

Tool Wear Modeling for Application to Gear Shaping

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Tool wear has a major impact on the productivity, economics, and sustainability of metal machining operations. While the topic of tool wear has been studied extensively for conventional metal cutting processes, like milling, turning, and drilling, there is a scarcity of studies in literature on modeling and predicting tool wear in gear machining operations. Gears, on the other hand, are essential components for a vast array of engineered systems, like automotive, aerospace, and various transportation vehicles, robotics, automation, and general machinery. This thesis has targeted developing a framework for the study and prediction of tool wear in the gear shaping operation. Gear shaping is among the most versatile methods of cutting gears.

In-house experiments were designed and performed to replicate the gear shaping process on a 5-axis milling machine. The kinematics were modeled, and custom NC code was generated and validated using polygon subtractions, to ensure that a gear shaping cutter would accurately produce a gear workpiece. The testing conditions were designed considering the physical capabilities of the machine tool, and the utilization of digital simulations of the gear cutting operation via ShapePro software (previously developed at the University of Waterloo), that predicts the kinematics, chip geometry, and cutting forces. As such, specimen gears were produced from AISI 1215 mild steel using HSS (high-speed steel) cutter material. The cutting edges and flanks of the tool were imaged throughout the tests, to monitor the development of wear. In the envelope of cutting speeds and feed rates that could be tested, only minimal wear was observed, and this was concentrated at the cutting tooth tips and corners, consistent with the prediction from ShapePro that these regions are subject to the largest chip thickness and longest distance of workpiece material cut. Nevertheless, these tests have demonstrated the proof-of-concept for performing shaping tests and progressively imaging the tool edges for wear. Future tests should focus on performing the cuts at more aggressive speeds and feeds to induce discernable wear.

To facilitate rapid characterization of tool wear for different workpiece and tool material pairs, an analogy testing method was also developed as an interrupted cutting operation on a lathe, designed to mimic cutting conditions similar to those in shaping. With this approach, a broader set of cutting speeds and feed rates could be explored in the machining of a similar kind of material (cold rolled 1020 steel). In this case, using HSS tooling brought practical limitations (e.g., built-up edge), thus the tooling material was changed to carbide. Nevertheless, a reasonable variation of cutting conditions could be

implemented and tool wear progression data, as a function of cutting distance (and time) be documented.

This data has informed the development of a progression-based tool wear model for predicting flank wear in interrupted cutting, which is presented as a new contribution in this thesis. Established tool life models, such as Taylor and Colding, can predict the cutting time required for reaching only a single value of tool flank wear, whereas the proposed model can be used to predict when different values of tool wear would be reached without requiring re-calibration. More importantly, the proposed model can be integrated inside a time-domain simulation of an interrupted cutting operation, like gear shaping, in order to predict and update the wear state along each node on the tool edge, which classical tool life models cannot achieve, as they are ‘tuned’ to predict the cutting time until a preset wear is reached.

The proposed model, as well as Taylor and Colding models, were benchmarked with respect to the experimental wear data collected across 12 different cutting conditions, and they all performed comparably in predicting tool life, with average prediction errors of roughly 21%-24%, thus indicating some confidence in the proposed new model.

Future research should focus on collecting further data, both in gear shaping and analogy orthogonal testing experiments, to ensure further repeatability of the data, as well as validating that a tool wear model calibrated using the lower cost and faster analogy experiments can indeed predict the distribution of tool wear progression in the much more complex gear shaping operation. Furthermore, it is also advised to expand the wear model to predict uncertainty bounds along with the tool wear values themselves, and to expand the study into the machining of different kinds of metals, with different tools substrates and coatings.

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Dedication

To my parents

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Nomenclature

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
<u>Cutting parameters</u>		
a_p	Depth of cut	mm
α_r	Rake angle	°
α_0	Flank angle	°
b	Length of uncut chip	mm
$F_{t,f,r,n}$	Orthogonal and oblique cutting forces (tangential, feed, radial, normal)	N
h	Uncut chip thickness	mm
i	Inclination angle	°
η	Chip flow angle	°
<u>Gear shaping parameters</u>		
α	Pressure angle of workpiece and tool pair	°
α_w	Working pressure angle of workpiece and tool pair	°
b	Face width of gear workpiece	mm
β	Helix angle	°
d_{cut}	Specified depth of cut for a gear shaping pass	mm
d_{stroke}	Length of a gear shaping stroke	mm
$d_{top,bottom}$	Gear shaping overrun distance above and below	mm
ε	Gear type modification factor (+1 for external, -1 for internal)	
f_{cut}	Cutting stroke frequency	DS/min
f_{rotary}	Rotary feed rate	mm/DS
f_{radial}	Radial feed rate	mm/DS
f_z	Axial feed rate for five axis CNC	mm/min
k	Number of teeth measured across for a spawn measurement W	

m	Module of tool and workpiece	mm
$\omega_{c,g}$	Cutter and workpiece rotational velocity	rad/s
ω_s	Cutting stroke frequency	rad/s
$\phi_{c,g}$	Angle of cutter and workpiece for gear shaping	°
$N_{c,g}$	Number of teeth on cutter and workpiece	
R	Gear ratio	
r_{curr}	Current radial distance between cutter and workpiece	mm
r_{safe}	Safety radius for gear shaping to avoid rubbing on the tool upstroke	mm
r_{scrape}	Radius at which the cutter and workpiece scrape	mm
$r_{start,end}$	Start and end radiuses for a single shaping pass	mm
r_{gc}	Nominal centre to centre distance between cutter and workpiece	mm
$r_{a,c,g}$	Addendum radius of cutter and workpiece	mm
$r_{p,c,g}$	Pitch radius of cutter and workpiece	mm
t_{step}	Time step	s
θ_{table}	Angle of C axis table	rad
W	Span measurement across a chosen number of teeth	mm
$x_{c,g}$	Profile shift coefficient of tool and workpiece	
y	Center distance increment factor	
$z_{top,bottom}$	Top and bottom Z axis positions of the shaping cutter	mm
<u>Tool life model parameters</u>		
a_p	Depth of cut	mm
$\alpha_{0,1}, m_{0,1}$	Kantöjärvi cutting constants for the Lindstrom Colding model	
f	Feed rate	mm/rev
$f(x), g(x), h(x)$	Logit progressive wear model	

h_e	Woxen's equivalent chip thickness	mm
$K, M, N_0, H,$ and L	Colding tool life model constants	
κ	Major cutting angle	°
m, α	Linstrom model constants	
m, C_t, p, q	Cutting constants for the Taylor's tool life model	
r_c	Tool condition value for Surmann et al. progression model	N/mm
r_ϵ	Cutting tool nose radius	mm
T	Tool life	min, m
VB_{max}	Flank wear criterion along the cutting edge	µm
VC_{max}	Flank wear criterion for the tool nose radius	µm
v_c	Cutting speed	m/min

Orthogonal analogy test parameters

a	Arc length	mm
doc	Depth of cut	mm
K, Q, m_1, m_2	Cutting constants for the progression-based wear model	
l	Half chord length (half thickness of the workpiece blank)	mm
L	Length of material cut	mm
n_{lathe}	Lathe rpm	rev/min
n	Initial wear value	mm
r	Radius to outer surface of the workpiece blank	mm
w	Flank wear value of progression-based wear model	mm
$w_{1,2}$	Flank wear value for linear and exponential function parts	mm
x	Length along workpiece blank	mm

**Appendix B: Safety calculations for orthogonal analogy testing workpiece
holder parameters**

A_s	Stress area of set screw	mm ²
d_{screw}	Set screw diameter	mm
$d_{2,3}$	Pitch diameter and minor diameter of set screw	mm
$F_{centrifugal}$	Centrifugal force	N
$F_{clamping}$	Clamping force	N
F_{feed}	Feed cutting force	N
$F_{friction}$	Friction force	N
$F_{tangential}$	Tangential cutting force	N
K	Clamping constant	
K_{tc}, K_{fc}	Cutting coefficients for orthogonal / oblique cutting models	N/mm ²
K_{te}, K_{fe}	Edge cutting coefficients for orthogonal / oblique cutting models	N/mm
m_{wkp}	Mass of workpiece blank	kg
τ	Clamping torque	Nm
τ_s	Shear stress	MPa
ψ	Side edge cutting angle	°

Chapter 1

Introduction

1.1 Tool wear development and wear prediction in machining

As tooling is a necessary component in machining processes, degradation of the cutting tool through repeated use (tool wear) is unavoidable. For metal cutting operations, the appearance of wear on the cutting tool can have a major impact on the process, potentially causing sub-par surface finish or, when pushed to extremes, errors in dimensional accuracy of the produced workpieces. Depending on the cutting process, the dominant wear mechanism appearing on the tool varies, with degradation of the cutting edge (flank wear) being the focus of this study. While the cost of tooling as a percentage of the total process costs can range from 4% [1] for traditional manufacturing and up to 13% for gear manufacturing [2], tooling has the potential to impact the process economics through machine down time, scrapped workpieces, or premature tooling failures [3]. The ability to predict the progression of wear to optimize process parameters and tool replacement for both economic and process efficiency is pivotal in machining process design. Should the tool be replaced or resharpened too early, unnecessary downtime may be created, while late replacement has the potential to cause workpiece scrappage or tool failure. One such method of tool life prediction is using tool life models such as the Taylor or Colding model, created to predict the cutting time needed to reach a wear criterion under a set of process parameters. However, in the context of digital machining applications, where the cutting mechanics and tool wear progression must be simulated concurrently, such tool life models are not useful and there is a need to develop a progression-based wear model.

1.2 Thesis objectives

The goal of this thesis has been to study and predict the development of flank wear on gear cutting tools that occurs during the gear shaping process. In this context, the sub-objectives of this thesis have been to develop an analogy testing method, to obtain wear data in a cost-effective manner, on a lathe, in an accelerated manner, and to develop a novel wear progression model, which can be incorporated into time-domain simulation alongside process mechanics, of various interrupted cutting operations, including gear shaping.

1.3 Thesis layout

In Chapter 2, a literature review is presented, discussing the background knowledge and assessing the state of existing research in studying tool wear and gear cutting. Commonly encountered tool wear types are reviewed, with the most commonplace being flank wear. The chapter also reviews established tool life models, created to predict the cutting time at which a tool will reach a prescribed wear value. However, their use has not been widely extended to gear manufacturing due to the complex and constantly changing in-process cutting conditions in gear cutting. While some studies have been performed, this area is underdeveloped when compared to other cutting processes, such as milling, drilling, or turning, and under-reported in literature, possibly due to commercial reasons.

The development of a gear shaping experiment is described in Chapter 3. Shaping is an interrupted cutting process in which a tool in the form of a modified gear is used to produce a gear workpiece. The process consists of three feed movements: reciprocating motion creating a cutting stroke, rotary motion creating a meshing of the workpiece and tool profiles (similar to meshing gears), and finally a radial motion changing the centre-to-centre distance until the workpiece teeth are cut to full depth. As a dedicated shaping machine was unavailable for cutting trials, the shaping process was performed using a DMU Deckel Maho 80 P Hi-Dyn (five-axis CNC machine). Custom NC code was developed to mimic the kinematics of shaping within the capabilities of the machine and validated using a gear cutting simulation software, ShapePro developed at the University of Waterloo. Polygon subtraction was used to validate that programmed toolpaths would ultimately produce the correct gear geometry. Finally, the experiment was performed while documenting the appearance of wear on the cutting tool across a series of trials for implementation into a tool wear model. Various technical challenges were encountered, but nevertheless, the proof-of-concept of the methodology was achieved.

To expedite the collection of wear data from cutting processes, analogy tests are developed, recreating similar conditions to the actual shaping process while developing wear in shorter time periods on the tool, thus requiring reduced financial and time investment. Chapter 4 documents the development of the analogy tests with the goal of reproducing gear shaping wear through interrupted orthogonal turning. The process was designed and tested, matching and expanding on the cutting parameters in Chapter 3. Due to the appearance of built-up edge on the cutting tools, the testing had to continue using alternate (carbide) tooling instead of high-speed steel (HSS). Due to this change, the wear obtained between the two processes could not be compared at this time. Nevertheless, the method established a

framework for future studies with matching materials. The wear collected from the analogy test was used to identify a progression-based tool wear model, which is both more general than standard Taylor and Colding tool life models, and can also be integrated alongside cutting mechanics simulation. The predictions of the proposed new model were also benchmarked, successfully, with Taylor and Colding models in terms of predicting tool life.

Finally, Chapter 5 conveys the main conclusions drawn from this research and future work recommendations.

Chapter 2

Literature Review

2.1 Introduction

In machining, tool wear is one of the important factors determining the productivity and economics of a cutting process. Higher throughput from the operation demands higher cutting speeds and feed rates, which typically accelerates the tool wear, degrades part dimensional accuracy and surface quality, and increases the cost of tooling by necessitating a larger number of tool replacements per a given number of parts. To be able to optimize productivity and cost, the modeling and prediction of tool wear has been a continual area of research in machining, particularly for widely used conventional processes like turning, milling, and drilling.

Gears, as mechanical transmission elements, are indispensable in many industries and products, such as automotive (including e-vehicles), aerospace (e.g., in new generation geared aircraft engines), as well as general machinery and automation components (e.g., geared servo drives, and harmonic drive gearboxes) [4]. In the field of gear cutting, the kinematics and chip geometries are significantly more complex than conventional cutting processes and tool wear studies are mainly conducted by industry, particularly tooling suppliers and machine tool manufacturers. Therefore, only limited literature exists presenting tool wear data for gear machining processes [5]. For example, widely accepted models that predict tool life (i.e., usable cutting duration) such as Taylor [6] and Colding [7] are, in the best of the author's knowledge, not applied extensively in the gear cutting literature. Moreover, in the pursuit of capitalizing on digital simulations for gear machining by building 'digital twins' of cutting processes [8], it is important to develop not just tool life models, but also expressions that accurately predict the incremental progression of wear along discretized portions of the cutting edges, based on the local cutting speeds, feeds, and wear states that can be computed and updated in the simulation environment.

The following sections in this chapter establish the relevant background knowledge and state-of-the-art in cutting mechanics, tool wear modeling, and gear machining, which will be referenced and used to develop preliminary studies to investigate tool wear in gear shaping (Chapter 3), and a new tool wear model presented in this thesis that predicts the tool wear progression incrementally (Chapter 4).

Section 2.2 reviews basic orthogonal (2D) and oblique (3D) cutting models in terms of orientation of the cutting edge with the respect to the cutting velocity. A general review of tool wear mechanisms and models is presented in Section 2.3, along with standardized and/or best practice protocols for measuring tool wear. Section 2.4 reviews mainstream gear cutting processes and associated geometric, kinematic, and cutting force prediction models recently developed.

While cutting forces typically do not appear as direct mathematical terms in established tool wear models, they do contribute to thermal energy dissipation and therefore temperature increase at the chip and tool interface. This can affect how the tool material and/or coating and the workpiece material interact with one another. Importantly, an over-arching objective of this thesis is to develop an elemental tool wear model which can be integrated inside a comprehensive simulation platform that holistically predicts the kinematics, uncut chip geometry, relative velocities, cutting forces, and part surface location errors (i.e., resulting gear tooth errors), as well as the gradual progression of tool wear (and consumption of tooling life) in the course of a gear machining operation. As such, many of the internal variables accessible within a simulation, such as relative cutting velocities, chip thicknesses, cutting widths, and cumulative length of material cut, may feed into such a tool wear model for predicting the localized tool wear at each point along the cutting edges in gear machining. Such models can facilitate more realistic prediction and optimization of gear machining operations, which will facilitate better balancing of the productivity, part quality, and overall economics of the process. Such models can also be used in designing gear machining for better sustainability, by mitigating material, labor, and energy waste.

Section 2.5 presents tool wear studies for application to gear machining. As gear cutting is complex, with access to specialized gear cutting machine tools and cutters being costly, researchers have developed analogous testing operations using conventional machining processes, like turning and milling, to gather sufficient data and insights that can be reasonably extrapolated to better understanding tool wear in gear cutting. Such examples are provided in Section 2.5.2. There have also been studies in which gear machining operations were directly utilized to generate tool wear data, as well as providing the necessary configuration and boundary conditions for numerical studies such as the Finite Element method. These are covered in Section 2.5.1. Overall, looking at the existing literature in tool wear and gear machining, there is a scarcity of progression-based tool wear models which can be used to predict gradual tool wear in the presence of varying cutting conditions along different portions of complex cutters. Working to close this gap has been the primary motivation of this thesis.

Finally, the chapter concludes in Section 2.6 with a summary of findings, indicating how the background knowledge informs the research steps followed in this thesis.

2.2 Basic (orthogonal and oblique) cutting models

Machining processes can be analyzed using basic cutting models to predict geometry, kinematics, forces, as well as various interactions between the cutting tool and workpiece. Depending on whether the cutting velocity is perpendicular to the cutting edge or is at an inclination (see Figure 2.1), elementary cutting models such as orthogonal cutting and oblique cutting can be used to analyze the chip formation and machining forces in 2D and 3D, respectively. By discretizing the complete tool geometry into small cutting edge segments, such elementary models can then facilitate the overall analysis and simulation of a wide range of more complex cutting operations, like turning, drilling, milling [9], and gear machining [10] [11] [12]. Such simulations perform the calculation of local cutting velocity vectors and chip geometries, which can also inform tool wear progression models.

The orthogonal cutting model is shown in Figure 2.1 (a) where the cutting edge is perpendicular to the cutting velocity [13]. It is assumed that the cutting forces are evenly distributed across the cutting edge, and their summations are expressed as the tangential force (F_t) in the direction of the cutting velocity, and the feed force (F_f), in the direction perpendicular to the cut workpiece surface. Extensive studies have been performed in developing empirical and analytical models aiming to accurately replicate the experimental observations from the orthogonal machining configuration [14].

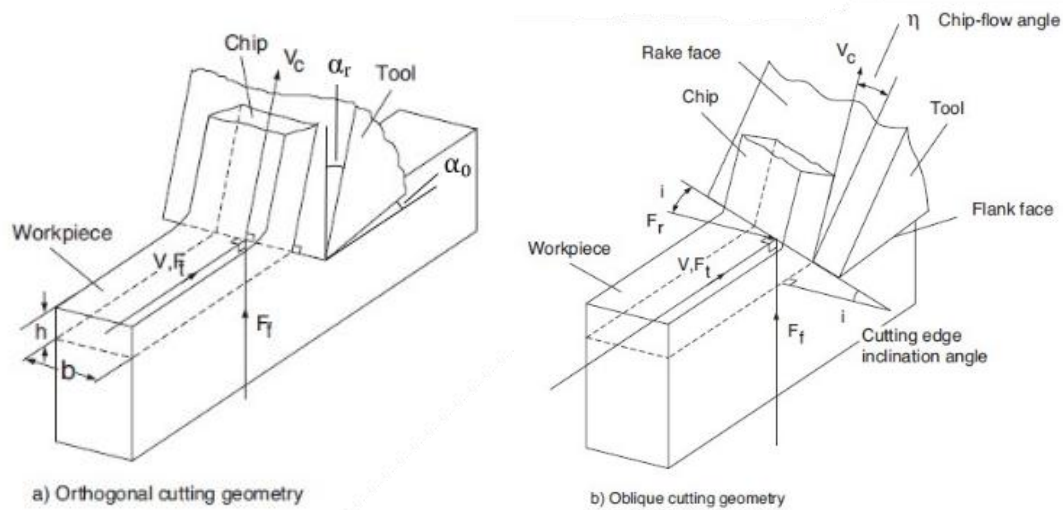


Figure 2.1: Orthogonal (a) and oblique (b) cutting models. Adapted from [9].

An extension of orthogonal cutting is the oblique cutting model seen Figure 2.1 (b), in which the cutting edge is oriented at an inclination angle (i) [9]. With the inclination, the process becomes three dimensional, leading to the flow of the cut chip along the rake face at an angle of η , denoted as the chip flow angle. In addition to F_t and F_f , there is a force component in the third direction, F_r , referred to as the radial force. A typical example of oblique cutting frequently encountered in industry is helical end milling, in which the helix angle of the cutting tool causes the cutting edge to be inclined at an oblique angle with respect to the (tangential) cutting velocity along the edge of the cutter [15].

Considering the basic cutting model geometries in Figure 2.1, the rake face is the tool surface that directs and influences the flow of the newly formed chip. In orthogonal cutting, the rake surface is defined by the rake angle α_r , and in oblique cutting, by both the rake and the inclination angles. The rake face geometry and surface characteristics have a major influence on the cutting forces and heat generation during the cutting process [16]. Larger rake angle typically helps reduce the machining forces and power requirement but can weaken the tool by reducing the load bearing geometry. The friction between the rake face and chip, which is influenced by the tribological properties of the rake surface, has an adverse effect on increasing the required machining forces [9].

The flank face, defined by the flank (or clearance) angle (α_0), is a relief surface that provides clearance between the cutting tool and the newly cut portion of the workpiece. Should the flank angle be zero, rubbing between the tool and workpiece occurs, lowering tool life, and increasing heat generation [16]. This contact also leads to degradation of the newly cut surface. Similarly, wear of the tool on the flank surface increases the contact area between the tool flank and machined surface, mimicking a limited zero flank angle region, which is both detrimental to part quality and accuracy. Therefore, wear of the tool flank must be monitored and controlled within acceptable bounds. In fact, the monitoring and control of flank wear is among the most widely practiced methods in industry for determining cutting tool life.

2.3 Tool wear mechanisms and models

During a machining operation, the cutting tool is subject to forces, thermal loads, and tribological/material interactions with the workpiece material and formed chips, which in combination leads to the degradation of the tool during its use. Tool wear is caused by a variety of mechanisms and

factors which influence the tool wear in varying degrees. The most common causes of tool wear are: abrasion, adhesion, diffusion and oxidation [9]. Extensive studies have been conducted in tool wear to predict the useful cutting time, the progression of wear using different tool life models, and to slow the wear progression through better tool design and coatings to help minimize tool replacement. Through this knowledge, process planners can optimize cutting operations. One important note is that tool life models function best when interpolating data within earlier observed or recorded experimental cases and are not particularly accurate in extrapolating to conditions or wear criterion outside earlier training measurements.

2.3.1 Tool wear types

Tool wear can be classified into different types depending on the location of the wear on the tool, as well as the dominant mechanism(s) governing the progression of wear. This thesis focuses on abrasive wear in the form of flank wear, as it was found to be the dominant wear type in the performed cutting experiments discussed in the latter chapters. Crater wear is also discussed to a limited extent in the following section.

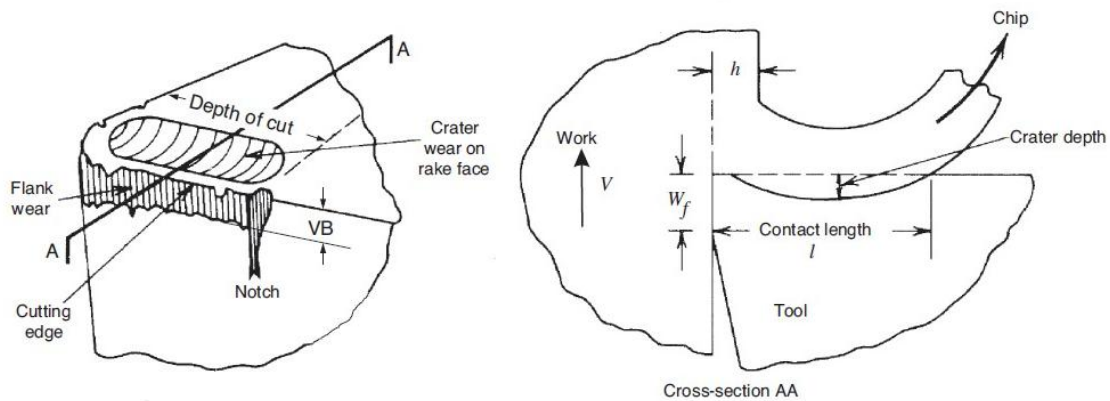


Figure 2.2: Crater wear and chip flow across rake face of cutting tool [9].

Flank wear

Flank wear is a form of wear characterized by a progressive growth of wear land (i.e., wear zone) starting from the cutting edge, growing down the flank face as shown in Figure 2.2. Flank wear is typically caused by abrasion between the tool and cut surface of the workpiece [9]. As the wear zone grows, the area in contact with the workpiece increases, trapping removed particles that further accelerate wear by acting as cutting grit. The growth of flank wear can be slowed down using cutting

lubricants that dissipate heat away from the tool and workpiece, flush the trapped particles, and reduce the friction between the rubbing workpiece and tool flank surfaces [17]. Flank wear affects the cutting process through its influence on the usable life of the tool. When progressed to extremes, it can also influence the surface finish [18] and geometric accuracy of the produced workpiece, due to its effect on the tool geometry. Flank wear typically takes the form of a series of parallel grooves in the direction of the cutting velocity [19]. An example of flank wear imaged by the author can be seen in Figure 2.3, showing the wear starting at the top of the tool (rake face) and growing down the tool's flank face.

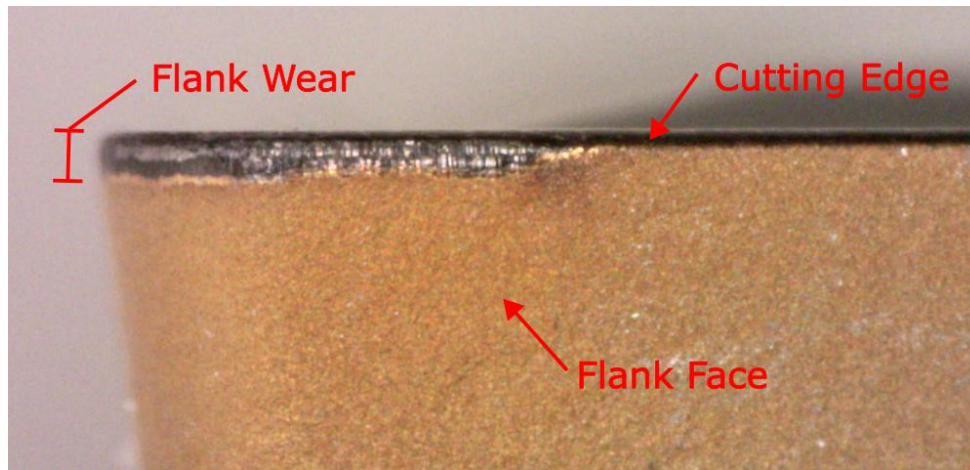


Figure 2.3: Flank wear observed on a carbide insert during interrupted tests conducted in this thesis.

