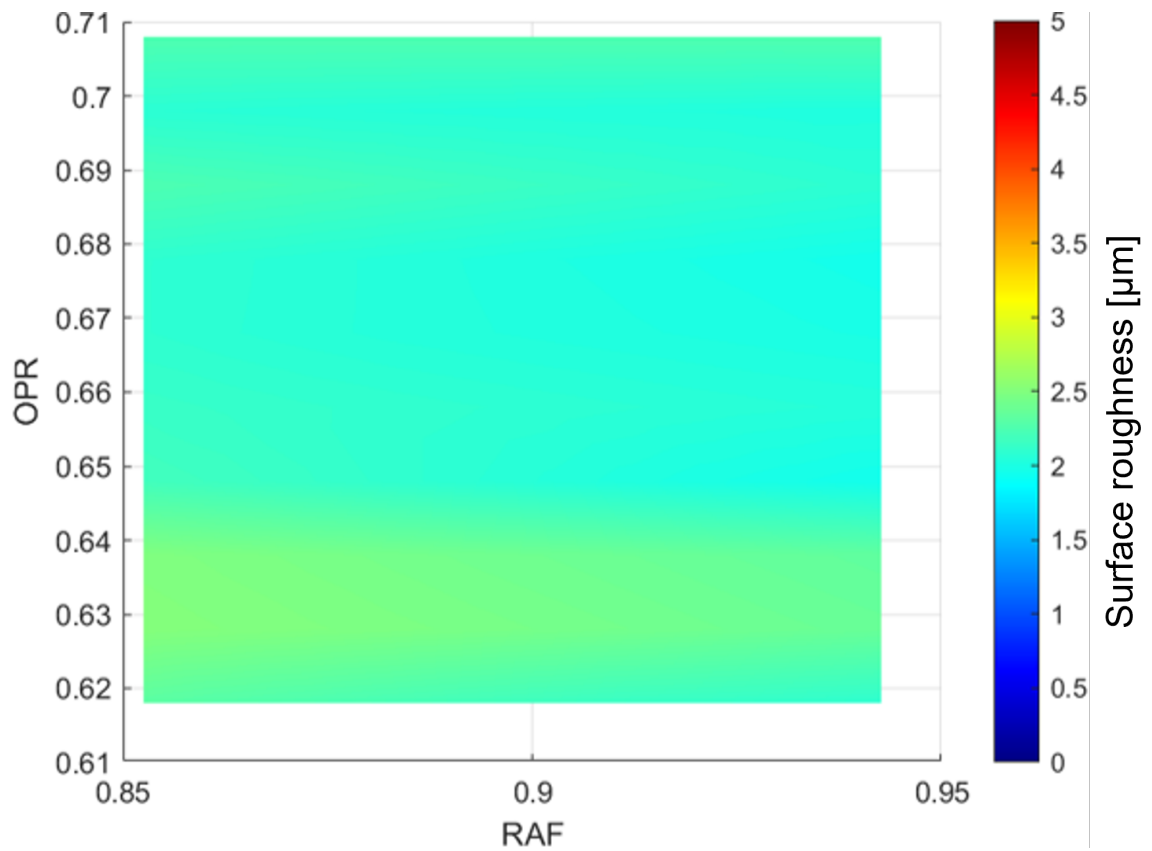


Figure 8.10: Surface finish heat map for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

be selected. This heat map can be used with the MTP GUI to optimize parameter selection for the best surface finish.

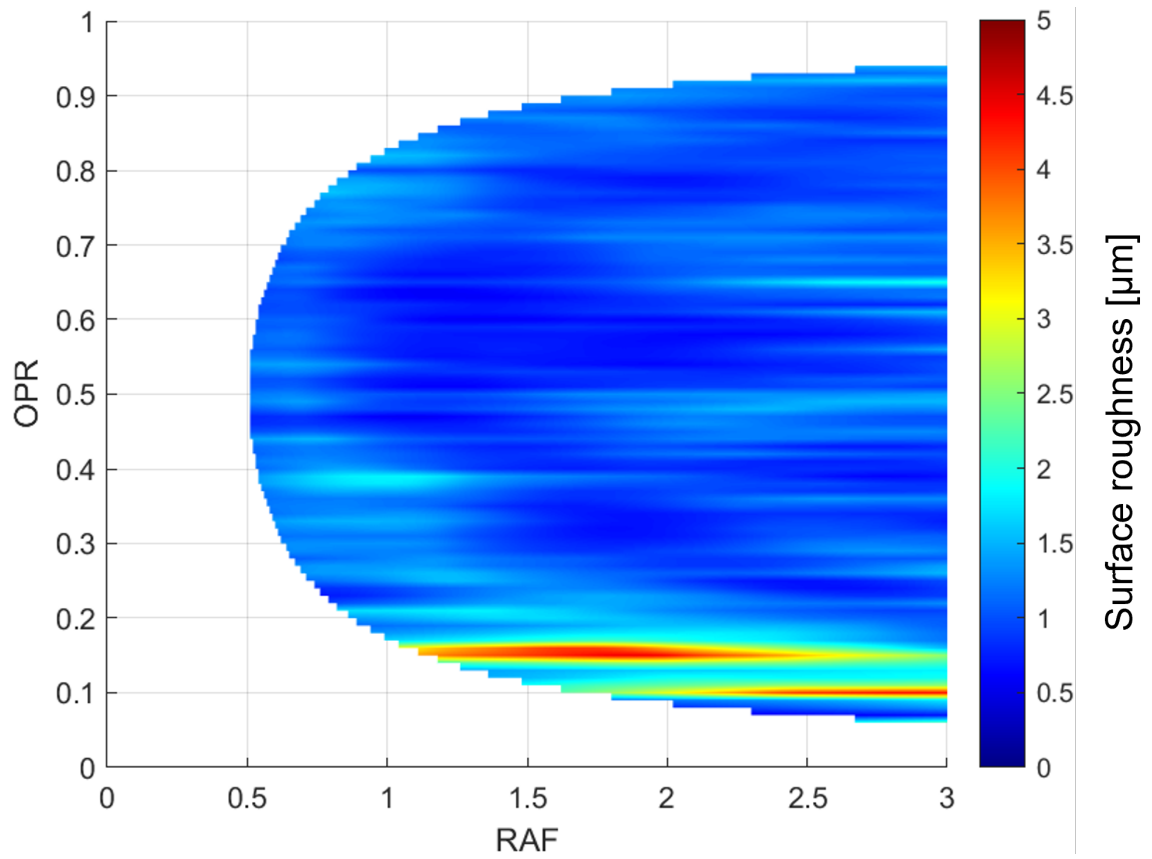


Figure 8.11: Surface finish heat map for 45 degree 0.0762 mm/rev stepped rpm.

Chapter 9

Machine tool test part

9.1 Experimental setup

The experimental setup that was used is a similar setup as shown in figures 6.1 and 6.2 described in chapter 6. The only difference was the machined jaws used to hold the machine tool test part (MTTP) shown in figure 9.1. The laser displacement sensors were used to record tool motion measurements for both the x and z axes; these measurements with the laser tachometer spindle speed measurements are used to calculate the MTP parameters that the machine achieved during test cuts for use in the time domain simulation.

The part drawing for the MTTP is shown in figure 9.2 for the purposes of the testing that was conducted. Only the outside contour was tested due to limitations with the machine setup available. Table 9.1 shows the MTP parameters and feedrates that were tested for the MTTP.

The MTTP surfaces were measured using the Alicona InfiniteFocusSL with the 50x objective lens. 3D-printed fixtures were used to hold the MTTP at different angles to allow scans at different angles. Figure 9.3 shows the setup that was used on the InfiniteFocusSL to measure the MTTP.

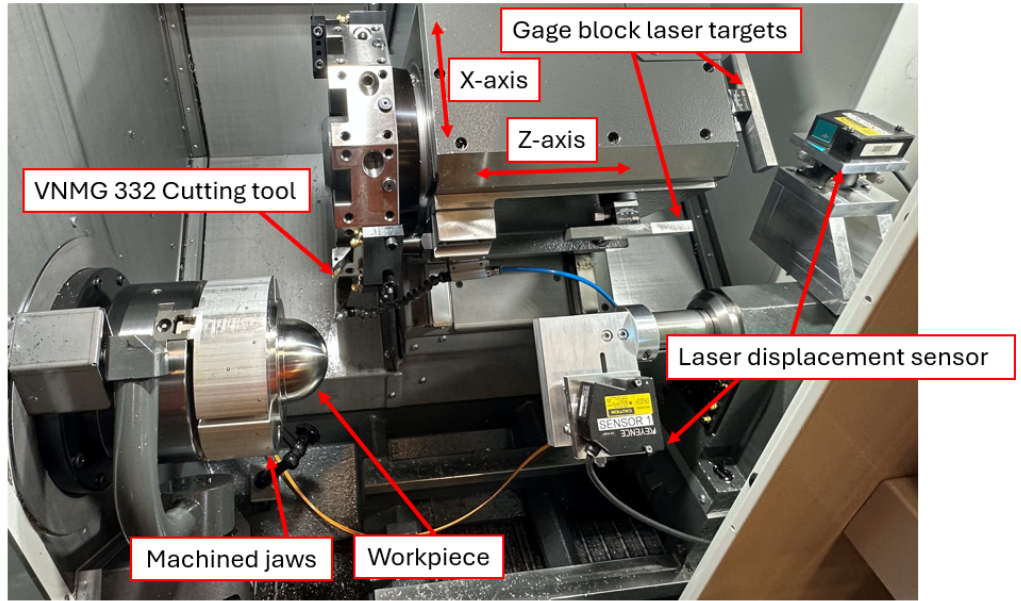


Figure 9.1: Experimental setup for MTTP on Haas ST-15.

Table 9.1: Cutting speed, chip width, feedrates, OPR, and RAF values for MTTP.

Cutting speed [m/min]	Chip width [mm]	Commanded feedrate [mm/rev]	OPR	RAF
91.4	0.127	0.127	0.6	1.0
91.4	0.127	0.127	0.5	1.5
91.4	0.127	0.0762	0.6	1.0
91.4	0.127	0.0762	0.5	1.5

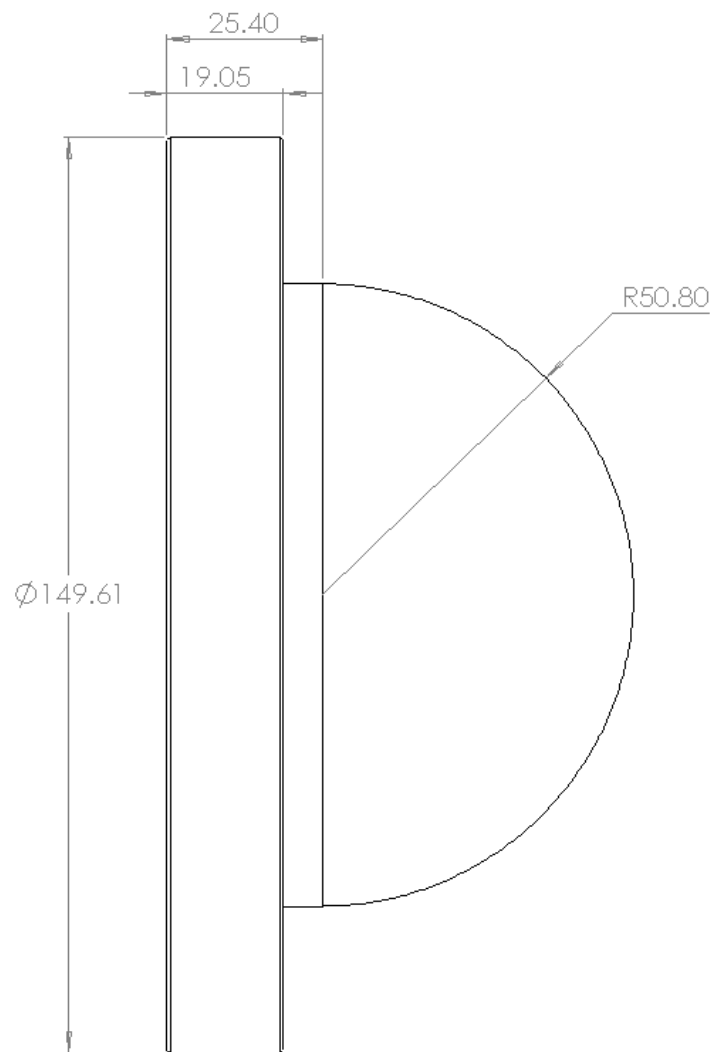


Figure 9.2: Machine tool test part drawing with dimensions shown in mm.



Figure 9.3: Alicona InfiniteFocusSL measurement setup with MTTP, angle fixture, and square stop.

9.2 Calculating MTP parameters

The same procedure that was described in chapter 8 was used to calculate the MTP parameters that the machine achieved during testing. The same approach for determining the OPR and RAF uncertainties was used to evaluate how slight changes in the OPR and RAF would affect the resulting calculated Ra value. Figures 9.4 and 9.5 show the laser displacement sensor measurements with the global motion removed so that only the MTP oscillations remain for the 0.127 mm/rev 0.6 OPR 1.0 RAF test cut. These two figures are then used to calculate the actual MTP parameters that the machine was able to achieve through the use of the method laid out in chapter 8. Figure 9.6 shows the resulting OPR throughout the duration of the test cut. The actual RAF values were also calculated using the same method laid out and demonstrated in chapter 8. Table 9.2 shows the summary of results for the different combinations of feedrates and MTP parameters tested for the MTTP.

9.3 Time domain simulation

Modifications to the time domain simulation had to be made in order to accommodate the changing spindle speed and changing feedrates for the x and z axis as the cutting tool moves along the outer contour of the MTTP. The spindle speed was changed from just a stepped response to incorporate a max spindle speed that was set on the machine. For the testing that was done, a max rpm of 500 rpm was used based on machine limitations. Figure 9.7 shows the spindle speed of the simulation as a function of time for feedrate of 0.127 mm/rev and MTP parameters of 0.6 OPR 1.0 RAF.

A coordinate rotation was sufficient for the tapered test cuts to extract the surface profile from the simulation. For the MTTP time domain simulation, however, a surface unwrap approach was necessary to prevent the resulting surface profile from being affected. The surface unwrap approach is used to remove the form from surface

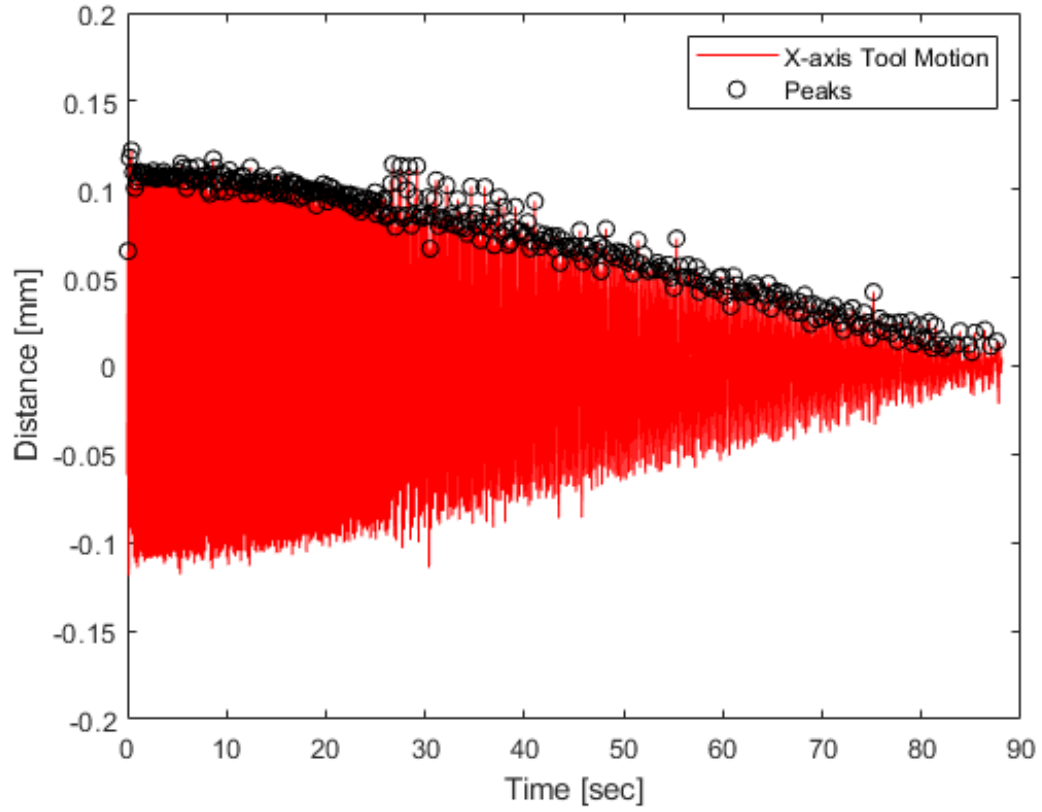


Figure 9.4: x-axis tool motion with peak locations for MTPP 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

Table 9.2: Summary of values for recorded MTP parameters.

Commanded feedrate [mm/rev]	Commanded OPR	Commanded RAF	Recorded OPR	Recorded RAF
0.127	0.6	1.0	0.6693 ± 0.0309	0.8422 ± 0.1691
0.127	0.5	1.5	0.5471 ± 0.0324	1.3099 ± 0.2993
0.0762	0.6	1.0	0.6665 ± 0.0378	0.8383 ± 0.1286
0.0762	0.5	1.5	0.5614 ± 0.0269	1.2868 ± 0.2647

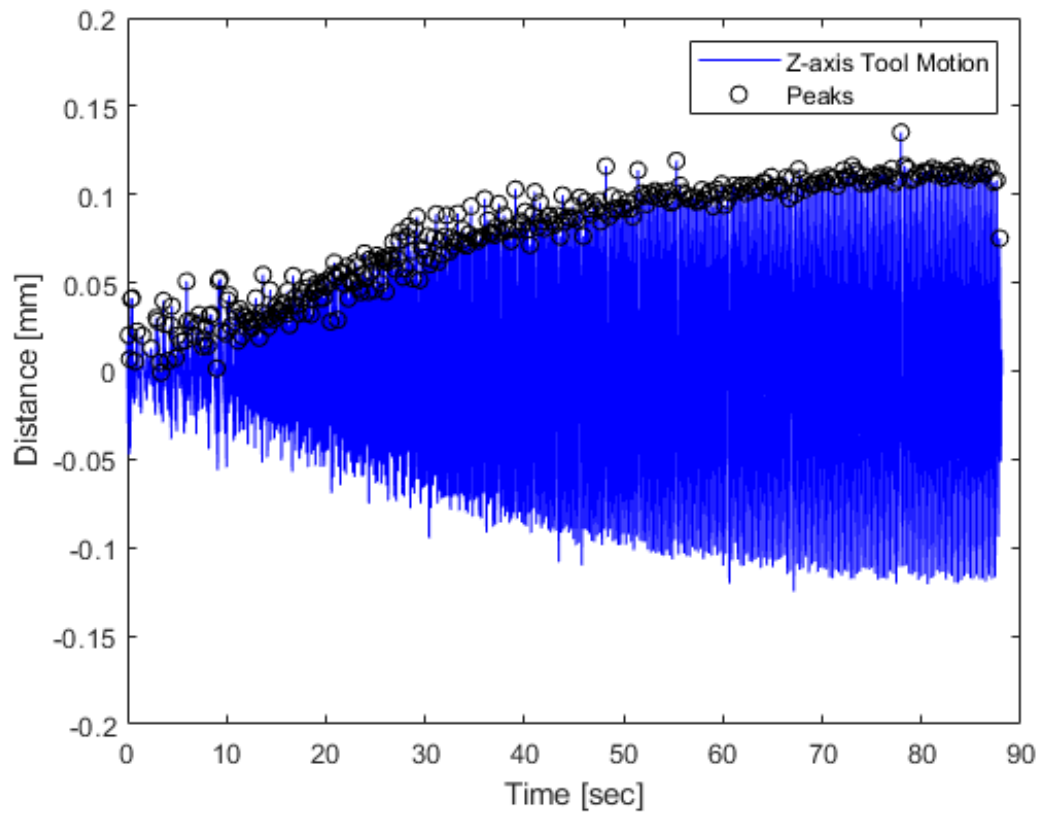


Figure 9.5: z-axis tool motion with peak locations for MTTP 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

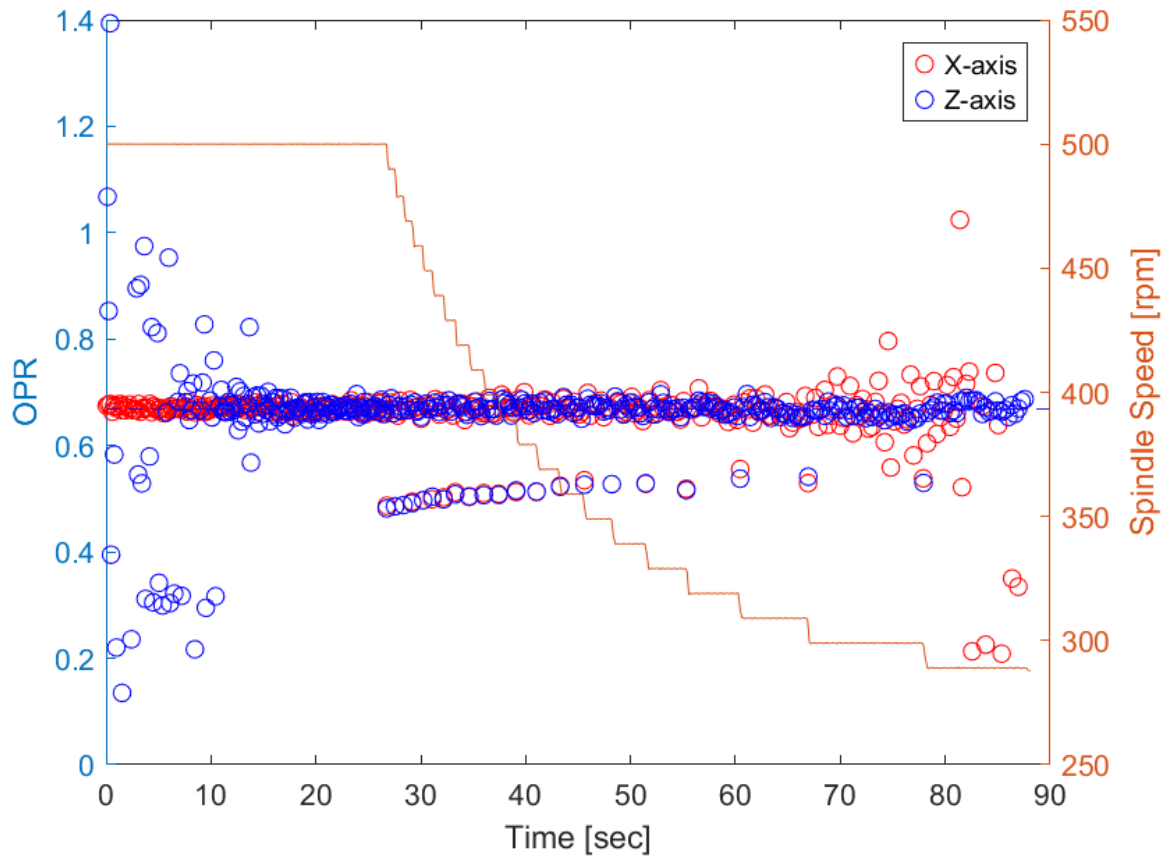


Figure 9.6: Calculated OPR values for test cuts with mean lines calculated for MTTP 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

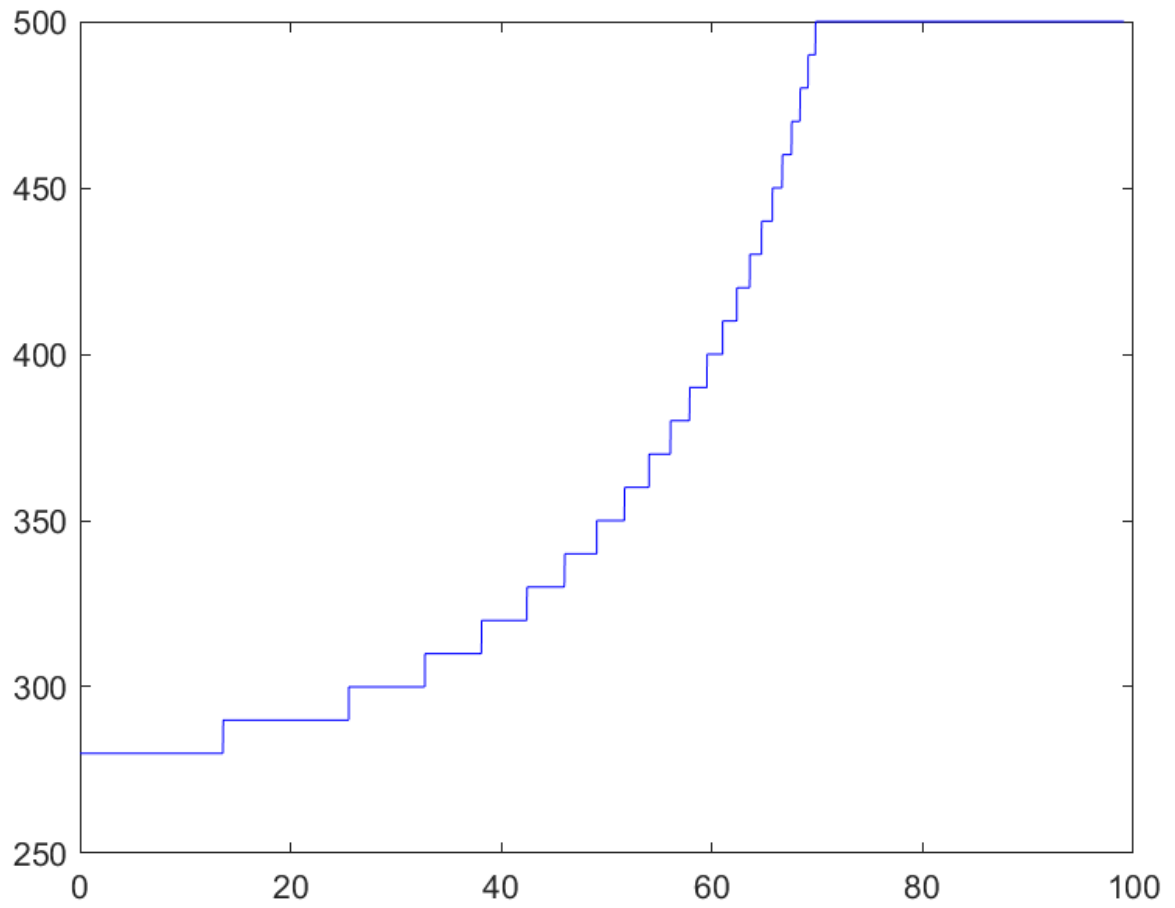


Figure 9.7: Time domain simulation spindle speed plotted versus time for 0.127 mm/rev 0.6 OPR 1.0 RAF simulation parameters.

trace measured on the Alicona InfiniteFocusSL. Figure 9.8 shows the measurement surface location and then how that surface is unwrapped across the contour. An example of how this surface unwrap approach works is shown in figure 9.9. The figure shows how a sine wave only in the x direction is unaffected when the unwrapped procedure is done. If a standard form removal approach was used, the frequency of the surface roughness peaks would be affected, and an accurate comparison of the simulation to measured surface profiles would not be possible. Figure 9.10 shows the effects of a simple form removal that compresses the overall trace length of the measurements.