The growth of flank wear typically follows a three-zone progression, as seen in Figure 2.4. Zone 1 shows a rapid growth of wear from the initial tool state, typically a clean tool with no discernable wear. The secondary zone shows steady growth along a gradual trend, typically linear. Finally, a rapid progression of wear can be seen in the third zone, continuing until the tool reaches failure [9]. Failure of the cutting tool can occur in a variety of ways. Depending on the use case, some common failure modes are chipping of the cutting edge, shattering of the tool, or the flank wear exceeding a predetermined maximum wear criterion (VB_{max}). The choice of the flank wear limit is further discussed in Section 2.3.2.

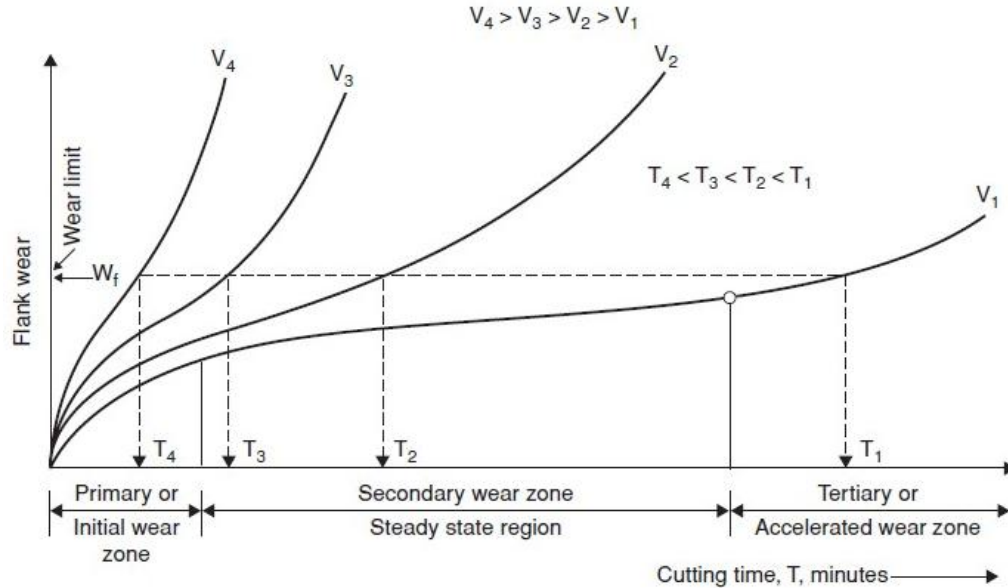


Figure 2.4: Three zone cutting wear progression [9].

Crater wear

Crater wear, sometimes called rake wear, is a form of wear that develops on the rake face of the tool, as seen in Figure 2.2, creating a divot on the rake face. As a tool is used and a chip is generated, material is exchanged between the rake face and the chip through both friction and high temperature material diffusion, indicating it is caused by a combination of both abrasive and diffusive processes [9]. Similarly to other forms of abrasive wear, progression can be slowed using cutting fluids and coolants that reduce the friction. Diffusive wear is influenced by local temperatures, with higher rates of diffusion occurring at higher temperatures. By lowering local temperatures through reducing cutting speeds and feed rates, or by the application of lubricants/coolants, diffusive wear can be slowed [20]. Other solutions to lowering diffusion are through the choice of workpiece material, tool substrate, and tool coatings.

The progression of crater wear can also be exacerbated through a phenomenon known as built up edge (BUE) seen in Figure 2.5. BUE occurs when cut chips seize on the rake face and cutting edge of the tool through adhesion. This build up modifies the effective tool geometry, creating a false edge which performs the cutting action instead of the tool's own edge [9]. The development of built-up edge is caused when the coefficient of friction between tool and workpiece is high, resulting in an initial build up of stuck material. Should the cutting speed be sufficiently low, the chip material layers will seize

due to cold work, with the local temperature being insufficient to cause a reduction of hardness leading to a growing mass of material [21]. As the operation continues and the BUE grows, it becomes unstable, breaking off from the tool and removing tool substrate with the stuck-on material. Many additional factors aside from cutting parameters may also affect the development of BUE, such as tool geometry (size of edge radius, rake angle, clearance angle, and sharpness of cutting edge), and the workpiece material [22].

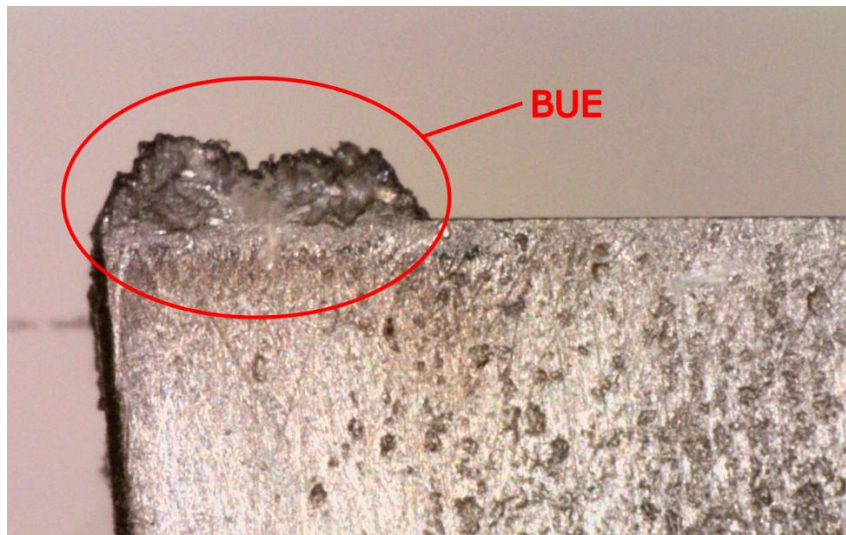


Figure 2.5: Built up edge (circled in red) on the rake surface of a turning tool.

Other types of tool damage

While crater and flank wear are the most common types of wear, there are other types of tool damage. One of them is chipping that results in a loss of material on the tool edge, usually caused by force impacts on the tool during interrupted cutting [9]. Similarly, shattering of the tool is another form of damage, typically classified as a larger loss of material than chipping and a total failure of the tool. There are also other types of cutting tool damage, such as oxidation wear, thermal cracking, and notching. Further information on these can be found in [23], [24], and [25], but these wear types are not the focus of this thesis.

2.3.2 Tool life models

Empirical wear models, typically known as tool life models, have been developed with the intent to predict the cutting time at which a tool will reach a pre-specified amount of wear, usually as a maximum

flank wear value (VB_{max}). The magnitude of VB_{max} is chosen considering the potential flank wear may have on the finished surface characteristics and desired geometric precision of the final workpiece [26]. Once the tool has reached the wear criterion, the used tooling may be reground to reveal a new cutting edge.

The main factor influencing the tool life (T), typically measured in minutes, is the cutting speed. Typically, higher cutting speeds result in lower tool life, and lower cutting speeds in longer tool life [27]. Using tool life models, process planners can optimize and adjust the cutting conditions, influencing tool replacement intervals, to optimize cost and productivity.

Tool life models are calibrated using measured wear data and the cutting parameters used in each trial. Once the model constants are determined, interpolation can be used to estimate tool life for different cutting conditions within an envelope. The parameters remain valid for the tool and work material pair and changing either requires the tool life model to be recalibrated with further tests. Different tool life models have been proposed, improving on earlier works, typically by modifying the mathematical expression and expanding the number of parameters to be identified.

Taylor's tool life model

First proposed by F.W. Taylor in 1907, Taylor's tool life equation predicts the cutting time (T) required for the flank wear on a turning tool's cutting edge to reach a prescribed wear criterion (VB_{max}) for a given cutting speed (v_c) [6]. Initially applied for predicting tool life in continuous cutting, Taylor's tool life model has been applied to a large range of cutting processes, varying the data used for calibration. Taylor's original tool life model can be seen in Eq. (2.1) considering only cutting speed and cutting time while incorporating two fitting constants m and C_T . An extended model, as shown in Eq. (2.2), adds consideration of the uncut chip area, by incorporating depth of cut (a_p) and feed rate (f), with the addition of model constants p and q . Further additions incorporate the Woxen-equivalent chip thickness model, shown in Eq. (2.3), to the Taylor model shown in Eq. (2.4), replacing the feed and depth of cut terms. Woxen's equivalent chip thickness is introduced to more accurately calculate the average chip thickness across the tool nose while considering the tool geometry, such as the nose radius (r_ϵ) and major cutting angle (κ) [28]. The major cutting angle κ can be seen in Figure 2.6 as well as the comparison between the real uncut chip geometry and the simplified chip geometry.

$$v_c T^m = C_T \quad (2.1)$$

$$v_c f^p a_p^q T^m = C_T \quad (2.2)$$

$$h_e = \frac{a_p f}{\frac{a_p - r_\epsilon(1 - \cos \kappa)}{\sin \kappa} + \kappa r_\epsilon + \frac{f}{2}} \quad (2.3)$$

$$v_c h_e^p T^m = C_T \quad (2.4)$$

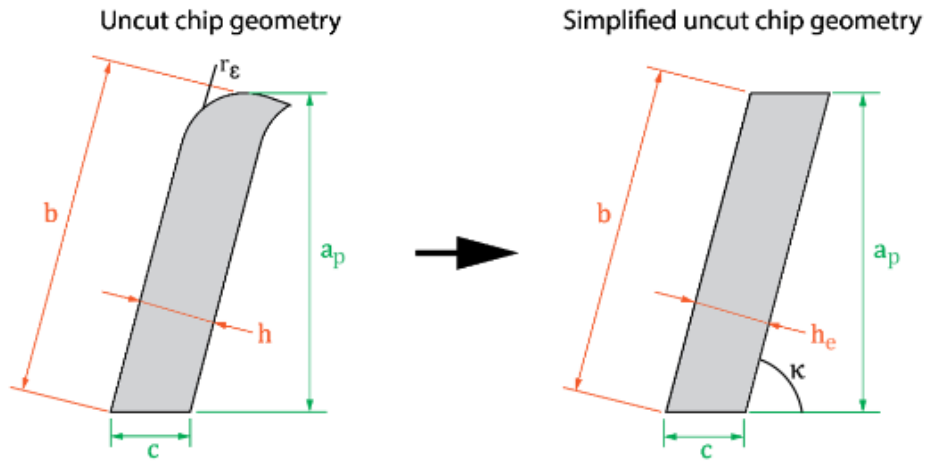


Figure 2.6: Uncut chip geometry comparison between real and simplified.

Colding tool life model

The Colding tool life model, created by Bertil N. Colding, is a tool life model that includes more constants than Taylor's tool life models [7], to facilitate more accurate prediction. However, the increased number of constants requires more experimental data for model calibration, leading to higher cost and time spent for tool life prediction. The first model proposed by Colding can be seen in Eq. (2.5) in the form of an extended Taylor type equation, where m is calibrated as a look-up table for a range of feed values based on h_e (the equivalent chip thickness) proposed by Woxen while α represents a model constant [29]. Later developments introduced a nine constant model, but was afterwards simplified to a five constant model, as presented in Eq. (2.6). This model predicts the recommended cutting speed (v_c) for a target cutting time (T) as tool life. This simplification helped achieve a better balance between accurate tool life prediction and the initial investment to collect cutting data. The five

constants in this model are K , M , N_0 , H , and L , and the variables are cutting speed (v_c), cutting time (T), and Woxen's equivalent chip thickness h_e .

Later developments by Lindstrom et al. replaced the model constants m and α in Eq. (2.5) with linear functions of h_e , as shown in Eq. (2.7) [30]. Afterwards, Kantojärvi et al. presented the relationship between Lindstrom et al.'s linear constant model Eq. (2.7) and Colding's model constants Eq. (2.6), concluding that the Colding model is an extension of the Taylor model [31] and a special case of Lindstrom's model. This relationship is derived in detail in Appendix C.

$$v_c T^{\alpha(h_e)} h_e^{m(h_e)} = C_0 \quad (2.5)$$

$$v_c = \exp \left[K - \frac{(\ln(h_e) - H)^2}{4M} - (N_0 - L \ln(h_e)) \ln(T) \right] \quad (2.6)$$

$$\alpha(h_e) = \alpha_0 + \alpha_1 \ln(h_e) \quad (2.7)$$

$$m(h_e) = m_0 + m_1 \ln(h_e)$$

While the Taylor and Colding tool life models are most used, additional wear models exist that may also be applied to cutting operations. One such model is the Archard sliding wear model [32], developed in 1953, describing the volume of material removed when two surfaces slide against one other. The wear volume is found to be proportional to the applied load and sliding distance while inversely proportional to the material hardness. However, oversimplifications in the model such as neglecting sliding velocity and the lack of model constants restrict the applicability in diverse wear conditions [33].

2.3.3 Tool wear progression models

Tool life models, while being useful in industry, have the drawback that they are only able to predict the cutting time, at a given cutting velocity, at which a tool will reach a predetermined wear criterion. Should this wear criterion be changed, the model would need to be recalibrated with a new dataset corresponding to the new criterion. While used to a lesser extent, wear progression models have been developed to incrementally predict the growing wear and general trends in wear progression over the life of the tool. They can be utilized regardless of changes in the wear criterion value (as long as it is in

the gradual wear envelope of the tool) and are also practical for accommodating changing cutting conditions throughout the use of the tool.

An example can be seen in the wear model proposed by Laakso et al. [34], where a logit-based function is used to predict wear and model wear data following the commonly seen three-zone wear progression. In this model, the function is scaled from the initial wear to the maximum wear across the tool life as determined using a tool life equation, such as Taylor or Colding models, and calibrated using a Levenberg-Marquardt method to determine the model constants. The log functions used can be seen in Figure 2.7, progressing from the base logit function $f(x)$ to a shifted version $g(x)$, and finally a normalized function $h(x)$ that is used in the wear model. The value of n is chosen to avoid numerical problems due to the $f(x)$ assuming unbounded values when $x = 0$ and $x = 1$. The wear function $VB(t)$ that incorporates the normalized and offset logit function $h(x)$ can be seen in Eq.(2.8), where t_{max} represents the overall tool life. a represents the initial wear amount. b is an exponential constant which controls the smoothness of the transition (increasing b predicts slower build up of wear).

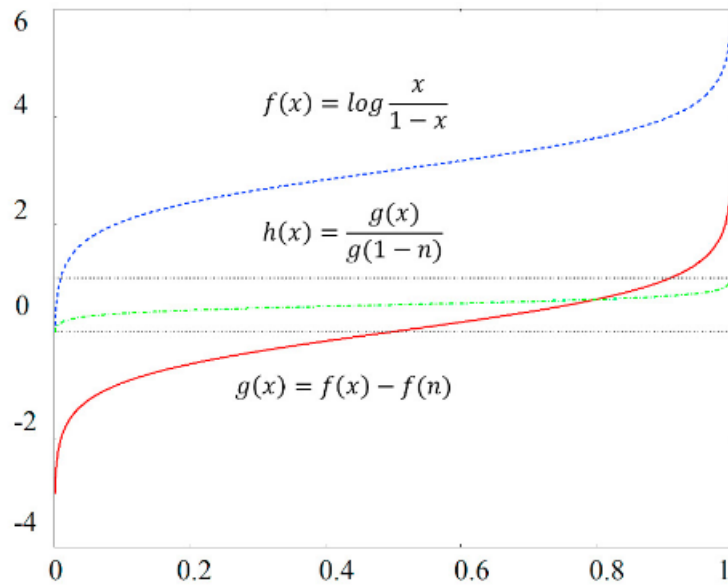


Figure 2.7: Scaled and shifted logarithmic (log) models used in the Laakso et al. wear progression function Laakso et al. [34]. Used under a CC-BY-NC-ND license

$$VB(t) = a + \left[h\left(\frac{t}{t_{max}}\right) \right]^b \times (VB_{max} - a) \quad (2.8)$$

In addition to tool life and wear modelling, in-process tool condition monitoring is another area of research. An example of such can be seen in Surmann et al. [35], relating spindle torque to tool condition. As the tool condition deteriorates, the spindle torque offset increases (due to increased tool flank ploughing or “edge” forces), requiring a higher torque to cut material when compared to a new tool. In previous work, the tool was replaced after a certain cut distance regardless of the cutting operation leading to inconsistently worn tools. Instead, a tool condition value $r_c \left[\frac{N}{mm} \right]$ is introduced, relating the offset of the cutting force to a visual inspection of the tool allowing prediction of wear based on the force input. Through the monitoring of the force offset (from the spindle motor current), in-process but indirect monitoring of the tool wear state was reported.

2.3.4 Standardized measurement of tool wear

To ensure consistent application of tool life and wear models, standardized methods have been created for the measurement and documentation of tool wear. ISO 3685: “Tool-life testing with single-point turning tools” provides such a measurement and documentation framework for turning, including a set of testing parameters for a range of tool and workpiece materials, as well as classification methods for wear appearing during the cutting operation [36]. When measuring flank wear, the measuring device – in this case a digital microscope, is placed perpendicular to the flank capturing an image focusing on the cutting edge. Once captured, the wear land is measured perpendicularly from the rake face of the tool to the location of highest wear or largest wear land. To ensure accurate measurements, calibration of the field of view is performed equating a known distance in the camera’s focus to a pixel measurement using the camera’s software. Similar wear characterization frameworks have been developed for other cutting operations as well, such as ISO 8688-1 [37] and ISO 8688-2 [38] for tool wear in milling. While visual measurement of wear is most common, other techniques can also be used. One such example can be seen in Polishetty et al. [39], where a 3D optical profilometer was used to document flank and crater wear of worn tooling.

2.4 Gear machining processes and models

The production of gears can be achieved through a range of manufacturing methods, from subtractive processes like hobbing, shaping, and power skiving seen in Figure 2.8, to forming processes, like stamping and extrusion, to additive processes, such as casting and powder metallurgy [40]. To enhance

productivity and efficiency, new processes and improvements to existing methods are continually being developed [41]. The focus of this thesis is on developing tool wear simulation models for gear shaping. Shaping, which is like a broaching operation with involute tooth profile generative motion built-in, is widely used in the production of gears. It is especially suited for cutting spur or helical internal ring gears, in which the geometric clearances for the tool motion are very limited. The kinematics of shaping is less dynamic than of hobbing or power skiving, which makes this process also suitable for being the first to incorporate tool wear simulation. Nevertheless, for completeness, in the proceeding a brief review of the three most prominent gear cutting processes (shaping, power skiving and hobbing) is presented.

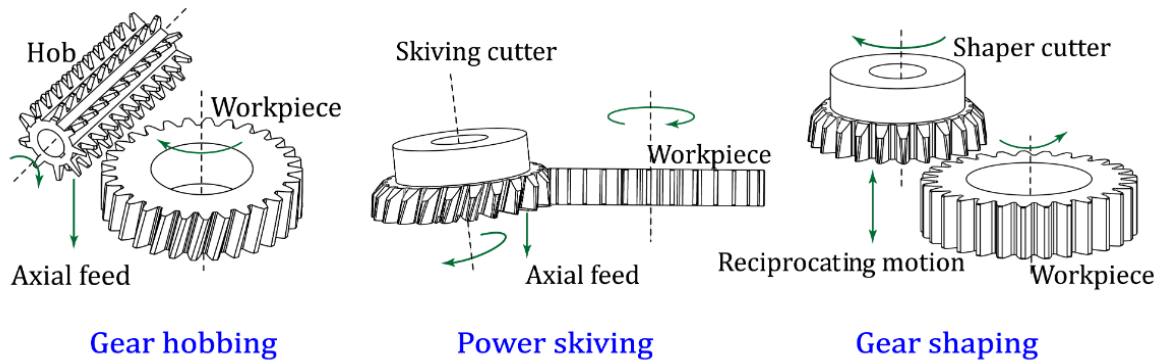


Figure 2.8: Basic overviews of three gear cutting processes [42].

2.4.1 Shaping

In gear shaping, a cutting tool in the form of a modified gear with matching gear parameters of the desired tooth profile of the workpiece (module, pressure angle, and helix angle) is used. The tool reciprocates vertically, removing material from the workpiece, while at the same time the workpiece and tool rotate synchronously through a rotary feed action, emulating the rolling of pitch circles as seen in Figure 2.9 [43]. As the process continues, the centre-to-centre radial distance is reduced (for external gears) or increased (for internal gears) from a starting safe distance to the final axis-to-axis offset for nominal gear tooth meshing gears, thus satisfying the cutting depths specified by the machining pass parameters. Both internal and external gears can be produced with shaping, as well as helical gears (in addition to spur), by rotating the tool during the cutting downstroke.

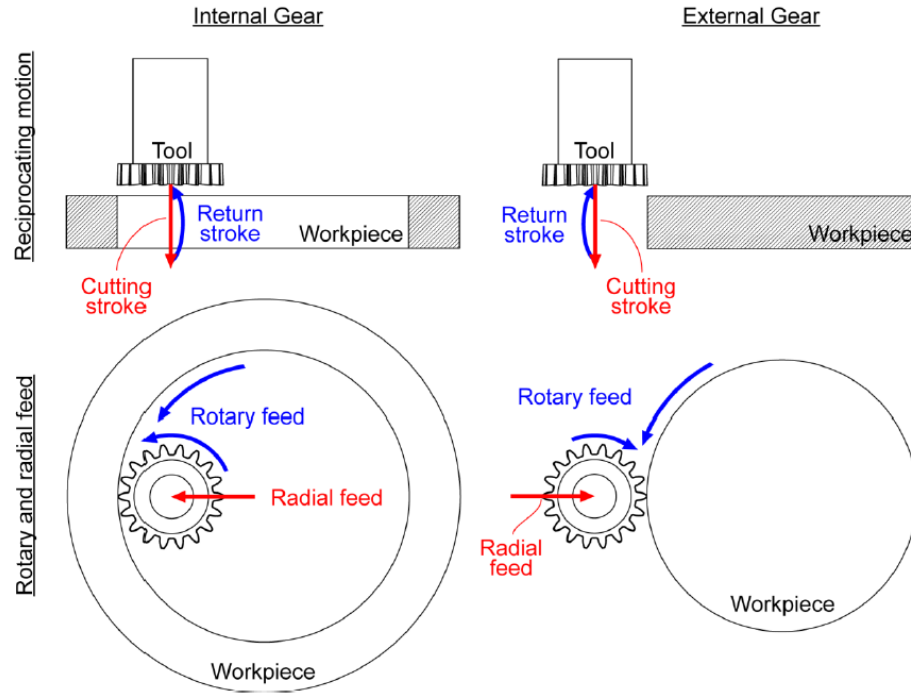


Figure 2.9: Diagram of the gear shaping process for internal and external gears [43].

During each cutting stroke, only a small section of the tool is in contact with the workpiece. As the process continues, due to the rotary feed motion, the sections in contact vary around the cutter profile, which creates continuously changing cutter-workpiece engagement (CWE) conditions. The complexity of the CWE also makes the estimation of the chip formation more challenging, despite constant cutting process parameters, which renders common chip formation models inapplicable. Therefore, Erkorkmaz et al. [10] have employed discrete geometric modeling, using a tri-dexel geometric engine, to compute the dynamic CWE, as well as the constantly evolving workpiece geometry, in an efficient manner.

2.4.2 Power skiving

Power skiving is a highly productive gear cutting process capable of producing spur and helical gears, both internal and external, as long as there is necessary tool clearance [44]. During the cutting process seen in Figure 2.10 a), a tool resembling an involute gear is oriented at an angle from the workpiece (the cross-axis angle Σ) and fed at a constant velocity along the z-axis of the workpiece (the axial feed v_f). The tool and workpiece both rotate, creating a cutting motion proportional to the cross-axis angle and the relative rotation [11]. As passes are cut, the radial distance is decreased (for external gears) to remove more material until the workpiece teeth are cut to full depth [45].

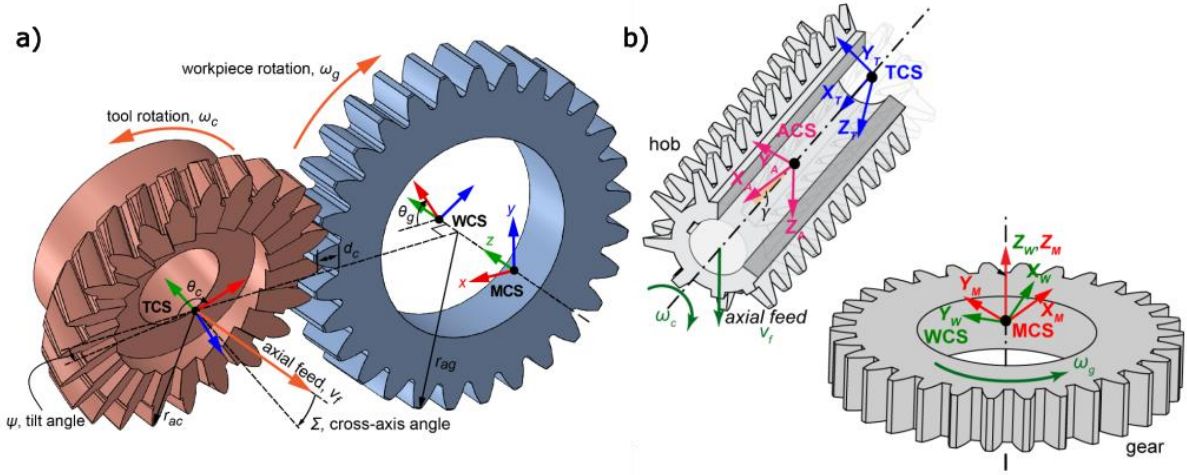


Figure 2.10: Schematics of a) power skiving process [46], and b) gear hobbing process [42].

2.4.3 Hobbing

Hobbing is a gear cutting process utilizing complex kinematics in which a specially formed tool (hob), resembling a modified worm gear, is used to cut tooth gaps on a rotating workpiece [44]. A schematic illustration of the gear hobbing process is shown in Figure 2.10 b). The hob is held at an angle to the workpiece (the lead angle) while the hob and workpiece are rotated synchronously. The hob is fed vertically along the z-axis of the workpiece, removing material progressively from the cut gear's tooth gaps [12]. While it is a highly productive method of producing external gears, hobbing cannot be used to produce internal gears. Also, due to the complex kinematics and chip formation, tool wear and cutting forces are challenging to model and predict.