The time domain simulation is run for the entire contour, and then the unwrapped surface is recorded for comparison to the measured surface profile. The sections that are being measured can then be compared to the sections of the simulation that correspond to the measurement location on the MTTP.

9.4 MTTP results

Following the approach laid out in chapter 8, both the surface profiles were compared, as well as the surface heat map was created. With the Alicona InfiniteFocusSL, it was impossible to scan the entire surface of the MTTP. A section-based approach was used, and the part was scanned at different angles to scan different surface sections. Figure 9.11 shows the locations from where the surface profiles were measured on the Alicona InfiniteFocusSL using the 3D printed fixtures.

The mean values for the OPR and RAF shown in table 9.2 were used as inputs for the time domain simulation. The results of the simulation profile for the 0.127 mm/rev 0.6 OPR 1.0 RAF MTTP at the 45 degree measurement compared to the measured profile are shown in figure 9.12. The time domain simulation was run over the range of the upper and lower limits for OPR and RAF to calculate a Ra value and the uncertainty associated with the Ra value to compare it to the measured surface profiles. The results from these simulations are shown in figure 8.10 in the form of a

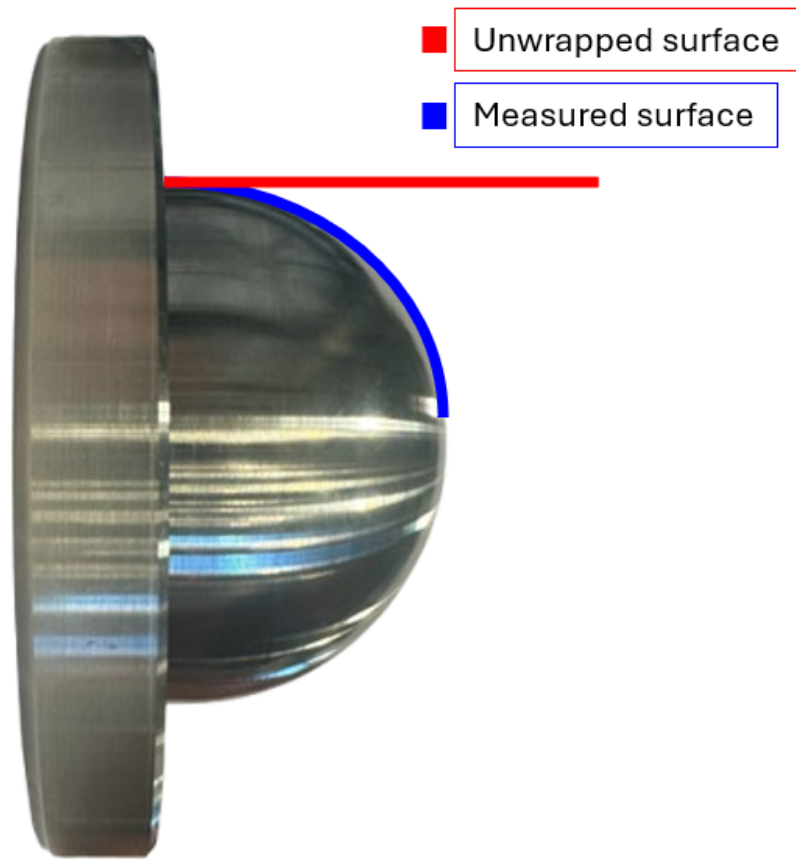


Figure 9.8: MTTP measured surface versus unwrapped surface.

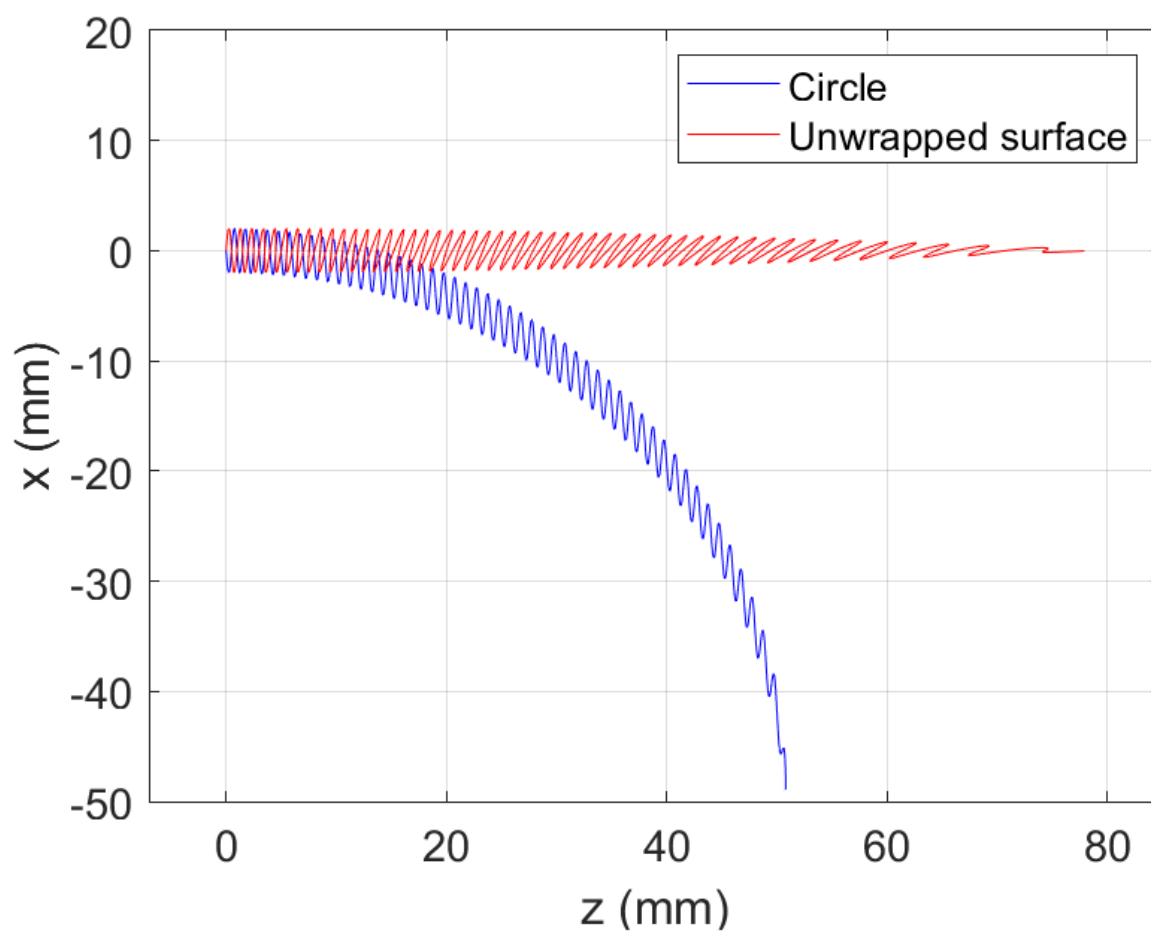


Figure 9.9: Surface unwrap example showing overall surface profile unaffected.

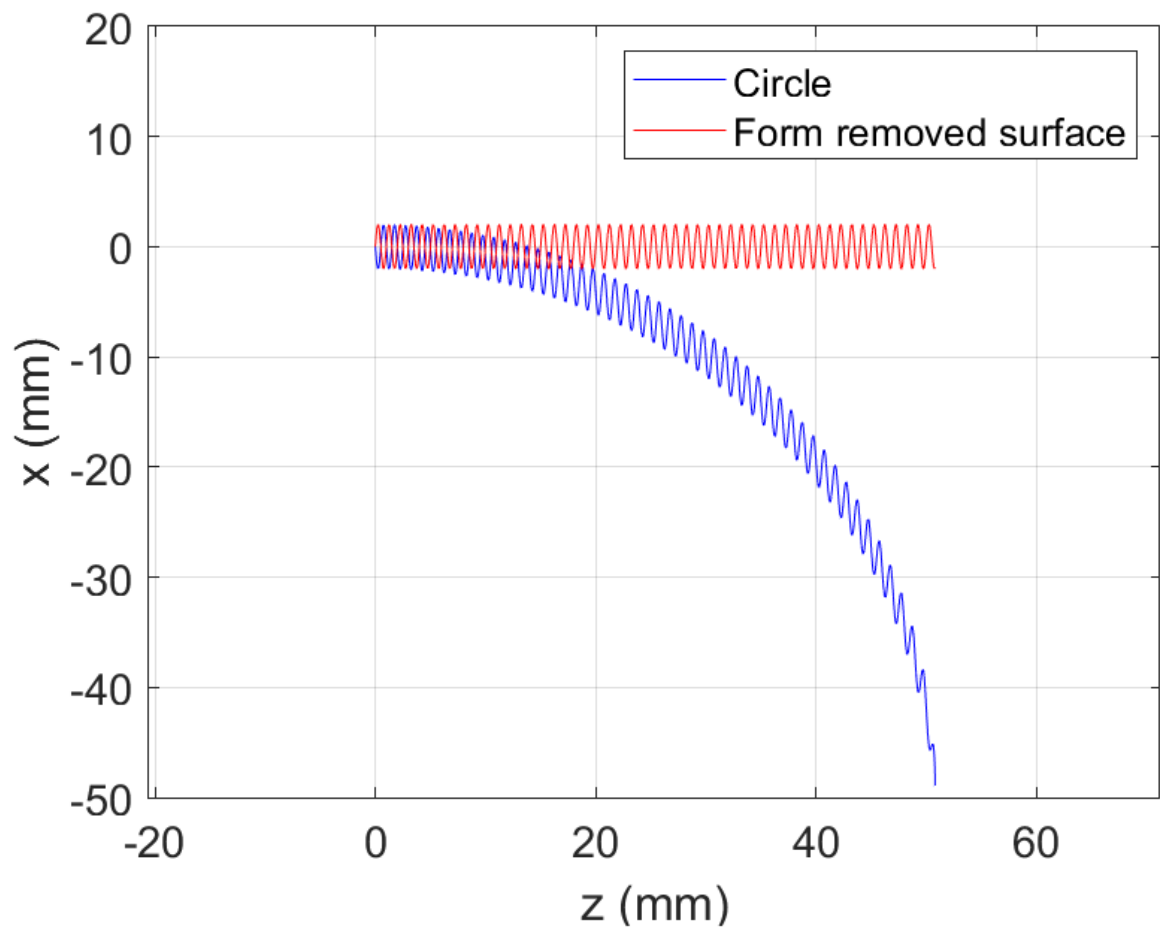


Figure 9.10: Surface with form removal example showing overall surface profile compressed.

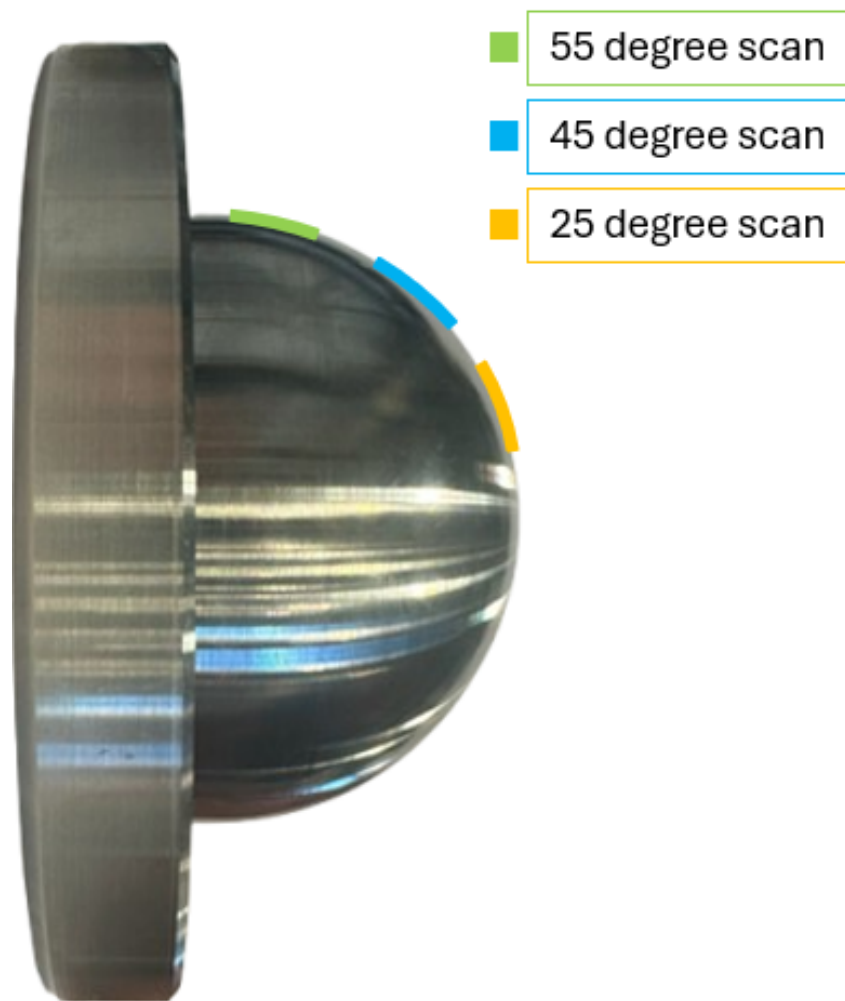


Figure 9.11: MTTP measurement locations.

heat map with RAF and OPR on the x-axis and y-axis of the plot and Ra represented by the different color gradients. The calculated Ra for the simulation is $3.1439 \mu m \pm 0.9849 \mu m$. The measured Ra for the 0.127 mm/rev 0.6 OPR 1.0 RAF MTTP at the 45 degree measurement was $3.0127 \mu m \pm 0.7678 \mu m$. Table 9.3 shows the results from all the taper MTP testing with the Ra of the simulation compared to the measured Ra values of the machined parts. Appendix B shows the resulting surface plots and localized heat maps for the different MTTP feedrate and MTP parameters, as well as the other measurement locations.

Based on the simulation results, there are no significant differences in the Ra across the surface of the MTTP; however, it is seen that there can be significant changes to the surface profiles for different locations on the MTTP.

It is also possible to develop heat maps for the MTTP, which allow for the optimization of the lowest Ra based on the OPR and RAF values selected. These maps require immense computational power; however, due to the increased duration of the simulations, they have not been created due to limitations in computational resources available. The code for these heat maps is found in appendix C.

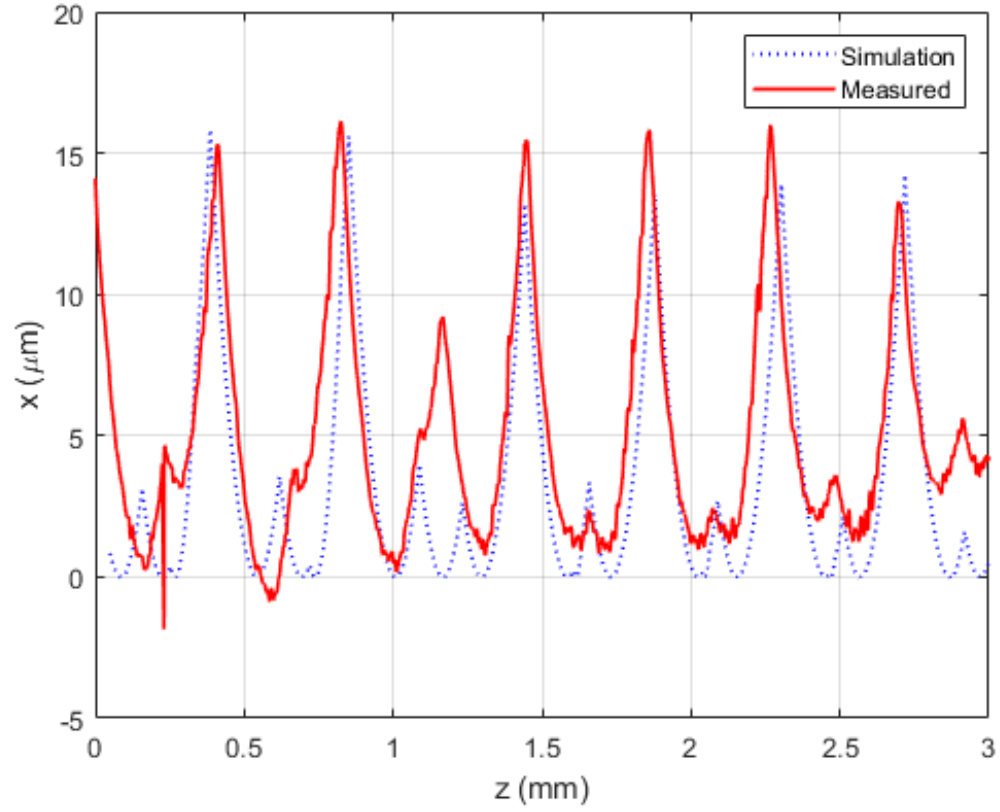


Figure 9.12: Simulation surface profile compared to measured profile for 45 degree scan on MTTP 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

Table 9.3: Summary of values for simulation Ra values compared to measured Ra values for MTTP.

Feedrate [mm/rev]	Commanded OPR	Commanded RAF	Measurement angle [deg]	Simulation Ra [μm]	Measured Ra [μm]
0.127	0.6	1.0	25	3.4397 ± 0.6539	2.5990 ± 1.6723
0.127	0.5	1.5	25	5.8864 ± 1.9330	2.2753 ± 0.2827
0.127	0.6	1.0	45	3.1439 ± 0.9849	3.0127 ± 0.7678
0.127	0.5	1.5	45	5.8820 ± 1.8838	2.0946 ± 0.2511
0.127	0.6	1.0	55	3.2683 ± 1.1371	3.0385 ± 0.7635
0.127	0.5	1.5	55	5.9041 ± 1.8839	2.0610 ± 0.3811
0.0762	0.6	1.0	25	1.4465 ± 0.2754	1.6448 ± 1.3099
0.0762	0.5	1.5	25	2.1888 ± 0.5515	1.2288 ± 0.2925
0.0762	0.6	1.0	45	1.4029 ± 0.3432	1.0656 ± 0.4981
0.0762	0.5	1.5	45	2.1858 ± 0.5302	1.2258 ± 0.2825
0.0762	0.6	1.0	55	1.4043 ± 0.3472	1.5182 ± 0.5245
0.0762	0.5	1.5	55	2.1880 ± 0.5242	1.1153 ± 0.1332

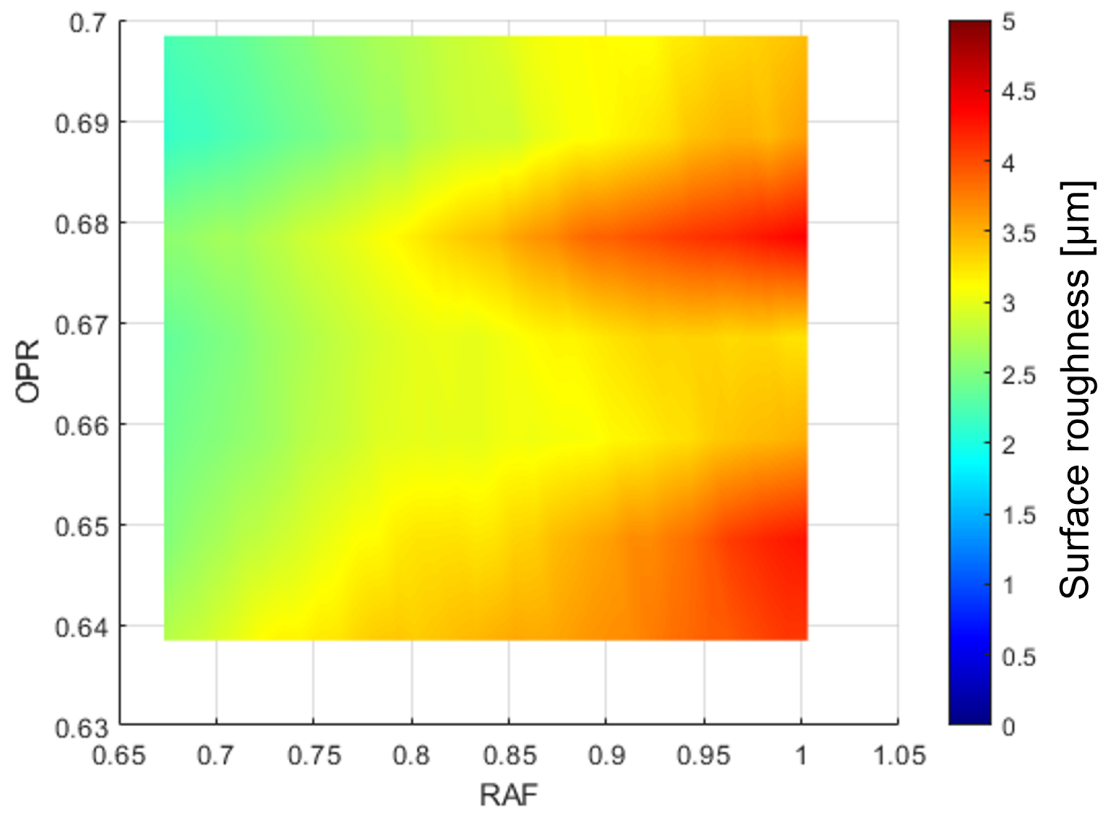


Figure 9.13: Surface finish heat map for 45 degree scan on MTTP 0.127 mm/rev 0.6 OPR 1.0 RAF test cut.

Chapter 10

Conclusions and future work

10.1 Conclusions

This study presented a time domain simulation used to predict surface finish for MTP turning operations, where the effect of side flow on surface finish was included using an effective tool nose radius model. The contributions of coolant to the side flow behavior was evaluated for the first time. Additionally, the ability to predict MTP turning surface finish for single-axis motion, two-axis linear motion, and curvilinear geometry was demonstrated. For two-axis motion, the simulation included the ability to account for changes in spindle speed that provide constant surface speed cutting conditions, which was shown to affect the surface profile of machined parts. This work represents the advancement of surface finish prediction for MTP turning, leading to improved productivity and reduced testing when selecting optimum parameters for MTP turning tool paths applied in finishing operations.

10.2 Future work

Future work can add the ability to incorporate more complex geometries in the time domain simulations. Additionally, allowing for changes to the OPR/RAF and feedrate for different sections of a part could be investigated for process optimization. Finally,

further testing could be completed to further explore the effect of coolant systems and types on side flow and the effective tool nose radius model.

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Appendix

Appendix A

Taper MTP test cut results

A.1 55 degree taper

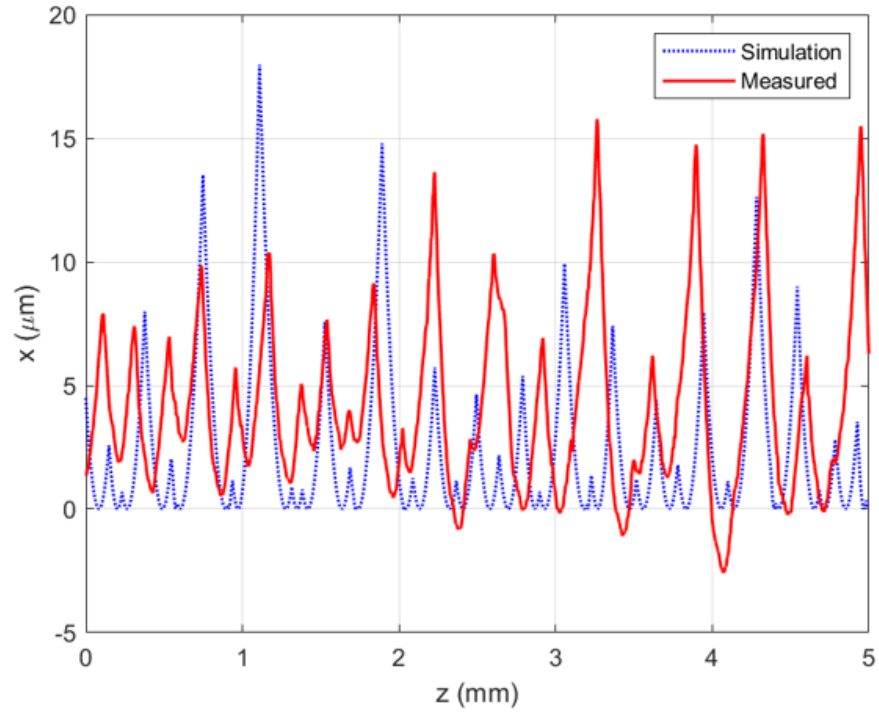


Figure A.1: Simulation surface profile compared to measured profile for 55 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut

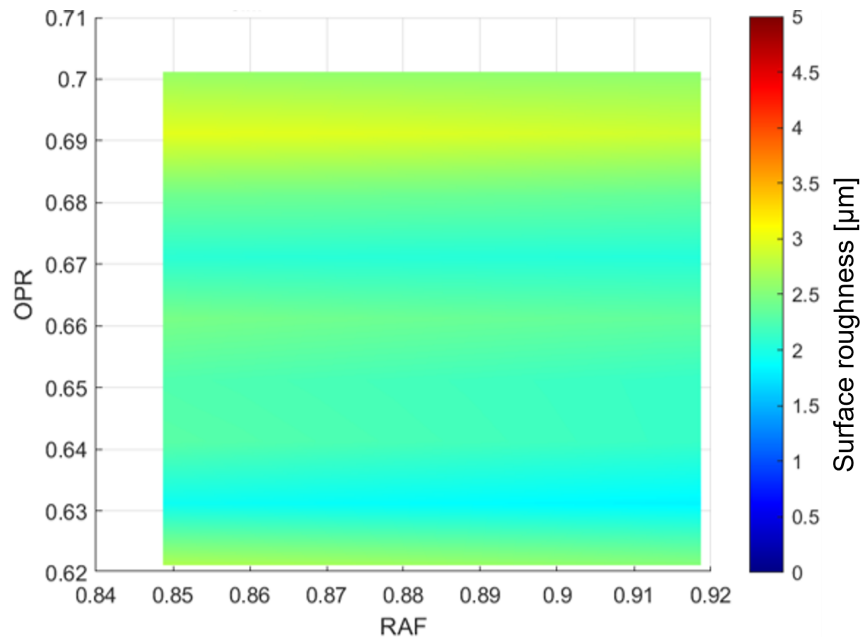


Figure A.2: Surface finish heat map for 55 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut

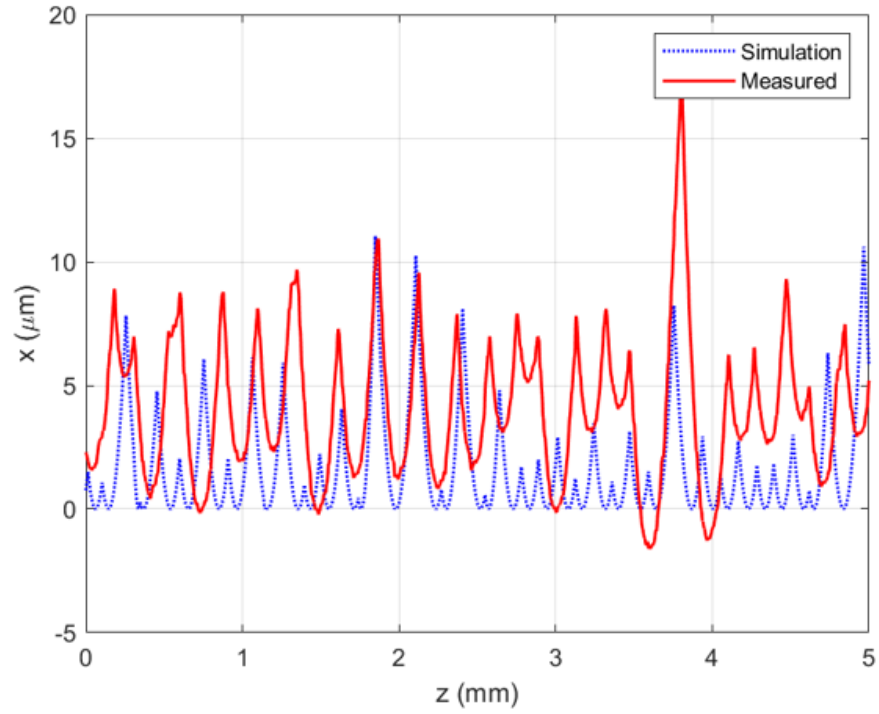


Figure A.3: Simulation surface profile compared to measured profile for 55 degree 0.127 mm/rev 0.5 OPR 1.5 RAF test cut

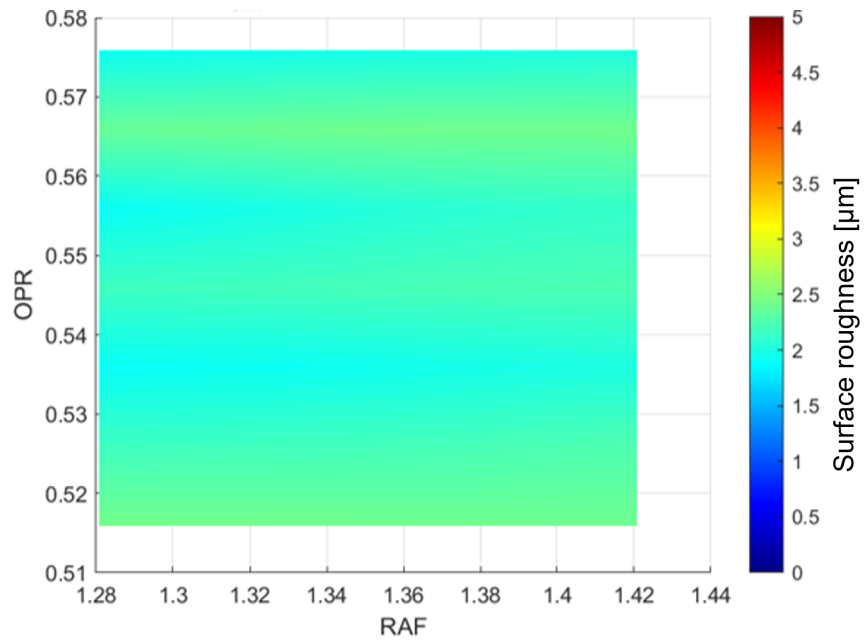


Figure A.4: Surface finish heat map for 55 degree 0.127 mm/rev 0.5 OPR 1.5 RAF test cut

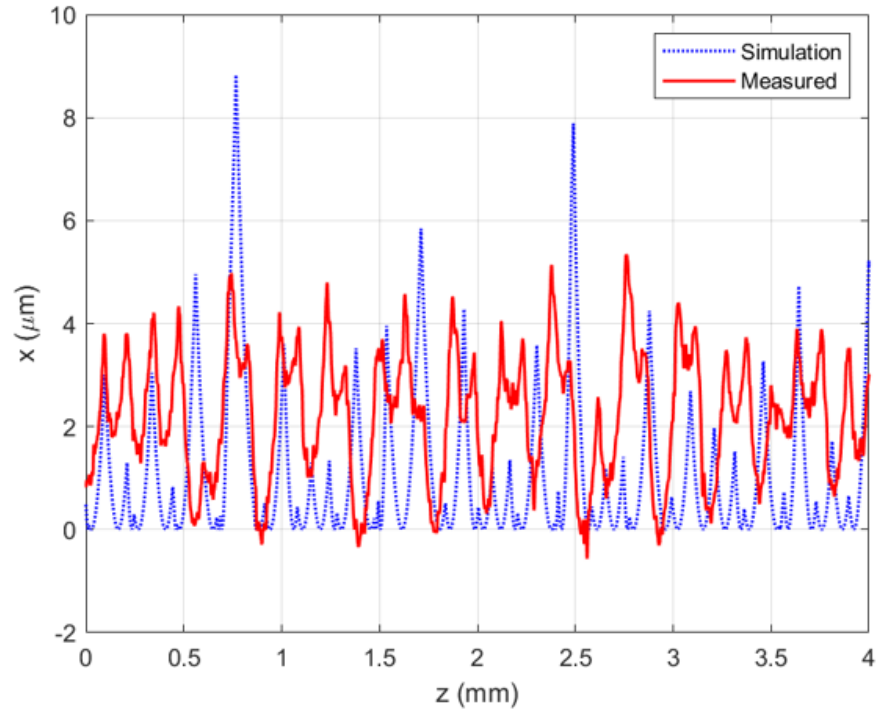


Figure A.5: Simulation surface profile compared to measured profile for 55 degree 0.0762 mm/rev 0.6 OPR 1.0 RAF test cut

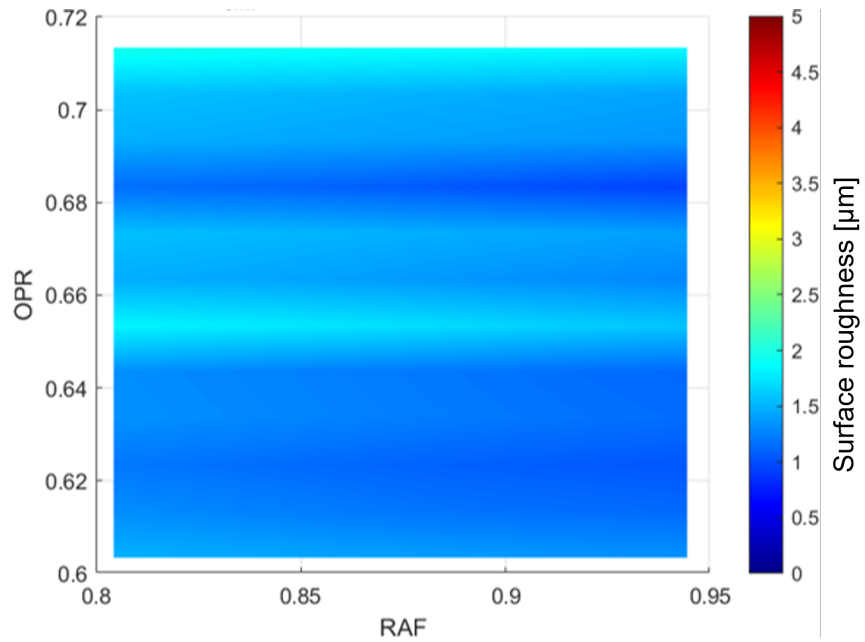


Figure A.6: Surface finish heat map for 55 degree 0.0762 mm/rev 0.6 OPR 1.0 RAF test cut

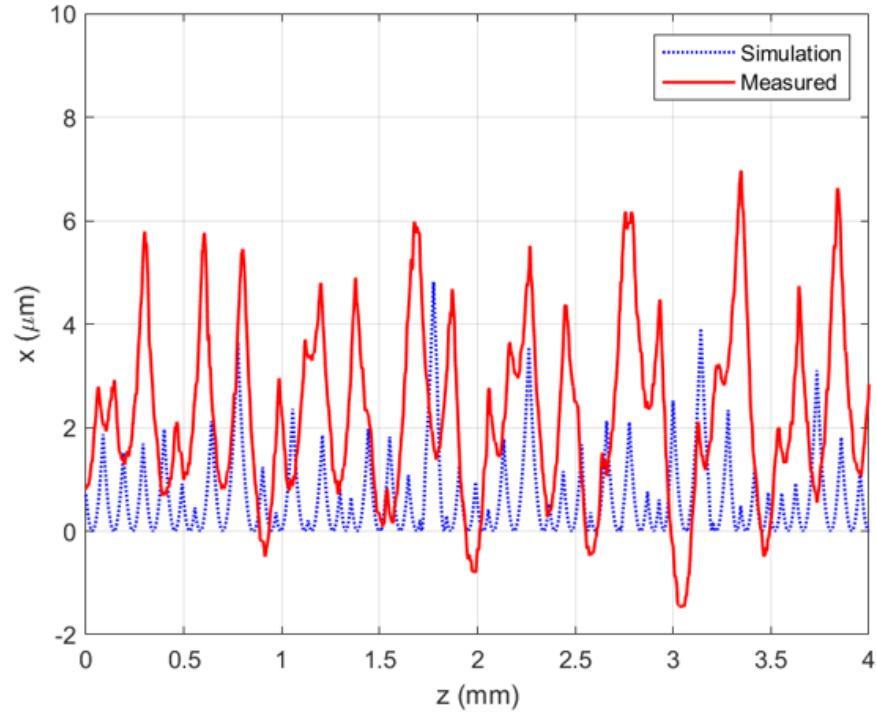


Figure A.7: Simulation surface profile compared to measured profile for 55 degree 0.0762 mm/rev 0.5 OPR 1.5 RAF test cut

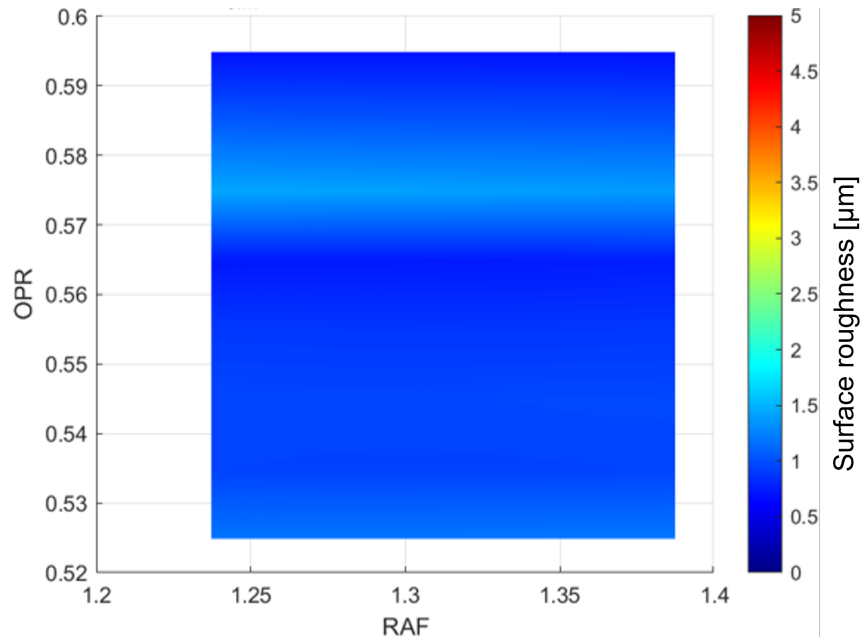


Figure A.8: Surface finish heat map for 55 degree 0.0762 mm/rev 0.5 OPR 1.5 RAF test cut

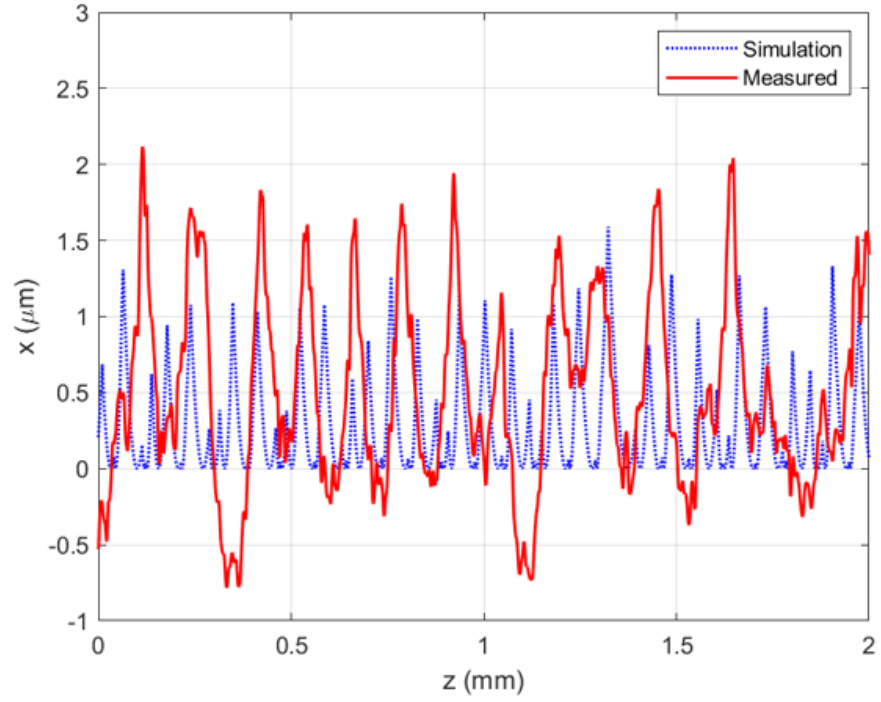


Figure A.9: Simulation surface profile compared to measured profile for 55 degree 0.0254 mm/rev 0.6 OPR 1.0 RAF test cut

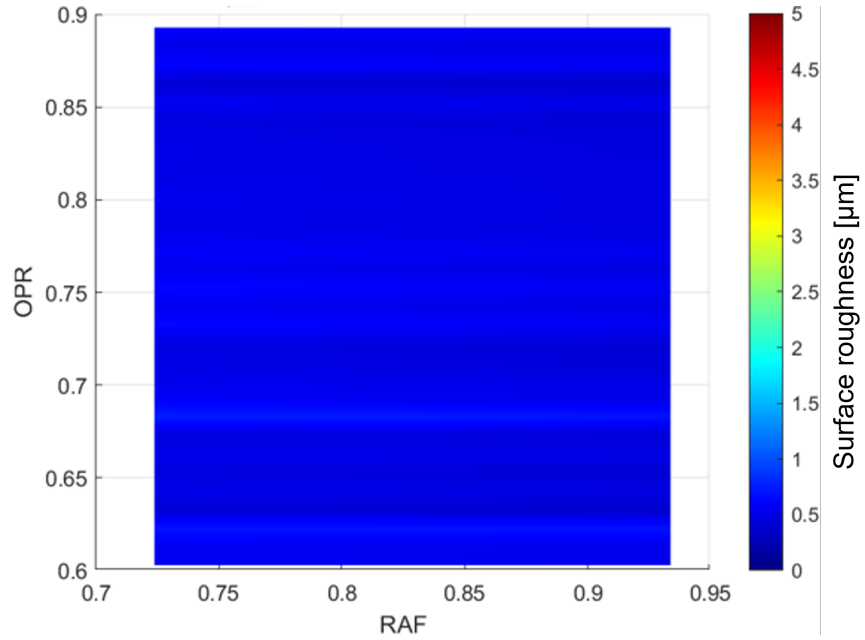


Figure A.10: Surface finish heat map for 55 degree 0.0254 mm/rev 0.6 OPR 1.0 RAF test cut

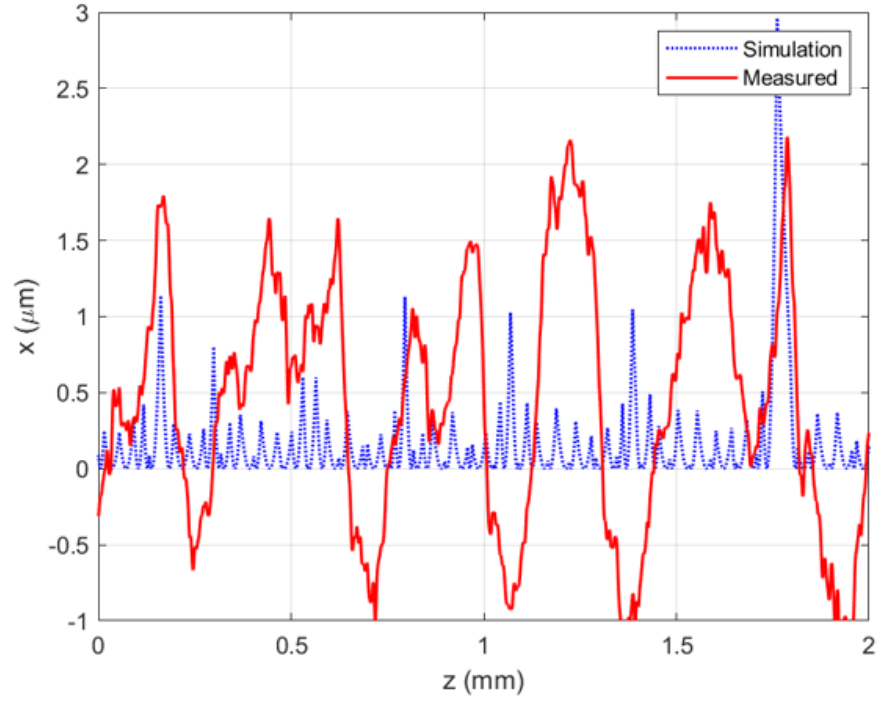


Figure A.11: Simulation surface profile compared to measured profile for 55 degree 0.0254 mm/rev 0.5 OPR 1.5 RAF test cut

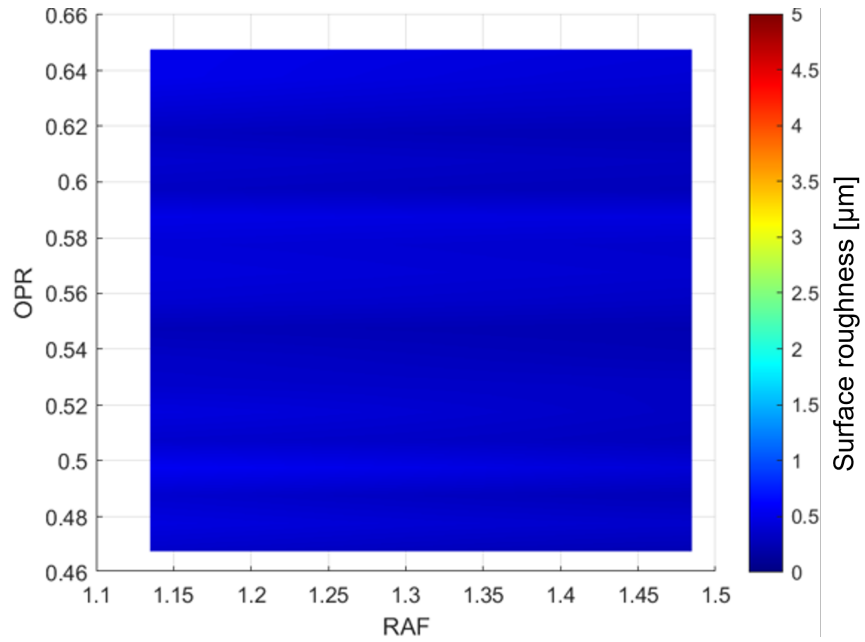


Figure A.12: Surface finish heat map for 55 degree 0.0254 mm/rev 0.5 OPR 1.5 RAF test cut

A.2 45 degree taper

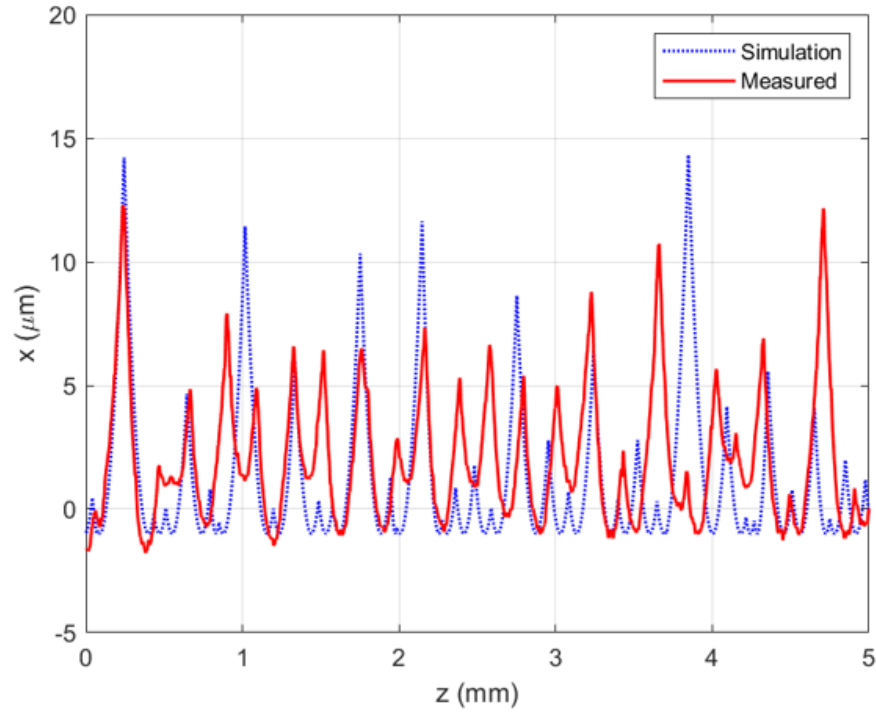


Figure A.13: Simulation surface profile compared to measured profile for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut

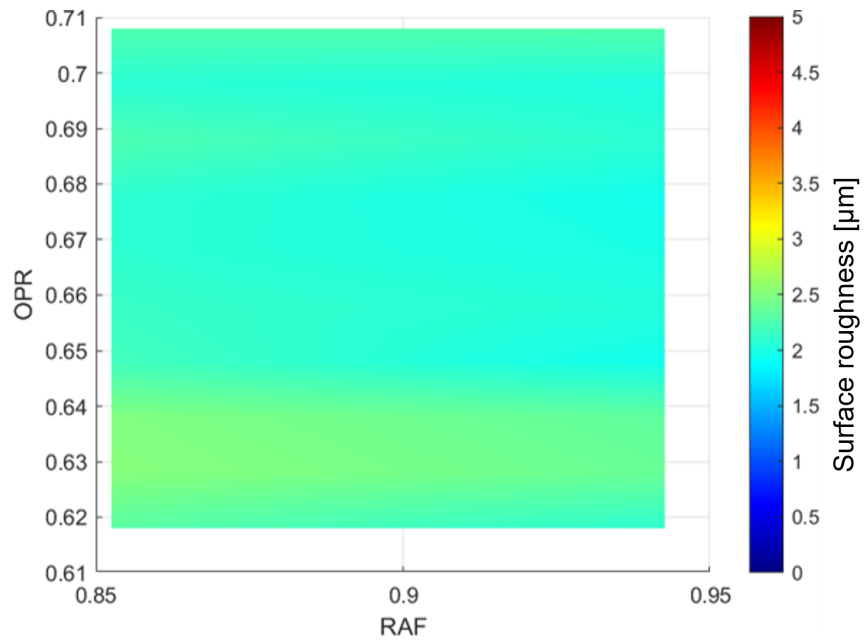


Figure A.14: Surface finish heat map for 45 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut

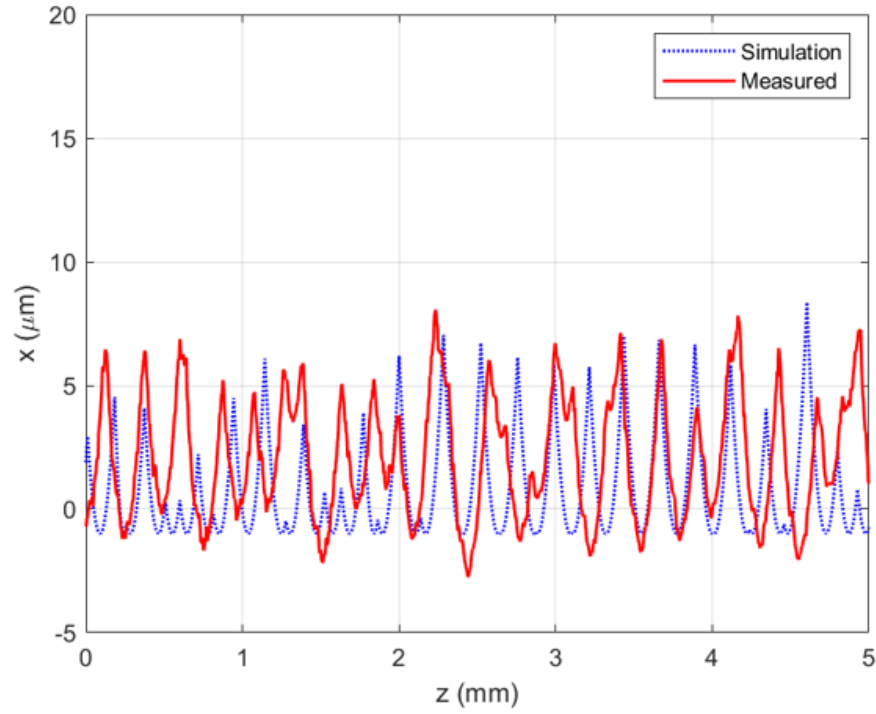


Figure A.15: Simulation surface profile compared to measured profile for 45 degree 0.127 mm/rev 0.5 OPR 1.5 RAF test cut

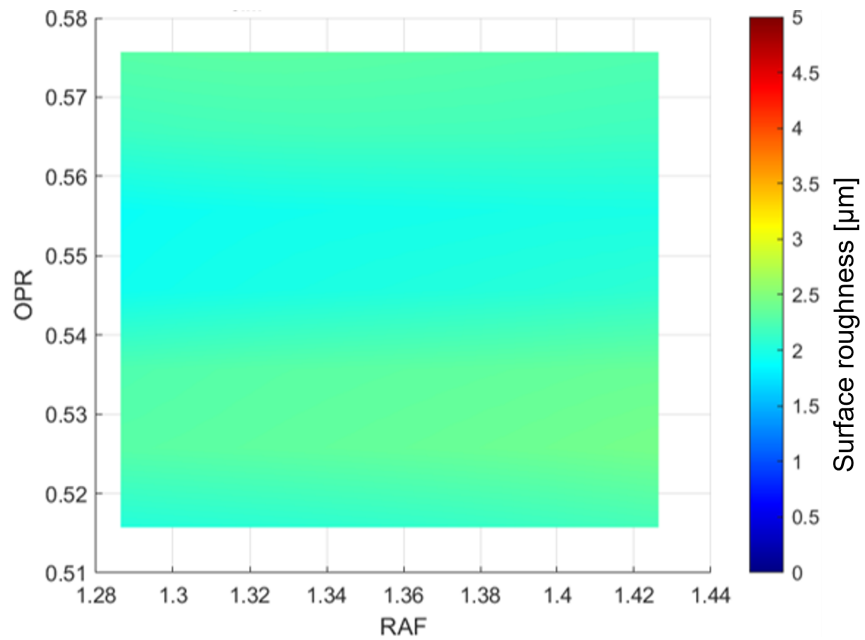


Figure A.16: Surface finish heat map for 45 degree 0.127 mm/rev 0.5 OPR 1.5 RAF test cut