2.4.4 UW's integrated gear cutting simulation platform - ShapePro

Digital simulation of cutting processes has become a large focus of study, allowing process planners to simulate manufacturing operations and optimize parameters without needing to physically run the process. ShapePro is a software package developed by the Precision Controls Laboratory at the University of Waterloo, providing digital models for gear shaping, hobbing, and power skiving. It was developed through the contributions of earlier graduate students with the goal to simulate the kinematics and mechanics of gear shaping [43], hobbing [12], and power skiving [11]. In these simulations, in-process conditions such as relative movements between the tool and workpiece, chip geometry, cutting

forces, and deflections due to static mechanical compliance are predicted at each time step [47]. Integrating these predictions with a discrete geometric modeler facilitates the prediction of the final gear profile, as well as gear and tooth imperfections, in a virtual environment. In this thesis research, ShapePro has been used to simulate the gear shaping process, validating kinematics and ensuring that the designed cutting process was feasible on the available machine tool at the University of Waterloo, used in the shaping experiments. The gear shaping experiments conducted in this thesis are detailed and discussed in Chapter 3. A sample ShapePro simulation can be seen in Figure 2.11 showing a simulated shaping process.

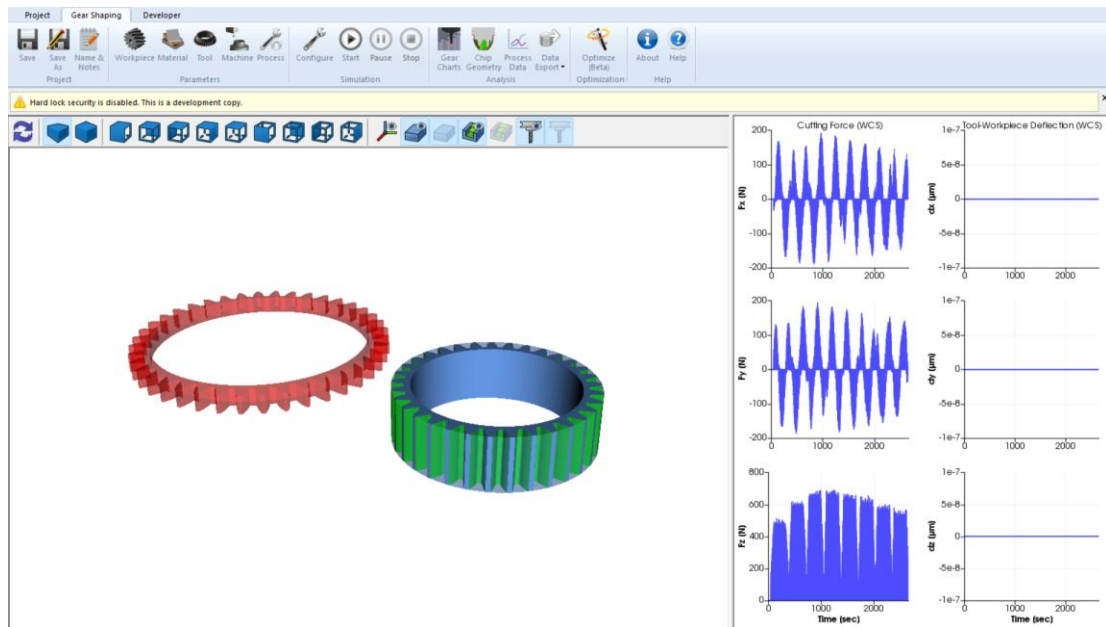


Figure 2.11: Screenshot of ShapePro gear cutting simulation software. Left: Visualization of the tool and workpiece. Right: Cutting force prediction.

2.5 Tool wear in gear machining studies

While less frequently studied compared to other machining methods, investigation of tool wear in gear cutting is increasingly gaining attention. This growing focus emphasizes the optimization of cutting parameters with the goal of enhancing economic efficiency via the optimization of tool life. The goals are to maximize the usable lifespan of tools, ensure the production of high-quality workpieces, minimize errors, and boost throughput. While some wear analysis data is publicly available, it is speculated that companies retain significant amounts of proprietary data to retain a competitive

advantage. Among the research reviewed by the author, the majority focuses on gear hobbing, and documentation on wear analysis and testing methods for gear shaping and power skiving remains comparatively scarce.

Across research, the approach towards application of wear data varies with some applying tool life equations, such as the Taylor or Colding models, to determine trends based on cutting parameters while others draw conclusions via analysis of the measured wear data. While methodologies vary, the testing remains the same with cutting experiments being performed and measuring the wear appearing on the tool. Some studies also utilize analogy testing methods to accelerate wear growth while recreating similar cutting conditions with a more affordable process.

2.5.1 Tool wear studies directly from gear cutting process

Tool wear studies for gear cutting processes often employ consistent testing methods to obtain cutting data, but the measurement and analysis of wear data can vary. The process typically involves cutting tests across a range of parameters. During these tests, the tool is periodically removed to measure the wear that has developed. The specific type of wear being assessed and measurement techniques used depend on the dominant wear mechanism that is present. Flank wear is commonly monitored, as it significantly affects the dimensional accuracy and final quality of cut gears.

In modeling wear, basic models are preferred that have been widely studied and accepted. Typically, the model will use a small number of constants capturing mainly the most significant factors. Such an approach has been used by Troß et al. [48], where a Taylor model using cutting speed and length of material cut was used to characterize the tool wear of a gear hob. More complex tool life models, such as the Colding or Archard model, are rarely used due to the large amount of testing required to calibrate the coefficients in the case of Colding or the requirement for in process data in the case of Archard. Complex geometry-based models have also been applied effectively, but require a more in depth analysis of the cutting process, as seen in Ren et al. [49]. This approach is also difficult to adapt to gear cutting, due to the constantly changing cutting conditions originating from the complexity of the kinematics and changing chip geometry.

Wear models implementing finite element analysis (FEA) to simulate the removal of material have also been proposed but are typically reserved for when a process simulation model, describing the kinematics and geometry, is available. This can be seen in Kamratowski et al. [50], where BevelCut software was used to discretize the tool and workpiece geometry while a friction-based model was

developed and validated using hobbing tests. Similarly Karpuchewski et al. [51] utilized a hobbing analogy test along with FEA software AdvantEdge to simulate chip formation and the development of crater wear. Once a wear model is calibrated, it can be used to optimize the machining parameters.

While empirical wear models can be adopted, they are not the only method for gear cutter wear analysis and optimization. Inspection and analysis approaches can also be applied to gathered cutting data for drawing conclusions. This can be seen in Gerth et al. [52] in which visual inspection of the tool was used to analyze wear progression, while surface finish of the final part were used to analyze the condition of the tool and success of the cutting parameters. Similarly in Kühn et al. [53], visual inspection of the tool was performed to gather wear data of the cutting tools. The wear trends were compared across varying feed rates and cutting speeds. The measured wear progressions were used to draw conclusions from analogy testing data and the cutting parameters that best satisfied the goals of the process planning were implemented into the gear cutting operation.

2.5.2 Analogy testing to recreate gear cutting conditions

Analogy testing methods are commonplace in which an alternative cutting method is used to replicate the conditions seen in the process of interest. These testing methods are employed in tool wear testing to reduce the monetary costs, by accelerating the growth of wear on a cutting tool, reducing the time needed to reach the wear criterion. Analogy testing methods allow testing to be performed on alternate machines without interfering with part production and enables testing on machines conveniently equipped with research instrumentation.

Gear hobbing analogy tests can take a range of forms with each test having distinct advantages and disadvantages as shown in Stein et al. [54], where three common analogy tests have been compared. These analogy tests include: planar or side milling with inserts, fly hobbing within a 5-axis machine, and fly hobbing within a hobbing machine. A commonality across these tests is the use of a single or small number of cutting inserts or teeth. This technique can also be seen in the analogy test developed by Gerd Sulzer, where a tooth is separated from a production hob and mounted within a gear hobbing machine using a specially made fixture [55]. The modified tool is then used in a gear hobbing operation and shifted between cuts to recreate all cutting positions cut by the original hob. This technique can be seen performed by Troß et al. [48] in Figure 2.12 for studying wear in dry hobbing of hard materials. Through this modified operation, the cutting time and volume of material removed from the workpiece is concentrated to a single tooth, reducing the total number of workpieces needed to reach the wear

criterion. This testing method can then be repeated for the chosen range of cutting parameters, reducing the total experiment time as well as the number of hobs needed. Alternative methods are also used as shown in Gerth et al. [52], in which the wear on a milling insert test is compared to the wear progression of a hobbing operation, and found to successfully recreate the wear seen in traditional hobbing.

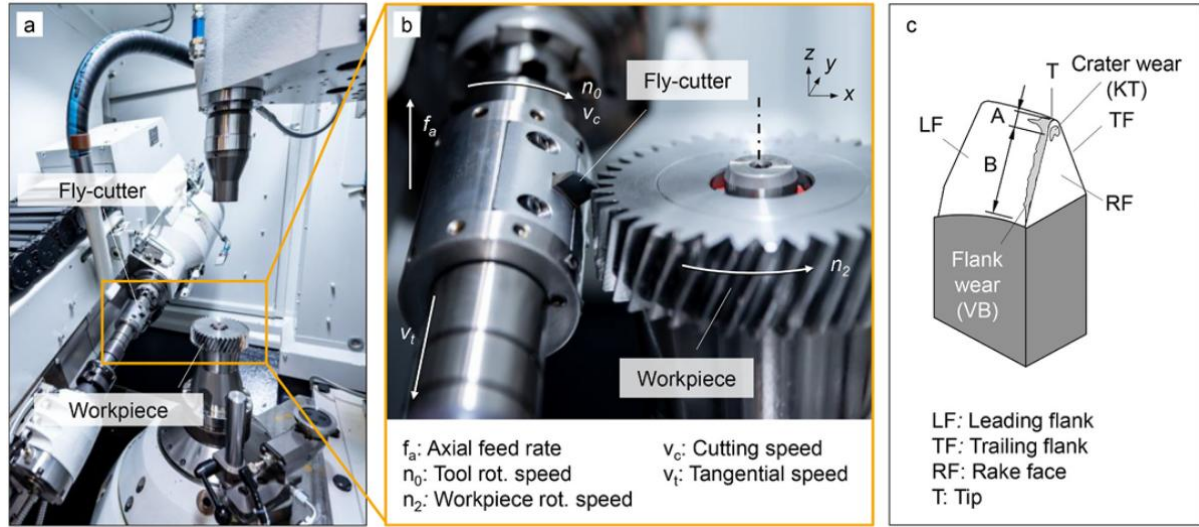


Figure 2.12: Experimental setup of a hobbing analogy test using a single cutting tooth. (a) Work space of gear hobbing machine LIEBHERR LC180, (b) magnification of fly-cutter including direction of motions, (c) fly-cutter nomenclature [48].

Another recently developed analogy test uses a lathe and a specialized workpiece holder to recreate the interrupted cutting conditions seen in gear shaping, while a modified gear shaper cutter is used in place of the lathe tooling, as seen in Figure 2.13 (cited from [53]). The shaping tool has been modified removing teeth to provide adequate clearance when cutting into the workpiece. As the process begins, the tool is fed radially into the workpiece removing material from the workpiece and creating tooth gaps. Once the gaps are cut to full depth, the cutter is shifted axially to the position of the next gap and cutting can resume. The tool is also removed periodically to measure the growing tool wear. Through this process, multiple tooth gaps can be cut faster with the same tooth edges, thus allowing tool wear to be induced in shorter testing times. However, this cutting process is more resemblant of broaching, as it does not recreate the generative meshing action typically seen in gear shaping.

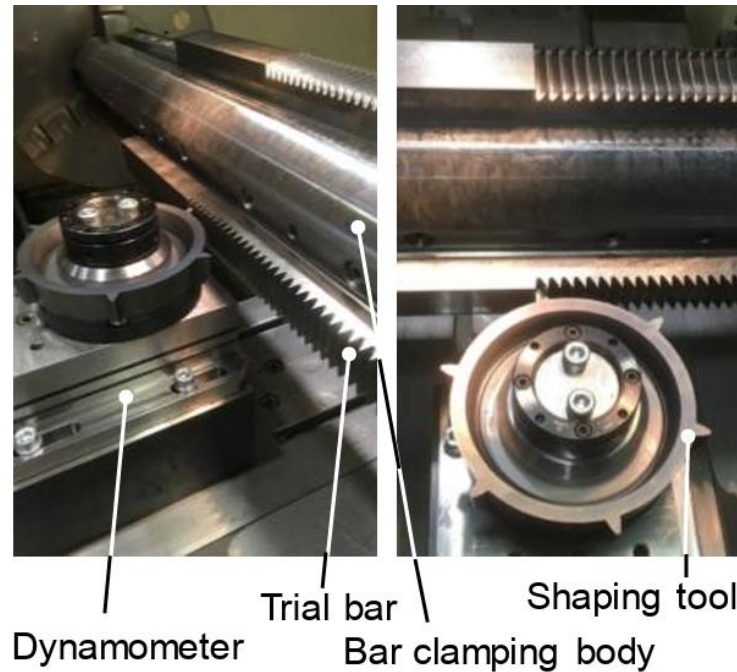


Figure 2.13: Interrupted turning gear shaping analogy test. Kühn et al. [53] Used under a CC-BY-NC-ND license

2.6 Conclusions and outlook

This chapter has reviewed the literature on basic cutting mechanics, tool wear types (measurement, characterization, and empirical modeling), gear machining configurations, and characterization of tool wear in gear cutting and related analogy tests. While tool wear models have been implemented in gear cutting, the focus has been on mainly gear hobbing with comparatively less research reported in literature for shaping and power skiving operations. Furthermore, in wear prediction, tool life models, like Taylor or Colding, are much more commonplace than wear progression models, which can be more suited for digital simulation. Hence, the surveyed literature has identified a knowledge gap in developing progression type models and applying them to gear cutting operations. In this thesis, gear shaping is chosen for study, as it is one of the easier generative gear cutting processes to model.

Henceforth, the surveyed literature informs the testing protocol developed for gear shaping, presented in Chapter 3 as well as tool wear measurement methods. Furthermore, it informs the progressive tool wear modeled developed as a new contribution in Chapter 4 of this thesis, as well as the comparison of results with established Taylor and Colding tool life models.

Chapter 3

Gear Shaping Tool Wear Testing

3.1 Introduction

The goal of this chapter has been to reproduce the gear shaping process using the available machine tool at University of Waterloo, and to collect wear data directly from shaper cutters to be used in wear analysis. To complete these goals, a shaping experiment was designed and performed using a five-axis CNC machine, as a dedicated gear shaping machine was not available for use. To perform the shaping movements within the available machine, custom numerical control (NC) code was created using gear shaping kinematics modelled by previous students as a base. The gear shaping kinematic feed motions were translated into movements achievable in the CNC using a custom MATLAB script, and output as a series of discrete movement commands readable by the CNC controller. Additional modifications to the chosen machine included a custom mounting systems for both tool and workpiece to provide appropriate clearance during the cutting strokes, as well as rigidly mounting the tool into the machine's spindle.

While the machine could accurately reproduce the shaping process, as verified by ShapePro simulation and polygon subtraction, there were clear limitations originating from the machine that restricted the process. These limitations were the maximum feed rate in the Z axis of 10 m/min as well as a lack of rigidity in the machine axes and spindle. It was found that when high forces were applied, excessive deflection and, in extreme cases, a loss of tool rotational position occurred due to the applied torque overcoming the spindle brake. To overcome these errors a maximum allowable force of 700 N was selected. Due to the machine limitations, the cutting process was split into eight-passes resulting in a long process time and limiting the number of experiments that could be performed. Furthermore, when comparing the workpieces to an ideal profile, it was found that the produced workpieces were of low surface quality.

3.2 Gear shaping kinematics

Gear shaping is an interrupted cutting process performed in a specialized cutting machine consisting of three feed movements: radial feed (altering the distance between tool and workpiece), reciprocating feed (cutting feed of the tool in the Z axis) and finally the rotary feed of the tool and workpiece about their Z axis as shown in Figure 2.9 [43]. The kinematic process can be described through four variables:

the angle of the cutter ϕ_c , angle of the workpiece ϕ_g , radial distance between tool and workpiece r and finally the vertical position of the cutter seen in Figure 3.1. Through the cutting process, the tool and workpiece profiles mesh, while the radial distance is reduced until the specified depth of cut d_{cut} is reached. During these movements, the tool is reciprocated removing material from the workpiece with each downward stroke.

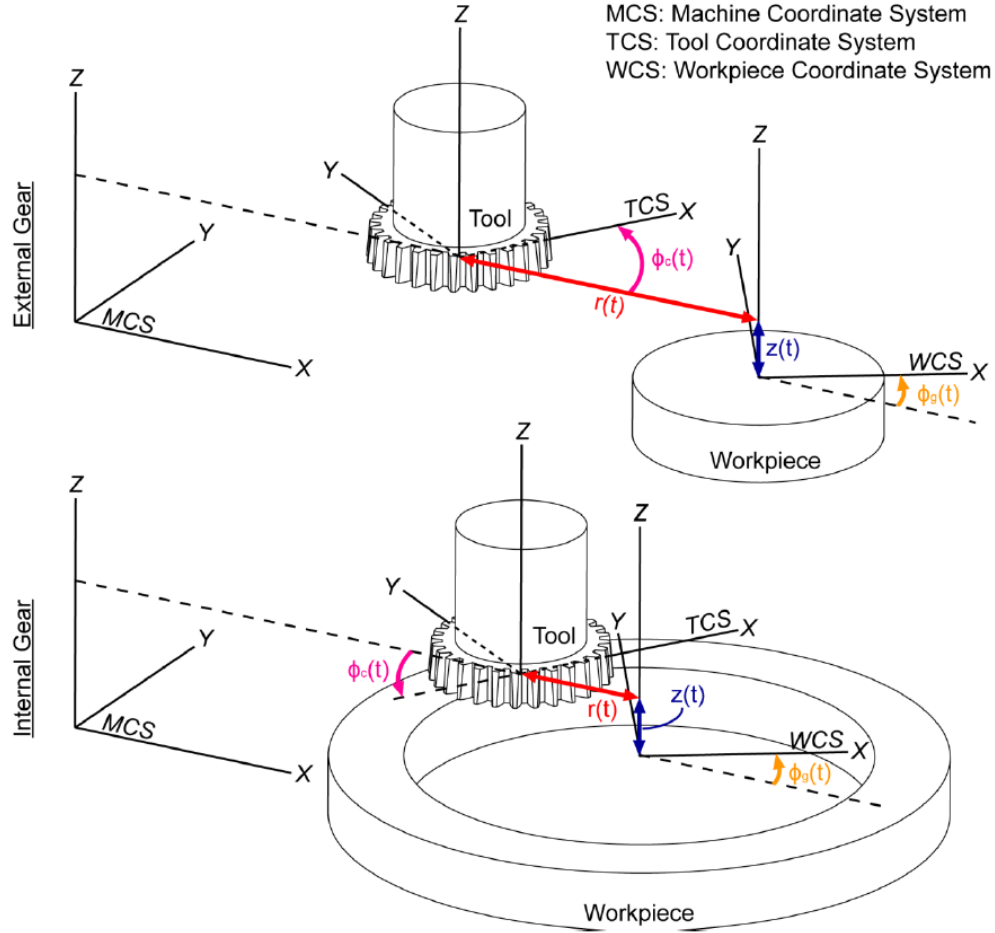


Figure 3.1: Coordinate systems of the gear shaping process. Katz et al. [56]

As mentioned earlier, since access to a dedicated gear shaping machine could not be secured, shaping experiments were performed on a Deckel Maho 80 P hi-dyn five-axis CNC milling machine. In implementing this change, the shaping kinematics, modelled from a traditional gear shaping machine in work performed by previous students, was used as a basis and modified to suit the machine. In traditional gear shaping, the tool and workpiece mesh synchronously through the process at the

specified gear ratio R . However, the available CNC machine was unable to synchronize the angular positioning of the tool and workpiece (C axis and spindle position). Instead, the angular position of the tool was locked, and the meshing action was performed using modified kinematics achievable on the machine. This change and the kinematics used is further explained in Section 3.2.4.

3.2.1 Reciprocating Z axis feed

The reciprocating motion of the tool is traditionally created by a slider and crank mechanism to move the tool vertically on the slider arm as the crank turns. The length of stroke d_{stroke} shown in Eq. (3.1), is a function of the face width of the gear workpiece (b) as well as the overrun distance both above and below the workpiece, d_{top} and d_{bottom} , respectively. The cutting stroke frequency f_{cut} is defined in units of double strokes per minute (double stroke describing one cutting stroke and one return stroke). Alternatively, the cutting stroke frequency can be defined in engineering units of radians per second by ω_s as seen in Eq. (3.2).

$$d_{stroke} [mm] = d_{top} + b + d_{bottom} \quad (3.1)$$

$$\omega_s \left[\frac{rad}{s} \right] = f_{cut} \left[\frac{DS}{min} \right] \left(\frac{2\pi}{60} \right) \quad (3.2)$$

To prevent rubbing between the tool and workpiece during the return stroke, a slight back off is implemented, changing the radial distance between the tool and workpiece on the return stroke. While this backoff motion is not been included in the above equations, it has been implemented in the modified kinematics and programming of the NC code as a safety radius (r_{safe}) outside the current centre-to-centre distance. Depending on the specification of the gear workpiece being cut (internal or external gear), the direction of backoff will change. When external gears are cut, the radial distance increases during backoff. On the other hand, when internal gears are cut, the radial distance decreases during backoff.

3.2.2 Rotary feed

The rotary feed motion of the tool and workpiece can be expressed by f_{rotary} in units of mm/DS. Using the chosen rotary feed rate and stroke frequency, the rotational velocity of the workpiece can be calculated as shown in Eq. (3.3). Finally, the rotational position of the workpiece can be found in Eq. (3.4). r_{p_g} represents the pitch radius of the workpiece.

$$\omega_g \left[\frac{rad}{s} \right] = f_{rotary} \left[\frac{mm}{DS} \right] \left(\frac{f_{cut} \left[\frac{DS}{min} \right]}{60 r_{p_g}} \right) \quad (3.3)$$

$$\phi_g[rad] = \omega_g t \quad (3.4)$$

To ensure the cutter and workpiece mesh, the rotational velocities are related by the gear ratio R shown in Eq. (3.5) relating the number of teeth between the cutter and workpiece. The rotational velocity of the workpiece ω_c can then be calculated as shown in Eq. (3.6). It is important to note the presented equation holds for spur gears only. For helical gears, an additional term would be included changing the rotational position of the cutter during the stroke to accommodate the additional rotation required of the cutter. To determine whether the gear being cut is an external or internal gear, an additional term ϵ is used (+1 for external gears, -1 for internal gears). Finally, the tool position ϕ_c can be calculated as shown in Eq. (3.7).

$$R = \frac{N_c}{N_g} \quad (3.5)$$

$$\omega_c \left[\frac{rad}{s} \right] = -\epsilon \frac{\omega_g}{R} \quad (3.6)$$

$$\phi_c[rad] = \omega_c t \quad (3.7)$$

3.2.3 Radial feed

The radial feed (f_{radial}), measured in units of mm/DS, is the feed rate used to change the centre-to-centre distance (r_{curr}) between the workpiece and tool as the cut progresses. Depending on whether the gear being produced is internal or external, the radial distance is increased or decreased, respectively. For each cutting pass, the radial distance between workpiece and tool begins at a value of r_{start} and ends with r_{end} . Determination of these values can be seen in Table 1 to n cutting passes. The r_{end} value for each pass is defined by the depth of cut d_{cut} and ϵ defining the direction of feed.

Table 1: Determination of r_{start} and r_{end} for each cutting pass.

	Cutting Pass		
	First ($i = 1$)	Intermediate ($1 < i < n$)	Last (n)
r_{start}	r_{scrape}	$r_{end_{i-1}}$	$r_{end_{i-1}}$
r_{end}	$r_{start} - \varepsilon d_{cut} \ (n > 1)$ $r_{gc} \ (n = 1)$	$r_{start} - \varepsilon d_{cut_i}$	r_{gc}

The value of r_{start} for the first pass begins at the value of r_{scrape} shown in Eq. (3.8) with r_{ag} and r_{ac} representing the addendum radius of the workpiece and tool, respectively. Similarly, the value of r_{end} for the n^{th} pass is given by r_{gc} , (the nominal centre-to-centre distance between tool and workpiece) calculated in Eq. (3.9) but is typically corrected by the machine operator to account for profile shift of the cutter, which is discussed in further detail in Section 3.3.3.

$$r_{scrape} = r_{ag} + r_{ac} \quad (3.8)$$

$$r_{gc} = r_{pg} + \varepsilon r_{pc} \quad (3.9)$$

$$r_{start} \geq r \geq r_{end} \quad (3.10)$$

Modern gear shaping machines allow the use of variable radial feed rates to optimize the cutting load. Larger radial feed rates are used at the start of the pass and lowered as the pass progresses and the engagement length between the cutter and workpiece increases. In this thesis, for the designed experiments a constant radial feed rate was used.

3.2.4 Modified kinematics and NC code generation for a 5 axis CNC mill

For the gear shaping process to be performed on the five-axis CNC mill, the original process kinematics must be transformed in such a way that the process is performable within the five axes and given the limitations of the machine tool. The major differences that will need to be considered when transforming the feed movements include the inability to synchronize the tool (spindle) and workpiece (C-axis) rotational positions, performing the cutting stroke using the Z axis feed instead of a slider crank mechanism, and transforming the continuous feed processes into a series of broaching-like movements implementable by the CNC controller. The machine limitations are primarily due to the

reduced stiffness and load carrying capacity of the servo axes when compared to a dedicated gear shaping machine tool.



Figure 3.2: Motion axes of the five-axis CNC milling machine.

The reciprocating feed of the shaping machine, traditionally produced through a slider crank mechanism, is performed using the machine z-axis, as shown in Figure 3.2, feeding vertically downwards to perform each cutting stroke. The tool will feed between two positions: z_{top} and z_{bottom} shown in Eq. (3.11) and Eq. (3.12). The z-axis origin is defined as the top surface of the workpiece. To ensure there is no rubbing or contact between tool and workpiece during the up stroke, the tool will move to a safe position r_{safe} outside of the previously cut radius r_{curr} .

$$z_{top}[mm] = d_{top} \quad (3.11)$$

$$z_{bottom}[mm] = -b - d_{bottom} \quad (3.12)$$

The rotary feed motions of the shaping process used to create the meshing action are modified, as the rotational position of the tool cannot be accurately controlled to ensure synchronization between the tool and workpiece. The workpiece rotation will be represented using the c-axis (table axis) shown in Figure 3.2. This can be seen in Eq. (3.13), where the table angle is equal to the workpiece angle. To ensure meshing action between the workpiece and tool, the tool angle ϕ_c is controlled using the x and y tool position shown in Eq. (3.14) This results in the tool moving around the perimeter of the workpiece

while the workpiece rotates, resulting in the appropriate meshing action. For each rotation of the workpiece, the tool completes the desired number of rotations according to the gear ratio R .

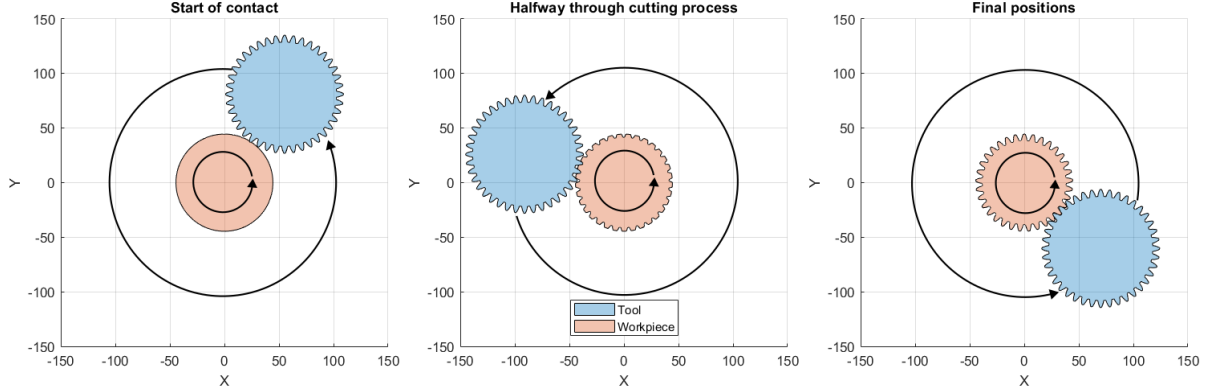


Figure 3.3: Diagram of the shaping process showing start, intermediate and final positions of the tool and workpiece.

$$\theta_{table}[\text{rad}] = \phi_g \quad (3.13)$$

$$[X_c \ Y_c] = [-r_{curr} \cos(\phi_c) \ r_{curr} \sin(\phi_c)] \quad (3.14)$$

Finally, the process is discretized into a series of cutting locations by finding the values of ϕ_c , ϕ_g and r_{curr} corresponding to the starting position of each downstroke (when the tool is at the z_{top} position). This was performed using a time interval t_{step} shown in Eq. (3.15) and solving for each cutting position across the cutting operation. The axial feed rate (f_z) of the tool was manually set in the CNC controller to the desired cutting speed.

$$t_{step}[\text{s}] = \frac{60}{f_{cut}} \quad (3.15)$$

The list of cutting locations was then used to generate an NC code file consisting of four basic movements:

- 1) Positioning of the tool in the X, Y, Z axis at the z_{top} position above the workpiece.
- 2) Move the tool to z_{bottom} at the specified f_z corresponding to the chosen f_{cut} , performing the cutting stroke.

- 3) Move the tool radially from the workpiece in the X and Y plane to the r_{safe} position clear of the workpiece.
- 4) Retract the tool to the z_{top} position above the workpiece.
- 5) Repeat the process from step 1, moving to the next cutting location as specified.

In addition to the NC code to perform the cutting movements, extra code was added to pause between cutting passes allowing for reapplication of cutting oil to the top surface of the workpiece. Additionally, as advised by the machine tool manufacturer, a sweep of the machine axes was performed between cutting passes to ensure proper distribution of lubrication. Hence, eight additional sweeping movements had to be included. A code excerpt can be seen in Figure 3.4 showing the general form of the NC code used to perform the shaping process.

1 BEGIN PGM 01 MM	1: Begin the Program
2 M19 M126	2: Orient and lock spindle position
3 L X 0 Y 0 Z 60 C 0 F10000	3: Travel to (0,0,60) at a feed rate of 10000 mm/min
4 L X 98.5919 Y 1.2616 C -1.6217	4: Feed to first cutting position
5 L Z -42	5: Downstroke to z_{bottom}
6 L X 99.5918 Y 1.2744 C -1.6217	6: Feed to safety radius in XY plane
7 L Z 15	7: Upstroke to z_{top}
8 L X 98.5577 Y 2.5227 C -3.2435	8: Feed to next cutting position
9 L Z -42	9: Downstroke to z_{bottom}
10 L X 99.5574 Y 2.5483 C -3.2435	10: Feed to safety radius in XY plane
11 L Z 15	11: Upstroke to z_{top}
12 L X 98.5074 Y 3.7831 C -4.8652	12: Feed to next cutting position

Figure 3.4: Annotated code excerpt showing the general form of the developed NC code.

3.3 Design of experiment

While the kinematics of the shaping process were modified into a form performable by the milling machine, additional work was required to finalize the design of the shaping experiment and ensure the process would be safe and repeatable for gathering tool wear data.

The chosen milling machine is not originally designed to perform the shaping process, unlike a traditional gear shaper. A major concern was the possibility of damage to the machine axes and spindle bearings due to the cutting forces, in addition to a lack of rigidity in the machine that may cause

deflection during cutting. To overcome this concern, the process was designed in consultation with the machine's manufacturer, and a maximum force limit was used to prevent damage.

Additionally, to accommodate the shaping process, modifications were required, such as a custom tool holder to mount the shaping tool to the spindle. A custom clamping solution was also needed for the workpiece blank, as traditional vices would not provide the necessary clearances required to perform the shaping experiments. Finally, to ensure the wear data could be collected, additional measurement setups were required.

3.3.1 Machine

The five axis CNC mill used for the gear shaping experiments is a DMU Deckel Maho 80 P Hi-Dyn. It features three linear (translating) axes: X, Y, and Z, as well as two rotary axes: C axis (rotating the table about the Z axis), and A axis (rotating the workpiece about the X axis) shown in Figure 3.2. A concern when performing the gear shaping experiments was the potential for damage to the axis drive units and spindle bearings due to the cutting forces. Upon consulting with the machine builder, as well as performing preliminary shaping tests in-house, it was decided to limit the thrust force to 700 N, to stay well below the loading limit of the spindle and feed drives, and also to avoid any potential for rotational slippage of the spindle locking mechanism.

3.3.2 Design of shaping parameters

The gear shaping process was designed using ShapePro software to simulate the cutting passes and determine the in-process cutting forces, spindle torque and estimated process time. To remain below the maximum Z-axis force component of 700 N, the process was split across multiple passes. Additionally, to aid in the analysis of tool wear and facilitate comparison to analogy tests, the maximum chip thickness across each pass was kept as consistent as possible.

Using these two process restrictions, the shaping passes were designed while holding the rotary and radial feed rates constant, only changing the depth of cut between passes, and adding additional passes until the required total depth of cut was reached. The depth of cut for each pass was first found through ShapePro pass optimization tools and later adjusted through manual trial and error checking. When high cutting forces were applied, this was observed to surpass the capability of the spindle lock and resulted in a machine error. Through additional tests, a safe and conservative force limit of 700 N and a maximum chip thickness of 0.2 mm was determined. The finalized cutting parameters can be seen in

Table 2. Once the process variables were chosen using the simulated force results as a guideline, the NC code to be supplied to the milling machine was generated through a custom MATLAB script.

Table 2: Cutting parameters for each pass of the simulated gear shaping process.

Pass #	Reciprocating Feed [DS/min] f_{cut}	Rotary Feed [mm/DS] f_{rotary}	Depth of Cut [mm] d_{cut}	Radial Feed [mm/DS] f_{radial}
1	87.7	0.65	1.6	0.01
2	87.7	0.65	0.84	0.01
3	87.7	0.65	0.75	0.01
4	87.7	0.65	0.72	0.01
5	87.7	0.65	0.68	0.01
6	87.7	0.65	0.62	0.01
7	87.7	0.65	0.58	0.01
8	87.7	0.65	0.532956	0.01

When testing each new cutting process, care was taken to ensure no machine errors or unexpected movement would occur. The process was first tested using the gear shaping tool mounted in the spindle without a workpiece to ensure that the expected path was followed and ensuring appropriate clearances had been applied to avoid collisions. Once the toolpath was verified, the process was then performed with a soft plastic workpiece to verify that the CNC code successfully generated a gear, and finally cutting was performed on AISI 1215 mild steel workpieces.

While best efforts were made to ensure consistent cutting conditions between passes, due to the nature of gear shaping (continuously varying tool engagement), there was some variation across the eight-passes, as well as during a single pass. This variation can be seen in Figure 3.5 which shows the average and maximum chip thickness across the eight-passes, as simulated in ShapePro. This changing chip thickness creates difficulty when designing analogy tests that would properly mimic the cutting process. While average values may be used, it may not accurately capture the progression of wear due to the changing values. Similarly to the chip thickness, the maximum force applied to the tool throughout a gear's cutting process varies due to the changing cutter–workpiece engagement, as can be seen in Figure 3.6.

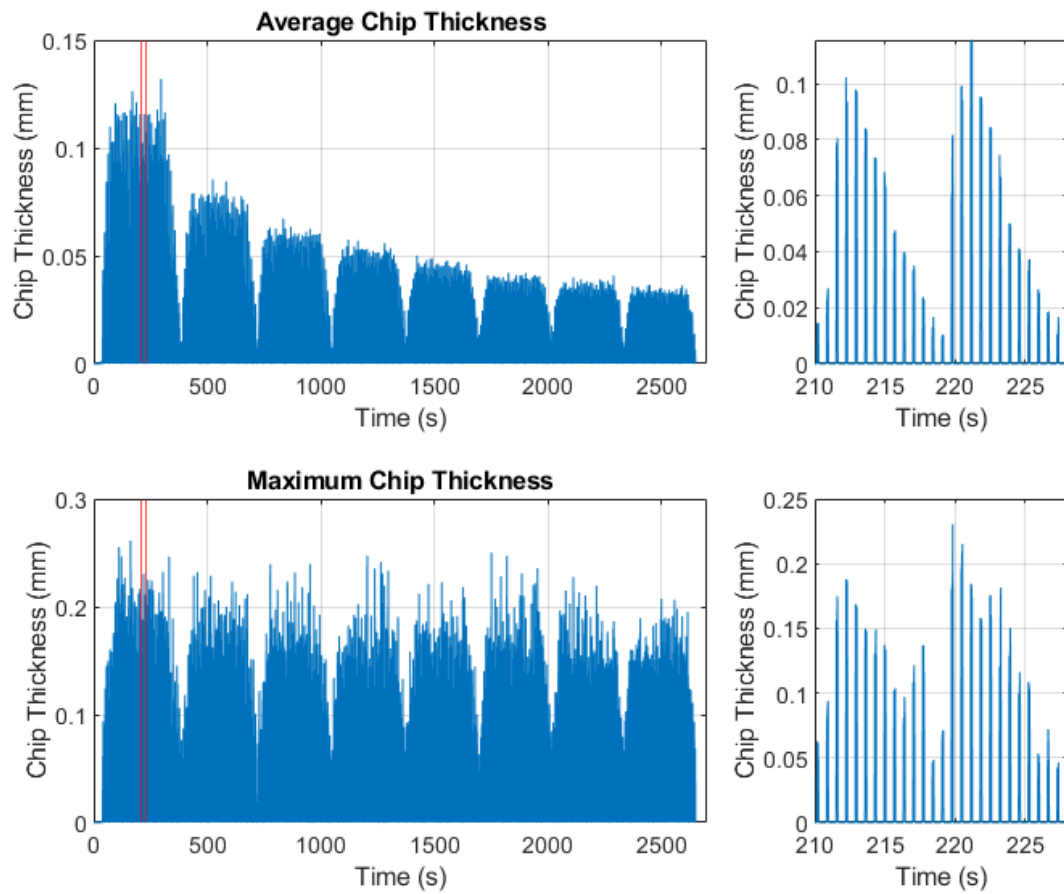


Figure 3.5: Simulated chip thickness across the designed gear shaping process. Right shows zoomed in section between red bars.

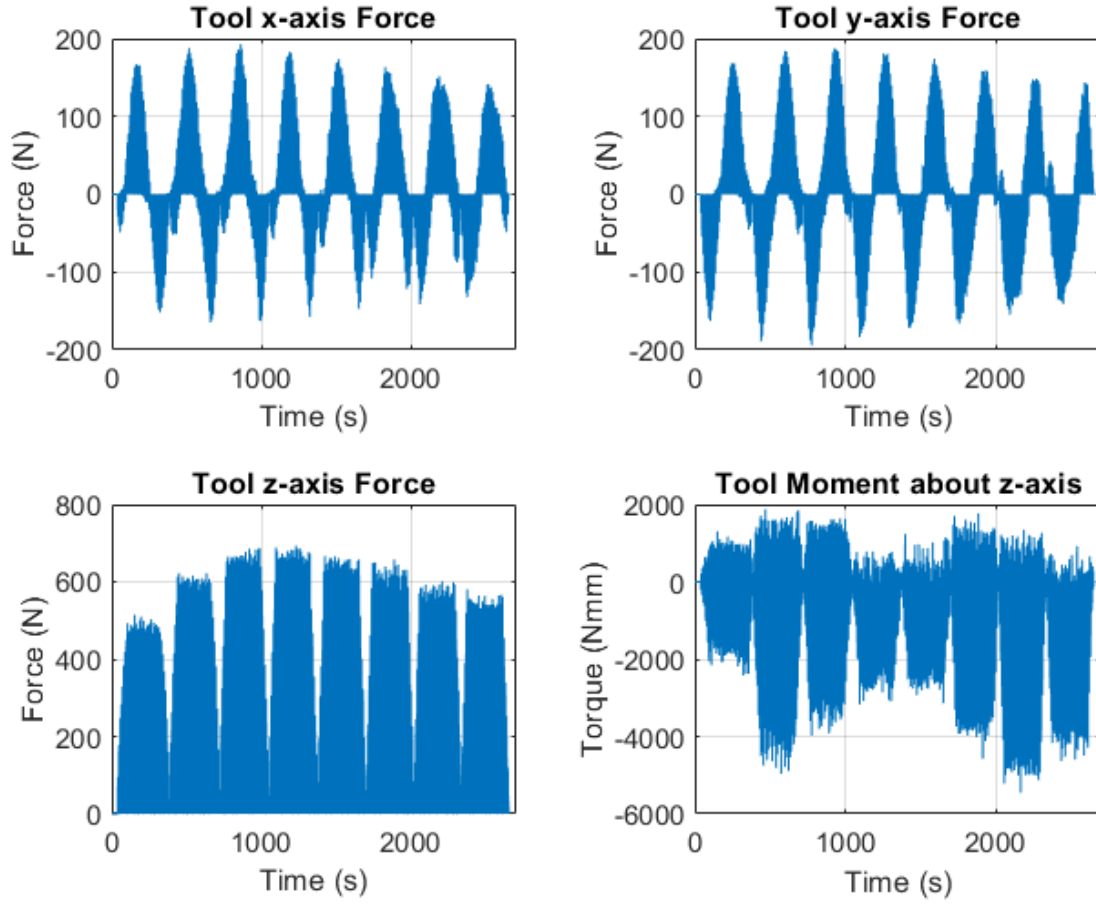


Figure 3.6: Simulated cutting forces in the workpiece coordinate system and moment about the tool Z-axis during the gear shaping process.

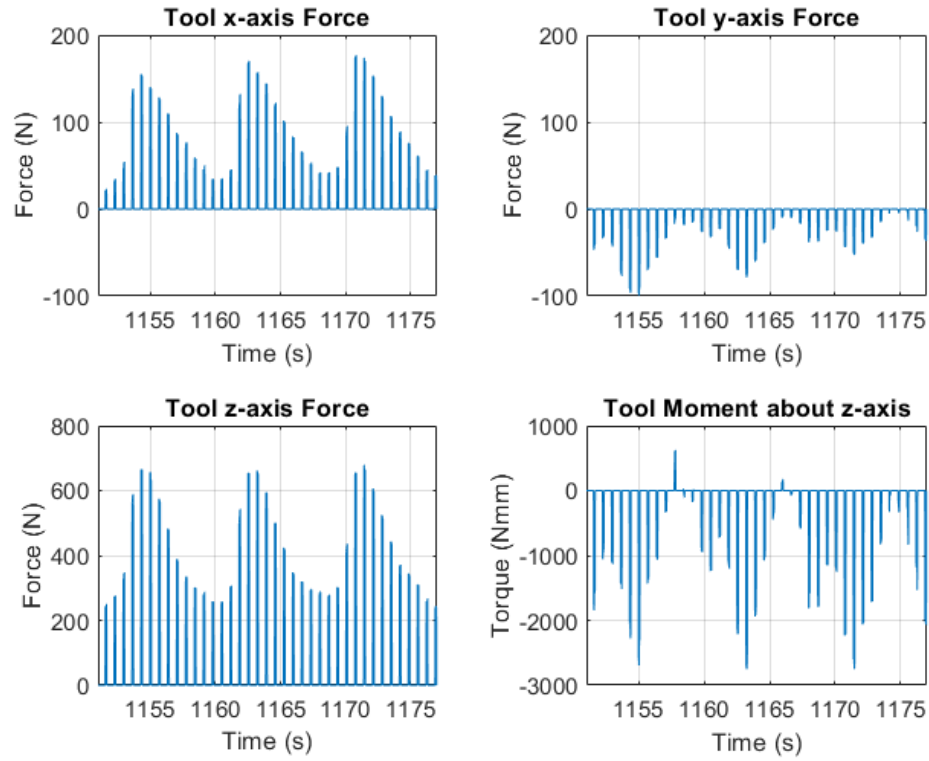


Figure 3.7: Zoomed in view of the shaping process shown in Figure 3.6

3.3.3 Shaping tool specifications and mounting

The tooling was sourced from Ash Gear and Supply. It was purchased used but had been reground to reveal a fresh cutting edge and rake face. Used tooling was chosen to limit the cost of experimentation, as the intention was to use multiple tools while varying the process parameters to collect a range of wear data. The tooling chosen was uncoated High-Speed Steel (HSS). HSS is a common tool material for shapers due to the repeated interrupted cutting behavior that may shatter carbide tooling. While coated tooling is typically used in shaping for extending tool life, uncoated tooling was used to reduce the cutting time required for wear to develop.

During tool regrinding, material is removed from the tool resulting in the cutting teeth exhibiting a profile shift. Profile shift of a gear results in a change of the tooth profile, with a positive shift resulting in a larger addendum and thicker tooth root while a negative shift results in a smaller addendum diameter [57]. The profile shift x was calculated per Eq. (3.16) using span measurements. W represents the span measured across a number of teeth using calipers, N represents the total number of teeth on the gear while k represents the number of teeth measured across. The optimal number of teeth to

measure depends on the gear parameters. In this case, measurements were taken across five teeth. The calculated profile shift can then be used to calculate the center distance increment factor y shown in Eq. (3.18) and finally the final center distance r_{gc} that will be used when cutting. The final tool specifications can be seen in Table 3.

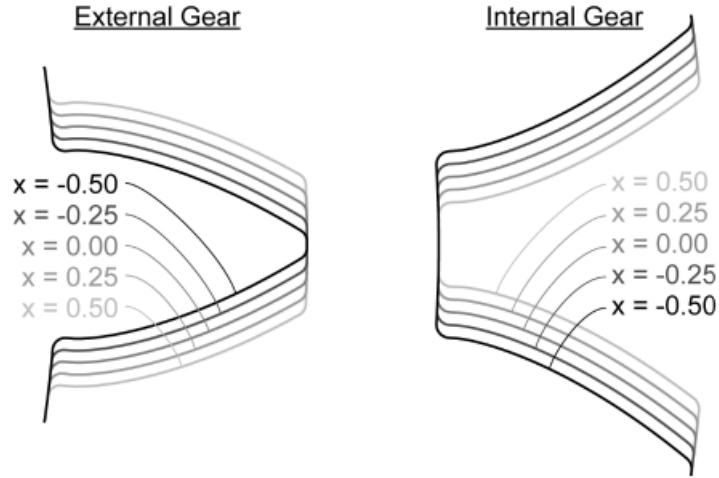


Figure 3.8: Gear tooth profile shift Katz et al. [56]

$$x = \frac{W - m \cos \alpha [\pi(k - 0.5) + N(\tan \alpha - \alpha)]}{2m \sin \alpha} \quad (3.16)$$

$$\text{inv}(\alpha_w) = 2 \tan \alpha \left(\frac{x_c + x_g}{N_c + N_g} \right) + \text{inv}(\alpha) \quad (3.17)$$

$$y = \left(\frac{N_c + N_g}{2} \right) \left(\frac{\cos \alpha}{\cos \alpha_w} - 1 \right) \quad (3.18)$$

$$r_{gc} = \left(\frac{N_c + N_g}{2} + y \right) m \quad (3.19)$$

Table 3: Tool parameters used in the gear shaping experiments.

Number of Teeth (N_c)	40
Module (m) [mm]	2.54
Pressure Angle (α) [$^\circ$]	20
Helix Angle (β) [$^\circ$]	0
Profile Shift (x_c)	-0.1674
Pitch Diameter [mm]	101.60
Addendum Diameter [mm]	107.30
Dedendum Diameter [mm]	95.25

To mount the cutter in the machine spindle, an adapter was designed and manufactured, as seen in Figure 3.9. The adapter holds the tool, while the adapter is held in a tool holder that fits in the machine spindle. Unintended rotation of the tool during a cutting stroke was a concern as any change in the rotational position of the tool will cause form and dimensional error in the resulting final cut workpiece, as well as potentially unstable cutting conditions (e.g., chip thickness and depth of cut). To avoid any possible rotation of the tool due to torque placed on the tool, a keyway was cut into the tools using wire electrical discharge machining (WEDM), along with a corresponding keyway in the adapter. Flats were also machined on the adapter shank to be held in the tool adapter to provide a flat clamping surface for the set screws of the tool holder. When the tool was mounted, runout of 51 μm was found in the cutter, which may have contributed to profile error in the produced workpieces seen in Section 3.4.1.

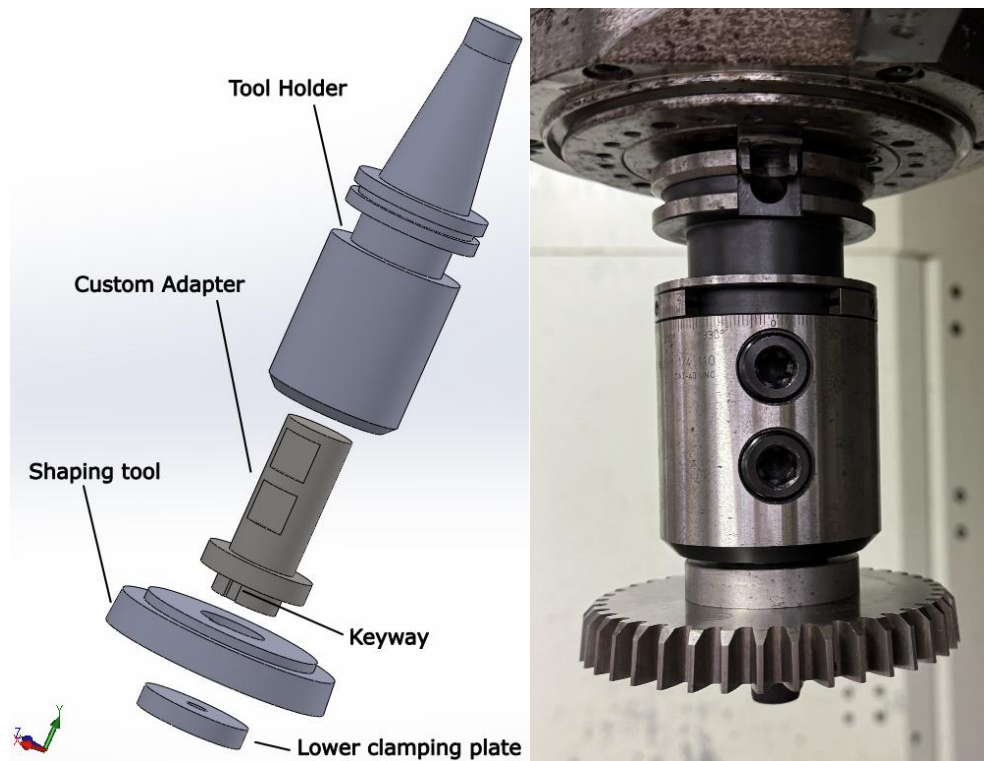


Figure 3.9: Tool holder assembly to mount the gear shaper tool in the machine spindle.

To determine the deflection of the tool and mounting fixture during a cutting stroke, a SolidWorks Finite Element Method (FEM) simulation was performed as shown in Figure 3.10. The machine tool holder and custom tool adapter were all simulated to determine the locations of deflection. Using the ShapePro simulation a sample stroke was selected applying a 700 N force in the Y-axis and a lateral force of 190 N in the X Z plane, additionally a torque of 2.5 Nm was also exerted onto the outside of the part. Ignoring the high localized deflection on the locations where force is applied it was found that the tool was deflecting between 4.0 μm and 8.0 μm . While not modeled in the simulation the individual cutting teeth of the cutter would also deform contributing the additional local deflection of the cutting edge.