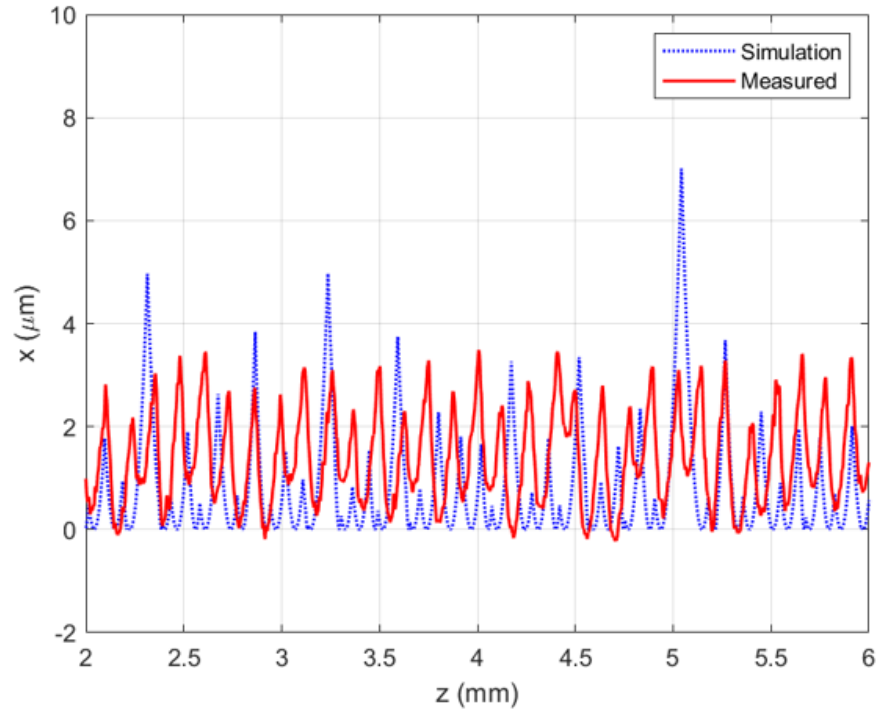


Figure A.17: Simulation surface profile compared to measured profile for 45 degree 0.0762 mm/rev 0.6 OPR 1.0 RAF test cut

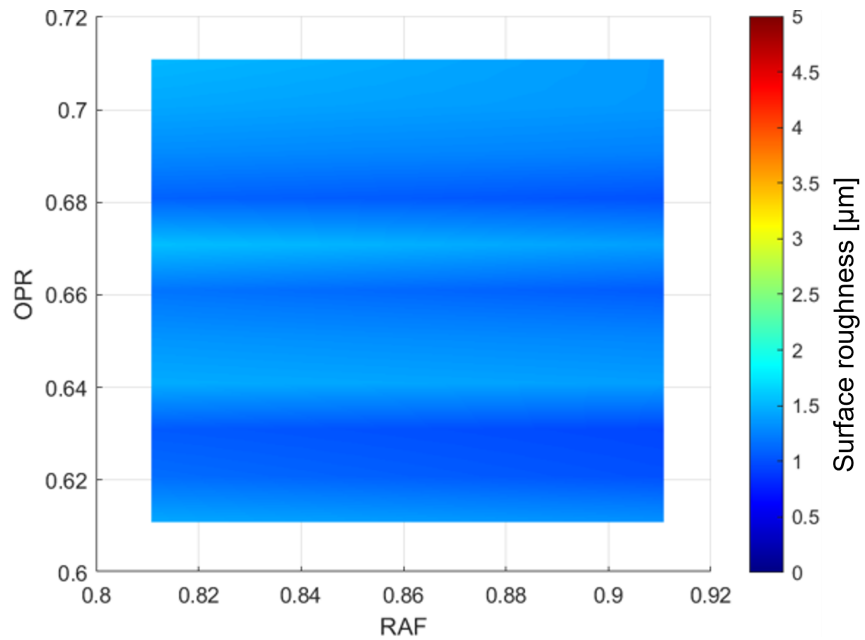


Figure A.18: Surface finish heat map for 45 degree 0.0762 mm/rev 0.6 OPR 1.0 RAF test cut

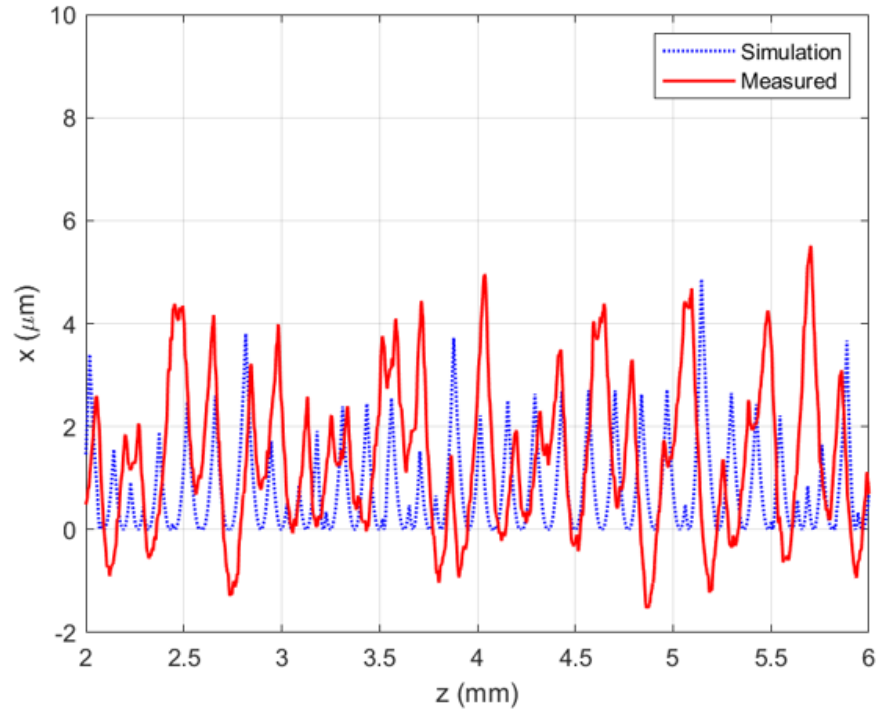


Figure A.19: Simulation surface profile compared to measured profile for 45 degree 0.0762 mm/rev 0.5 OPR 1.5 RAF test cut

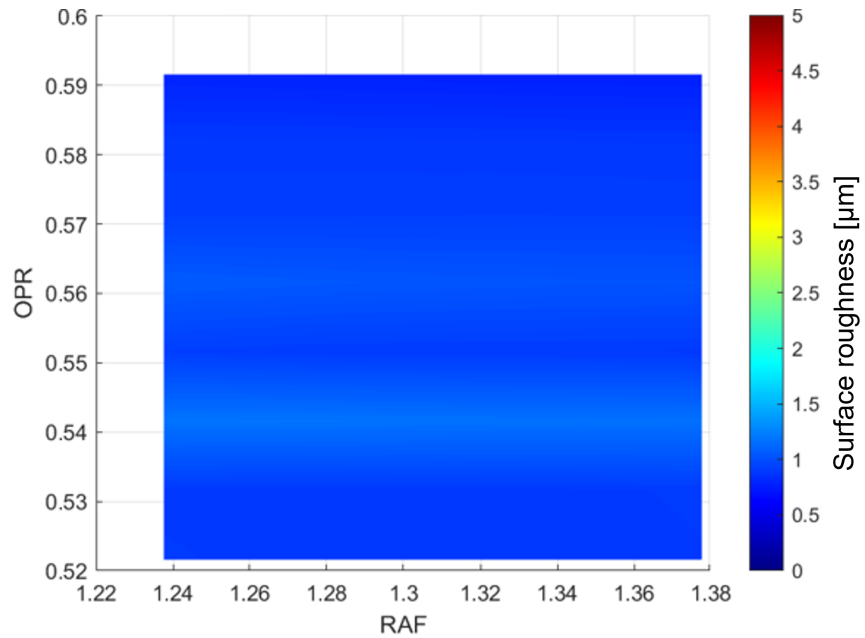


Figure A.20: Surface finish heat map for 45 degree 0.0762 mm/rev 0.5 OPR 1.5 RAF test cut

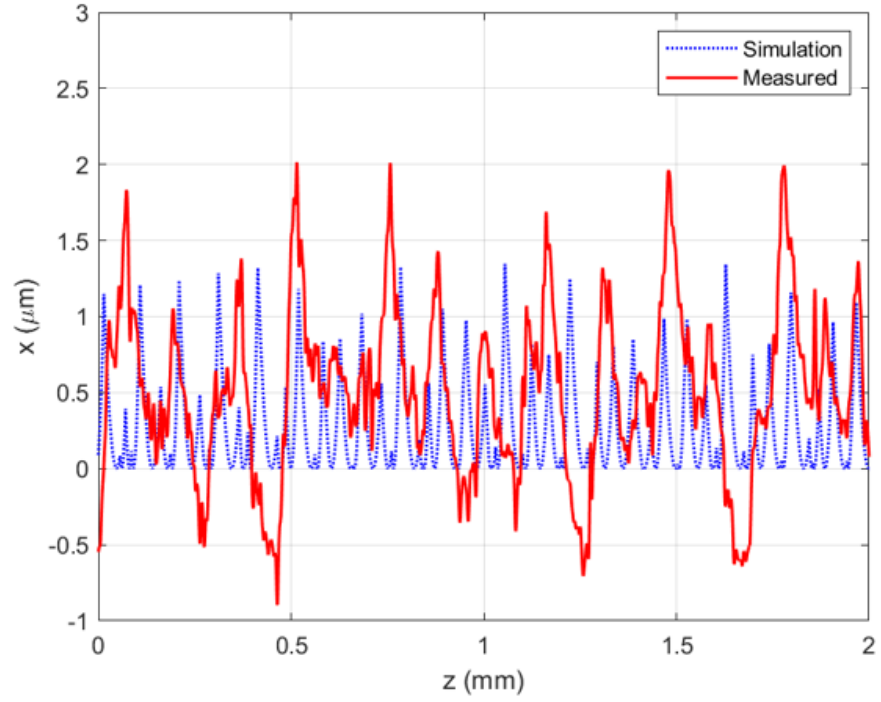


Figure A.21: Simulation surface profile compared to measured profile for 45 degree 0.0254 mm/rev 0.6 OPR 1.0 RAF test cut

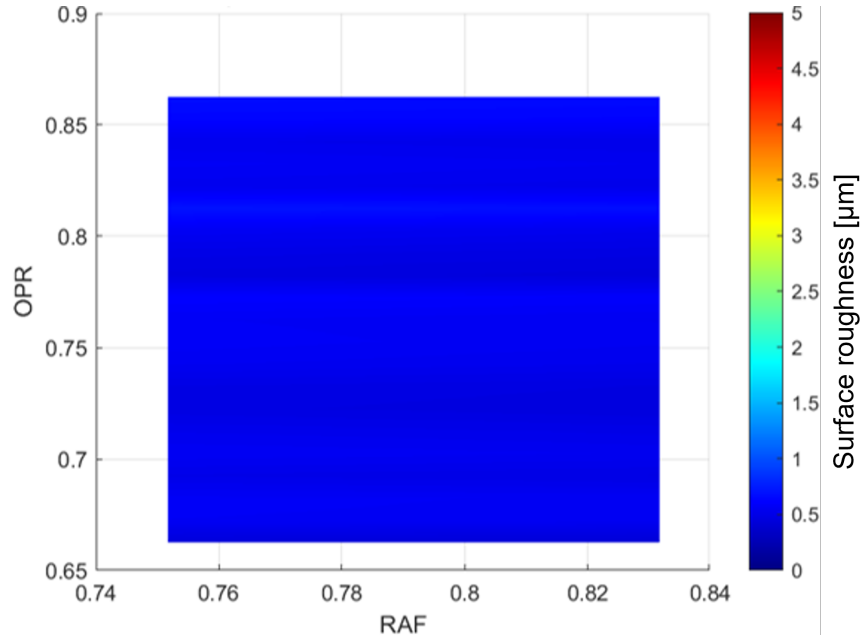


Figure A.22: Surface finish heat map for 45 degree 0.0254 mm/rev 0.6 OPR 1.0 RAF test cut

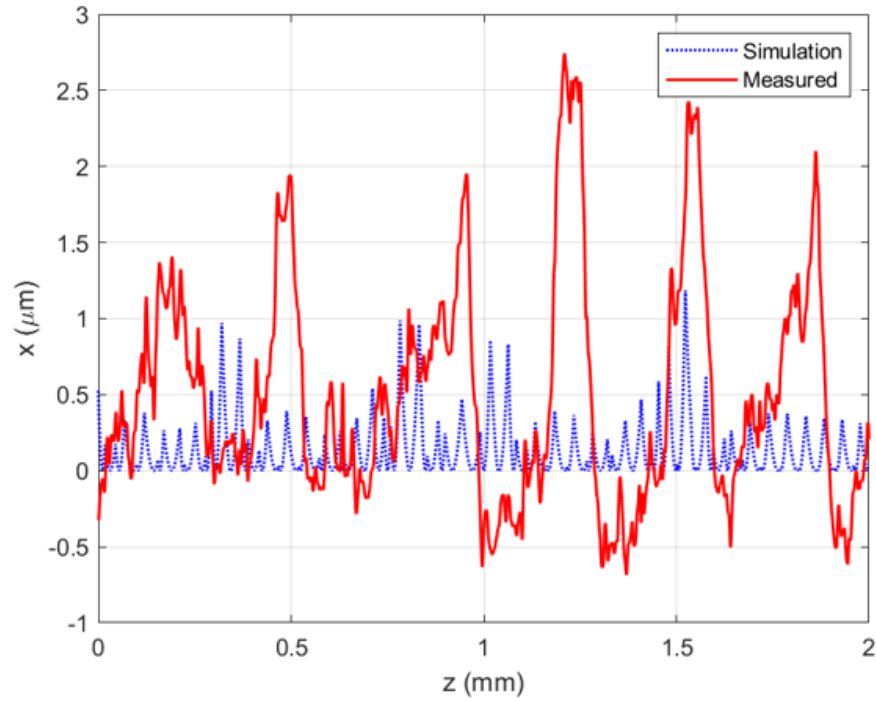


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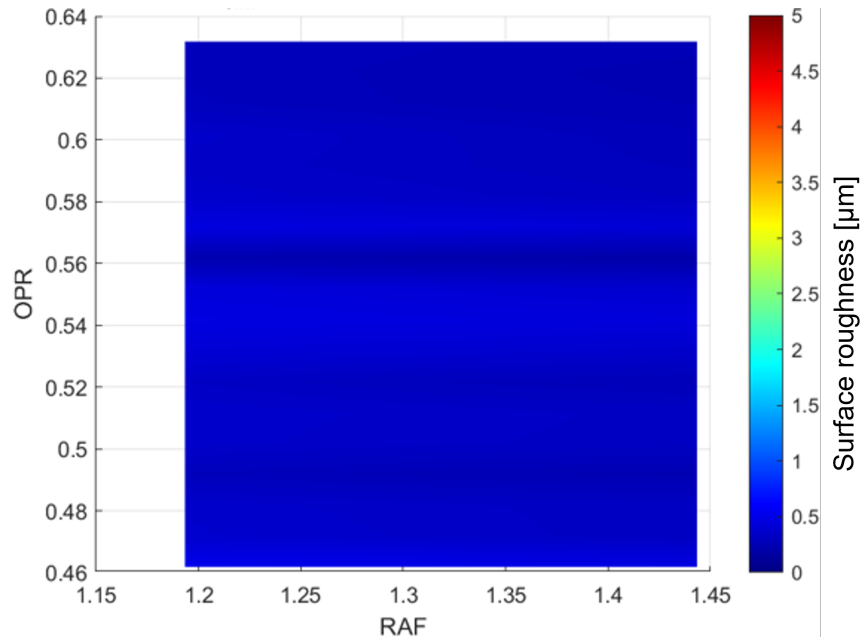


Figure A.24: Surface finish heat map for 45 degree 0.0254 mm/rev 0.5 OPR 1.5 RAF test cut

A.3 35 degree taper

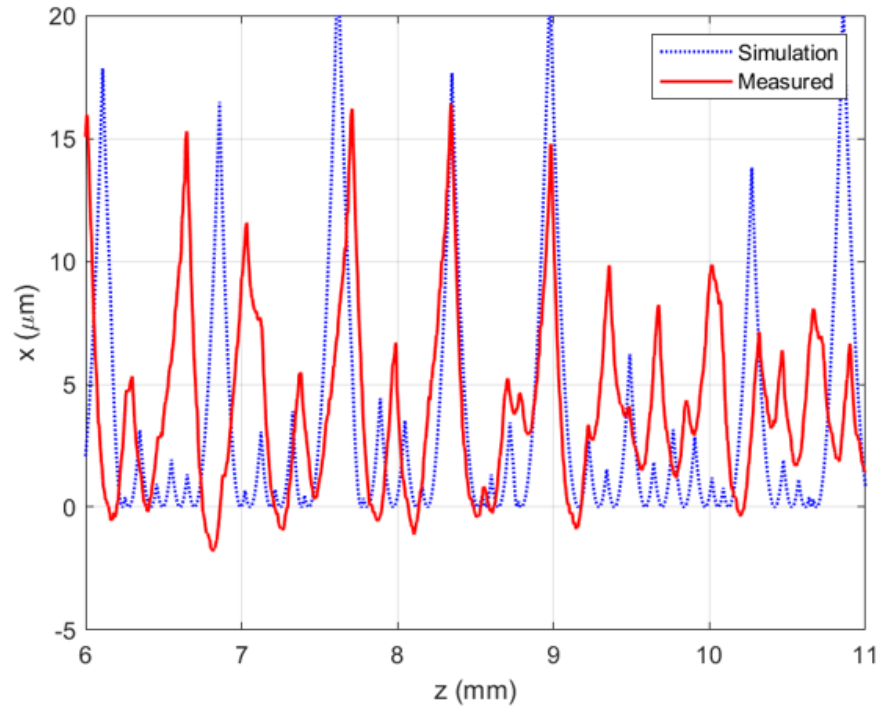


Figure A.25: Simulation surface profile compared to measured profile for 35 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut

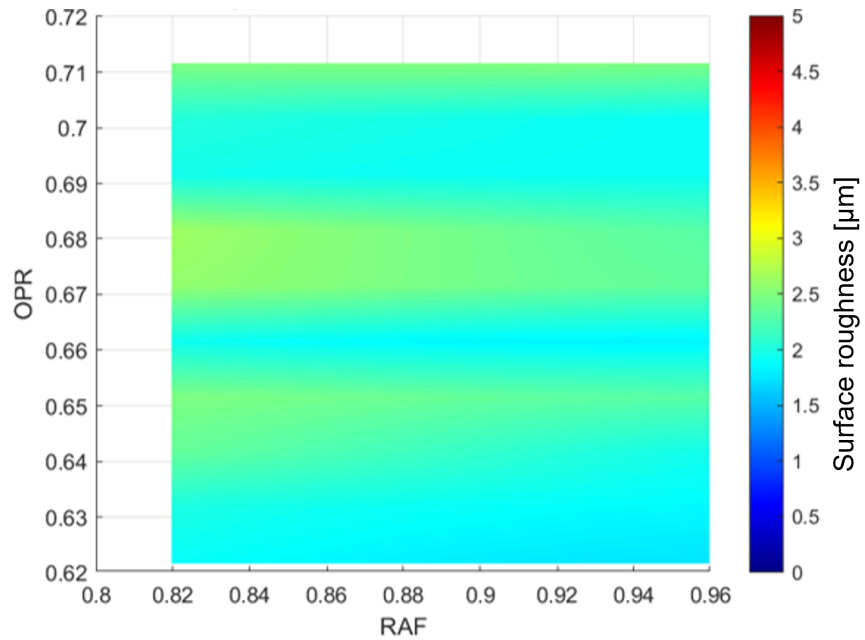


Figure A.26: Surface finish heat map for 35 degree 0.127 mm/rev 0.6 OPR 1.0 RAF test cut

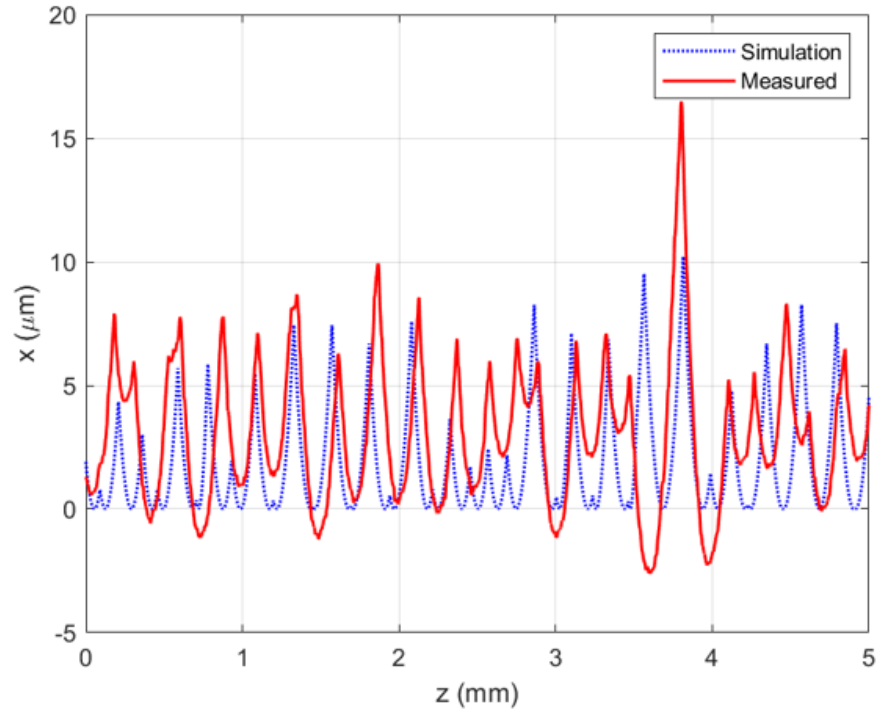


Figure A.27: Simulation surface profile compared to measured profile for 35 degree 0.127 mm/rev 0.5 OPR 1.5 RAF test cut

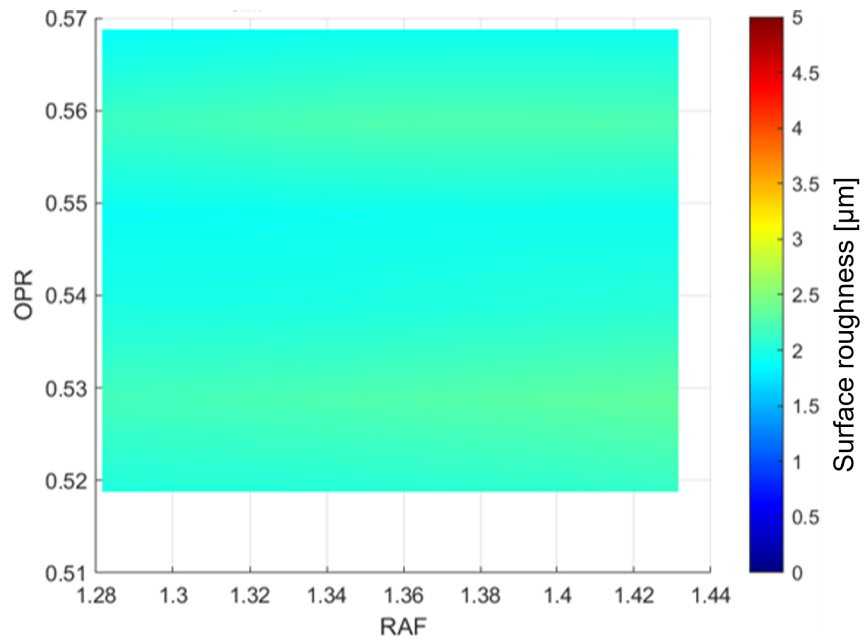


Figure A.28: Surface finish heat map for 35 degree 0.127 mm/rev 0.5 OPR 1.5 RAF test cut

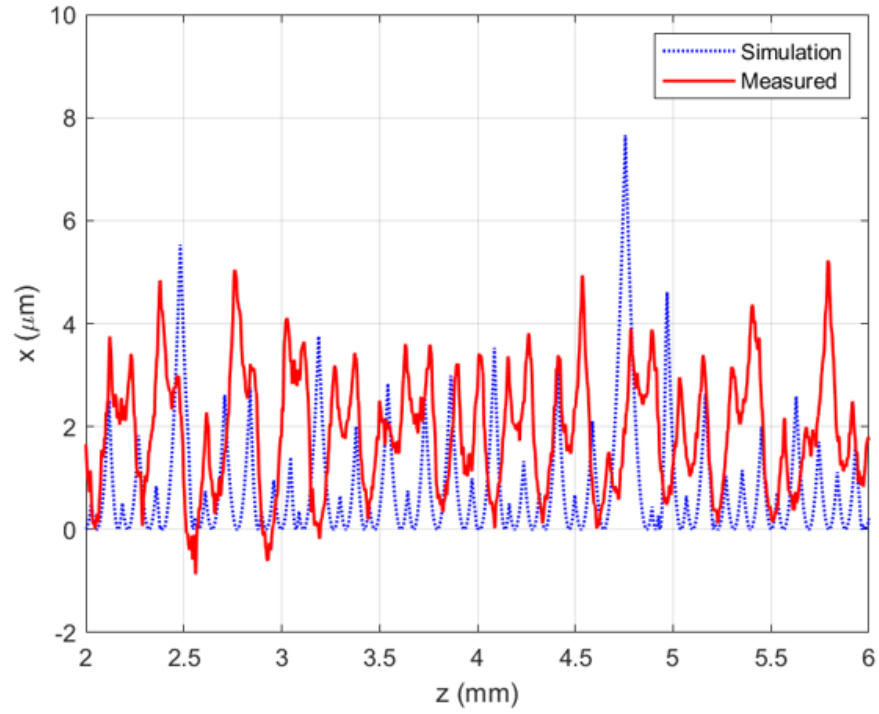


Figure A.29: Simulation surface profile compared to measured profile for 35 degree 0.0762 mm/rev 0.6 OPR 1.0 RAF test cut

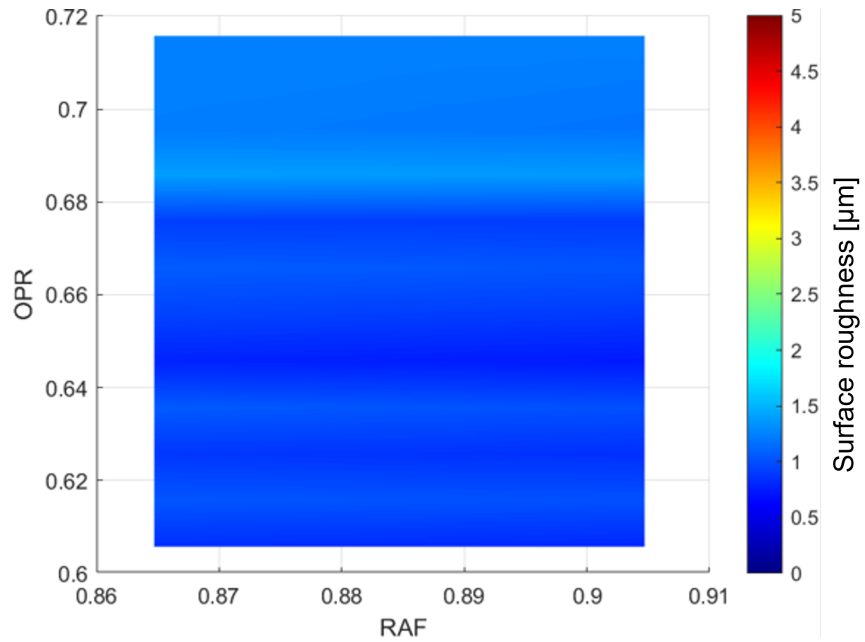


Figure A.30: Surface finish heat map for 35 degree 0.0762 mm/rev 0.6 OPR 1.0 RAF test cut

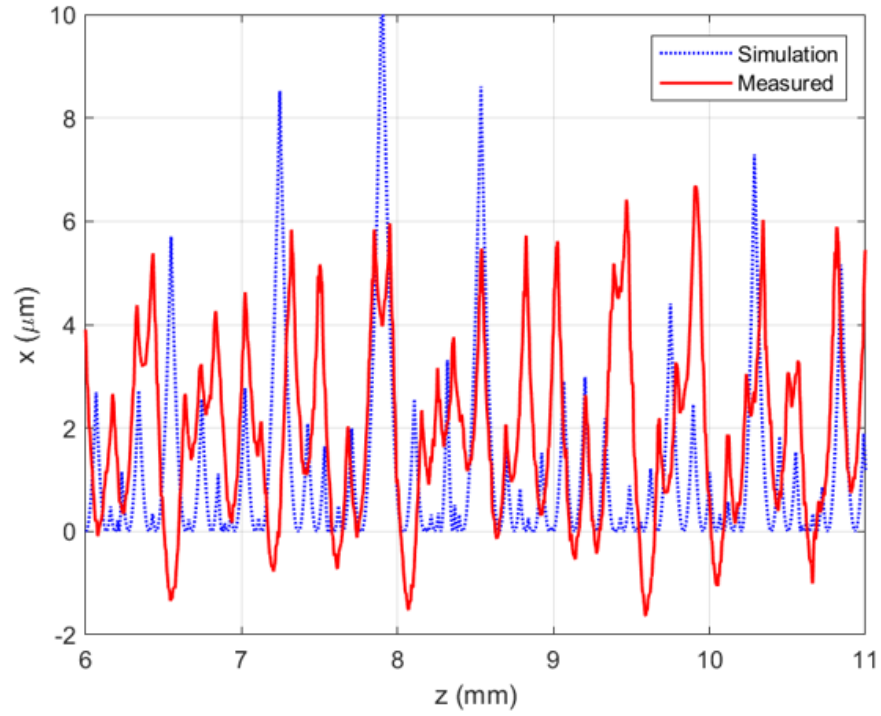


Figure A.31: Simulation surface profile compared to measured profile for 35 degree 0.0762 mm/rev 0.5 OPR 1.5 RAF test cut

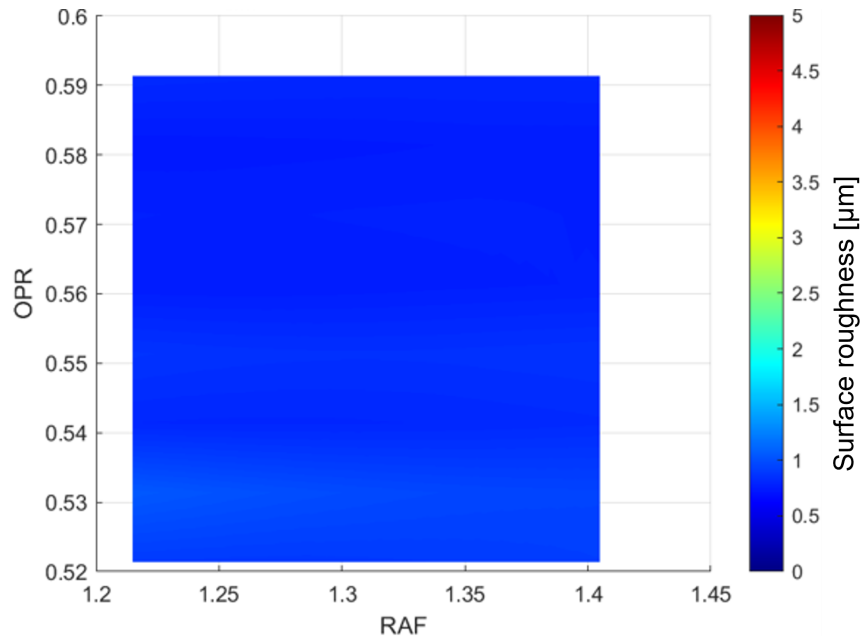


Figure A.32: Surface finish heat map for 35 degree 0.0762 mm/rev 0.5 OPR 1.5 RAF test cut

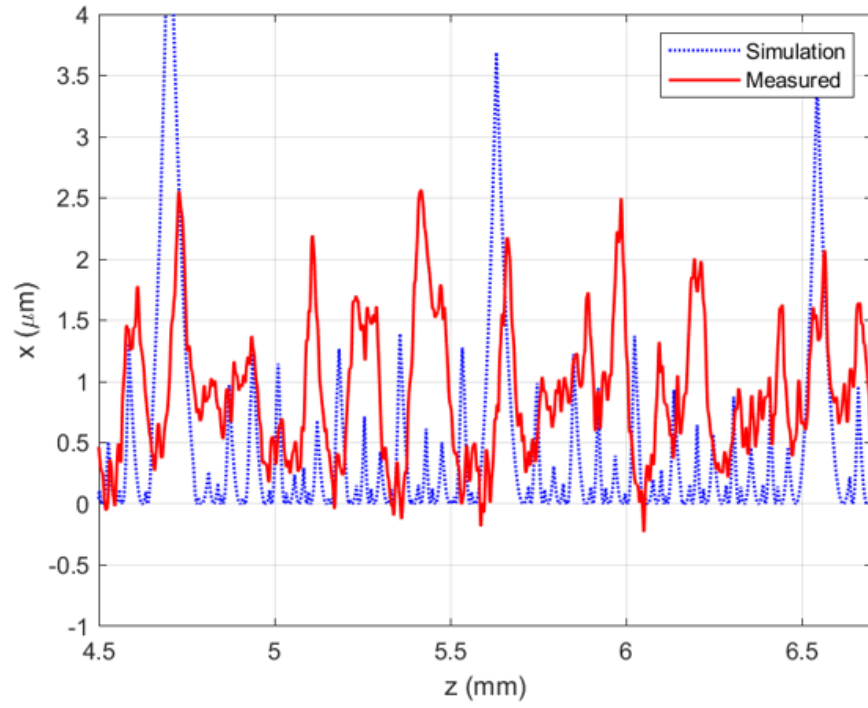


Figure A.33: Simulation surface profile compared to measured profile for 35 degree 0.0254 mm/rev 0.6 OPR 1.0 RAF test cut

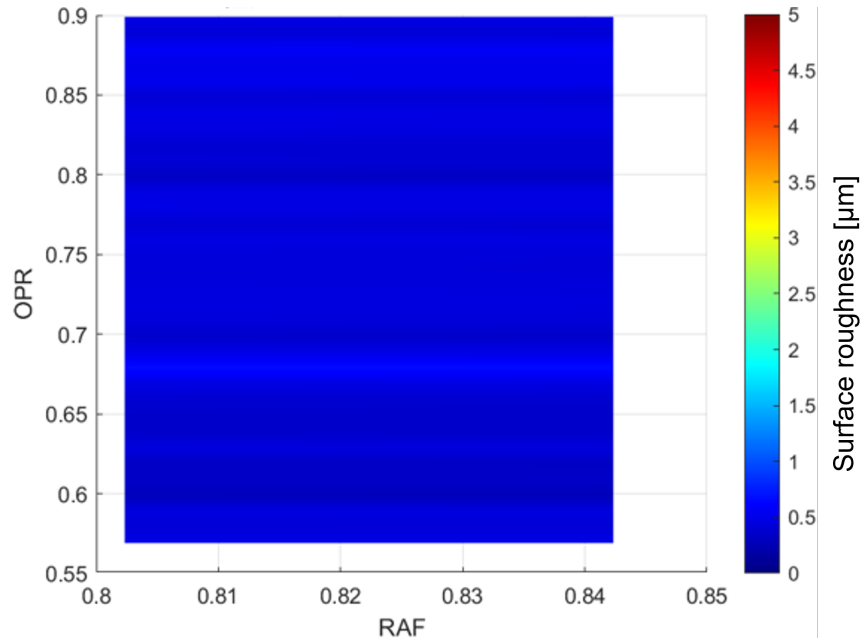


Figure A.34: Surface finish heat map for 35 degree 0.0254 mm/rev 0.6 OPR 1.0 RAF test cut

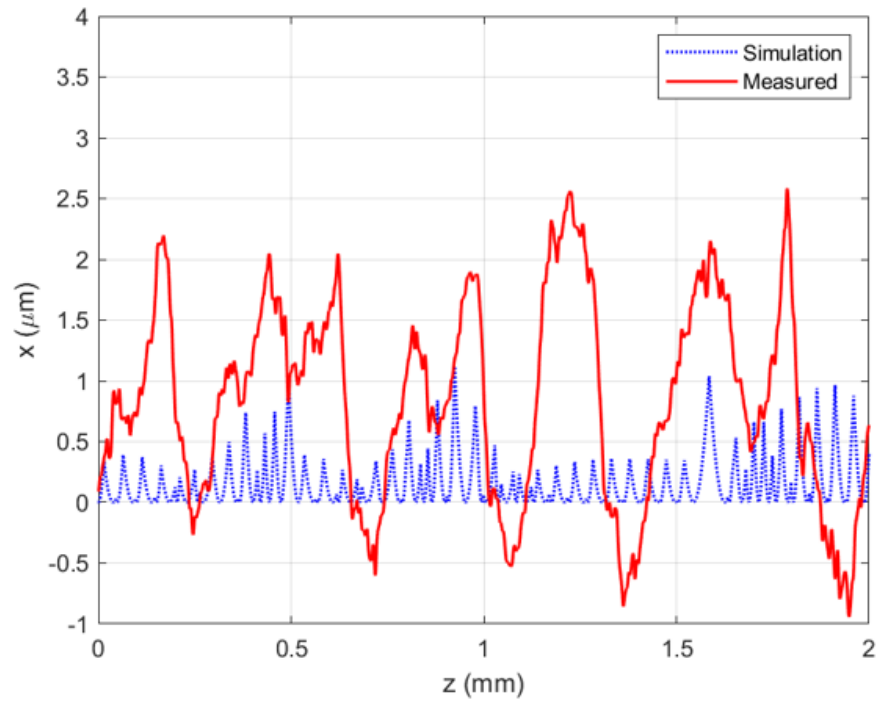


Figure A.35: Simulation surface profile compared to measured profile for 35 degree 0.0254 mm/rev 0.5 OPR 1.5 RAF test cut

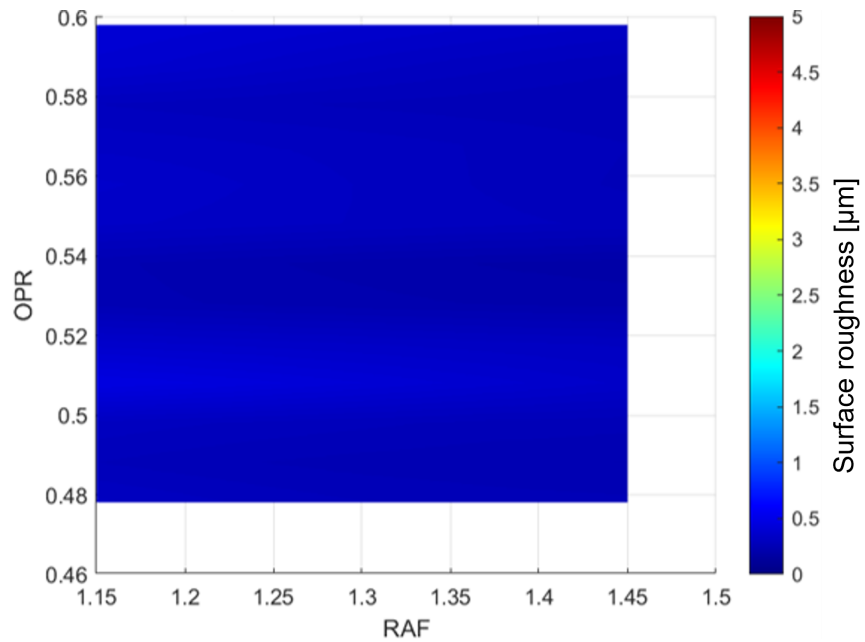


Figure A.36: Surface finish heat map for 35 degree 0.0254 mm/rev 0.5 OPR 1.5 RAF test cut

Appendix B

MTTP results

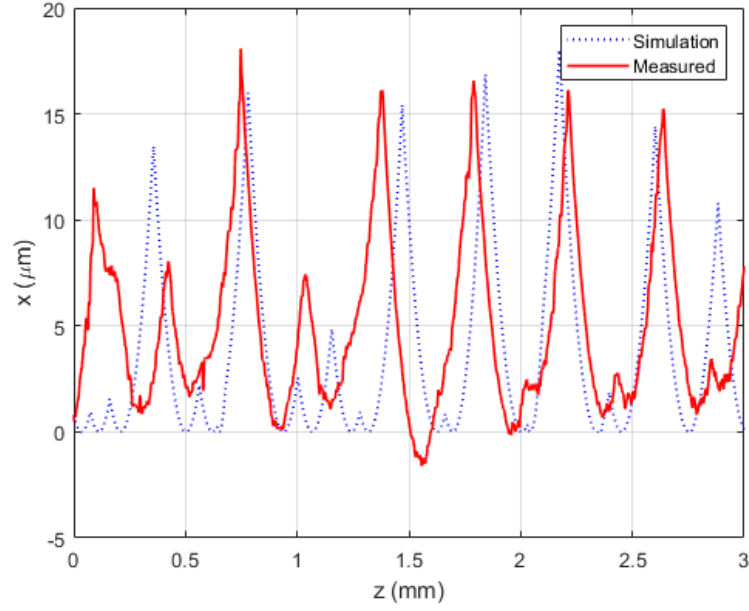


Figure B.1: Simulation surface profile compared to measured profile for MTTP at the 25 degree location for 0.127 mm/rev, 0.6 OPR, 1.0 RAF test cut

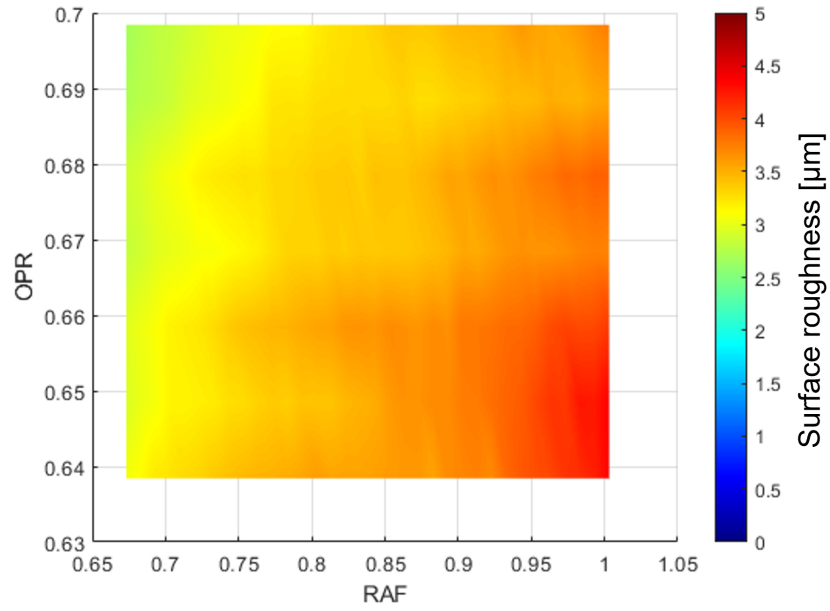


Figure B.2: Surface finish heat map for MTTP 0.127 mm/rev, 0.6 OPR, 1.0 RAF at 25 degree position.

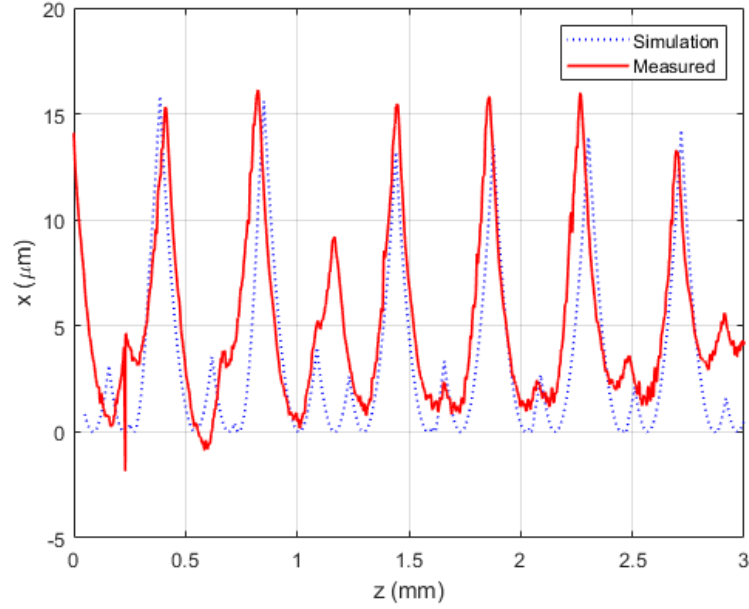


Figure B.3: Simulation surface profile compared to measured profile for MTTP at the 45 degree location for 0.127 mm/rev, 0.6 OPR, 1.0 RAF test cut

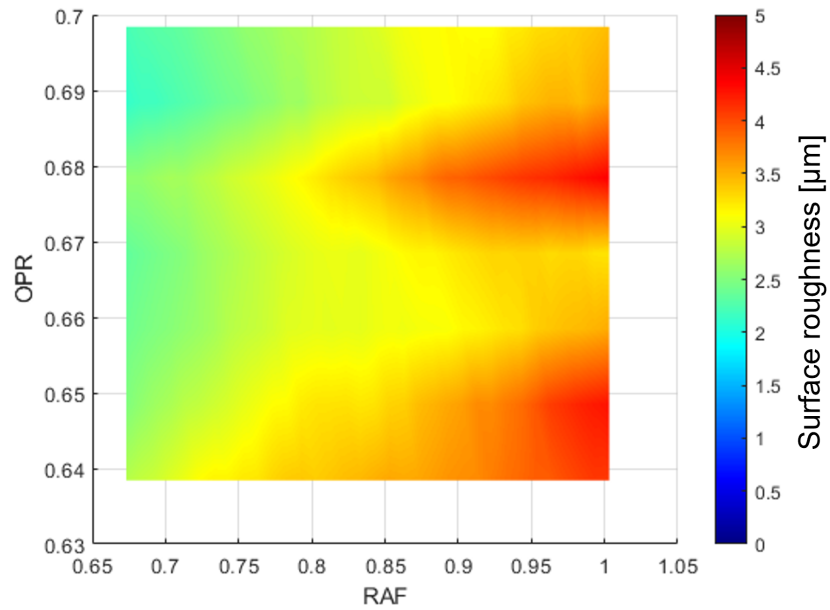


Figure B.4: Surface finish heat map for MTTP 0.127 mm/rev, 0.6 OPR, 1.0 RAF at 45 degree position.

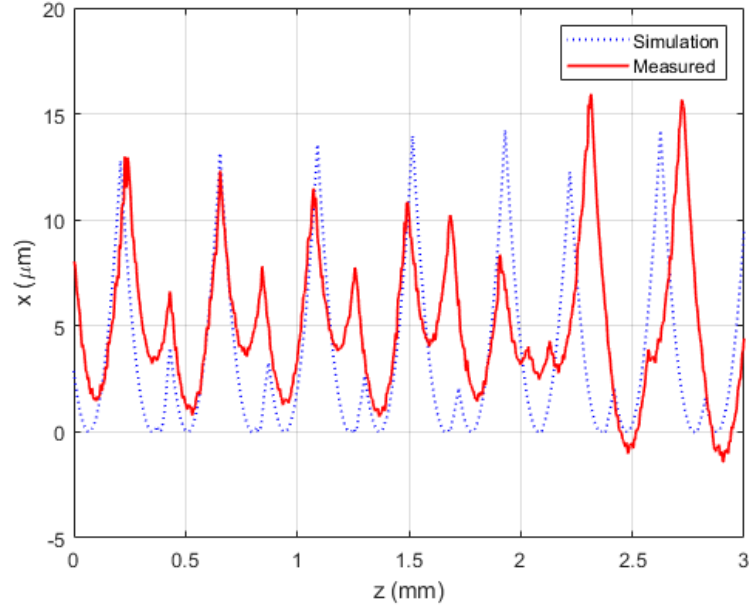


Figure B.5: Simulation surface profile compared to measured profile for MTTP at the 55 degree location for 0.127 mm/rev, 0.6 OPR, 1.0 RAF test cut

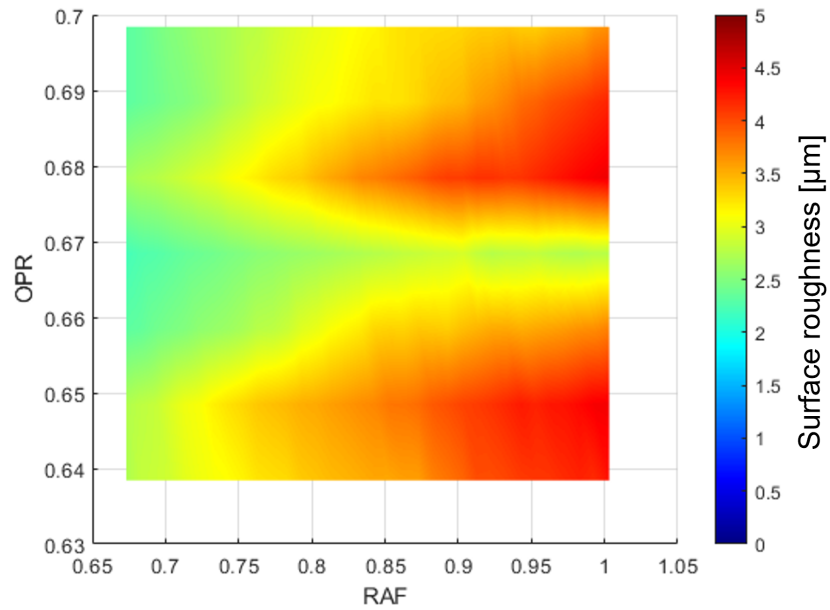


Figure B.6: Surface finish heat map for MTTP 0.127 mm/rev, 0.6 OPR, 1.0 RAF at 55 degree position.

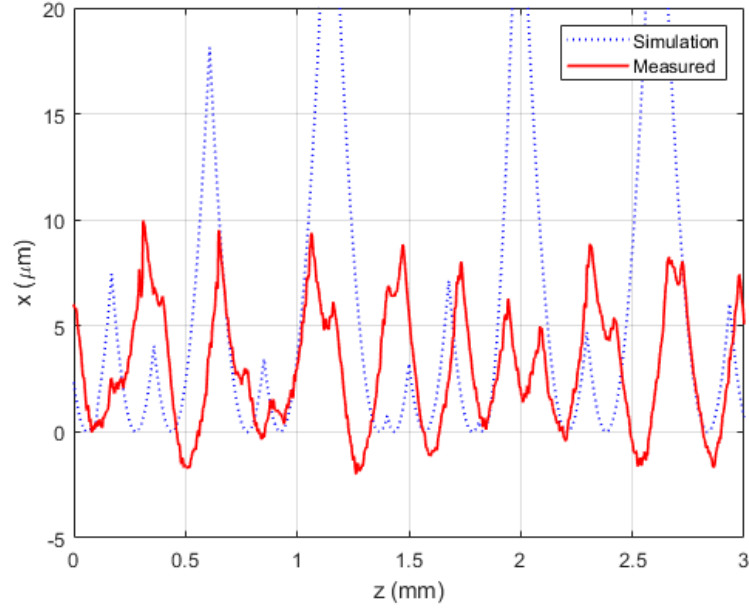


Figure B.7: Simulation surface profile compared to measured profile for MTTP at the 25 degree location for 0.127 mm/rev, 0.5 OPR, 1.5 RAF test cut

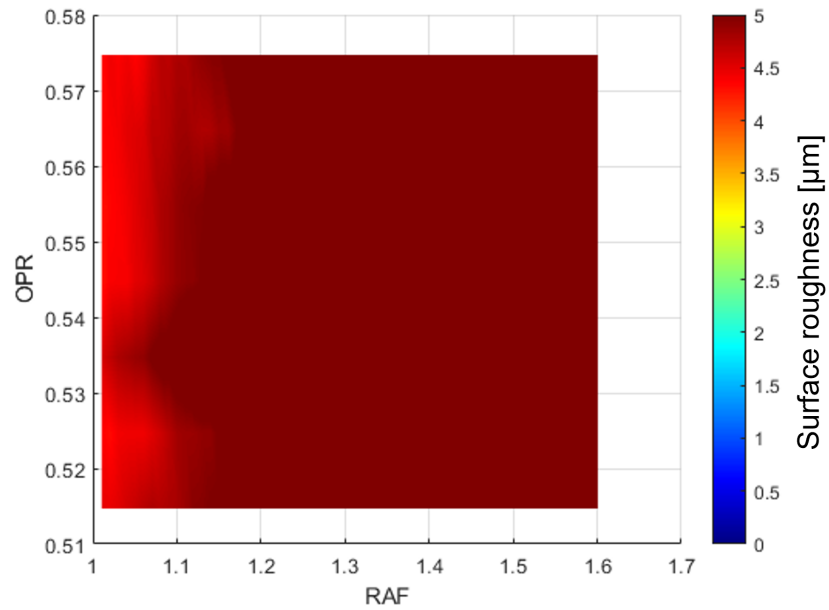


Figure B.8: Surface finish heat map for MTTP 0.127 mm/rev, 0.5 OPR, 1.5 RAF at 25 degree position.