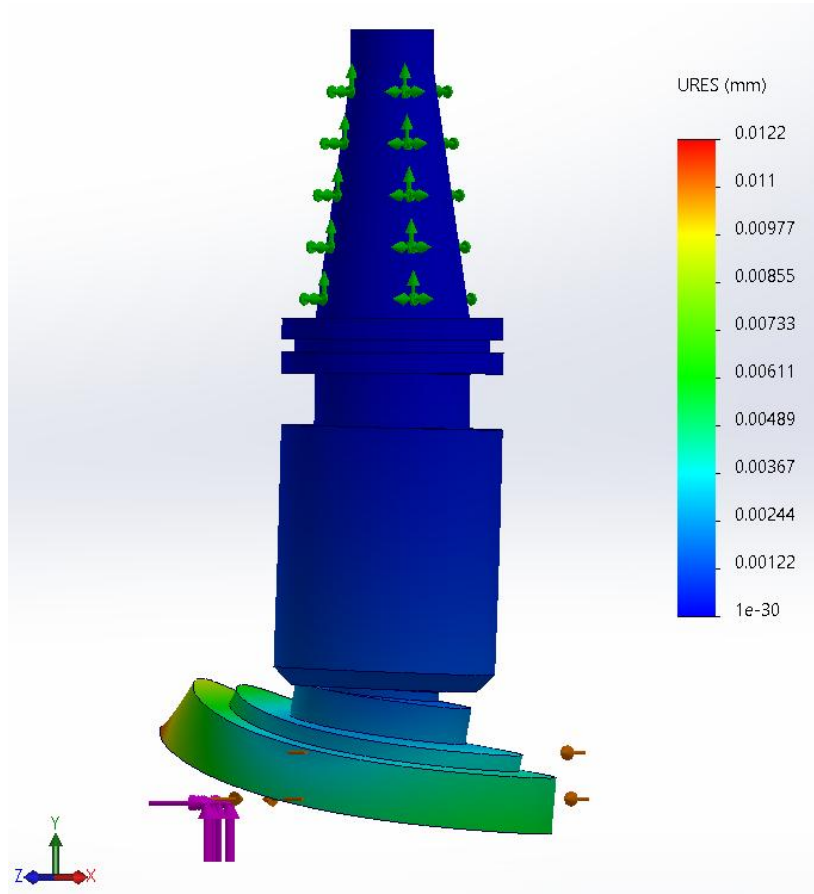


Figure 3.10: Deflection simulation results from the finite element analysis of the shaping tool and tool holder. Green arrows show fixed geometry while purple arrows show the applied force.

3.3.4 Workpiece specifications and mounting

The workpieces were designed as a 33-tooth gear with a module of 2.54 mm corresponding to an outer diameter of 88.9 mm and a face width (b) of 25.4 mm. Additional workpiece specifications can be seen in Table 4. The blanks were produced from cylindrical stock, cut to width, and turned on a lathe to the desired outside surface. Additional mounting features were then added, such as a central bore and alignment holes to prevent rotation of the blank. When the cutting operation was performed, the workpiece blanks could not be mounted in a standard machine vice as clearance around the perimeter and below the blank was needed for the full cutting stroke of the tool. A custom pedestal fixture was designed, as seen in Figure 3.11.

Table 4: Workpiece specifications used in the gear shaping experiments.

Teeth (N_g)	33
Module m [mm]	2.54
Pressure Angle α [$^\circ$]	20
Helix Angle [$^\circ$]	0
Profile Shift (x_g)	0
Pitch Diameter [mm]	83.82
Addendum Diameter [mm]	88.90
Dedendum Diameter [mm]	77.47
Face width [mm]	25.40

The mounting pedestal was designed to provide support to the underside of the workpiece while allowing appropriate clearance for the cutting of the gear teeth to full depth, meaning the pedestal diameter could not be larger than the dedendum diameter of 77.47 mm. To clamp the workpiece, a central shaft was used with a tapped hole for a bolt and a stack of washers to apply a downwards clamping force to secure the top of the workpiece. Similarly to the tool, should the blank have unintended rotation during cutting, dimensional error in the resulting final cut workpiece will occur, as well as the potential for unstable cutting conditions. To avoid any possible rotation, two alignment pins were added on each side of the blank. To ensure the fixture was aligned with the table axis, a central diameter was used that would index with a central mounting hole in the machine table. The machine origin was set using the central shaft on the top of the mounting fixture, and the fixture was centered on the table axis to ensure concentricity of the workpiece while rotating using the table rotary axis.

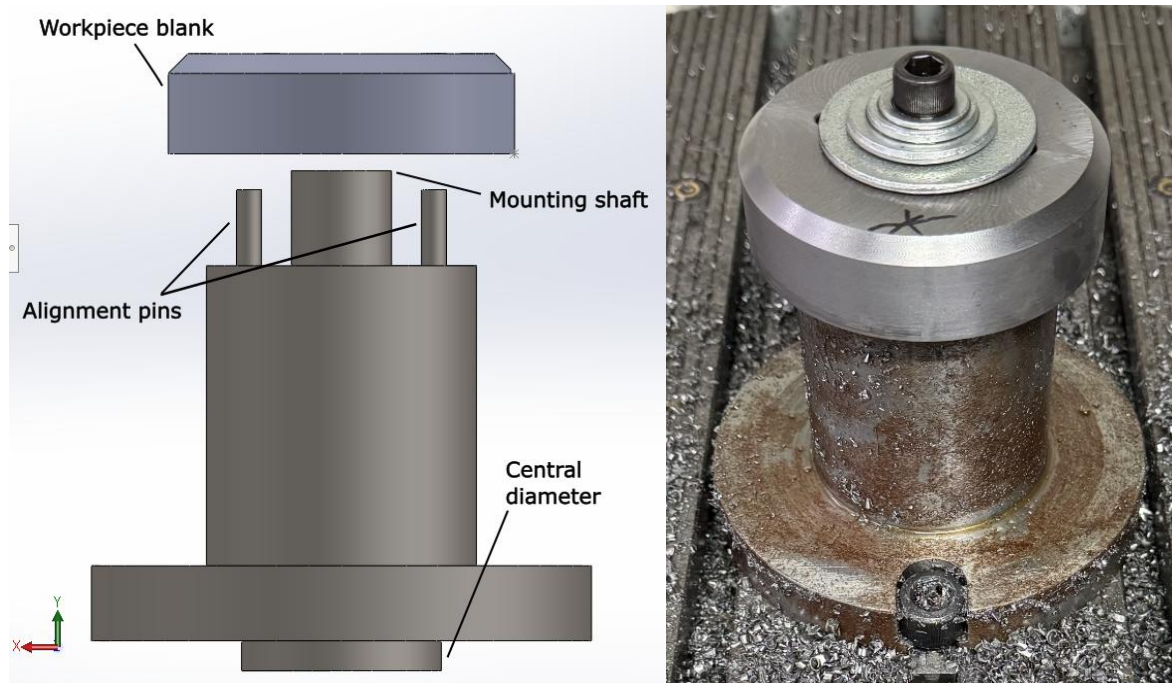


Figure 3.11: Pedestal mounting fixture for the workpiece.

Similarly to the tool, an elementary SolidWorks FEM simulation, shown in Figure 3.12, was performed to analyze the deflection of both the workpiece and mounting fixture during a cutting stroke. Using the ShapePro simulation a sample stroke was selected creating a 700 N force in the y-axis and a lateral force of 190 N in the X Z plane, additionally a torque of 2.5 Nm was also exerted onto the outside of the part. Ignoring the high localized deflection around the point of force application the deflection of the workpiece ranges from 0.5 μm to 1.0 μm . The clamping force of the screw and washer was not considered to be a concern during the cutting operation as the cutting forces applied are in the same direction as the clamping force.

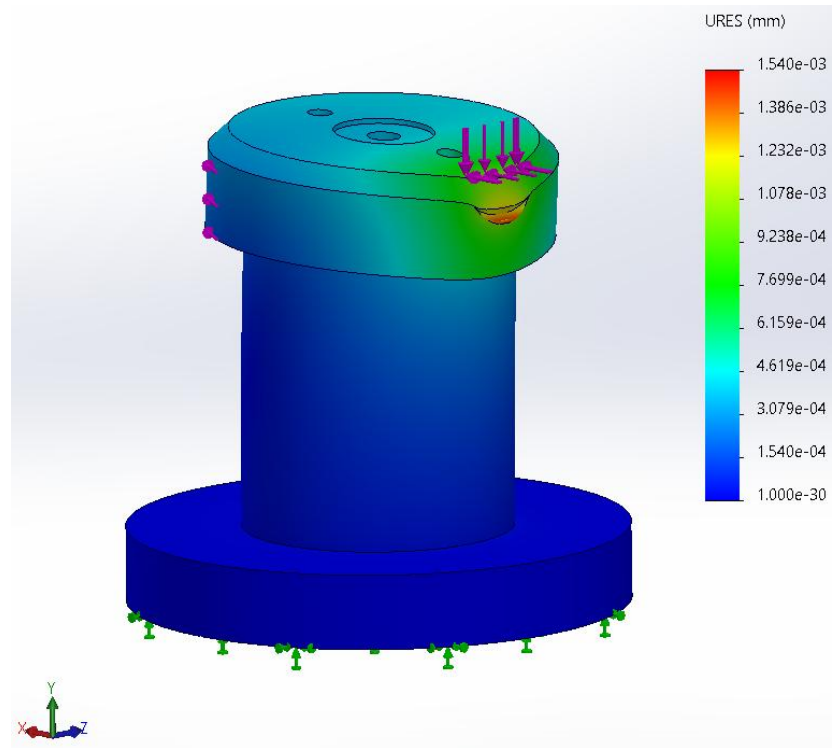


Figure 3.12: Deflection results of the workpiece found using SolidWorks simulation. Green arrows show the fixed geometry while the purple arrows show the applied force.

3.3.5 Flank wear measurement for gear shaping tools

Measurement of the accumulating flank wear was performed following ISO 3685 measurement standard using a Dino-Lite AF7115 digital microscope. While the standard refers specifically to single point lathe turning tools, to ensure consistent measurement methods are applied to both the shaping and orthogonal cutting tests (discussed in Chapter 4), the standard was used. To accommodate the shaping tools, the measurement setup was modified as the tooth flanks of interest were visually obstructed by adjacent teeth when measuring perpendicular to the cutting edge.

To ensure consistent positioning of the microscope and tool between trials, a fixture plate was designed and 3D printed, as seen in Figure 3.13. The indexing fixture holds the tool inverted on an upper plate that rotates on the lower plate to allow for incremental adjustment of the tool position. On the lower plate, holes were added to allow a pin to be inserted, locking the rotation of the upper plate at fixed locations. After the tooth is photographed, the pin can be removed and the upper plate rotated to the next hole, positioning the next tooth in view of the microscope. This design allowed for consistent

increments of the tool with the number of holes in the lower plate matching the number of teeth on the cutter.

The lower plate features three dovetail slots for positioning of the microscope in the three views required of each tooth while allowing adjustment of the focal distance. The secondary microscope holder was designed in multiple parts with a flexible TPU (thermoplastic polyurethane) sleeve to firmly hold the body of the microscope, and slots to allow the microscope to be adjusted vertically and tilted to facilitate the adjustment of the viewing angle. Essentially, the holder was designed to enable adjustment in the positioning of the microscope and tool, which was needed to properly capture images of wear without visual obstruction from the adjacent teeth.

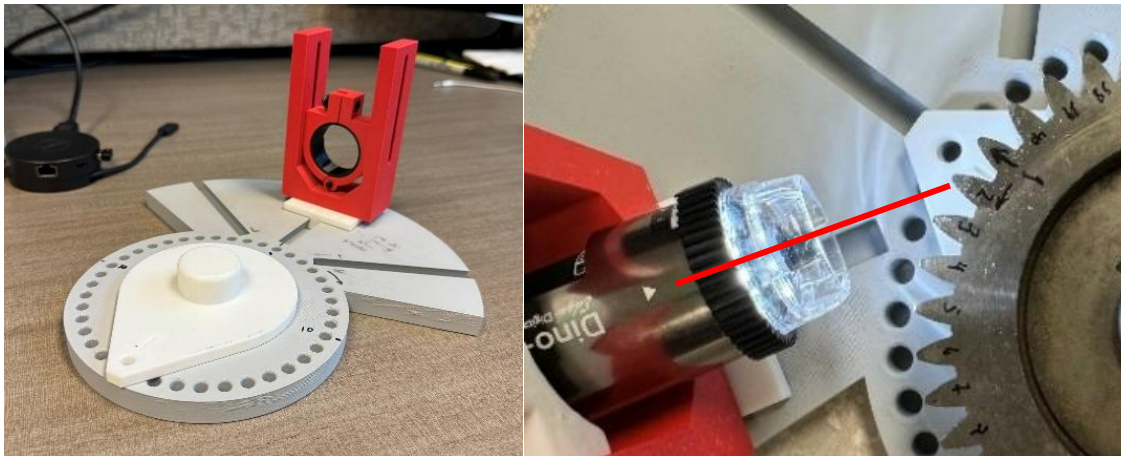


Figure 3.13: 3D printed fixture for measurement of flank wear.

When photographing wear on the tool, three images were taken of each tooth: both left and right flanks, as well as the tooth tip. The camera could be positioned perpendicularly to the tooth tip, but when photographing the flanks, it needed to be positioned above the tool angled down on the cutting edge. While this angle introduced some measurement parallax to the images, it could not be avoided and alternative measuring strategies, such as angling the camera rather than positioning perpendicular to the flank, introduced more errors and increased the difficulty of focusing the camera due to the small depth of field when zoomed. The measurement process was performed before the tool was used, to record any preexisting damage to the teeth. After cutting each workpiece, the tool was removed from the machine tool, cleaned and photographed to record the wear that resulted from each subsequent cutting operation. Once photographed, the wear was quantified using the Dino Lite camera software DinoCapture.

3.3.6 Validation of modified kinematics and analysis of machine CNC tracking error

To validate the modified kinematics planning for gear shaping, a polygon subtraction simulation was created. The polygon subtraction uses a tool profile, exported from ShapePro, and a simulated workpiece blank to perform the shaping process by applying the calculated cutting positions found in the modified kinematics described in Section 3.2.4. Using the list of cutting locations and orientations computed in MATLAB, the tool and workpiece are translated and rotated as required, while the geometric intersection between the tool and workpiece is subtracted (cut) from the workpiece polygon. As the process continues, more of the workpiece material is removed and the final gear profile revealed. Finally, the produced workpiece polygon is compared to the ideal workpiece profile in ShapePro. Through this process, it was found that the simulated workpiece had a slight profile error across the 33 teeth with the total error per tooth for both left and right flanks being less than two microns, as seen plotted in Figure 3.14. While there is a small amount of profile error, it is likely due to the surface scallops produced by the machining process itself and rounding of the cutting positions when supplied to the polygon subtraction program. Through this process, it was found that the designed modified kinematics for use in the CNC machine was able to accurately reproduce the shaping movements for the purpose of performing tool wear tests.

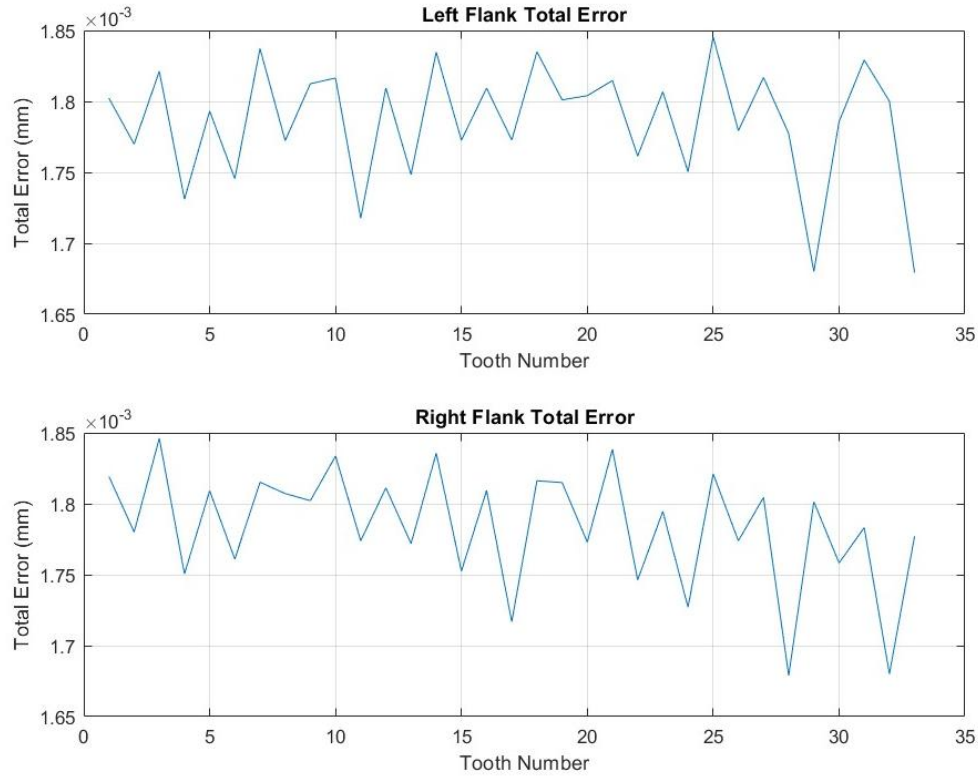


Figure 3.14: Profile error between ideal and simulated workpiece using polygon subtraction.

When designing the shaping experiments, CNC tracking errors of the machine axes and damage to the spindle bearings during a cutting stroke were major concerns. The 5 axis CNC machine used for the experiment is not designed to withstand the large Z axis cutting forces and achieve the same level of stiffness as a specialized gear shaping machine. While the cutting parameters were chosen to remain below the maximum recommended force for the machine, significant CNC tracking error may cause significantly different uncut chip geometries than the shaping process. To verify the servo tracking behavior, feed drive signals were collected using the oscilloscope measurement utility built into the Heidenhain TNC 430N CNC controller. Signals for the X, Y, Z, and C axes, as well as spindle rotational position, were collected for both nominal (i.e., commanded) and actual (encoder) positions using 0.6 ms and 8.4 ms sampling intervals. As the oscilloscope function only allows for collection of 4096 samples for each measurement, measurements were performed at varying sampling rates during the cut, capturing a range of movements both during a cutting stroke and repositioning. The recording process was repeated during different passes to ensure there was no error accumulation that occurs over time

Actual vs nominal Z axis position

The first movement captured was the Z axis position during a cutting stroke. As seen in Figure 3.15, comparing the nominal (i.e., commanded) versus actual position, a lag can be seen between the commanded position and the actual position of the tool. While there is a lag, it would not cause errors during a cutting movement as all other axes are stationary during the cutting downstroke. Furthermore, the movement profile remains smooth, indicating there were no significant Z axis errors caused by contact with the workpiece during the cut. When analyzing the velocity during the cutting stroke, it was found that the tool reached the target feed rate of 10 m/min before contacting the workpiece and remained at a constant cutting speed for the duration of cut. The stroke length for later tests was reduced to remove unnecessary movements that increased cutting time.

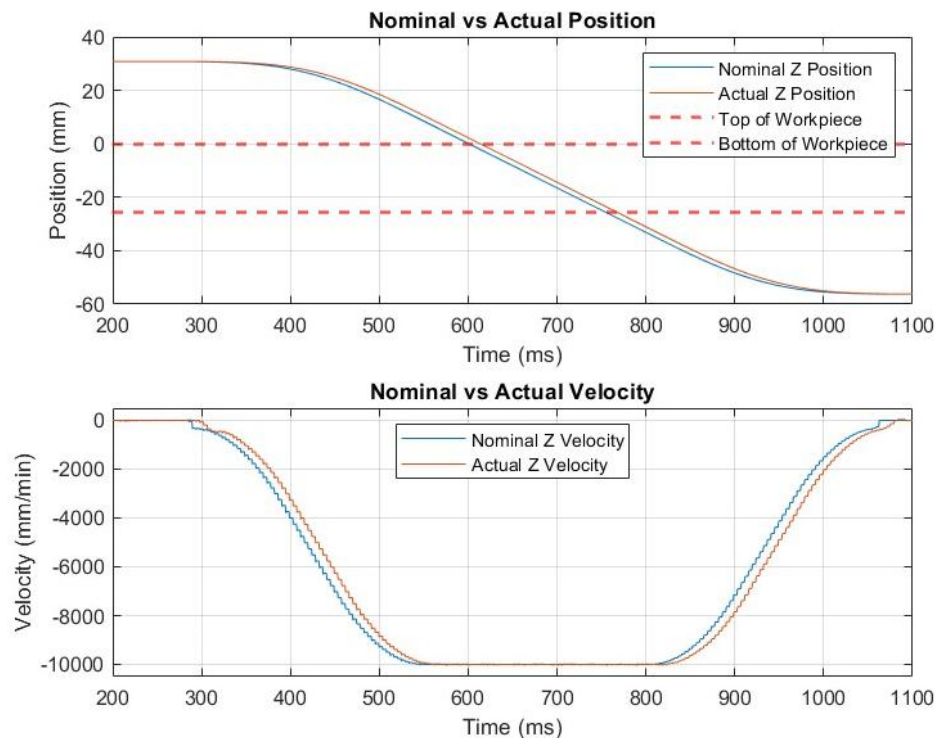


Figure 3.15: Nominal vs. actual position and velocity of the Z axis during a cutting stroke.

C axis behavior during a cutting stroke

Measurements were taken for the C axis (table) position during a cutting stroke to check for rotation of the table induced by the cutting forces, as seen in Figure 3.16. Similarly to the Z axis tracking, there is a time lag between the commanded and actual position during repositioning, as seen in subplot 3

between 180 and 300 ms before the Z axis stroke begins. During the cutting stroke the tool is in contact with the workpiece from 600 ms to 750 ms performing cutting action while the C axis is stationary as seen in subplot 3. This can be seen in further detail in subplots 2 and 4, showing a zoomed in version of subplots 1 and 3 during the cutting stroke. As seen in subplot 4, the C axis shows no discernable difference between the nominal and actual position.

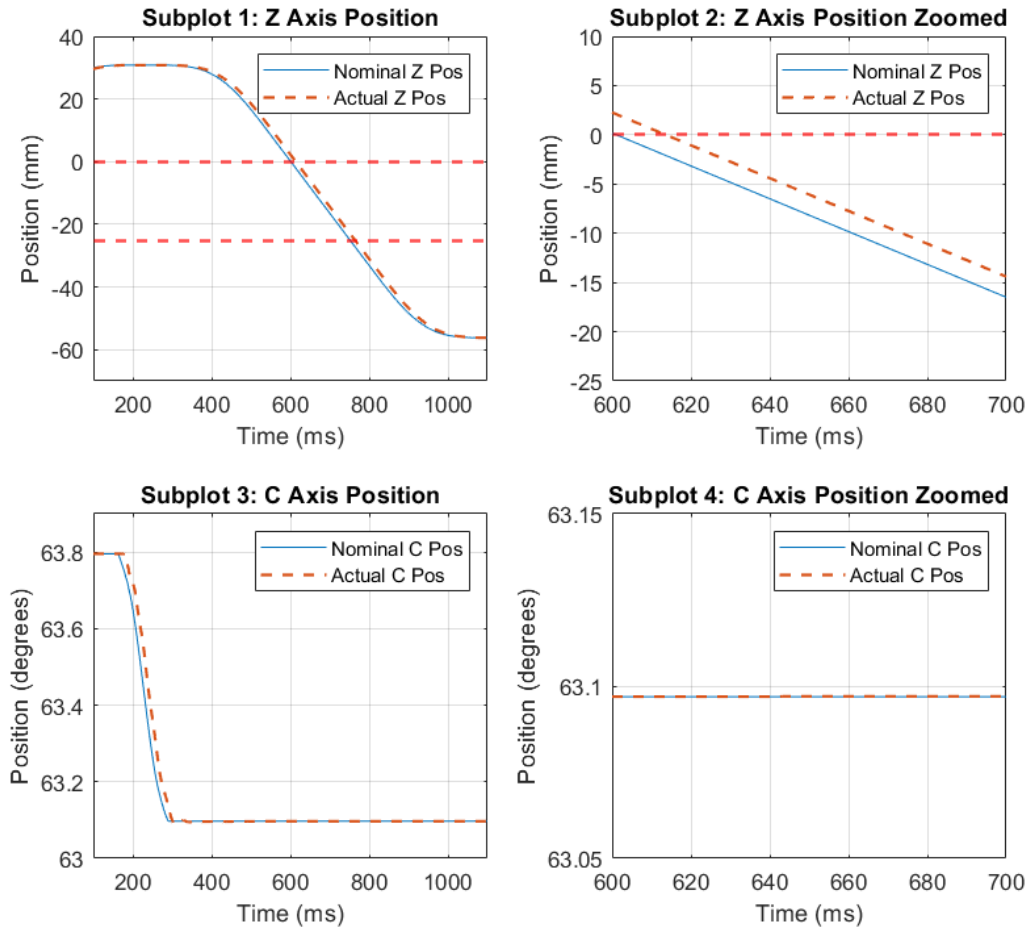


Figure 3.16: Z axis and C axis measurements for a cutting stroke.

Spindle CNC tracking error during cutting stroke

In previous experiments, when the maximum simulated force was very high, the spindle brake failed to secure the tool rigidly resulting in a machine error during a cut due to the change of rotational position. The limit value of 700 N was chosen to ensure this would not happen. The rotational position of the spindle during a cutting stroke was recorded, as seen in Figure 3.17. The tool is in contact with

the workpiece between the dashed red lines roughly between 880 ms and 1020 ms. During this time, the spindle position shows a very slight tracking error moving from the steady position of 0.999753 turns to 0.999509 turns (i.e., a change of 0.08785°). This deflection is believed to be due to the torque generated by the cutting force, briefly causing the deflection, and then the spindle position rebounding back to steady state. Once the cutter leaves the workpiece on the underside of the workpiece at the Z position of -25 mm (and the cutting force is removed), the controller overcorrects due to feedback with possibly integral action, causing a spike in the spindle position in the other direction. This positional error is then corrected and the position decays back to the steady state value. This spindle tracking error most likely causes errors in the profile of the finished workpiece which will be further discussed in Section 3.4.1. Considering a tool addendum diameter of 107.3 mm, this would result in a deflection of 0.0822 mm at the tip of the cutting teeth.

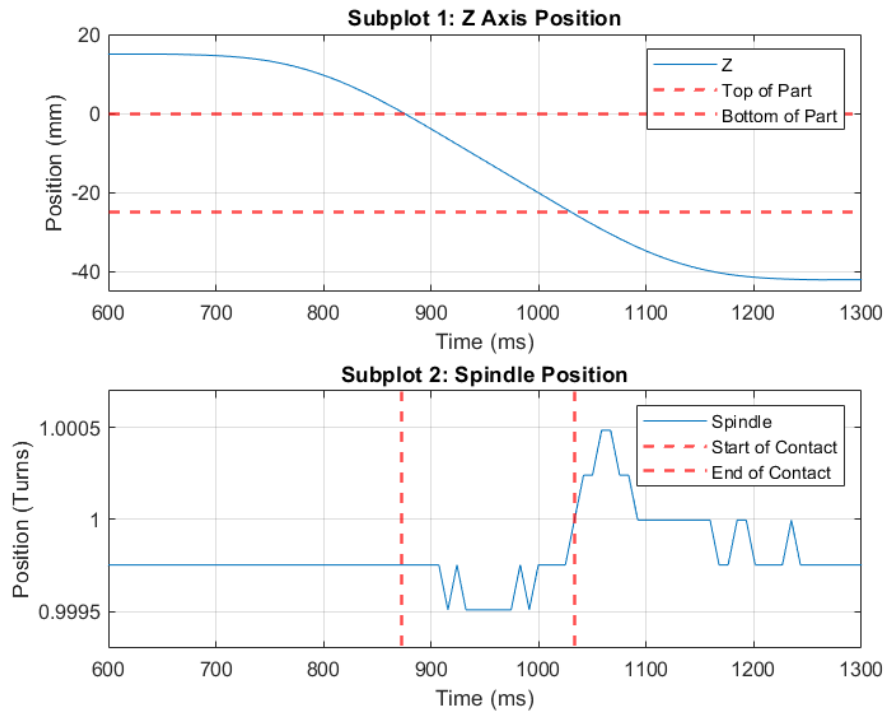


Figure 3.17: CNC tracking error in the spindle during a cutting stroke.

3.4 Experimental Results

Using the eight-pass shaping process designed in Section 3.3.2, a total of 17 shaping experiments were performed recording the growing wear on the cutting tool using the described measurement process

between operations. More cutting tests were intended to be performed utilizing a group of tools with identical specifications and applying varying cutting speeds and the varying growth rates of flank wear would be analyzed. However, when performing the cutting experiments, it was found that the process time was much longer than expected and the CNC machine was unable to achieve a range of cutting speeds matching industrial shaping machines. Due to these reasons, the experiment was reduced to a single cutting speed of 10 m/min and halted after the 17 tests had been performed.

When simulating the cutting process using ShapePro, the total machining process time was predicted to be 44 minutes and 10 seconds within a traditional gear shaping machine. However, when performed with the five-axis CNC, the cutting time was found to be around 90 minutes. This additional process time is most likely due to performing the feed movements as a series of steps rather than synchronously. In traditional gear shaping, the workpiece and tool continuously mesh so both the downstroke and upstroke can occur while the radial and rotary feed are performed. In contrast, the tool angular position could not be controlled in the five-axis CNC machine, and the upstroke was performed separately from the repositioning for the next cut, while also adding an additional step to move to the r_{safe} backoff distance. Due to the extra time required for these additional steps, the total process time increased accordingly. Additional process time was also added when applying lubricating oil between cutting passes and performing the axis sweep as recommended by the machine tool manufacturer. The photographing process of the cutting tool also added an extra 30 minutes between operations to capture images of all three views of the 40 teeth. Periodically, the rake face was inspected for the development of crater wear, but no discernable crater wear was found that may affect the cutting operation.

Due to this long process time, only 17 workpieces were produced using a single cutting speed of 10 m/min. Due to the small number of tests performed, a tool life model could not be applied, as calibrating and testing a model requires a range of cutting parameters to be tested. To ensure accurate results, the test should be performed multiple times, considering the wear found across multiple tools using the same cutting parameters to check for statistical outliers or irregular accelerations of wear or chipping.

3.4.1 Quality issues in workpiece finish

As the shaping experiments progressed, the workpieces were inspected, and it was found that the produced gears (shown in Figure 3.18) were of low quality with several issues present on the tooth flanks and gear profile shown in Figure 3.19. Some of these quality issues include major burrs on the underside of the workpiece, a rough surface finish on the cut flanks as well as lead error of the cut

flanks. The lead error is expressed as a deviation of the gear tooth from the ideal path along its length. These errors were found across multiple workpieces, indicating that the error was reproducible and were caused by the cutting process being carried out on the milling machine.



Figure 3.18: Sample gear produced using the five-axis milling machine.

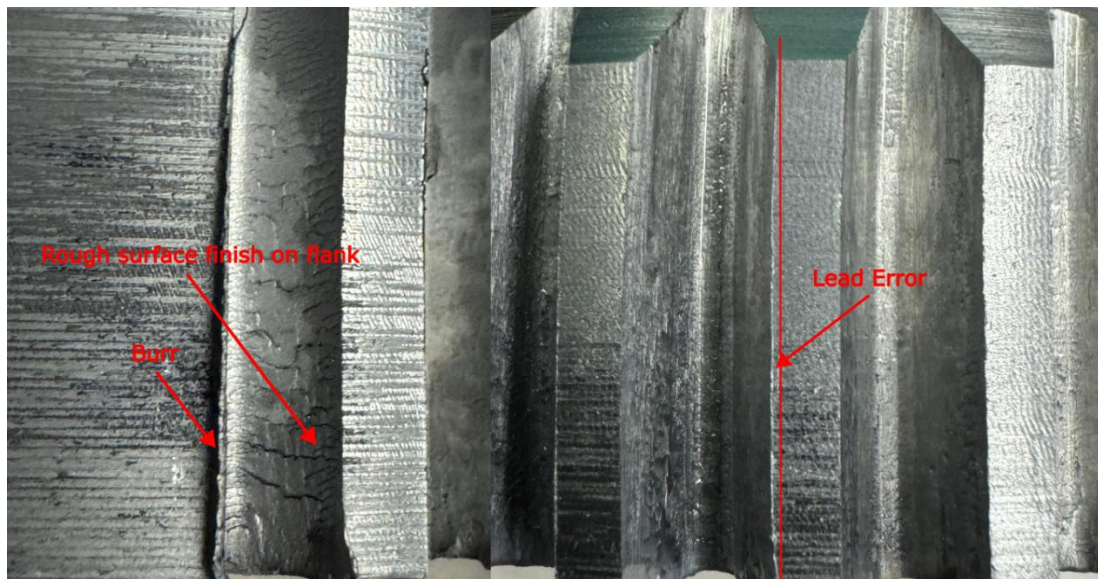


Figure 3.19: Quality issues found on an example workpiece created during the gear shaping experiments. Left: Rough surface found on tooth flanks. Right: Lead error of flanks as well as burrs on underside of part.

Despite the efforts made to minimize rotation and run out of the cutter, as well as deflection of the overall cutting setup, there was still some amount present that caused errors during cutting. While not measured in this experiment, future work could involve impact hammer testing to determine stiffness of the cutting setup to determine if the designed fixtures and clamping methods were adequate. Other testing may involve the use of accelerometers and dynamometer setups to record any potential movement not captured during the CNC signal analysis in Section 3.3.6. Finally, another source of the poor part quality may be due to the use of manually applied lubrication during the cutting. Traditional gear shaping involves the use of flood cooling which may improve the surface finish and minimize cutting temperatures. Minimal lubricant was applied manually, to match the cutting conditions to the analogy testing experiments performed in Chapter 4 where flood coolant was not feasible.

Further investigation included measurement of the gear profile error. The gear profile was measured using a Mitutoyo CRYSTA-Apex S coordinate measurement machine (CMM) and compared using ShapePro to a simulated ideal workpiece of the same parameters. When comparing the two profiles, it was found that there was a significant difference between the two profiles with the produced workpiece showing large profile errors. Figure 3.20 shows the total profile error for both the left and right tooth flanks. The observed profile errors are most likely a result of runout in the tooling as well as misalignment of the workpiece blanks. While the machine was setup using the mounting fixture as the origin for aligning the coordinate system, there may have been some amount of misalignment between tool and workpiece. Furthermore, as the purchased tooling was previously used and relatively inexpensive, the tooling profile was of low quality, imparting the error from the tool onto the workpieces.

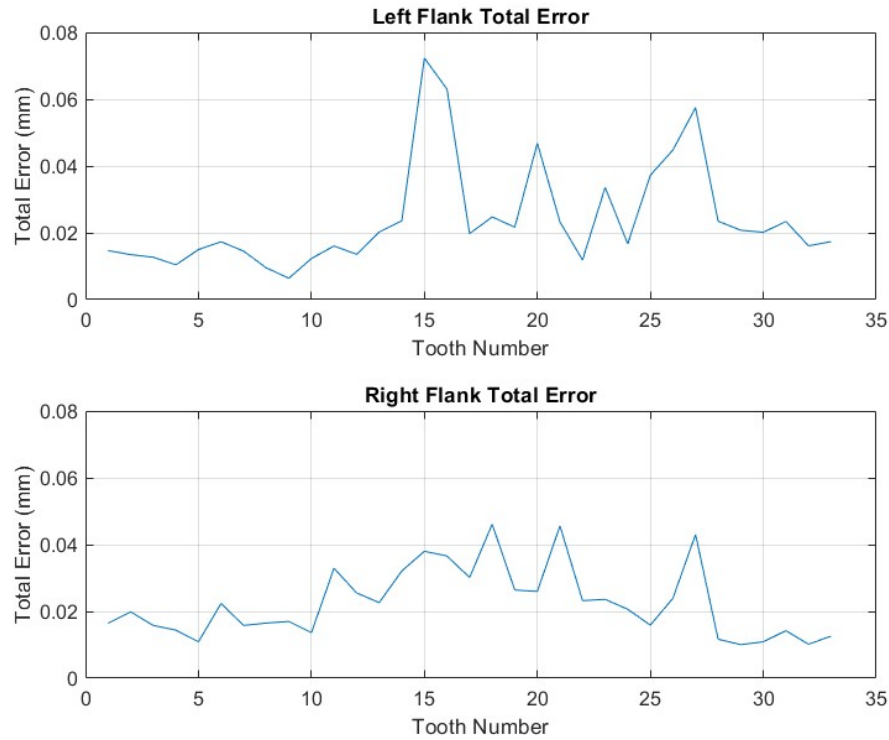


Figure 3.20: Profile total error compared between cut workpiece and an ideal simulated workpiece.

Pre-existing damage to tool teeth

Before beginning the cutting experiments, the initial condition of the tool was photographed to be used as a starting measurement for wear growth on the cutting edge. While the tool was freshly ground from the supplier, it was found that several teeth showed pre-existing damage, as exemplified in Figure 3.21. As can be seen on the tooth tip, there is a dent on the left side and a flattening of the cutting edge on the right side. When damage was found, the initial tooth state was documented, and any damaged teeth were neglected when analyzing wear progression of the cutting tool. While it is likely that there would be minimal effect on the cutting operation, it may affect the wear development on that tooth contributing to an initial wear value or accelerated wear growth.

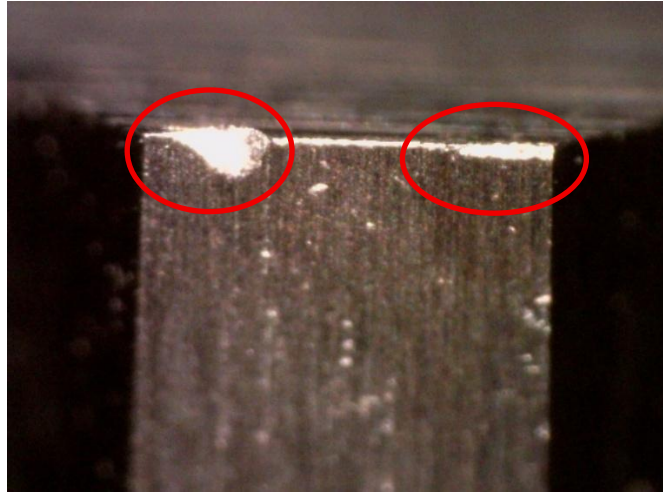


Figure 3.21: Initial condition of tooth 30, showing tooth tip damage.

3.4.2 Summary of tool wear data

After performing the cutting experiments and measuring the flank wear, it was found that the wear accumulated on the cutting tool was low despite the 17 workpieces being cut. The cutting teeth showed only mild wear at the corners of the teeth and the cutting edge at the tooth tips. Minimal flank wear was observed at the tooth flanks. Of the teeth that showed some amount of wear development, the flank wear was distributed similarly showing a consistent pattern across the teeth. This result is supported by ShapePro simulation showing that the highest length of material cut and the highest average chip thickness is concentrated at the tips and corners of the teeth. This result is shown in Figure 3.22 for the full tool profile and a single tooth. Table 5 shows the chip thicknesses throughout the cutting process averaged across all 40 teeth of the cutting tool. Furthermore, due to the cutter's geometry, the corners of the teeth have the least supporting material leading to a weaker portion for the cutting edge. While most teeth showed wear, the maximum wear was not equal and some teeth showed little to no wear.

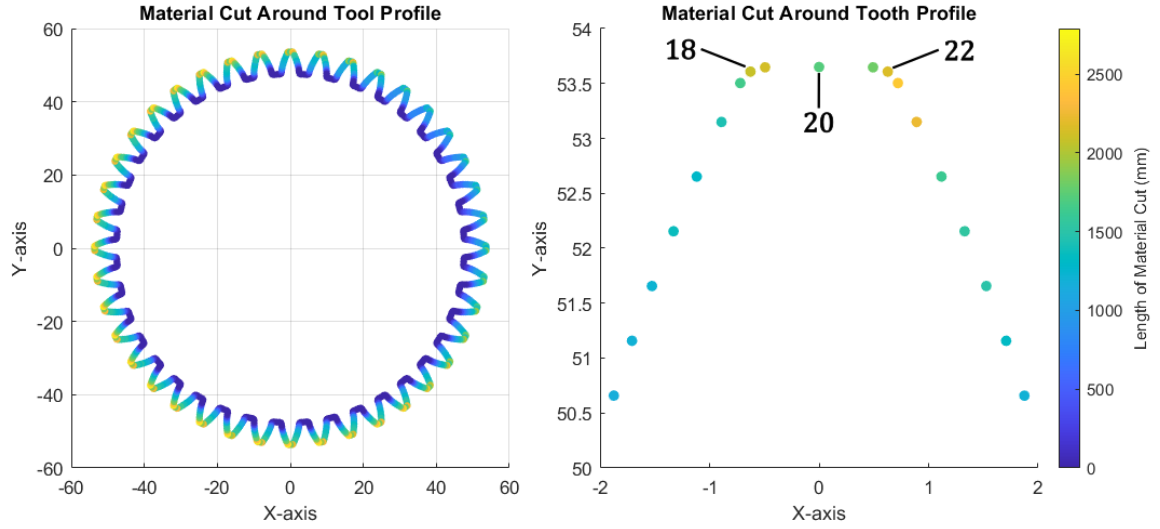


Figure 3.22: Length of material cut by each node around the tool profile left and a single tooth right.

Table 5: Chip thickness data across the eight cutting passes for nodes around a tooth. Green highlights indicate the highest values corresponding to the corners of a tooth.

	Node Number								
	16	17	18	19	20	21	22	23	24
Minimum [mm]	0.0087	0.0283	0.0620	0.0449	0.0406	0.0470	0.0614	0.0339	0.0210
Average [mm]	0.0170	0.0433	0.0799	0.0664	0.0671	0.0701	0.0780	0.0482	0.0307
Maximum [mm]	0.0196	0.0525	0.0900	0.0755	0.0774	0.0788	0.0869	0.0544	0.0348

Due to the low depth of cut across the eight-passes, with the maximum being 1.6 mm and the average being 0.79 mm, the tooth tips perform most of the cutting. This leads to the wear being concentrated on the tooth tips and a small amount along the tooth flanks. Typical gear shaping would use a larger depth of cut, resulting in a more even distribution of cutting along the cutting edge, but the small depths of cut were necessary due to low setup rigidity in performing the shaping on a milling machine tool.

General wear growth trend at tooth tips

When analyzing the progression-based wear across all teeth, the results generally followed the same progression, starting with a clean cutting edge and the worn sections of the cutting edge growing as the

tool is used. Wear first shows at the tooth corners where the originally sharp corner begins deforming as flank wear develops. As the wear progresses, it slowly grows across the tooth tip and progresses downwards on the flank face. An example of this behaviour can be seen below in Figure 3.23, showing the initial condition of the tooth compared to the final condition of the tooth.

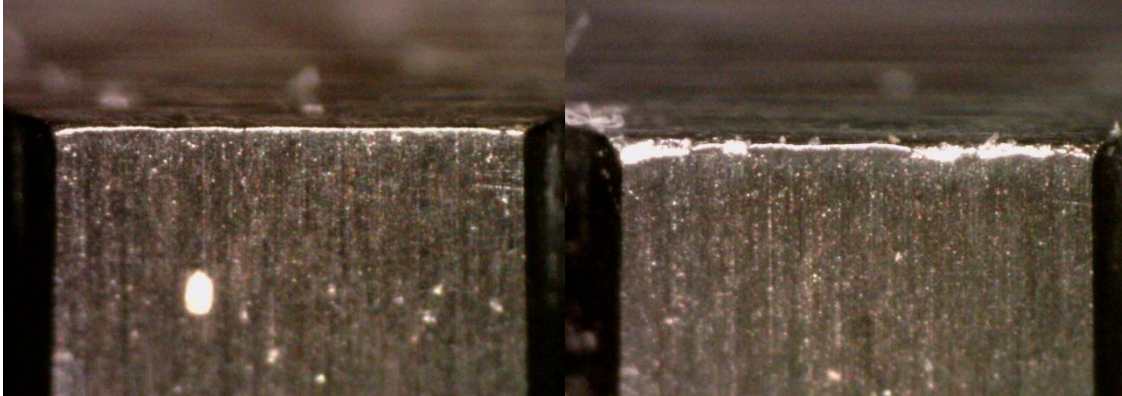


Figure 3.23: Tooth 10 initial condition and condition after cutting 17 workpieces.

Wear across all 40 teeth was not consistent with some teeth showing minimal wear while others showing larger amounts of wear growth. Furthermore, wear across a single tooth is not consistent as can be seen in Figure 3.24 with varying wear measurements between the flat tip and the tooth corners. Additionally, the wear progression of a single tooth across all 17 workpieces can be seen in Figure 3.25 with measurements being taken at three different locations along the tooth tip (both corner nodes 18 and 22, and the central node 20).

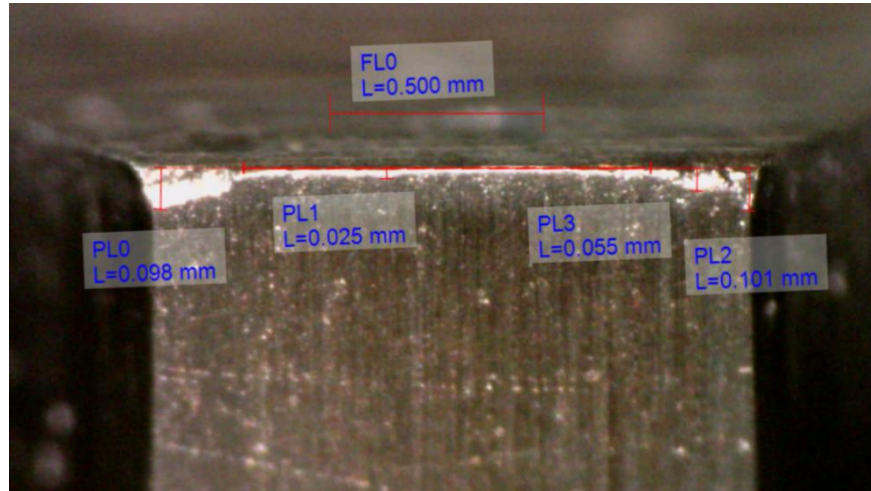


Figure 3.24: Final wear measurements for a single tooth showing different measurements for the two corners as well as the flat middle section.

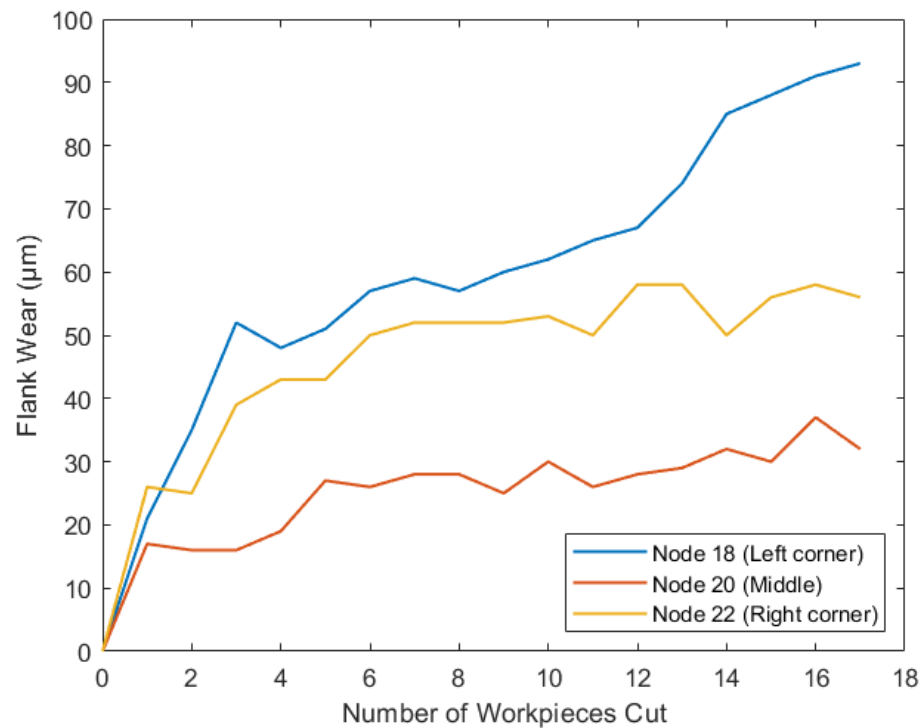


Figure 3.25: Wear progression of the flank wear on a single tooth across the workpieces produced, at three locations (two tooth corners and the middle of the flat tip).

Flank wear growth at tooth flanks

Very little flank wear was found on the tooth flanks with any wear that did occur being concentrated near the tooth tip. Instead of the traditional flank wear growth that was expected, a change in surface finish on the flank face was observed. This change in surface finish may indicate contact between the flank face and the workpiece causing rubbing and interference. This change can be seen in Figure 3.26 where the initial condition shows a smooth surface finish while the final surface after cutting shows a textured surface. Note however the cutting edge showing little to no flank wear except for the tooth tip.

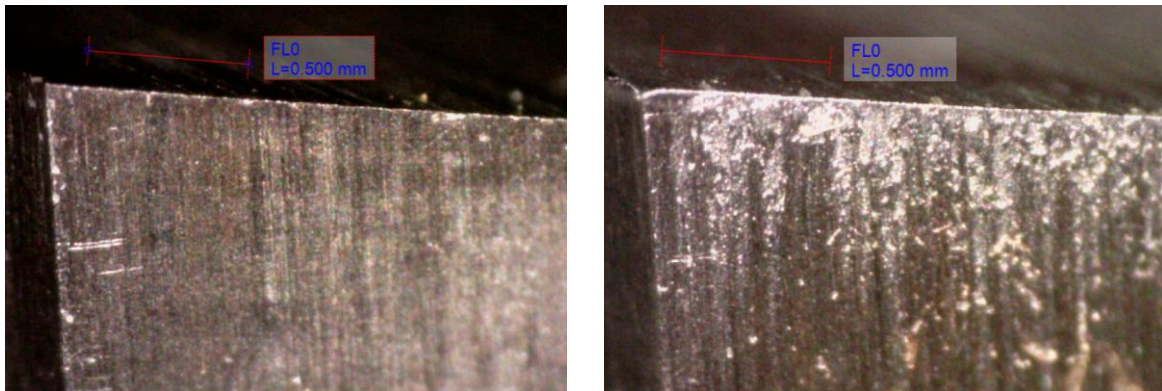


Figure 3.26: Initial condition vs final condition of the left flank of tooth 17.

This change in surface finish was not consistent between the left and right flanks with the right flank shown in Figure 3.27, where the textured surface has only progressed on a small amount for the right flank face, while the left flank shows a much larger area affected by the rubbing. This result may be caused by differences in the cutting condition between leading (left) and trailing (right) flanks depending on the direction of rotary feed, as well as the deflection in the spindle position during cutting. This result is further reinforced through Figure 3.22 where the left and right flanks show varying lengths of material cut with the leading (left) flank showing higher lengths,

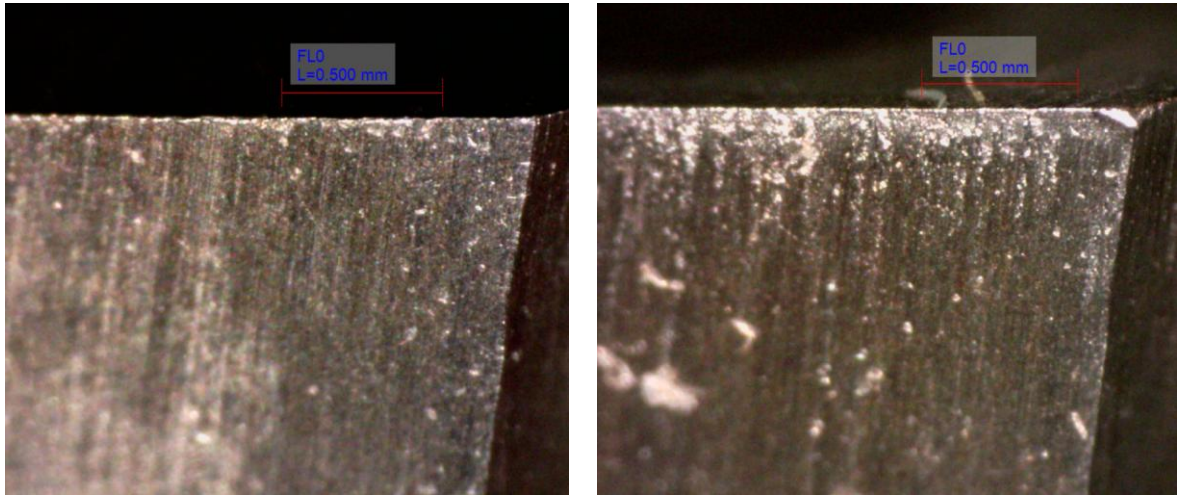


Figure 3.27: Initial condition vs final condition of the right flank of tooth 9.

3.5 Conclusions

In this chapter, a flank wear testing process for gear shaping was designed and implemented. From initial design of experiment to testing results, the full process was documented and discussed, including discussion on the difficulties of adapting the shaping process to a five-axis CNC machine and the wear results collected using the designed process.