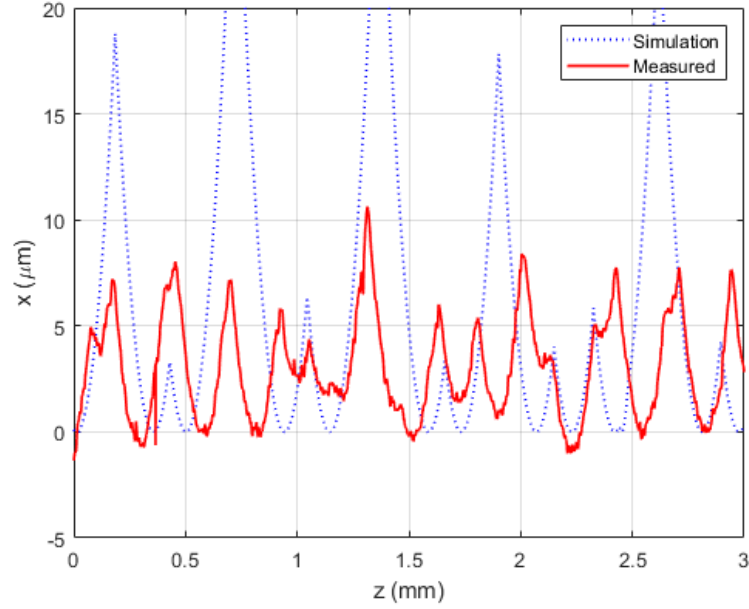


Figure B.9: Simulation surface profile compared to measured profile for MTTP at the 45 degree location for 0.127 mm/rev, 0.5 OPR, 1.5 RAF test cut

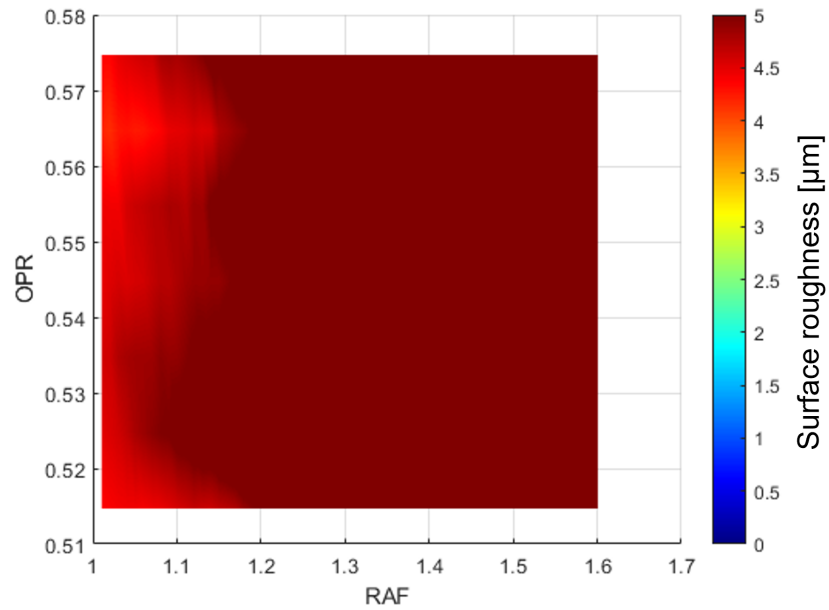


Figure B.10: Surface finish heat map for MTTP 0.127 mm/rev, 0.5 OPR, 1.5 RAF at 45 degree position.

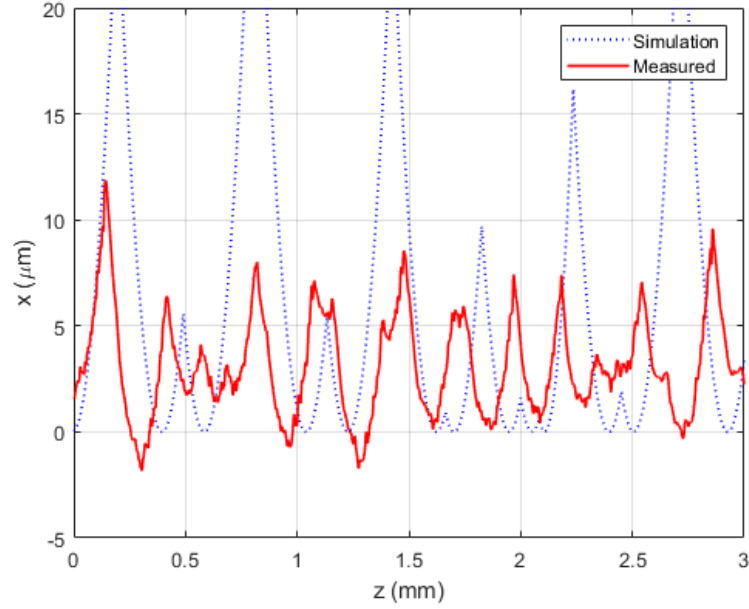


Figure B.11: Simulation surface profile compared to measured profile for MTTP at the 55 degree location for 0.127 mm/rev, 0.5 OPR, 1.5 RAF test cut

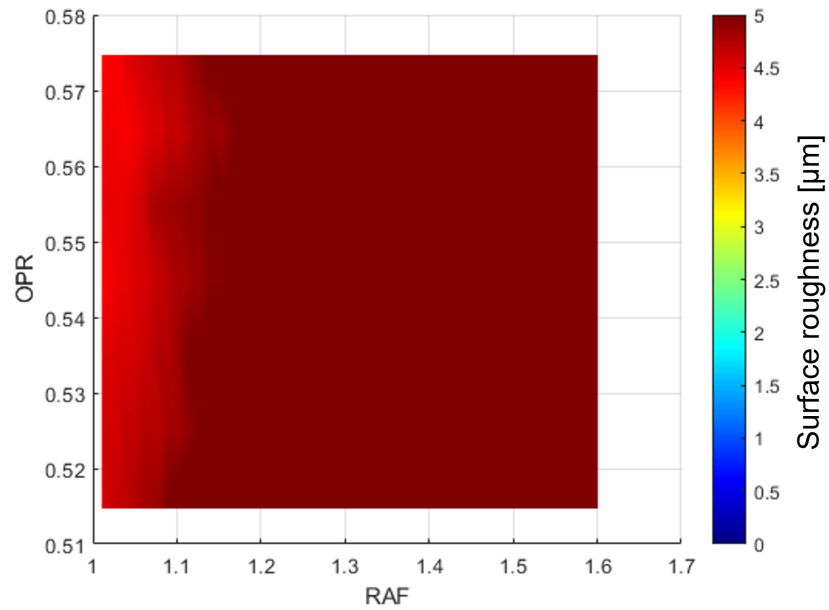


Figure B.12: Surface finish heat map for MTTP 0.127 mm/rev, 0.5 OPR, 1.5 RAF at 55 degree position.

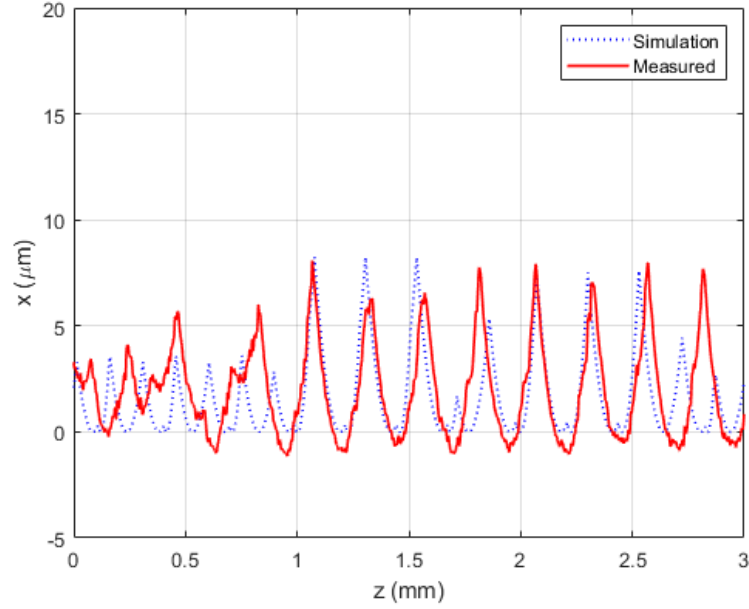


Figure B.13: Simulation surface profile compared to measured profile for MTTP at the 25 degree location for 0.0762 mm/rev, 0.6 OPR, 1.0 RAF test cut

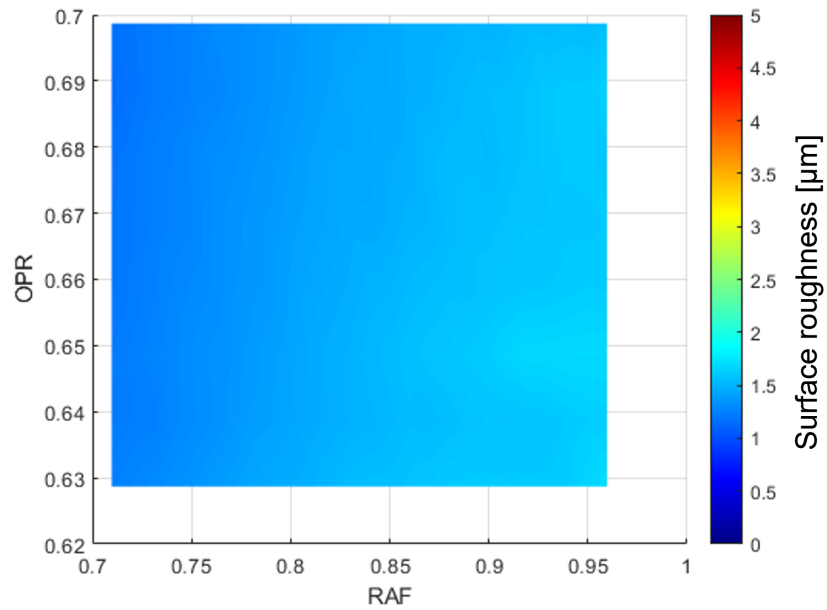


Figure B.14: Surface finish heat map for MTTP 0.0762 mm/rev, 0.6 OPR, 1.0 RAF at 25 degree position.

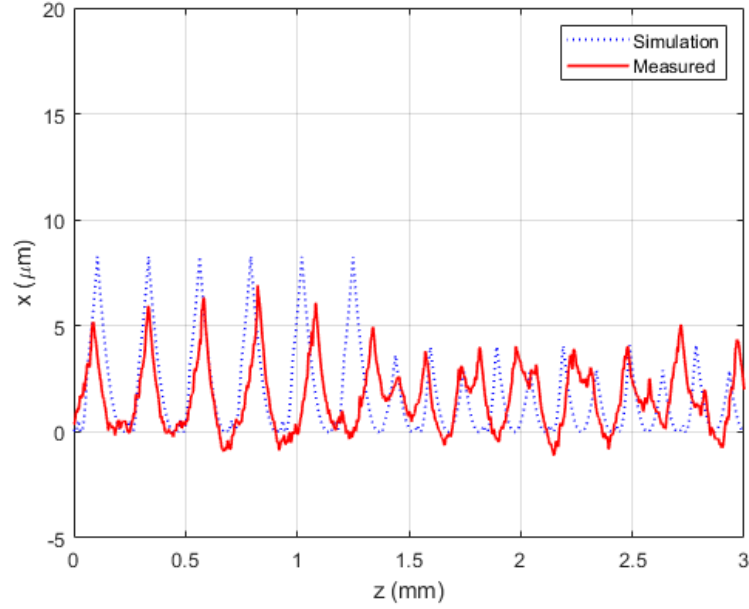


Figure B.15: Simulation surface profile compared to measured profile for MTTP at the 45 degree location for 0.0762 mm/rev, 0.6 OPR, 1.0 RAF test cut

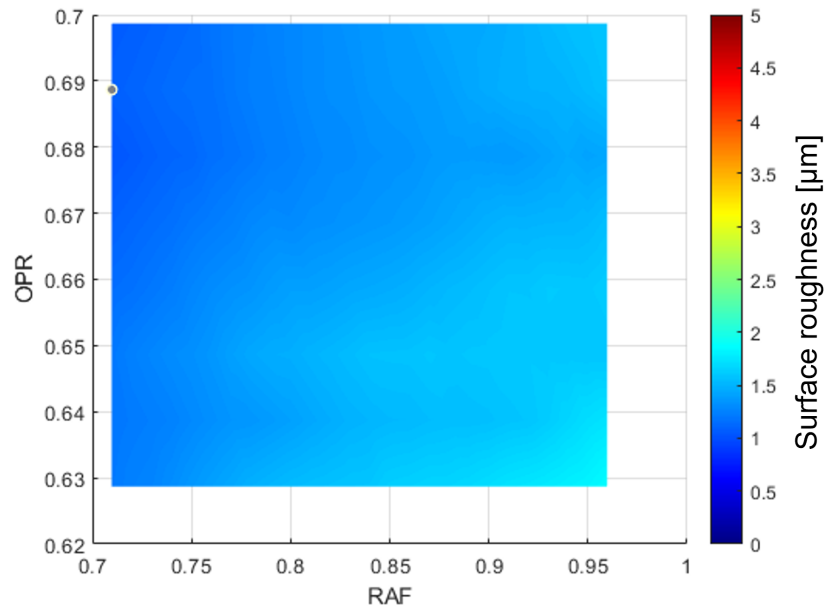


Figure B.16: Surface finish heat map for MTTP 0.0762 mm/rev, 0.6 OPR, 1.0 RAF at 45 degree position.

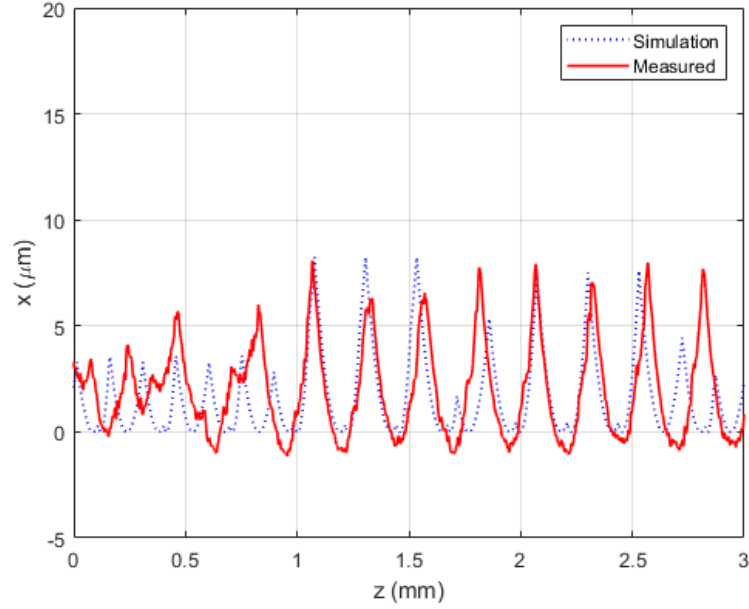


Figure B.17: Simulation surface profile compared to measured profile for MTTP at the 55 degree location for 0.0762 mm/rev, 0.6 OPR, 1.0 RAF test cut

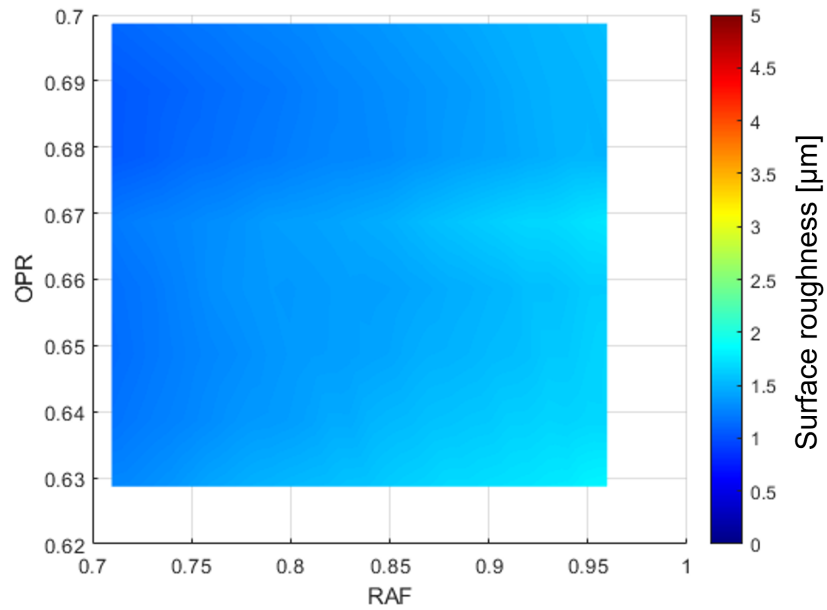


Figure B.18: Surface finish heat map for MTTP 0.0762 mm/rev, 0.6 OPR, 1.0 RAF at 55 degree position.

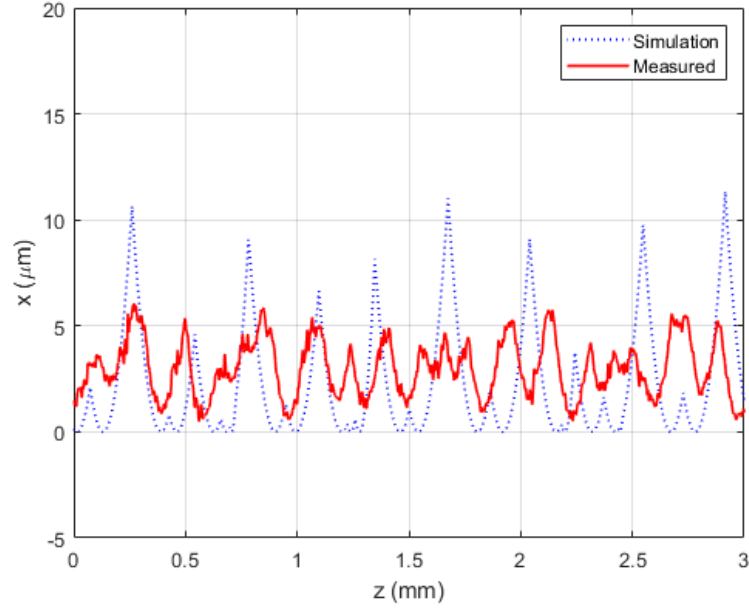


Figure B.19: Simulation surface profile compared to measured profile for MTTP at the 25 degree location for 0.0762 mm/rev, 0.5 OPR, 1.5 RAF test cut

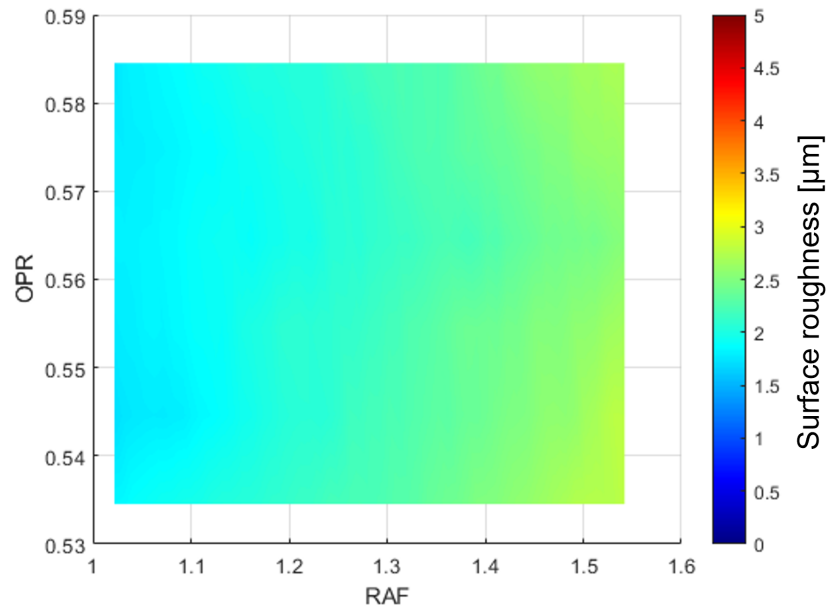


Figure B.20: Surface finish heat map for MTTP 0.0762 mm/rev, 0.5 OPR, 1.5 RAF at 25 degree position.

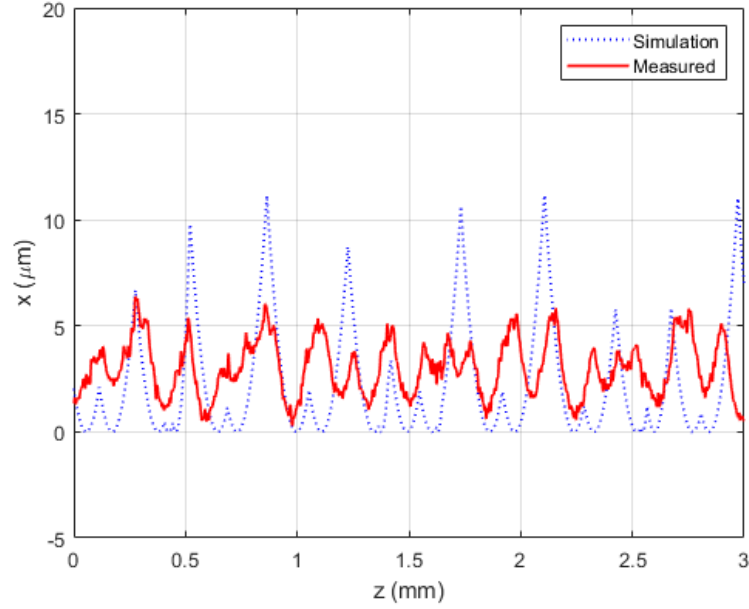


Figure B.21: Simulation surface profile compared to measured profile for MTTP at the 45 degree location for 0.0762 mm/rev, 0.5 OPR, 1.5 RAF test cut

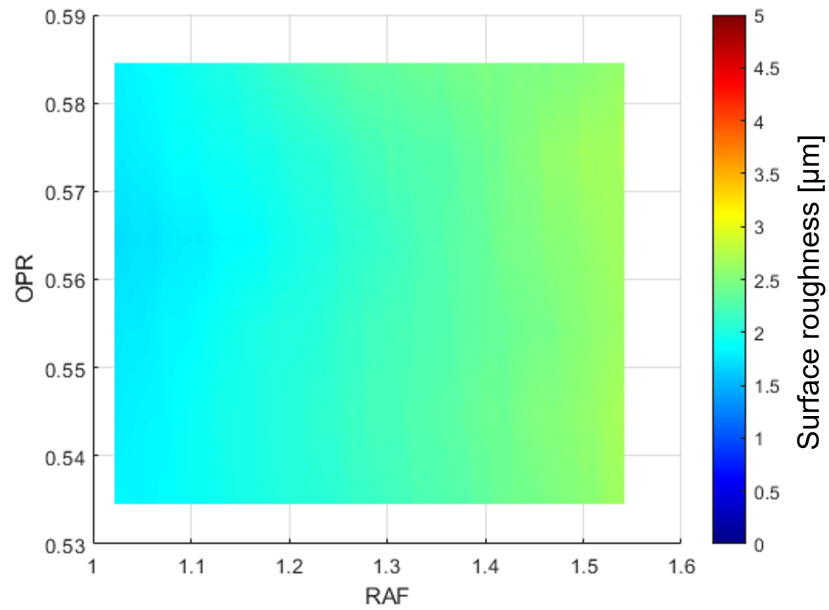


Figure B.22: Surface finish heat map for MTTP 0.0762 mm/rev, 0.5 OPR, 1.5 RAF at 45 degree position.

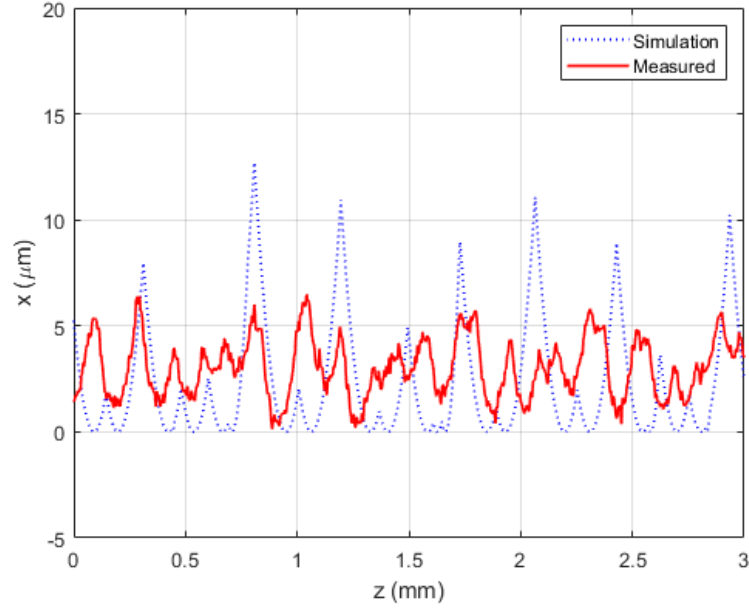


Figure B.23: Simulation surface profile compared to measured profile for MTTP at the 55 degree location for 0.0762 mm/rev, 0.5 OPR, 1.5 RAF test cut

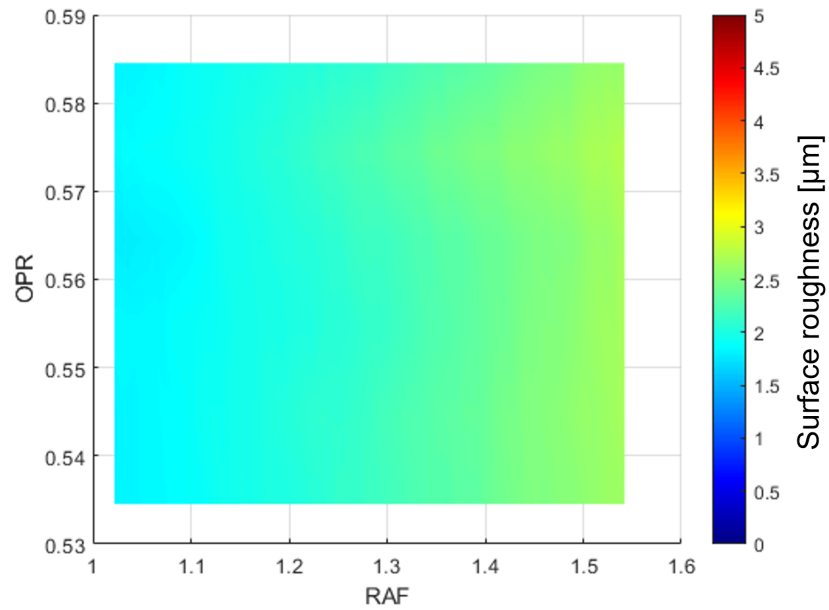


Figure B.24: Surface finish heat map for MTTP 0.0762 mm/rev, 0.5 OPR, 1.5 RAF at 55 degree position.