Through work performed by previous students, the traditional gear shaping kinematics were known and used as a starting point for recreating the process. The shaping movements were divided into discrete actions performable on the CNC, with the help of a MATLAB script converting the radial and rotary feed into movements in the XY plane and rotations of the C axis. The Z axis was used to perform the cutting strokes. Through custom CNC code, as well as custom mounting systems for the workpiece and tooling, the process was performed and tested on a five-axis CNC machine. To further ensure the performed actions properly replicated gear shaping, the CNC code was validated by comparing the profile generated by the CNC code using a polygon subtraction algorithm to that of an ideal gear profile generated in ShapePro. Real-time CNC servo signals were collected through the build-in oscilloscope function of the machine tool and analyzed finding that the process exhibited minimal CNC errors during the cutting stroke, except for the tool spindle axis which showed a small discernable error as a result of the cutting torque.

Despite this success, clear limits of the machine were found as the spindle lock was unable to remain in position during heavy tool engagements, resulting in a loss of rotational position and generating machine errors that would end the cutting experiment early. Through consultation with the machine builder, and this experimentation, a conservative thrust force limit of 700 N was imposed, to avoid this problem altogether. However, this required reduced tool engagements and depths of cut per pass, leading to an eight-pass process. Additional consideration was taken to ensure that the maximum chip thickness was consistent between the passes. While the eight-pass cutting process was feasible, it led to a long cutting time of 90 minutes excluding the time to setup the machine and measure wear.

Because of the long cutting time, only 17 cutting operations were performed at a single cutting speed of 10 m/min, resulting in low amounts of wear being visible on the tool. Due to the low depths of cut, any tool wear found on the cutting tool was concentrated on the tips of the teeth. While some changes were observed on the tooth flanks, any changes were most likely caused by rubbing between the workpiece and tool and did not appear to be flank wear caused by cutting.

Despite the low number of cutting experiments performed due to time constraints, the designed process performed well, successfully recreating the gear shaping process. Should additional time be allocated, the testing and wear documentation could continue, and tool life equations could be calibrated using the collected data. However, to compare results that would be usable in industrial processes on traditional machines, the cutting parameters would need to be increased to reflect those used in a production environment. Due to the machine limitations (imposed thrust force limit of 700 N and low maximum cutting speed of 10 m/min), this would not be possible, and an analogy process would need to be designed, or an alternative machine used that alleviated the limitations. As a complement to this work, an analogy test is designed and discussed in Chapter 4. It is recommended that in future studies, either an actual gear shaping machine tool, or a more rigid milling machine be used.

Chapter 4

Orthogonal Cutting Analogy Test and Wear Analysis

4.1 Introduction

As a complement to the gear shaping experiments, an analogy test using orthogonal lathe cutting was designed and performed. The goal of the analogy test is to calibrate a tool life equation predicting the flank wear of a gear shaping tool for a range of cutting parameters (e.g., cutting velocity v_c , feedrate f , etc.) for a given workpiece material and tool combination. This goal is achieved using a simplified interrupted lathe cutting method removing the requirement to perform time consuming and potentially expensive gear shaping experiments. However, before an analogy testing method can be implemented the wear results from the analogy tests must be compared to actual shaping experiments to ensure the analogy test is a successful recreation of the original process. Through this comparison, the performance of the analogy test can be evaluated and conclusions drawn.

Using the flank wear data obtained through a series of lathe tests a variety of tool life models are calibrated and used to predict the tool life at which the chosen set of cutting parameters should reach the wear criterion. Using the predictions obtained and the measured wear data, the accuracy of the tool life equations can be verified and compared with actual gear wear cutting results, to determine the effectiveness of the analogy testing method and the implemented tool life models. However, due to limitations in experimentation time committed to the gear shaping experiments in Chapter 3, insufficient data was collected to accurately compare between the shaping experiments and the analogy test. In spite of this, the evaluation of the analogy testing process and the experimental setup was still possible and is discussed in this chapter.

In Section 4.2, the experimental design of the lathe analogy test is described in detail. While the overall process mimics an interrupted turning operation, the experimental setup, and design of cutting parameters are critical in recreating the cutting conditions experienced during gear shaping. The analogy test uses specially designed workpiece and tool pairs to reproduce the shaping conditions observed on an easily accessible machine, i.e., a lathe. As the tool is used, the flank wear growth on the cutting edge is photographed periodically following the measurement techniques applied during the shaping experiments. Despite best efforts to recreate the shaping process and matching as many features

as possible, unexpected errors still did occur during the testing process as discussed in Section 4.3 and further expanded upon in Appendix A

The analogy testing experiments were performed for a range of cutting parameters and wear was measured using microscope image processing software. The wear results and trends analyzed from these experiments are discussed in Section 4.4. In Section 4.5, a progression-based tool wear model is developed as a new contribution in this thesis. Instead of being calibrated for a only specific flank wear limit, this model is designed to be able to predict the general progression of tool wear in the presence of changing cutting conditions, thus be applicable to different wear limits. In Section 4.6, predictions of the proposed tool wear model, as well as those from the Taylor and Colding models, are compared against experimental measurements. The conclusions for this chapter are presented in Section 4.7.

4.2 Development of the analogy test

While the shaping experiments were performed successfully on the five-axis CNC machine, the experiments resulted in low quality workpieces while requiring a long process time of 90 minutes as well as very low accumulation of wear due to the large number of teeth (40) in engagement. An analogy testing method would be able to remedy many of these issues using carefully designed workpiece fixtures, cutting parameters, and cutting tools. Furthermore, a wider range of parameters could be tested and incorporated into wear models that were not possible due to the limitations of the experimental setup used in Chapter 3. Some of the parameters that could be tested are: higher cutting speeds above $10 [m/min]$, higher chip thicknesses, larger depths of cut and subsequently higher cutting forces. However, this solution only works if the analogy method successfully recreates the cutting engagement conditions and wear seen in gear shaping.

The designed analogy test uses orthogonal cutting on a lathe and a specially designed workpiece to match the interrupted cutting behaviour seen in gear shaping. Through this test, the wear is concentrated to a single cutting tool performing similar lengths of interrupted cuts as would be seen in shaping tests thus inducing wear in a shorter time period. The designed analogy test has some similarity to the interrupted turning bar test explained in Section 2.5.2, but with certain variations as well as adjustments to mitigate some of the issues that were encountered during a preliminary round of testing, as discussed in the following sections.

4.2.1 Design of tooling

To ensure comparability between the shaping experiments and the analogy testing, the implemented tooling should match the tool geometries and design of the tested shaper cutter. To achieve this, custom tooling was produced for use in the analogy tests, as readily available pre-ground tooling could not be procured with the involute gear tooth profile. However, when the custom tooling was used, issues occurred that were not observed during the shaping experiments despite best efforts to match as many parameters as possible. To continue with the wear experiments and test the analogy process, alternative tooling had to be sourced and used in place of the custom tooling. Further discussion about the custom tooling that failed is presented in Appendix A where the design, troubleshooting and failure modes are discussed.

The alternative tooling used for study of wear was coated carbide cutting inserts sourced from SOWA Tools seen in Figure 4.1. The tool parameters can be seen summarized in Table 6. The selected tools use a CVD (chemical vapor deposition) multilayer coating process where a TiCN (titanium carbide) base layer is used before the external TiN (titanium nitride) layer is deposited. The ISO style designation refers to the shape, clearance angle, tolerance and hole / chip breaker combination, with CCMT being a 80° rhombic shape suitable for use across a range of cutting operations [58].



Figure 4.1: Image of the selected carbide tooling

Table 6: Summary of tooling parameters used in analogy tests [59].

ISO Style	CCMT
Size	32.51
Material	Carbide
Inscribed Circle (Inch)	3/8"
Length (Decimal Inch)	0.382
Thickness (Inch)	5/32"
Corner Radius (Inch)	1/64"
Manufacturer's Grade	PT25C
Coating Style	CVD multilayer

A concern when using the carbide inserts was that the cutting speeds chosen for use in the analogy experiments are vastly different than the manufacturer recommended parameters. The inserts are stated as suitable for a wide range of cutting speeds (150 m/min to 350 m/min) as well as recommended for all purpose cutting conditions including interrupted cutting. However, the intended cutting speeds to match gear shaping are far below the recommended range which may be suboptimal for the inserts and potentially negatively affect the life of the tooling, resulting in premature failure. Additionally, carbide cutters are more prone to chipping when used in interrupted cutting conditions compared to high-speed steel tooling.

4.2.2 Design of workpieces and work holding method

Similarly to the design of tooling, any workpieces used for tool wear analysis must be designed to match the gear shaping workpieces to allow for recreation of the cutting conditions observed in Chapter 3. The main consideration when designing the analogy testing workpiece was to ensure interrupted cutting behavior was maintained while matching the length of material cut during the cutting stroke. For this purpose, the workpiece was designed as a flat bar, where the radial perimeters along the two outer edges of the bar would match the distance cut in a single downstroke of the shaper. The interruption in cutting created by the milled flat recreated the distance travelled by the cutter to reset for the next cut, as seen in Figure 4.2. This distance between cuts was designed to allow the tool to cool between cuts, but during testing it was found that the time outside of the material did not result in any noticeable cooling of the tool and workpiece. Instead, the temperature would slowly increase during cutting until the tool was removed for photographing where both the tool and workpiece were warm to the touch. This increase of temperature occurred as the same tool (tooth) is cutting with each rotation

of the workpiece in contrast to shaping where new teeth are introduced periodically as the meshing action between tool and workpiece occurs during the process.



Figure 4.2: Initial design of the workpieces used for the orthogonal cutting analogy test.

As seen in Figure 4.3, the workpiece was designed so that the arc length a , calculated in Eq. (4.1), matched the length of material cut during each stroke of the shaping operation, corresponding to the face width of the workpiece b . r represents the radius from the center of the workpiece to the outermost edge c . l represents the half chord length or half the thickness of the bar. Each revolution of the workpiece results in a cutting length of two strokes (one for each side of the bar). The total length of material removed (L) for a given length along the workpiece (x) can then be calculated using Eq. (4.2). f represents the feed rate of the cutting tool along the workpiece. To ensure the cut length of material matched the shaping experiments, the half chord length l and radius of the workpiece r were modified until the desired arc length a was found. The cutting speed (v_c) can be found using Eq. (4.3) with n representing the selected rpm of the lathe.

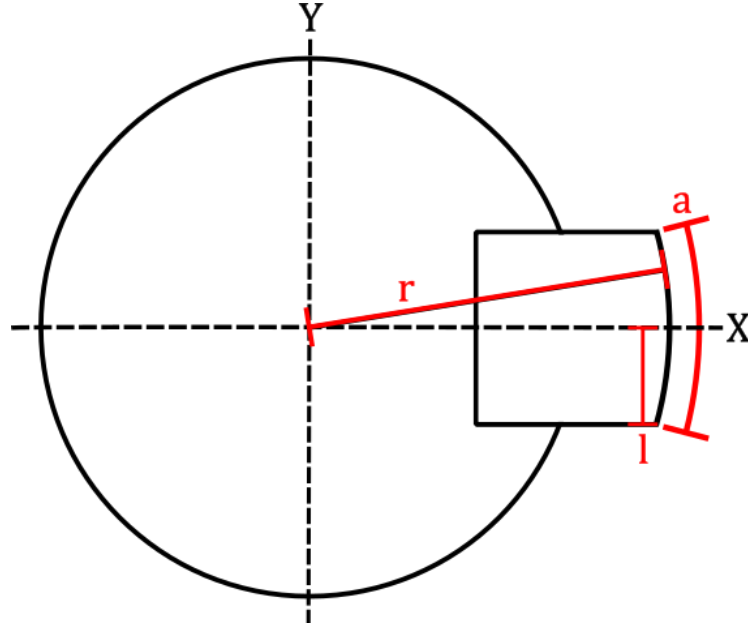


Figure 4.3 Design of the orthogonal analogy testing workpiece.

$$a [mm] = 2r \sin^{-1} \left(\frac{l}{r} \right) \quad (4.1)$$

$$L[mm] = 2a \left(\frac{x}{f \left[\frac{mm}{rev} \right]} \right) \quad (4.2)$$

$$v_c \left[\frac{mm}{min} \right] = 2 r n \left[\frac{rev}{min} \right] \pi \quad (4.3)$$

As workpiece material is cut during the experiments the radius decreases, lowering the cutting speed experienced by the tool. This change was considered by adding extra material to the workpiece diameter ensuring that over the length of the tool testing interval, the average cutting speed experienced by a single tool approximately matched the intended parameters for the test.

The initial tests were performed using the above-described flat bar design. However, the preparation of workpieces was time consuming and wasteful due to the large amount of material that needed to be removed to create the flat section, typically from cylindrical stock. To address this imbalance, the workpiece was redesigned so that a holder, designed to accommodate square bar stock that would be cut during testing, could be reused across the tests. This method would allow for less time spent on

stock preparation between tests. The testing method remains the same and dimensions found for the previous flat bar design were reused and applied to the new design seen below in Figure 4.4. While there was still a certain amount of waste as a section of workpiece was needed to clamp the bars securely in the holder, it was minimal compared to the previous workpiece design.

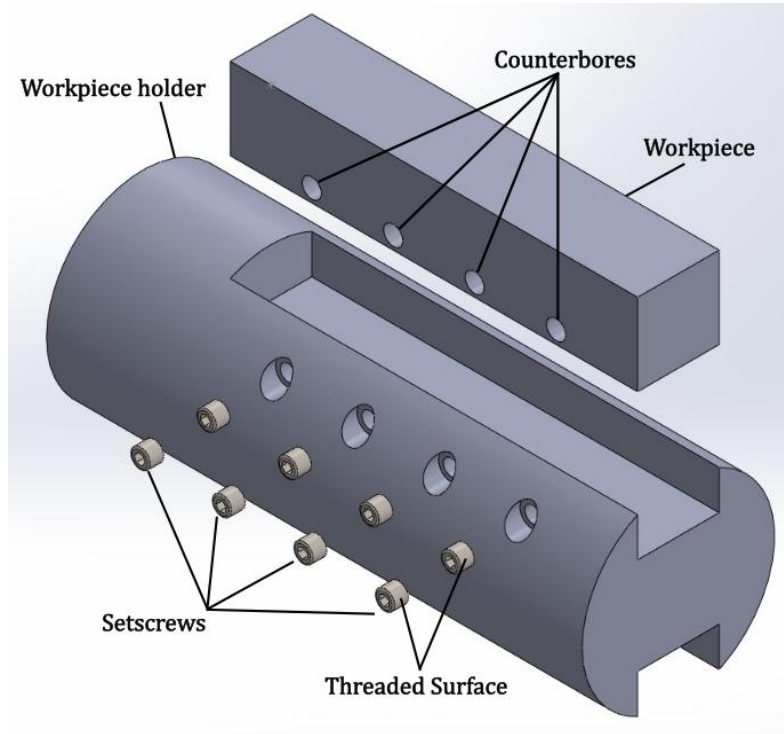


Figure 4.4: Model of the finalized workpiece holder used for the orthogonal analogy testing.

The workpiece holder design uses four set screws and a milled slot on either side of the holder to locate and secure the square stock. To ensure safety during the testing process, the holder was evaluated to ensure that the combination of cutting forces and centrifugal force during cutting did not exceed the holding capability of the setscrews and the frictional force against the backwall. To further ensure operator safety and that no material would be tossed outwards from the holder during the testing, each of the workpiece blanks had a counter bore milled to trap the end of the setscrews when tightened down. If the bar did shift due to insufficient clamping forces, the counter bore would help retain the bar in place by acting as a geometric hard stop against the installed set screw. Two setscrews were used in each hole tightened against each other to avoid any potential loosening due to vibrations during cutting. The performed safety calculations and further design details can be seen in Appendix B.

This holder design closely follows the turning bar analogy test explained in Section 2.5.2 performed for gear shaping experiments [53]. The major change, however, is the use of a traditional turning tool as opposed to a modified shaping tool, as well as the direction of cutting feed. In the performed experiment, the cutting tool is fed along the length of the workpiece (i.e., cylindrical turning) and stopped after a set distance to pause and photograph the tool and document the wear progression. In contrast, in the turning bar analogy test described in Section 2.5.2, the tool is fed radially into the workpiece. In both testing methods, the meshing action between the tool and workpiece, normally seen in gear shaping, is not fully recreated.

4.2.3 Selection of cutting parameters

For the purpose of comparing wear between the analogy test and the shaping process, the cutting parameters are chosen to match those observed in Chapter 3 while expanding the testing interval to calibrate a tool life model. Due to the nature of gear shaping and the constantly changing in-process cutting conditions, the orthogonal analogy test may have difficulties in fully reflecting the shaping operation. Instead, average cutting parameters across the process were targeted for the testing.

ShapePro software was used to simulate the shaping process used in Chapter 3 and the simulated cutting data (total length of material cut, chip thickness, cutting speed, and cutting forces) was exported for use. The exported in-process data was analyzed using MATLAB to determine averages across the cutting process around the perimeter simulation nodes of the tool. The cutting parameters in the analogy testing were chosen to match specific nodes along the cutting edges where the largest evidence of wear / scraping was observed during the gear cutting tests in Section 3.4.2. These coincided with the tooth tips and corners, and on the flanks slightly away from the tip, which are subject to the depths of cut and material removal lengths, as can be seen in Chapter 3, Table 5 and Figure 3.22.

During early proof of concept testing using HSS tooling, it was found that the cutting parameters identified using the ShapePro simulation were not feasible due to the appearance of built-up material on the cutting tool. This appearance affects the wear progression by changing the wear type from abrasion to adhesion and invalidating the test, as this wear phenomena was not observed in the shaping experiments. Ultimately, in the interest of developing a wear model, alternative tooling and parameters were chosen for the orthogonal experiments so that the overall method could still be tested, even if it was not possible to make a direct comparison with gear shaping for the collected data set. More

information about the usage of HSS tooling and general design of the tooling used, which ultimately was not used, can be seen in Appendix A.

The final tested cutting parameters consisted of four cutting speeds and three feed rates for a total of 12 cutting experiments summarized in Table 7. The range of cutting speeds was chosen by first selecting parameter used in Chapter 3 of 10 m/min and then expanding to speeds used in industrial shaping. Higher feed rates were initially chosen, closer to 0.1016 mm/rev, to align with the chip thicknesses observed during the shaping experiments. However, through testing, it was found that the carbide inserts were more prone to shattering at the high feed rates, resulting in early chipping/failure of the cutting edge rather than gradual flank wear. The depth of cut for all experiments was chosen to be 1 mm as it was a value within the recommended tool parameters while also being larger than the nose radius of 0.397 mm. Using this depth of cut, the tool is thus cutting with both the nose radius and the flat side of the tool. The wear of the two regions can be compared to ensure there are no major differences.

Table 7: Tested cutting parameters during orthogonal analogy testing.

$f \left(\frac{\mu m}{rev} \right)$	40.6	50.8	63.4	
$v_c \left(\frac{m}{min} \right)$	10	20	30	40
$doc \text{ (mm)}$	1			

4.2.4 Machine

A Boehringer Göppingen VDF manual lathe, seen in Figure 4.5, was used for the tests. The machine is equipped with automatic feed in X and Z axes, as well as a digital read out (DRO). As it is a manual lathe, the values of the feed rate and spindle speed were limited to discrete steps did not exactly align with the originally selected cutting parameters. Instead, the parameters were rounded to the nearest available setting during implementation. A CNC lathe would be preferred due to the increased control capability, but one was not available at the time of testing. Between passes, the spindle speed (in revolutions per minute - rpm) was adjusted to keep the cutting speed as consistent as possible as material was removed and the workpiece radius decreased. Similarly, it was not possible to choose exact feed

rates to recreate the chip thickness experienced by the gear shaping tool. Instead, feed rate was also rounded to the closest available option.



Figure 4.5: Manual lathe used for the orthogonal analogy wear tests.

4.2.5 Wear measurement protocol

The tool was photographed using a Dino-Lite AF7115 digital microscope and the accompanying Dino Capture software. Before any cutting was performed and after cutting a prescribed distance, two photographs of the tool were taken, one focusing on the side flank face below the cutting edge, and the second focusing on the top rake face of the insert. Following ISO 3685 standards, the microscope was positioned perpendicular to the surface of interest and the microscope was held stationary using an adjustable stand [36]. The tool was manually positioned to ensure the area of interest was in the camera field of view. To ensure the face was in focus, the adjustable depth on the microscope stand was used, changing the distance between tool and camera until the cutting edge was within the focal depth of the camera. Images of the top rake surface were captured to monitor for any development of crater wear that may be occurring during the cutting process, which could cause a weakening of the cutting tool or a drastic failure. However, crater wear was not measured or quantified for any tool wear modeling.

Images of the tooling was captured using the measurement setup shown in Figure 4.6 A white cloth was used below the tool to increase contrast between the tool and background, allowing for better

imaging of the tool. Wear was measured from the top surface of the cutting tool to the farthest location of wear on the flank face, measuring perpendicular to the top rake surface, as can be seen in the annotated photo in Figure 4.7. Tool wear of the cutting inserts was recorded separately for both the nose radius (VC_{max}) annotated PL0 and the tool flank (VB_{max}) annotated PL1. Custom scaling factors were created using a calibration scale to ensure accurate measurements of the wear value when viewed on the computer.



Figure 4.6 : Measurement setup for flank wear on the flank face of the cutting insert.

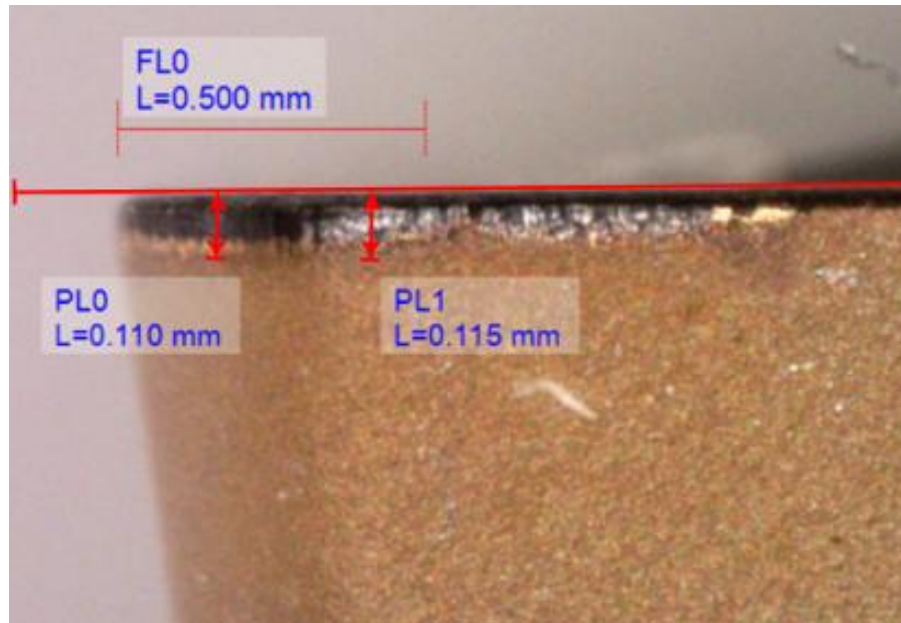


Figure 4.7: Image showing the measurement of the flank wear on a sample cutting insert.

4.3 Cutting procedure for the analogy test

The experiments were performed on the lathe, mounting the fixture in a three-jaw chuck using a live center in the tailstock to provide end support, as seen in Figure 4.8. Initial tests were performed without end support, but excessive deflection occurred resulting in an inconsistent depth of cut as the workpiece rotated. Before cutting, the workpiece was prepared by surfacing the outermost edge to a consistent outer diameter by removing the corners from the square stock using a spare cutter. The carbide inserts were then loaded into the tool holder and touched off on the workpiece surface to zero the digital read out. The DRO was used to ensure a consistent depth of cut between passes, as well as to cut a consistent length along the workpiece in the Z direction. When performing the cutting experiments, an increment of 25 mm along the length of the part was used between photographs, with the length of material cut between each image varying with the effective radius of the workpiece. Increments of 25 mm were chosen as it was an easily repeatable distance that divided the total workpiece length into roughly five steps, ensuring that each imaging increment occurred at a similar radius simplifying analysis. Smaller increments were used towards the start of each trial to better capture the rapid initial growth of flank wear.

Once the length along the Z axis is reached, the spindle it stopped and the tool is removed from the lathe and photographed, as described in Section 4.2.5. Rapid Tap cutting oil was used during the experiments, distributed on the surface of the workpiece, as well as the top of the tool, to provide lubrication during the cut and reduce temperature of the tool. Before being photographed, the tool was cleaned of any debris or fluid that may affect the imaging using compressed air and a rag. Care was taken to avoid damaging the cutting edge, ensuring any developed wear was a result of cutting and not unintentional during cleaning.

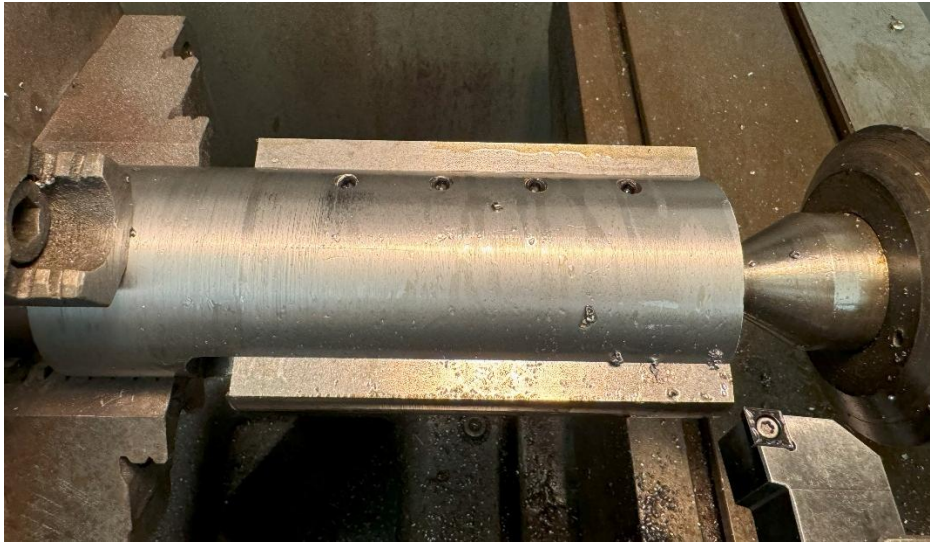


Figure 4.8: Experimental setup for the orthogonal analogy testing process.