Appendix C

Matlab code

C.1 Single axis turning

```
% mtp_simulation_single_surface_side_flow.m
% R. Garcia
% Last Edited: 5-Aug-2022
% Program to predict surface finish from time domain
  simulation for MTP.

clear
close all
clc

% Modal parameters
% Modal parameters in the plane of the cut (feed direction
  , lathe YZ plane)
% u1 direction (cutting, lathe Y)

%Frequency (Hz)
```

```

wnu1 = [207
331
402
574
686
904
1003
1325
1363
1933
]'*2*pi;          % rad/s

```

```

%Stiffness (N/m)

```

```

ku1 = [1.48E+08
1.87E+07
7.76E+07
1.97E+08
7.89E+08
6.72E+07
1.19E+08
1.49E+08
4.71E+07
5.26E+08
]';              % N/m

```

```

%Damping (%)

```

```

zetau1 = [2.86
2.67

```

```

2.44
4
1.36
3.48
3.77
2.21
1.5
1.49
]'/100;

mu1 = ku1./(wnu1.^2);           % kg
cu1 = 2*zetau1.*(mu1.*ku1).^0.5; % N-s/m
u1_modes = length(ku1);        % number of modes
    in u1 direction, integer

% u2 direction (surface normal in plane of cut, lathe Z)
%Frequency (Hz)
wnu2 = [187
375
873
1730
2036
3022
4554
5659
7043
8831
]'*2*pi;    % rad/s

```

```
%Stiffness (N/m)
```

```
ku2 = [1.00E+11  
6.09E+07  
3.94E+07  
3.81E+08  
1.62E+08  
8.11E+08  
1.89E+08  
1.72E+08  
8.35E+07  
2.84E+08  
' ; % N/m
```

```
%Damping (%)
```

```
zetau2 = [1.41  
4.21  
72.79  
10.47  
7.68  
7.42  
10  
8.67  
10.56  
8.61  
' /100;
```

```
mu2 = ku2./(wnu2.^2); % kg
```

```

cu2 = 2*zetau2.*(mu2.*ku2).^0.5;           % N-s/m
u2_modes = length(ku2);                     % number of modes
    in u2 direction, integer

% Modal parameters in the radial direction
% u3 direction (radial direction of cylindrical part,
    lathe X)
%Frequency (Hz)
wnu3 = [265
318
359
440
611
647
809
994
1352
1933
]'*2*pi;   % rad/s

%Stiffness (N/m)
ku3 = [1.25E+08
3.35E+07
1.14E+08
1.92E+08
2.48E+08
2.67E+08
4.23E+08

```



```

5.80E+07
3.52E+07
5.93E+08
]';          % N/m

%Damping (%)
zetau3 = [2.97
2.54
2.1
2.23
1.08
1.43
1.9
3.45
2.41
1.03
]'/100;

mu3 = ku3./(wnu3.^2);          % kg
cu3 = 2*zetau3.*(mu3.*ku3).^0.5; % N-s/m
u3_modes = length(ku3);      % number of modes
    in u3 direction, integer

% Cutting model directions (lathe, YZ plane)
alpha1 = 90;
alpha2 = 90 - alpha1;
alpha1 = alpha1*pi/180;
alpha2 = alpha2*pi/180;

```

```

% MTP parameters
OPR = 0; %Set to zero because MTP disabled
RAF = 0; %Set to zero because MTP disabled
%OPR = 0.585;
%RAF = 2.05;
%OPR = 0.575;
%RAF = 2.15;

% Simulation inputs
sfm = 800; % Surface feet per
           minute
diameter = 2.8; % Diameter of work
               piece

omega = (sfm*(12/pi()))/diameter; % rpm
b = 0.127e-3; % commanded chip width
    , m (0.005 in)
%fr = 1.2702e-05; % feed per revolution,
    m (0.0005in/rev)
%fr = 2.54015e-05; % feed per revolution,
    m (0.001in/rev)
%fr = 5.07472e-05; % feed per revolution,
    m (0.002in/rev)
%fr = 0.000101441; % feed per revolution,
    m (0.004in/rev)
%fr = 0.000126805; % feed per revolution,
    m (0.005in/rev)

```

```

%fr = 0.000152173;           % feed per revolution,
    m (0.006in/rev)
%fr = 0.000202921;           % feed per revolution,
    m (0.008in/rev)
%fr = 0.000253621;           % feed per revolution,
    m (0.010in/rev)
fr = 0.000304387;            % feed per revolution,
    m (0.012in/rev)

fnu1 = ((ku1./mu1).^0.5)/2/pi; % Hz
fnu2 = ((ku2./mu2).^0.5)/2/pi; % Hz
fnu3 = ((ku3./mu3).^0.5)/2/pi; % Hz
maxfn = max([fnu1 fnu2 fnu3]);
dt = 1/(100*maxfn);           % time step size,
    s
w = (omega/60)*2*pi;           % rotating
    frequency, rad/s
steps_rev = round(1/(dt*omega/60)); % number of steps
    per revolution
sampling_period = round(steps_rev/OPR); % number of
    samples for once per period sampling
OPR = steps_rev/sampling_period; % reset OPR with
    integer values of steps_rev and sampling_period
time_rev = 60/omega;           % time per
    revolution, s/rev
num_rev = 75;                  % number of
    revolutions

```

```

total_steps = num_rev*(steps_rev + 1); % total steps
dphi = dt*omega*(2*pi)/60;           % angular step
    size, rad

% Define MTP motion
t = (0:total_steps-1)*dt;             % time, s
z = (omega/60*fr)*t + RAF*fr*sin(w*OPR*t); % feed
    motion, m, positive into cut in feed direction (lathe
    Z)
dz = (omega/60*fr) + w*OPR*RAF*fr*sin(w*OPR*t); % feed
    velocity, m/s, positive into cut

% Set zero initial conditions
u1 = 0; velu1 = 0;
u2 = 0; velu2 = 0;
u3 = 0; velu3 = 0;
dp = zeros(1, u1_modes);
p = zeros(1, u1_modes);
dq = zeros(1, u2_modes);
q = zeros(1, u2_modes);
dr = zeros(1, u3_modes);
r = zeros(1, u3_modes);

% Predefine vectors
Force = zeros(1, total_steps);
F_thrust = zeros(1, total_steps);
zz = zeros(1, total_steps);           % tool motion, m,
    positive out of cut in surface normal direction

```

```

dzz = zeros(1, total_steps);           % tool velocity, m/s,
    positive out of cut
ddzz = zeros(1, total_steps);          % tool acceleration, m
    /s^2, positive out of cut
thick = zeros(1, total_steps);          % chip thickness, m
radial = zeros(1, total_steps);         % tool motion, m,
    positive away from part in radial direction

% Simulation begins here
for n = (steps_rev + 1):total_steps
    zmax = z(n - steps_rev) - zz(n - steps_rev);           %
        surface from prior pass

    for cnt = 2:(ceil(n/steps_rev) - 1)
        ztest = z(n - cnt*steps_rev) - zz(n - cnt*steps_rev
            );
        if ztest > zmax
            zmax = ztest;           % select maximum surface
                from all previous passes
        end
    end

    h = (z(n) - zz(n-1)) - zmax;      % instantaneous chip
        thickness in plane of cut, surface normal direction
        (lathe YZ)

```

```

kn = 0.83*(h*1e3).^(-2.07) + 732.63;      % N/mm^2,
      linear polynomial, LLNL Ra testing, 304 SS, positive
      rake, finish cut, surface normal direction (lathe Z
      )
kn = kn*1e6;                               % N/m^2
kt = 4.94*(h*1e3).^(-1.83) + 2820.52;      % N/mm^2,
      linear polynomial, LLNL Ra testing, 304 SS, positive
      rake, finish cut, cutting speed direction (lathe Y)
kt = kt*1e6;
Ks = (kt^2 + kn^2)^0.5;
beta = atan(kt/kn);                        % rad
kr = 2.19*(h*1e3).^(-2.07) + 2213.8;      % N/mm^2,
      linear polynomial, LLNL Ra testing, 304 SS, positive
      rake, finish cut, radial direction (lathe X)
kr = kr*1e6;

if h < 0      % no cutting
    h = 0;
end
thick(n) = h;

F = Ks*(b - u3)*h;                          % reduce chip width by
      u3, vibration in radial direction
Fu1 = F*cos(beta - alpha1);
Fu2 = F*cos(beta + alpha2);
Force(n) = F;                               % N
F_thrust(n) = F*cos(beta);
Fu3 = kr*(b - u3)*h;

```

```

% Perform Euler integrations
u1 = 0;
velu1 = 0;
accelu1 = 0;
u2 = 0;
velu2 = 0;
accelu2 = 0;
u3 = 0;

% u1 direction (cutting)
for cnt = 1:u1_modes
    ddp = (Fu1 - cu1(cnt)*dp(cnt) - ku1(cnt)*p(cnt))/
        mu1(cnt);
    accelu1 = accelu1 + ddp;
    dp(cnt) = dp(cnt) + ddp*dt;
    velu1 = velu1 + dp(cnt);
    p(cnt) = p(cnt) + dp(cnt)*dt;
    u1 = u1 + p(cnt);          % m
end

% u2 direction (surface normal in plane of cut)
for cnt = 1:u2_modes
    ddq = (Fu2 - cu2(cnt)*dq(cnt) - ku2(cnt)*q(cnt))/
        mu2(cnt);
    accelu2 = accelu2 + ddq;
    dq(cnt) = dq(cnt) + ddq*dt;
    velu2 = velu2 + dq(cnt);

```

```

        q(cnt) = q(cnt) + dq(cnt)*dt;
        u2 = u2 + q(cnt);          % m
    end

    % radial direction
    for cnt = 1:u2_modes
        ddr = (Fu3 - cu3(cnt)*dr(cnt) - ku3(cnt)*r(cnt))/
            mu3(cnt);
        dr(cnt) = dr(cnt) + ddr*dt;
        r(cnt) = r(cnt) + dr(cnt)*dt;
        u3 = u3 + r(cnt);          % m
    end

    % surface normal direction in plane of cut
    zz(n) = u1*cos(alpha1) + u2*cos(alpha2); % m
    dzz(n) = velu1*cos(alpha1) + velu2*cos(alpha2); % m/s
    ddzz(n) = accelu1*cos(alpha1) + accelu2*cos(alpha2); %
        m/s^2
    radial(n) = u3; % m
end % end of simulation for loop
%{
% Plot results
% tool motion
figure(1)
subplot(211)
plot(t, zz*1e6)
set(gca, 'FontSize', 14)
ylabel('z_t (\mum)')

```



```

zoom on
subplot(212)
plot(t, radial*1e6)
set(gca,'FontSize', 14)
xlabel('t (s)')
ylabel('r (\mu m)')
zoom on

% cutting force
figure(2)
plot(t, Force)
set(gca,'FontSize', 14)
xlabel('t (s)')
ylabel('F (N)')
zoom on

% chip thickness
figure(3)
plot(t, thick*1e3)
set(gca,'FontSize', 14)
xlabel('t (s)')
ylabel('h (mm)')
zoom on
%}

% total motion is difference of z (positive into cut) and
    zz (positive out
% of cut)

```

```

z_total = z - zz;

r = 73.4e-3/2;                                % workpiece radius, m
surface_dist = (0:steps_rev-1)*dphi*r;        % surface
distance, m

z_parse = z_total(1:steps_rev);
n_parse = radial(1:steps_rev);

%{
figure(4)
plot(surface_dist*1e3, z_total(1:steps_rev)*1e3, 'b')
set(gca,'FontSize', 14)
xlabel('d (mm)')
ylabel('z (mm)')
xlim([0 2*pi*r*1e3])
hold on
zoom on
%}

for cnt = 2:num_rev
    z_parse = [z_parse; z_total(((cnt-1)*steps_rev + 1):(
        cnt*steps_rev))];
    if rem(cnt, 2) == 1
        plot(surface_dist*1e3, z_total(((cnt-1)*steps_rev
            + 1):(cnt*steps_rev))*1e3, 'b')
    else

```

```

        plot(surface_dist*1e3, z_total(((cnt-1)*steps_rev
            + 1):(cnt*steps_rev))*1e3, 'r')
    end
    n_parse = [n_parse; radial(((cnt-1)*steps_rev + 1):(
        cnt*steps_rev))];
end

%nr = 0.794e-3;          % tool nose radius, m
%nr = 0.25e-3;
nr = 7.9375e-4;
%nr = 0.25e-3*RAF; %nr = 0.25e-3;
%nr = 0.4e-3*RAF; %nr = 0.4e-3;

test_point = round(steps_rev/4);
z_total_test = z_parse(:, test_point);
n_total_test = n_parse(:, test_point);
surface_dist_test = ones(num_rev, 1)*surface_dist(
    test_point);
plot(surface_dist_test*1e3, z_total_test*1e3, 'mo')

% set nr using feed since previous revolution
fr_eff = abs(diff(z_total_test));
fr_eff = [fr; fr_eff];

nr = zeros(1, num_rev);
for cnt = 1:num_rev

```

```

    if fr_eff(cnt) < 0.022e-3
        nr(cnt) = 0.1e-3;
    elseif fr_eff(cnt) > 0.1562e-3
        nr(cnt) = 0.794e-3;
    else
        nr(cnt) = 5.1724*fr_eff(cnt) - 0.0138e-3;
    end
end

z_temp = linspace(z_total_test(1)-0.5*nr(1), z_total_test
    (1)+0.5*nr(1), 25000);
n_temp = -((nr(1)^2 - (z_temp - z_total_test(1)).^2).^0.5)
    + n_total_test(1);

%{
figure(5)
plot(z_temp*1e3, n_temp*1e3, 'b')
set(gca,'FontSize', 14)
xlabel('z (mm)')
ylabel('n (mm)')
hold on
zoom on
%ylim([(-nr*1e3) (-nr*1e3 + 1e-3)])
%}

z_interp = linspace(z_total_test(1)-0.5*nr(1),
    z_total_test(num_rev)+0.5*nr(1), 1e5);

```

```

n_interp = interp1(z_temp, n_temp, z_interp);
n_vector = [n_interp];
for cnt = 2:num_rev
    z_temp = linspace(z_total_test(cnt)-0.5*nr(cnt),
        z_total_test(cnt)+0.5*nr(cnt), 25e3);
    n_temp = -((nr(cnt)^2 - (z_temp - z_total_test(cnt))
        .^2).^0.5) + n_total_test(cnt);
    if rem(cnt, 2) == 1
        plot(z_temp*1e3, n_temp*1e3, 'b')
    else
        plot(z_temp*1e3, n_temp*1e3, 'r')
    end
    n_interp = interp1(z_temp, n_temp, z_interp);
    n_vector = [n_vector; n_interp];
end

n_final = min(n_vector);
[peaks, index] = findpeaks(-n_final);
n_final = n_final(index(1):index(length(index)));
z_interp = z_interp(index(1):index(length(index)));
n_final = n_final - mean(n_final);

figure(6)
plot(z_interp*1e3, n_final*1e6, 'b')
title('Surface Finish Comparison')
set(gca, 'FontSize', 14)
xlabel('z (mm)')
ylabel('n (\num)')

```

```

hold on
zoom on
grid on

load '800_sfm_0120_Constant_OD cleaned data (Detrend).mat'
    %0.012 in/rev surface roughness data (800 sfm)
% load '800_sfm_010_Constant_OD cleaned data (Detrend).mat'
    ' %0.010 in/rev surface roughness data (800 sfm)
% load '800_sfm_008_Constant_OD cleaned data (Detrend).mat'
    ' %0.008 in/rev surface roughness data (800 sfm)
% load '800_sfm_004_Constant_OD cleaned data (Detrend).mat'
    ' %0.004 in/rev surface roughness data (800 sfm)
% load '800_sfm_002_Constant_OD cleaned data (Detrend).mat'
    ' %0.002 in/rev surface roughness data (800 sfm)

x_height_measured = new_data(:,1); %Saves the first column
    of the data to the variable
z_distance_measured = new_data(:,2); %Saves the second
    column of the data to the variable

% x_height_measured = x_height_measured.'; %Transposes
    matrix
% z_distance_measured = z_distance_measured.'; %Transposes
    matrix

```

```

z_distance_offset = abs(z_distance_measured(1)-0); %finds
    the offset from 0 of the data set
z_distance_measured = z_distance_measured -
    z_distance_offset; %shifts the data set to zero

plot(z_distance_measured*1e2,x_height_measured*1e4) %plots
    the measured data to compare it to the simulation
hold off

% saveas(6,'0.012 in/rev 800sfm.png');

%plot(z_meas_m*1e3 + 0.0, x_meas_m*1e6 + 0.15, 'r')
%plot(z_meas_m*1e3 + 0.062, x_meas_m*1e6 + 0.25, 'r')
%plot(z_meas_m*1e3, x_meas_m*1e6, 'r')
%plot(z_meas_m*1e3 + 0.0, x_meas_m*1e6 + 0, 'r')
%axis([2.45 2.8 -1 1.5])
%axis([1.7 2.3 -1.5 2])
%axis([0.5 3.5 -4 10])%axis([1.5 2.8 -4 10])
%axis([0.5 3.5 -4 8])%axis([1 3 -4 12])

```

C.2 Two axis linear turning

```

% css_taper_surface_r1.m
% R. Garcia
% 25-Sep-2024
% Constant surface speed for taper turning (linear
    interpolation) with
% stepped rpm approach

```

```

tic

clear

close all

clc

% Define turning parameters
fr = (0.001*25.4)*1e-3;           % feed per revolution
    in path direction, m/rev
% fr = (0.0022*25.4)*1e-3;       % feed per
    revolution in path direction, m/rev
% fr = (0.0926)*1e-3;           % feed per revolution in
    path direction, m/rev
theta = 35;                      % taper angle, deg
theta = theta*pi/180;           % taper angle, rad
frz = fr*cos(theta);            % feed per revolution in z
    direction, m/rev
frx = fr*sin(theta);            % feed per revolution in x
    direction, m/rev

omega0 = 388.446;               % spindle speed at starting
    radius, rpm
r0 = 37.4650e-3;                % starting radius, m
V = omega0*r0*2*pi/60;          % cutting speed, m/s

%% Simulation

```



```

% Perform simulation in equal rotation steps, dphi
dphi = 0.1; % angular step size, deg/
step
dphi = dphi*(2*pi)/360; % angular step size, rad/
step
% num_rev = 500; % number of revolutions
, -
num_rev = 250; % number of revolutions,
steps_rev = round((2*pi)/dphi); % steps per revolution, -
steps = num_rev*steps_rev; % number of steps, -

dz = frz/steps_rev; % z motion per step, m/step
z = (0:steps)*dz; % z motion, m
dx = frx/steps_rev; % x motion per step, m/step
x = (0:steps)*dx; % x motion, m

r = r0 - z*tan(theta); % part radius, m
rpm = calculate_spindle_speed(x*1e3, V*60, r*1e3);
ss = V./r*60/(2*pi); % spindle speed, rpm

fx = frx*ss/60; % x direction feed rate, m/s
fz = frz*ss/60; % z direction feed rate, m/s

% fx = frx*rpm/60; % x direction feed rate, m/
s
% fz = frz*rpm/60; % z direction feed rate, m/
s

```

```

dt = dphi./ss*(60/(2*pi)); % time step, s/step
t = (0:steps).*dt;          % time vector, s

% figure(1)
% plot(z*1e3, r*1e3, 'b')
% set(gca,'FontSize', 14)
% xlabel('z (mm)')
% ylabel('r (mm)')
% grid on
%
% figure(2)
% plot(x*1e3, r*1e3, 'b')
% set(gca,'FontSize', 14)
% xlabel('x (mm)')
% ylabel('r (mm)')
% grid on
%
% figure(3)
% plot(r*1e3, ss, 'b')
% set(gca,'FontSize', 14)
% xlabel('r (mm)')
% ylabel('Spindle speed (rpm)')
% grid on
%
% figure(6)
% plot(z*1e3, fz*1e3, 'b')
% set(gca,'FontSize', 14)

```

```

% xlabel('z (mm)')
% ylabel('f_z (mm/s)')
% grid on
%
% figure(7)
% plot(x*1e3, fx*1e3, 'b')
% set(gca,'FontSize', 14)
% xlabel('x (mm)')
% ylabel('f_x (mm/s)')
% grid on
%
% plot(t, ss, 'b')
% set(gca,'FontSize', 14)
% xlabel('t (s)')
% ylabel('Spindle speed (rpm)')
% xlim([0 max(t)])
% grid on
%
% figure(9)
% plot(t, r*1e3, 'b')
% set(gca,'FontSize', 14)
% xlabel('t (s)')
% ylabel('r (mm)')
% xlim([0 max(t)])
% grid on
%
% figure(10)
% plot(t, z*1e3, 'b')

```

```

% set(gca,'FontSize', 14)
% xlabel('t (s)')
% ylabel('z (mm)')
% xlim([0 max(t)])
% grid on
%
% figure(11)
% plot(t, x*1e3, 'b')
% set(gca,'FontSize', 14)
% xlabel('t (s)')
% ylabel('x (mm)')
% xlim([0 max(t)])
% grid on
%
% cs = r.*ss*2*pi/60;      % cutting speed, m/s
%
% figure(12)
% plot(t, cs, 'b')
% set(gca,'FontSize', 14)
% xlabel('t (s)')
% ylabel('V (m/s)')
% xlim([0 max(t)])
% grid on

%% Simulation Start

```

```

% Define MTP parameters
OPR = 0.7531;      % oscillations per revolution, 1/rev
% OPR = 0.6211;      % oscillations per revolution, 1/rev
% RAF = 1.1073;      % ratio of oscillation amplitude to
    feed
RAF = 0.7739;      % ratio of oscillation amplitude to feed

% OPR_x = 0.6131;
% OPR_z = 0.6111;
% RAF_x = 0.7031;
% RAF_z = 0.7031;

alpha = 0;          % phase lag, deg
alpha = alpha*pi/180; % phase lag, rad

zntp = RAF*frz*sin(ss/60*2*pi*OPR.*t);          % z
    direction MTP motion, m
xntp = RAF*frx*sin(ss/60*2*pi*OPR.*t + alpha); % x
    direction MTP motion, m

figure(13)
plot(t, zntp*1e3, 'r', t, xntp*1e3, 'b--')
hold on
plot(t, detrend(zntp*1e3), 'r', t, detrend(xntp*1e3), 'b--
    ')
set(gca, 'FontSize', 14)
xlabel('t (s)')
ylabel('z/x_{ntp} (mm)')

```

```

xlim([0 max(t)])
legend('z_{mtp}', 'x_{mtp}')
grid on
zoom on

figure('Name','RPM vs Time')
yyaxis left
plot(t,rpm)
xlabel('t (s)')
ylabel('Spindle Speed [rpm]')

% zmtp = zmtp*-1;
% xmtip = xmtip*-1;

yyaxis right
plot(t, zmtp*1e3, 'r', t, xmtip*1e3, 'b--')

t_motion = t;

figure(14)
plot(zmtp*1e3, xmtip*1e3, 'b')
set(gca,'FontSize', 14)
xlabel('z_{mtp} (mm)')
ylabel('x_{mtp} (mm)')
grid on
zoom on

% pmtip = (xmtip.^2 + zmtp.^2).^0.5;

```

```

%
% figure(15)
% plot(t, pmt*1e3, 'b')
% set(gca,'FontSize', 14)
% xlabel('t (s)')
% ylabel('p (mm)')
% xlim([0 max(t)])
% grid on
% zoom on

x_total = x + xmt; % total x motion, m
z_total = z + zmt; % total z motion, m

% parse into individual revolutions
z_parse = z_total(1:steps_rev);
x_parse = x_total(1:steps_rev);
for cnt = 2:num_rev
    z_parse = [z_parse; z_total(((cnt-1)*steps_rev + 1):(
        cnt*steps_rev))];
    x_parse = [x_parse; x_total(((cnt-1)*steps_rev + 1):(
        cnt*steps_rev))];
end

test_point = round(steps_rev/4);
z_total_test = z_parse(:, test_point);
x_total_test = x_parse(:, test_point);

figure(16)

```

```

plot(z_total*1e3, x_total*1e3, 'b')
set(gca, 'FontSize', 14)
xlabel('z (mm)')
ylabel('x (mm)')
grid on
zoom on
hold on
plot(z_total_test*1e3, x_total_test*1e3, 'bo')

% Perform coordinate rotation about the y axis
t = 0*z_total;
n = 0*x_total;
t_test = 0*z_total_test;
n_test = 0*x_total_test;

R = [cos(-theta) -sin(-theta); sin(-theta) cos(-theta)]; %
    rotation matrix

for cnt = 1:length(x_total)
    original_data = [z_total(cnt); x_total(cnt)];
    new_data = R*original_data;
    t(cnt) = new_data(1);
    n(cnt) = new_data(2);
end
plot(t*1e3, n*1e3, 'g')

for cnt = 1:length(x_total_test)

```



```

        original_data = [z_total_test(cnt); x_total_test(cnt)
            ];
        new_data = R*original_data;
        t_test(cnt) = new_data(1);
        n_test(cnt) = new_data(2);
    end
    plot(t_test*1e3, n_test*1e3, 'go')

% nr_fit = (0.03125*25.4)*1e-3;          % fit value for
    tool nose radius from constant feed test, m
% nr_fit = (0.4728)*1e-3;              % fit value for tool
    nose radius from constant feed test, m
% nr = zeros(1, num_rev);              % tool nose radius for each
    revolution, m
% nr = nr + nr_fit;

% Calculate feed since previous revolution
fr_eff = abs(diff(t_test));
fr_eff = [fr; fr_eff];

% Use current feed to set nose radius (calibrated from
    constant feed tests)
for cnt = 1:num_rev
    if fr_eff(cnt) < 0.0254*1e-3 %[m]
        nr(cnt) = 0.1219*1e-3; %[m]
    elseif fr_eff(cnt) > 0.0781*1e-3 %[m]
        nr(cnt) = 0.7937*1e-3; %[m]
    end
end

```

```

else
    nr(cnt) = (12.7593*(fr_eff(cnt)*1e3) - 0.2022)*1e
        -3; %[m]
end
end

t_temp = linspace(t_test(1)-0.5*nr(1), t_test(1)+0.5*nr(1)
    , 25e3);
n_temp = -((nr(1)^2 - (t_temp - t_test(1)).^2).^0.5) +
    t_test(1);

% Adjust to set minimum of n_temp to zero
% n_temp = n_temp - min(n_temp);

figure(17)
plot(t_temp*1e3, n_temp*1e3, 'b')
set(gca, 'FontSize', 14)
xlabel('t (mm)')
ylabel('n (mm)')
hold on
zoom on
grid on

t_interp = linspace(t_test(1)-0.5*nr(1), t_test(num_rev)
    +0.5*nr(1), 1e5);
n_interp = interp1(t_temp, n_temp, t_interp);
n_vector = n_interp;

```

```

for cnt = 2:num_rev
    t_temp = linspace(t_test(cnt)-0.5*nr(cnt), t_test(cnt)
        +0.5*nr(cnt), 25e3);
    n_temp = -((nr(cnt)^2 - (t_temp - t_test(cnt)).^2)
        .^0.5) + n_test(cnt);
    % n_temp = n_temp - min(n_temp); Shifts the curve
        minimum back to zero
    if rem(cnt, 2) == 1
        plot(t_temp*1e3, n_temp*1e3, 'b')
    else
        plot(t_temp*1e3, n_temp*1e3, 'r')
    end
    n_interp = interp1(t_temp, n_temp, t_interp);
    n_vector = [n_vector; n_interp];
end

n_final = min(n_vector);
[peaks, index] = findpeaks(-n_final);
n_final = n_final(index(1):index(length(index)));
t_interp = t_interp(index(1):index(length(index)));
n_final = n_final - mean(n_final);

figure(18)
plot(t_interp*1e3, n_final*1e6, 'b')
set(gca, 'FontSize', 14)
xlabel('t (mm)')
ylabel('n (\mu m)')
zoom on

```

```

grid on

% axis([min(t_interp)*1e3 max(t_interp)*1e3 1.1*min(
    n_final)*1e6 1.1*max(n_final)*1e6])

x_height_sim = n_final*1e6;
sim_avg = mean(x_height_sim);
Ra_sim = mean(abs(sim_avg-x_height_sim));

%% Saving data set for comparison with measured surface
    profiles
% savename = '300_sfm_001_ipr_VNMG_332_MTP 45 Deg 0.7531
    OPR 0.7739 RAF ETNR R1';
% filepath = 'C:\Users\ryana\Dropbox\UTK\Research\MTP
    Research\Simulation Results\45 Deg Taper';
% % zntp_mm = zntp * 1e3;
% % xntp_mm = xntp * 1e3;
% % save(savename, 't_motion', 'zntp_mm', 'xntp_mm')
% save_surface(t_interp'*1e3,n_final'*1e6,savename,
    filepath)
% % save_surface(t_fine'*1e3,n_min_envelope'*1e6,savename,
    filepath)

toc

function rpm = calculate_spindle_speed(x_position,
    surface_speed, radius)
    % Calculate spindle speed based on surface speed and
        diameter

```

```

    spindle_speed = (surface_speed * 1000) ./ (pi * radius
        *2);

    % Round the spindle speed to the nearest 10 RPM
    rounded_spindle_speed = floor(spindle_speed ./ 10)*10;

    % Return the rounded spindle speed
    rpm = rounded_spindle_speed;
end

% function rpm = calculate_spindle_speed(x_position,
    surface_speed, radius)
%     % Calculate spindle speed based on surface speed and
    diameter
%     spindle_speed = (surface_speed * 1000) ./ (pi *
    radius*2);
%
%     % Calculate MTP oscillation based on x position
%     % This is a placeholder; replace with your actual
    sine wave logic
%     sin_wave = sin(x_position * 2 * pi);
%
%     % Find the index of the minimum value in the sine
    wave
%     [~, min_index] = min(sin_wave);
%
```

```

%      % Round the spindle speed at the bottom of the sine
      wave
%      spindle_speed = spindle_speed(min_index);
%      rounded_spindle_speed = floor(spindle_speed ./ 10)
      *10;
%
%      % Return the rounded spindle speed
%      rpm = rounded_spindle_speed;
% end

```

C.3 MTTP simulation

```

% taper_simulation.m
% R. Garcia
% Last Edited: 18-Oct-2024
% Constant surface speed for MTTP testing with stepped rpm
      additions
tic

clear
close all
clc

%% Define turning parameters

feedrate = 0.005;
OPR = 0.66934;      % oscillations per revolution, 1/rev
RAF = 0.84224;      % ratio of oscillation amplitude to feed

```

```

fr = (feedrate*25.4)*1e-3;          % feed per revolution in
    path direction, m/rev
V = 91.4/60;                        % cutting speed, m/s
r0 = 50.8*1e-3;                     % starting radius, m
R = r0;                             % radius of the quarter
    circle, m

%% Simulation

% Calculate the arc length of the quarter circle
arc_length = (pi / 2) * R; % quarter circle arc length, m

% Calculate the number of revolutions needed to complete
    the quarter circle
num_rev = floor(arc_length / fr);

% Define angular step size along the quarter circle
% num_rev = 1000;                    % number of revolutions
steps_rev = 3600;                    % steps per revolution (
    adjust as needed)
steps = num_rev * steps_rev; % total number of steps

% Parameterize the quarter circle
theta_arc = linspace(0, pi/2, steps); % angle from 0 to
    90 degrees

% Calculate positions along the quarter circle

```

```

x_c = 0; % center x-
coordinate (adjust if needed)
z_c = 0; % center z-
coordinate (adjust if needed)

% Since x typically represents diameter in turning, we
adjust accordingly
x = x_c + R * cos(theta_arc); % x positions (
diameter), m
z = z_c + R * sin(theta_arc); % z positions (
axial), m

% Calculate differential movements per step
dx = diff(x); % dx has length n-1
dz = diff(z); % dz has length n-1

% Pad dx and dz to match the size of x and z
dx = [dx, dx(end)]; % Append the last
difference to dx
dz = [dz, dz(end)]; % Append the last
difference to dz

% Calculate feed per revolution in x and z directions
fr_total = fr * ones(1, length(dx)); % total feed
per revolution
step_distance = sqrt(dx.^2 + dz.^2); % distance
moved per step

```



```

% Normalize dx and dz to match the feed per revolution
dx_normalized = (dx ./ step_distance) * fr / steps_rev;
dz_normalized = (dz ./ step_distance) * fr / steps_rev;

% Recalculate positions using normalized feed rates
x = cumsum([x(1), dx_normalized]);
z = cumsum([z(1), dz_normalized]);

% Calculate radius at each step
radius = x;                                     % radius is half of
diameter

% Plot the x and z positions to visualize the arc
figure;
plot(z, x, 'o');
xlabel('Z Position (m)');
ylabel('X Position (Diameter, m)');
title('Tool Path Along Quarter Circle');
axis equal;
grid on;

% Calculate spindle speed at each step
rpm = calculate_spindle_speed(V * 60, radius * 1e3, 500);
% ensure radius in mm
rpm = rpm(2:end);

% Calculate feed rates in x and z directions

```

```

ss = rpm; % spindle speed
    in rpm
% fx = fr * (dx_normalized ./ step_distance) .* ss / 60;
    % x direction feed rate, m/s
% fz = fr * (dz_normalized ./ step_distance) .* ss / 60;
    % z direction feed rate, m/s
fx = fr * (dx_normalized ./ step_distance); % x direction
    feed rate, m/s
fz = fr * (dz_normalized ./ step_distance); % z direction
    feed rate, m/s

% % Calculate time steps
% dt = (2 * pi) ./ (ss * steps_rev); % time per
    step, s
% t = cumsum([0, dt(1:end-1)]); % time vector,
    s

% Calculate time per revolution
time_per_rev = 60 ./ ss; % Time for one revolution in
    seconds (ss is in RPM)

% Calculate time per step (fraction of time_per_rev)
dt = time_per_rev / steps_rev; % Time for each step, s

% Cumulative sum to get the time vector
t = cumsum([0, dt(1:end-1)]); % Update time vector, s

```

```

%Plot feedrates
figure
plot(t,fx,'b')
hold on
plot(t,fz,'r')
xlabel('Time [sec]')
ylabel('Distance [m]')
legend('x-motion','z-motion')

%% Simulation Start

% % Define MTP parameters
% OPR = 0.66934;      % oscillations per revolution, 1/rev
% % OPR = 0.6211;      % oscillations per revolution, 1/rev
% % RAF = 1.1073;      % ratio of oscillation amplitude to
    feed
% RAF = 0.84224;      % ratio of oscillation amplitude to
    feed

% OPR_x = 0.6131;
% OPR_z = 0.6111;
% RAF_x = 0.7031;
% RAF_z = 0.7031;

alpha = 0;           % phase lag, deg
alpha = alpha*pi/180; % phase lag, rad

```

```

% zntp = 0.0394e-3* t + RAF*frz*sin(ss/60*2*pi*OPR.*t);
           % z direction MTP motion, m
% xntp = 0.0343e-3* t + RAF*frx*sin(ss/60*2*pi*OPR.*t +
           alpha); % x direction MTP motion, m

zntp = RAF*fz.*sin(ss/60*2*pi*OPR.*t);           % z
           direction MTP motion, m
xntp = RAF*fx.*sin(ss/60*2*pi*OPR.*t + alpha); % x
           direction MTP motion, m

figure
plot(t, zntp*1e3, 'r', t, xntp*1e3, 'b--')
hold on

set(gca, 'FontSize', 14)
xlabel('t (s)')
ylabel('z/x_{ntp} (mm)')
xlim([0 max(t)])
legend('z_{ntp}', 'x_{ntp}')
grid on
zoom on

figure('Name', 'RPM vs Time')
yyaxis left
plot(t, rpm)
xlabel('t (s)')
ylabel('Spindle Speed [rpm]')

```

```

% zmtp = zmtp*-1;
% xmtp = xmtp*-1;

yyaxis right
plot(t, zmtp*1e3, 'r', t, xmtp*1e3, 'b--')

t_motion = t;

figure
plot(zmtp*1e3, xmtp*1e3, 'b')
set(gca, 'FontSize', 14)
xlabel('z_{mtp} (mm)')
ylabel('x_{mtp} (mm)')
grid on
zoom on

% pmt = (xmtp.^2 + zmtp.^2).^0.5;
%
% figure(15)
% plot(t, pmt*1e3, 'b')
% set(gca, 'FontSize', 14)
% xlabel('t (s)')
% ylabel('p (mm)')
% xlim([0 max(t)])
% grid on
% zoom on

```

```

x_total = x(2:end) + xntp; % total x motion, m
z_total = z(2:end) + zntp; % total z motion, m

% parse into individual revolutions
z_parse = z_total(1:steps_rev);
x_parse = x_total(1:steps_rev);
for cnt = 2:num_rev
    z_parse = [z_parse; z_total(((cnt-1)*steps_rev + 1):(
        cnt*steps_rev))];
    x_parse = [x_parse; x_total(((cnt-1)*steps_rev + 1):(
        cnt*steps_rev))];
end

test_point = round(steps_rev/4);
z_total_test = z_parse(:, test_point);
x_total_test = x_parse(:, test_point);

figure
plot(z_total*1e3, x_total*1e3, 'b')
set(gca, 'FontSize', 14)
xlabel('z (mm)')
ylabel('x (mm)')
grid on
zoom on
hold on
plot(z_total_test*1e3, x_total_test*1e3, 'bo')

%% Unwrap the circle to create a horizontal line

```

```

dz_test = diff(z_total_test);
dx_test = diff(x_total_test);

arc_lengths_test = sqrt(dz_test.^2 + dx_test.^2); %
    distance between consecutive points
cumulative_arc_length_test = [0; cumsum(arc_lengths_test)
    ]; % cumulative sum to get total arc length at each
    point

z_unwrapped = cumulative_arc_length_test; % Treat as the
    new "z" coordinate
x_unwrapped = zeros(size(z_unwrapped)); % x remains
    constant, unwrapped into a straight line

% Plot the unwrapped coordinates
figure(17);
plot(z_unwrapped * 1e3, x_unwrapped * 1e3, 'bo-');
title('Unwrapped Arc Points');
xlabel('Unwrapped Length (mm)');
ylabel('x (mm)');
grid on;

t_test = z_unwrapped;
n_test = x_unwrapped;

%% Tool Nose Radius

```

```

% nr_fit = (0.03125*25.4)*1e-3;          % fit value for
    tool nose radius from constant feed test, m
% nr_fit = (0.4728)*1e-3;              % fit value for tool
    nose radius from constant feed test, m
% nr = zeros(1, num_rev);              % tool nose radius for each
    revolution, m
% nr = nr + nr_fit;

% Calculate feed since previous revolution
fr_eff = abs(diff(t_test));
fr_eff = [fr; fr_eff];

% Use current feed to set nose radius (calibrated from
    constant feed tests)
for cnt = 1:num_rev
    if fr_eff(cnt) < 0.0254*1e-3 %[m]
        nr(cnt) = 0.1181*1e-3; %[m]
    elseif fr_eff(cnt) > 0.078*1e-3 %[m]
        nr(cnt) = 0.7937*1e-3; %[m]
    else
        nr(cnt) = (12.8383*(fr_eff(cnt)*1e3) - 0.2080)*1e
            -3; %[m]
    end
end

t_temp = linspace(t_test(1)-0.5*nr(1), t_test(1)+0.5*nr(1)
    , 25e3);

```



```

n_temp = -((nr(1)^2 - (t_temp - t_test(1)).^2).^0.5) + nr
    (1);

% Adjust to set minimum of n_temp to zero
% n_temp = n_temp - min(n_temp);

figure(17)
plot(t_temp*1e3, n_temp*1e3, 'b')
set(gca, 'FontSize', 14)
xlabel('t (mm)')
ylabel('n (mm)')
hold on
zoom on
grid on

t_interp = linspace(t_test(1)-0.5*nr(1), t_test(num_rev)
    +0.5*nr(1), 1e5);
n_interp = interp1(t_temp, n_temp, t_interp);
n_vector = n_interp;
for cnt = 2:num_rev
    t_temp = linspace(t_test(cnt)-0.5*nr(cnt), t_test(cnt)
        +0.5*nr(cnt), 25e3);
    n_temp = -((nr(cnt)^2 - (t_temp - t_test(cnt)).^2)
        .^0.5) + nr(cnt);
    % n_temp = n_temp - min(n_temp); Shifts the curve
    % minimum back to zero
    if rem(cnt, 2) == 1
        plot(t_temp*1e3, n_temp*1e3, 'b')

```

```

else
    plot(t_temp*1e3, n_temp*1e3, 'r')
end

% Ensure t_temp has unique values before interpolation
[t_temp_unique, unique_idx] = unique(t_temp, 'stable')
;
n_temp_unique = n_temp(unique_idx);

% Perform the interpolation
n_interp = interp1(t_temp_unique, n_temp_unique,
    t_interp, 'linear');

% n_interp = interp1(t_temp, n_temp, t_interp);
n_vector = [n_vector; n_interp];
end

n_final = min(n_vector);
[peaks, index] = findpeaks(-n_final);
n_final = n_final(index(1):index(length(index)));
t_interp = t_interp(index(1):index(length(index)));
n_final = n_final - mean(n_final);

%% Final Surface Plot
figure(18)
plot(t_interp*1e3, n_final*1e6, 'b')
set(gca, 'FontSize', 14)
xlabel('t (mm)')

```

```

ylabel('n (\mum)')
zoom on
grid on
% axis([min(t_interp)*1e3 max(t_interp)*1e3 1.1*min(
    n_final)*1e6 1.1*max(n_final)*1e6])

x_height_sim = n_final*1e6;
sim_avg = mean(x_height_sim);
Ra_sim = mean(abs(sim_avg-x_height_sim));

%% Saving data set for comparison with measured surface
    profiles
savename = sprintf('300_sfm_%.5f_ipr_VNMG_332_MTTP %.5f
    OPR %.5f RAF ETNR',feedrate, OPR, RAF);
filepath = 'C:\Users\ryana\Dropbox\UTK\Research\MTP
    Research\Simulation Results\MTTP';
save_surface(t_interp'*1e3,n_final'*1e6,savename,filepath)
toc

function rpm = calculate_spindle_speed(surface_speed,
    radius, max_rpm)
    % Calculate spindle speed based on surface speed and
        diameter
    spindle_speed = (surface_speed * 1000) ./ (pi * radius
        * 2);

    % Round the spindle speed down to the nearest 10 RPM

```

```

rounded_spindle_speed = floor(spindle_speed ./ 10) *
    10;

% Cap the rounded spindle speed at the maximum RPM
rounded_spindle_speed(rounded_spindle_speed > max_rpm)
    = max_rpm;

% Return the rounded spindle speed
rpm = rounded_spindle_speed;
% rpm = spindle_speed;
end

```

C.4 MTTP heatmap simulation

```

%Surface_simulation_parameter_sweep_par_MTTP
%R. Garcia
% Last Edited 18-Oct-2024

clc;
clear;
close all;

tic

% Step 1: Define Input Parameters
OPR = 0.66934;
% OPR_std = 0.01;
OPR_std = 0.03091;

```

```

RAF = 0.84224;
% RAF_std = 0.01;
RAF_std = 0.16906;

% Use single precision to reduce memory usage
OPR_values = single(OPR-OPR_std:0.01:OPR+OPR_std);
RAF_values = single(RAF-RAF_std:0.01:RAF+RAF_std);
feedrate_values = single(0.005);

% Step 2: Preallocate for Results
num_OPR = length(OPR_values);
num_RAF = length(RAF_values);
num_feedrate = length(feedrate_values);
Ra_sim_values = zeros(num_OPR, num_RAF, num_feedrate, '
    single'); % Use single precision

% % Step 3: Initialize Waitbar with Reduced Updates
% hWaitBar = waitbar(0, 'Processing...');
% totalIterations = num_OPR * num_RAF * num_feedrate;
% updateStep = floor(totalIterations / 10); % Update
    waitbar every 10% of total iterations

% % Step 4: Set up Parallel Pool and DataQueue for
    Parallel Processing
% pool = gcp('nocreate'); % Get current parallel pool
% if isempty(pool)
%     % Set number of workers to max available (or choose
        a specific number)

```

```

%      parpool('local'); % By default, it uses the max
      number of workers
% end

% queue = parallel.pool.DataQueue;
%
% % Step 5: Function to Update Waitbar (Handles Progress
      Updates)
% function waitbarProgress(~, hWaitBar, updateStep,
      totalIterations)
%      persistent iterationCount; % Retains value between
      function calls
%
%      if isempty(iterationCount)
%          iterationCount = 0; % Initialize the first time
%      end
%
%      iterationCount = iterationCount + 1; % Increment
      iteration count
%      if mod(iterationCount, updateStep) == 0 ||
      iterationCount == totalIterations
%          waitbar(iterationCount / totalIterations,
      hWaitBar);
%      end
% end
%
% % Assign callback for DataQueue, passing necessary
      variables to the function

```

```

% afterEach(queue, @(data) waitbarProgress(data, hWaitBar,
    updateStep, totalIterations));

% Suppress figure visibility globally
set(0, 'DefaultFigureVisible', 'off');

% Profile performance to detect bottlenecks
profile on

% Step 6: Run Simulations Using Parallel for Loop
for i = 1:num_OPR
    for j = 1:num_RAF
        for k = 1:num_feedrate
            OPR = OPR_values(i);
            RAF = RAF_values(j);
            feedrate = feedrate_values(k);

            % Call the function to calculate Ra_sim (this
                is where vectorization might help)
            Ra_sim_values(i, j, k) =
                MTP_surface_simulation_opr_raf_MTTP(OPR,
                    RAF, feedrate);

            % Send progress update to the DataQueue
            % send(queue, 1);
        end
    end
end
end

```

```

% Close the waitbar after the loop is finished
% close(hWaitBar);

% Step 7: Re-enable figure visibility after computations
    are done
set(0, 'DefaultFigureVisible', 'on');

% Stop profiling and display the profile report
profile off
% profile viewer

%% Step 8: Create Surface Plots for Each Feedrate
[X, Y] = meshgrid(RAF_values, OPR_values); % X and Y
    should be 2D matrices with size [num_OPR, num_RAF]

for k = 1:num_feedrate
    % Extract the Ra_sim matrix for the current feedrate
    Ra_sim_matrix = squeeze(Ra_sim_values(:, :, k)); %
        Squeeze to ensure it's 2D

    % Check if Ra_sim_matrix has the correct dimensions
    if size(Ra_sim_matrix, 1) == size(X, 1) && size(
        Ra_sim_matrix, 2) == size(X, 2)
        % Create a new figure for each feedrate
        figure;
        surf(X, Y, Ra_sim_matrix);
        hold on
    end
end

```



```

% Customize the plot for top-down view
xlabel('RAF');
ylabel('OPR');
zlabel('Ra_{sim}');
title(['Surface Plot of Ra_{sim} vs OPR and RAF
      for Feedrate = ', num2str(feedrate_values(k)
      *25.4), ' mm/rev']);
colorbar;
shading interp;
colormap jet;

% Add limit to the Ra (z-axis) from 0 to 5
zlim([0, 5]); % Sets the z-axis limit for Ra
              values

% Set the view to top-down (looking directly down
      onto the XY plane)
view(0, 90);

% Ensure the axes start from the origin in the
      bottom left
set(gca, 'YDir', 'normal'); % Ensures Y-axis is
      not flipped

```

```

else

```

```

        warning('Ra_sim_matrix size does not match X and Y
                dimensions for feedrate index %d', k);
    end
end

%% Step 9: Calculate Mean and Standard Deviation for
Ra_sim_values
mean_Ra = mean(Ra_sim_values(:)); % Calculate the mean of
    all values
std_Ra = std(Ra_sim_values(:)); % Calculate the
    standard deviation of all values

% Calculate the range: mean    2 * standard deviation
lower_bound = mean_Ra - 2 * std_Ra;
upper_bound = mean_Ra + 2 * std_Ra;

% Print the results
fprintf('Mean Ra: %.5f\n', mean_Ra);
fprintf('Standard Deviation Ra: %.5f\n', std_Ra);
fprintf('Ra Range: %.5f    %.5f = [%.5f, %.5f]\n', mean_Ra
    , 2*std_Ra, lower_bound, upper_bound);

toc % Output the time taken for the entire process

```

C.5 Surface roughness filtering

```

%% Header
% Ryan Garcia

```

```

% rgarci15@vols.utk.edu
% 24-Feb-2024
% Alicona_Data_Processing

clc
clear
close all

filepath = 'C:\Users\ryana\Dropbox\UTK\Research\MTP
           Research\Alicona Measurements\ST-15 Testing\MTTP\MTP
           Test\'; %Folder where surface profiles are saved
filename = '0.005 ipr 0.5 OPR 1.5 RAF 55 Deg (RAW)
           unwrapped'; %Name of surface profile files in .csv
format    FORM_REMOVED_SURFACE_TRACE

% cd (filepath) %Changes to folder where the data set is
               stored

%% Importing Measured Surface Profile

start_val = 0.0;
end_val = 100.0;

[x_height,z_distance] = Alicona_surf_import(filename,
      filepath,start_val,end_val);

%% Coordinate Rotation

```

```

% [z_distance_rot, x_height_rot] = surface_rot(
    z_distance_offset_1,x_height_offset_1,0);

%% Filtering Surface Data

% fs = 1/(z_distance(2)-z_distance(1));
% w_highpass = 10;
% x_height_highpass = highpass(x_height,w_highpass,fs);
%
% x_height_waviness = x_height-x_height_highpass;
%
% w_lowpass = 0.1;
% x_height_lowpass = lowpass(x_height,w_lowpass,fs,
    Steepness=0.999);

% x_height = detrend(x_height); % Removing linear trend

lambdac = 0.8; % cutoff in mm
dx = z_distance(2)-z_distance(1); % spacing in mm
[x,w4] = npspline(x_height, dx, lambdac); % generate
    spline waviness profile

x_surface_rough = x_height-w4;

alpha = 1/(2*sin(pi*dx/lambdac));

```

```

lambda = (0.002:dx:8)'; % generate wavelength axis for
    transmission plot
T = 1./(1+16*alpha^4*sin(pi*dx./lambda).^4); % sample the
    spline transmission equation
figure
semilogx(lambda,T*100);
xlabel('Wavelength (mm)');
ylabel('Amplitude (%)');
hold on

%% Plotting the Surface Profile

figure
plot(z_distance, x_height, 'b');
xlabel('Distance [mm]');
ylabel('Height [\num]');

figure
tiledlayout(3,1)
ax1 = nexttile;
plot(z_distance, x_height, 'b');
title('Profile')
ax2 = nexttile;
plot(z_distance, w4, 'k');
% plot(z_distance, x_height_waviness, 'k');
title('Waviness')
ax3 = nexttile;

```

```

plot(z_distance, x_surface_rough, 'r');
% plot(z_distance, x_height_highpass, 'r');
title('Roughness')
xlabel('Distance [mm]');
ylabel('Height [\mu m]');
linkaxes([ax1 ax2 ax3], 'xy')

figure
% plot(z_distance_offset_1, detrend(x_height_offset_1), 'b
    ');
plot(z_distance, x_surface_rough, 'r');
hold on
% plot(z_distance_offset_1, x_height_fitted, 'k');
% plot(z_distance, x_height_highpass, 'r');
% plot(z_distance, x_height_lowpass, 'k');
% plot(xnew, ynew, 'r')
% plot(curve_fit_x, curve_fit_y);
hold on
% plot(xnew, ynew_detrend)
hold off
xlabel('Distance [mm]');
ylabel('Height [\mu m]');
% legend('Raw data', 'Linear fit')
% legend('Raw data', 'Linear fit', 'Detrended data')

% figure
% plot(z_distance, x_height_lowpass, 'k');

```

```

%% Calculating FFT of Surface profile

[wavelength_uf,amplitude_uf] = surface_fft(z_distance,
    x_height);
plot_fft_wavelength(wavelength_uf,amplitude_uf,'Profile',
    [0 .5], [0 0.75],'b')
% plot(wavelength_uf,amplitude_uf); % plot half of the %
    FFT array
% xlabel('Wavelength (mm)');
% ylabel('Amplitude (\mum)');
% [f_uf,P1_uf] = execute_fft(z_distance,x_height);

% plot_fft_surface(f_uf,P1_uf,'Unfiltered Surface FFT',[0
    100])

%% Calculating FFT of Filtered Surface Roughness

[wavelength_f,amplitude_f] = surface_fft(z_distance,
    x_surface_rough);
plot_fft_wavelength(wavelength_f,amplitude_f,'Roughness',
    [0 .5], [0 0.75],'r')

%
% [wavelength_f,amplitude_f] = surface_fft(z_distance,
    x_surface_rough);
% figure
% plot(wavelength_f,amplitude_f); % plot half of the % FFT
    array

```

```

% xlabel('Wavelength (mm)');
% ylabel('Amplitude (\mum)');
%
% [f_hf,P1_hf] = execute_fft(z_distance,x_height_highpass)
%
%
% plot_fft_surface(f_hf,P1_hf,'Filtered Surface FFT
    Highpass',[0 100])

%% Saving the surface profile data

%%% Uncomment the line below to save the surface profile
    to the desired
%%% folder for use later in comparing the recorded data
    set with the
%%% simulation surface

save_surface(z_distance,x_surface_rough,filename,filepath)

%% Calculating FFT of Filtered Surface Lowpass filter
%
% [f_lf,P1_lf] = execute_fft(z_distance,x_height_lowpass);
%
% plot_fft_surface(f_lf,P1_lf,'Filtered Surface FFT
    Lowpass',[0 100])

% cd(current_folder)

```



```
[f_x, P1_x] = execute_fft(z_distance,x_surface_rough);

figure
plot(f_x, P1_x)
xlabel('Frequency (1/mm)')
ylabel('Amplitude (mm)')
```

Vita

Ryan Garcia received his B.S. in Mechanical Engineering from the University of Florida in 2021. In the summer of 2021, he started at the University of Tennessee Knoxville to pursue a Ph.D. in Mechanical Engineering under Dr. Tony Schmitz, where he works as a graduate research assistant in the Machine Tool Research Center.

Ryan's research has focused on studying turning modeling and measurement, including modulated tool path for chip and surface finish control in collaboration with Y-12. He has worked on studying tool wear in partnership with the Army Research Lab and the University of Tennessee Space Institute. Additionally, he has also worked on machining strategies for carbon-carbon.