The cutting process was repeated, removing 1 mm depth of cut passes from the workpiece until the insert reached the selected flank wear criterion (VB_{max}) of 0.1 mm or the workpiece could no longer be cut due to insufficient clearance in the holder. When the tool reached the VB_{max} value, the insert was replaced, and new cutting parameters were used continuing with the current workpiece. If the tool suffered from catastrophic damage, such as major chipping, the tool was replaced, and the next experiment was started continuing with the same workpiece. If there was no longer clearance to continue with the workpiece, it was replaced and the new workpieces were surfaced, as previously described. The testing process was repeated for each of the tested cutting speeds and feed rates, using a new tool for each experiment.

4.4 Tool wear testing results

A total of 12 tests were performed using the coated carbide inserts varying between the selected cutting speeds and feed rates. Three of the cutting tests were repeated due to premature failure of the cutting edge caused by the appearance of chipping damage before the prescribed flank wear reached the 0.1 mm wear criterion. When premature chipping failure was observed, the test was repeated using a new cutting insert applying the same cutting parameters. These failures could be caused by a range of issues, such as heterogenous material or mechanical properties of the workpiece. In future studies, more experimentation must be performed to properly assess the cause of the failure.

Across the tested cutting parameters, the trends in wear progression remained consistent across the twelve tests. As seen in Figure 4.9, the top left image a) shows the cutting insert before any cutting with no discernable wear on the cutting edge and no damage to the flank face or the surface of the tool coating (shown in gold). As seen in the bottom left image b) flank wear has started at the top of the tool and progresses down the flank face. As the flank wear progresses, the tool coating is worn through, exposing the tool substrate (grey) underneath. As the flank wear grows, a larger surface (wear land) is in contact with the cut surface, leading to rubbing and contributing to further flank wear growth. When this occurs, both the tool substrate and coating are in contact with the workpiece. As the flank wear progresses, the softer substrate begins to show areas of chipping damage, as seen in the top right image c). This chipping indicates the substrate is wearing faster than the coating and the tool is more likely to experience wear by chipping rather than flank wear. This result aligns with what is known of tool coatings as they are typically applied to tooling as they are much harder than the substrate. Finally, the tool wear progresses as shown in the bottom right image d) with flank wear continuing down the flank face, wearing out the tool coating, while the chipping damage of the substrate material also progresses. This process continues until the flank wear criterion is exceeded and the test is ended, or a large chip in the cutting edge occurs ending the useful life of the tool (as shown in Figure 4.10). Wear of the cutting edge occurred in all locations of contact between the tool and workpiece, beginning from the tip of the tool, around the nose radius, and finally along the flat flank of the tool until the cutting edge is no longer in contact with the workpiece. While showing the raw measurements in the following, flank wear is depicted as a function of cutting time, which is a conventional way of representing data in machining tool wear studies. However, in developing the progression-based wear model in 4.5, cutting distance was considered as a free variable instead of cutting time. This is more applicable to the gear shaping, where a specific tooth or a part of a tooth may spend a large amount of time without

cutting material, whereas other section may engage in far more workpiece material, as was analyzed in Chapter 3.

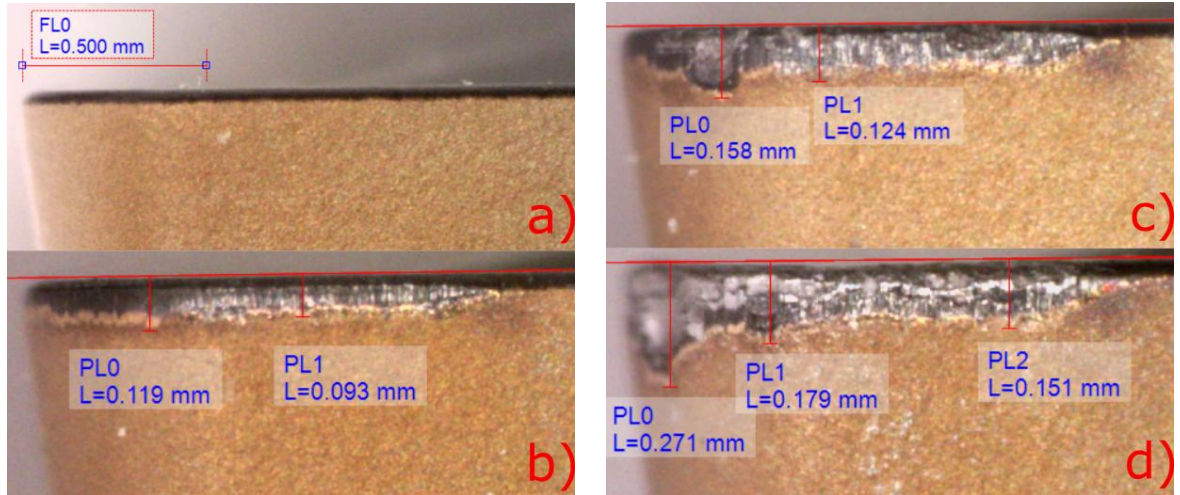


Figure 4.9: General wear progression of a cutting insert starting with a) unused cutting tool, b) slight growth of flank wear, c) chipping of the tool substrate d) final image before tool failure by chipping.

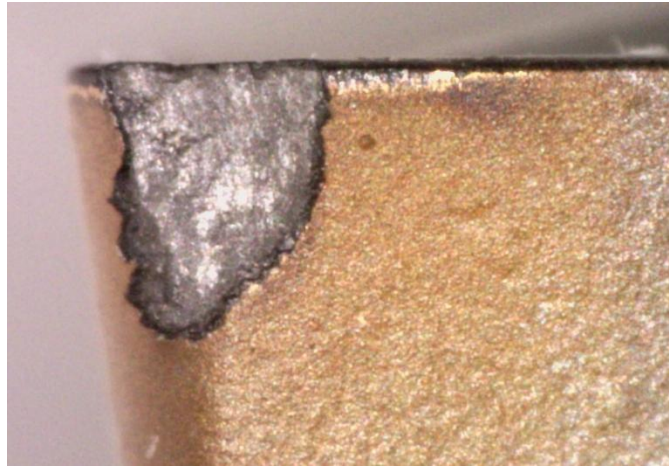


Figure 4.10: Example image of tool failure due to chipping damage.

Repeatability of wear progression across tests with identical conditions

When performing wear analysis for the purpose of optimizing a cutting process, it is important that the wear results obtained are repeatable between tests and that random wear growth is not dominating the wear process. Should data be included in a tool life model that shows extreme outliers, it may skew the model resulting in unreliable predictions. For these reasons, it was important to check that the analogy test shows repeatable results for flank wear growth by performing some of the cutting trials multiple times. To test this, a trial using a cutting speed of 20 m/min and a feed rate of 0.0508 mm/rev was repeated and the wear measurements of the two tests compared in Figure 4.11. The two trials show similar results in zone 1 (initial growth) with the first trial lagging slightly behind. The transition to zone 2 occurs at a similar flank wear value in both trials, around 0.06 mm. The two trials then follow similar wear growth until the first trial experiences a jump in wear due to a chipping on the cutting edge. While there is variation in the wear result between the two tests, it occurs after the wear criterion indicating that the gathered wear results may be applicable to the tool life models with a criterion at or below 0.1 mm. Should the criterion be increased, the results may carry less confidence. It is acknowledged that only a single repeat is not sufficient to guarantee repeatability. In future research, to improve accuracy and reliability in building wear models, cutting tests should be repeated multiple times, and the wear measurements should be averaged, while also considering their statistical distributions, and large outliers that may skew the results should be removed as adequate.

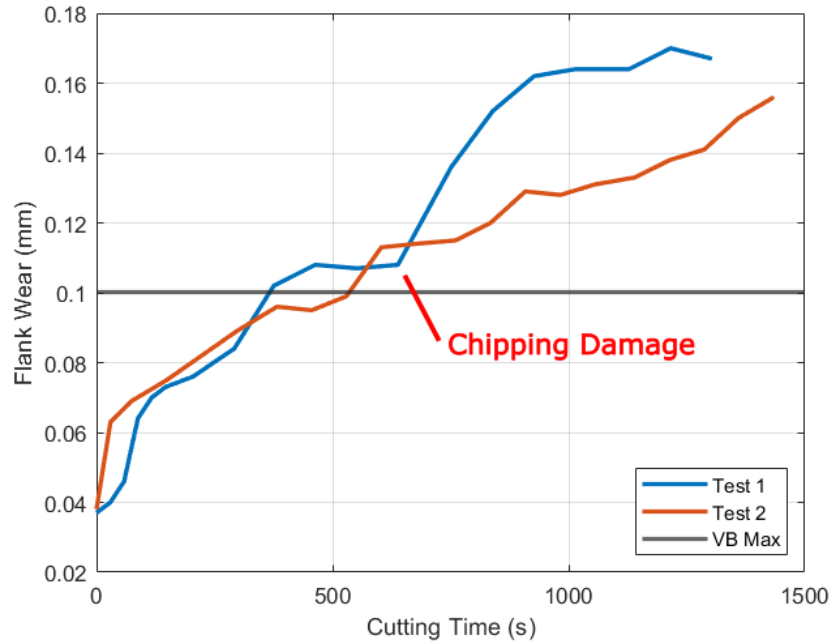


Figure 4.11: Comparison of two trials with the same cutting parameters to examine repeatability of the cutting process.

Wear comparison between the flat and corner radius portions

Wear development was measured for both the corner nose radius VC_{max} and the flat flank VB_{max} and determined whether there are any noticeable differences between the two locations on the cutting edge and which location would exhibit the highest wear value. When comparing the wear development across the 12 cutting parameter groups, the VC_{max} was typically found to be slightly that higher than the VB_{max} and was more likely to experience failure by chipping. Of the 13 tests performed, 11 experienced failures by chipping at the nose radius rather than the flat flank.

Wear comparison across varying feed rate with a constant cutting speed

To determine the largest contributor to a decrease in useful tool life, the recorded datasets can be grouped to isolate variables and determine trends across the cutting data. First, when comparing across static cutting speeds with a variable feed rate seen in Figure 4.12, it was found that there were no clear trends across the four cutting speed groups, contrary to what was expected. The tested feed rate values followed similar wear progressions with slight variation in reaching similar flank wear values in similar cutting times. The expectation was that with increased feed rates and, in turn increased cutting forces

caused by the larger chip thickness, the flank wear would progress faster reaching failure in a shorter length of material cut and shorter cutting times. This relationship may change if a larger range of feed rates were tested or a larger depth of cut were used, but from the data collected, definitive trends across the grouped datasets could not be observed. When observing Figure 4.12 note that the final points of each plotted dataset are captured just before tool failure in all cases. Measurements of the final wear value after tool failure were not included as the large jump in wear dominated the plot and obscured the relevant wear progression data. It is also interesting to note that until the wear criterion on 0.1 mm is reached, the wear profiles for the same cutting speed but changing feed rate remained fairly similar.

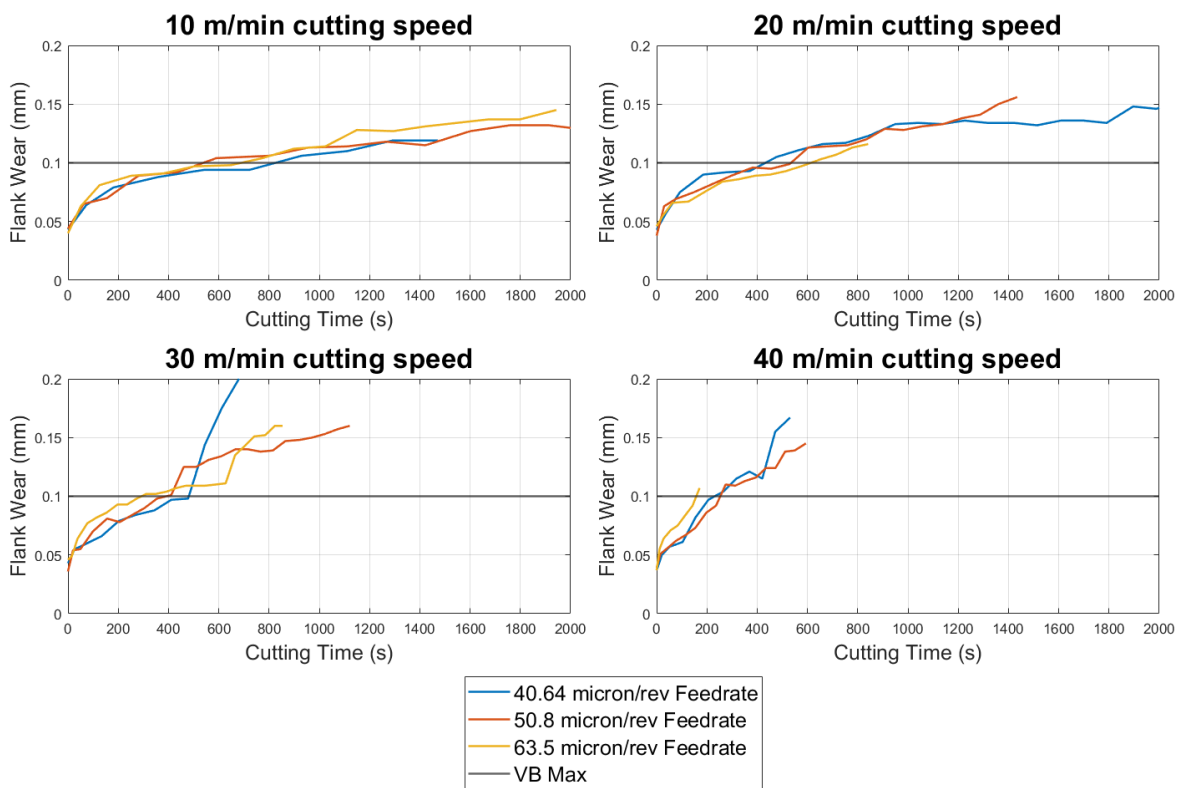


Figure 4.12: Wear progression for varying feed rates and constant cutting speed.

Wear comparison across varying cutting speed with constant feed rates

When observing the cutting data, isolating for constant feed rate groups while varying the cutting speed allowed a clearer trend to be observed from the same data, as seen in Figure 4.13. Generally, it can be seen that higher cutting speeds are reaching the flank wear criterion in shorter cutting times with the 40 m/min cutting speed trials reliably reaching the highest flank wear values first. This observed trend

matches the general wear convention seen in tool life models in which increasing cutting speed results in a reduction in tool life (i.e., cutting time). The other trials follow this convention as well with the 10 m/min trials resulting in the longest tool life.

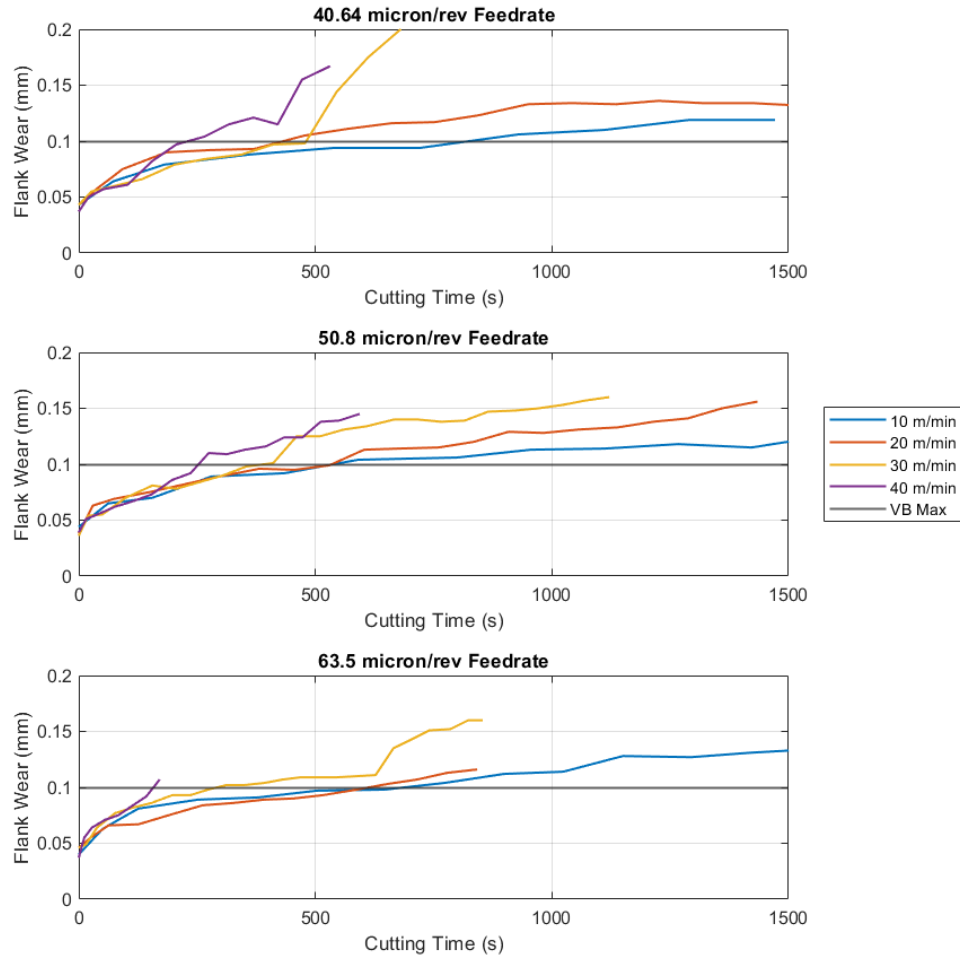


Figure 4.13: Wear progression for groups of constant feed rates and varying cutting speeds.

4.5 Progression based wear model

When using a tool life equation such Taylor or Colding, a single tool life (T) value obtained from each wear test, corresponding to the flank wear criterion, is used to calibrate the model. Once calibrated the model can be used to predict tool life values for varying cutting parameters. However, the estimated tool life values all correspond to the wear criterion (i.e., flank wear limit) that was used to calibrate the model.

Should the wear criterion be changed (e.g., to a different flank wear value), new model constants would need to be calibrated taken from a dataset corresponding to reaching the new wear limit, which may necessitate additional testing to be conducted. Furthermore, a process planner may wish to integrate the prediction of tool wear progression inside a time-domain simulation model, for example accurately capturing the transition between the different wear zones. To develop a more versatile wear prediction mechanism, which can also be successfully integrated within time-domain process simulations, in this thesis a new progression-based wear model is proposed that considers the incremental development of flank wear, by fitting a two-component function to the collected wear data.

4.5.1 Structure of proposed wear function

When analyzing the data presented in Section 4.4 collected from the orthogonal analogy tests and comparing the data to the traditional progression of flank wear seen in Figure 2.4, both zone 1 (rapid acceleration of wear) and zone 2 (steady growth of flank wear) can be observed. While zone 3 (rapid acceleration to failure) is present in some of the wear experiments, there is insufficient data across all tests to reliably include it in the progressive function as many tests were either ended before the tool reached this zone or the insert failed due to major chipping before reaching this zone. To match the wear progression, a two-component model (w) was developed incorporating both an initial exponential function, labelled as w_1 , and a linear function, labelled w_2 . The exponential function (w_1) models the behavior seen in zone 1 before approaching a steady state value, while the linear function (w_2) models the linear growth seen in zone 2. The implemented function can be seen in Eq. (4.4) showing the addition of the two functions, while Eq. (4.5) shows the exponential component and Eq. (4.6) shows the linear component. The cutting speed is represented by v_c while L represents the cutting distance (i.e., domain of the function). The model constants are then represented by K , Q , m_1 and m_2 . The initial wear of the cutter is represented by n . The value of K affects the steady state value of the exponential function while Q affects how rapidly the function reaches the value of K with higher values increasing the initial slope and lower values decreasing. To illustrate the model, the two linear and exponential functions as well as their summation is shown in Figure 4.14, representing the linear portion in orange, exponential function in blue, and their summation in yellow.

$$w = w_1 + w_2 \quad (4.4)$$

$$w_1 = K \left(1 - e^{-\frac{L}{v_c Q}} \right) \quad (4.5)$$

$$w_2 = \frac{m_1}{v_c} L + m_2 L + n \quad (4.6)$$

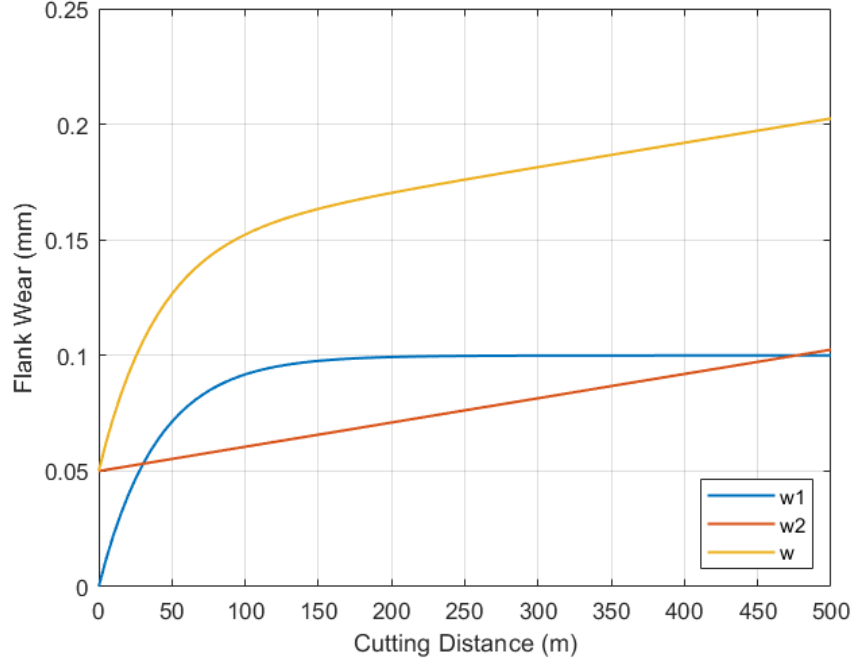


Figure 4.14: Illustration of the linear and exponential portions of the proposed tool wear function, with $n = 0.05$, $K = 0.1$, $m_1 = m_2 = 0.0001$, $Q = 0.5$, and $v_c = 20$ m/min.

When analyzing the experimental data (shown in Figure 4.15), it was observed that with increasing cutting velocity (v_c), the length of cutting distance including the transition zone in wear (i.e., zone 1) increased. Additionally, the amount of cutting distance to reach a given wear criterion during steady-state wear also increased as a general trend. Hence, the exponential term $\exp(-L/(v_c Q))$ in Eq. (4.5) and the slope decreasing term $(m_1/v_c)L$ in Eq. (4.6) were incorporated to capture these effects.

The model was first fit to individual datasets, manually changing the model constants while plotting to analyze the fit between the calculated and measured wear. Using this process, a range of values for model constants was found that roughly fit the datasets. Later, the MATLAB **lsqr** algorithm, an adaptation of the conjugate gradients method [60], was used to solve the least squares problem

$\min_x \|Ax - b\|$ to determine the constants K , m_1 , and m_2 . The algorithm iteratively minimizes the residual norm, fitting the model constants to the experimental cutting data [61]. The A and x matrices can be seen in Eq. (4.7) and Eq. (4.8) while the b vector is seen in Eq. (4.9). The value of n , representing the initial wear, was not found through least squares fitting but instead through averaging the initial wear across all tests. Ideally, the initial wear of each tool is zero. However, due to the employed flank wear measurement method, measuring from the rake surface to the point of furthest wear on the flank face, the initial value was found to be an average of 0.0436 mm measured across the used cutting tools due to the large radius on the cutting edge.

$$A = \begin{bmatrix} 1 - e^{-\frac{L}{v_c Q}} & \frac{L}{v_c} & L \end{bmatrix} \quad (4.7)$$

$$x = \begin{bmatrix} K \\ m_1 \\ m_2 \end{bmatrix} \quad (4.8)$$

$$b = w - n \quad (4.9)$$

As Q could not be calibrated using a linear solver, it was calibrated instead using an iterative solution looping through a range of potential values of Q while performing the least squares fit during each iteration to solve for the other constants K , m_1 , and m_2 . To determine the optimal values of model constants, the absolute difference between the calculated model and the measured wear data was found and the iteration of constants that minimized the difference were chosen for use.

As the number of datapoints in each experiment varied, it was found that the calculated model constants skewed the plotted wear progression towards the datasets with the largest number of datapoints. Instead, a weighted least squares solver, **lscov**, was used introducing a weighting matrix w so as to allow each dataset to be considered equally regardless of the number of data points when calibrating the model constants. The **lscov** algorithm returns the solution that minimizes $r' \text{diag}(w) r$ where $r = b - Ax$.

While feed rate and cutting speed were both varied across the tested parameters, feed rate was not included in the model as there were no discernable trends related to feed rate that could be determined from the collected cutting data. To ensure the selected model best represented the cutting data, a variety of function forms were tested and applied. These different forms varied the number of constants used and the location within the function but still maintained a two-component exponential and linear function. The presented model was selected by balancing various factors, such as observing the fit of

overall trends in the cutting data, minimization of error between the calibrated model and raw data, the number of model constants used and the number of cutting trials needed to calibrate the model. While more cutting data and constants may improve the fit, the costs of performing extra experiments may not always justify the small gain in prediction accuracy and may also bring the risk of overfitting.

4.5.2 Comparison of progression-based model with measured wear data

Using the procedure explained Section 4.5.1, the progression-based wear function model constants were estimated, and have been summarized in Table 8. With the model constants, the flank wear can be predicted as a function of the cutting distance for the different cutting speeds used in the experiments. As feed rate was not incorporated into the wear model, experiments sharing the same cutting speed but different feed rates would lead to the prediction of the same flank wear. Furthermore, since the actual cutting speed during the change vary, due to the reduction of the workpiece radius across passes, to find the average cutting speed value to use in the model (i.e., v_c in Eqs. (4.5) and (4.6)), a weighted average was estimated based on the actual workpiece radius and tangential velocity values for each wear measurement point. The predicted flank wear progressions for the four different cutting speed groups are depicted in Figure 4.15.

Table 8: Calculated model constants for the progression-based wear model.

Q	K	m_1	m_2	n
1.31	0.0304	0.000859	0.000123	0.0436

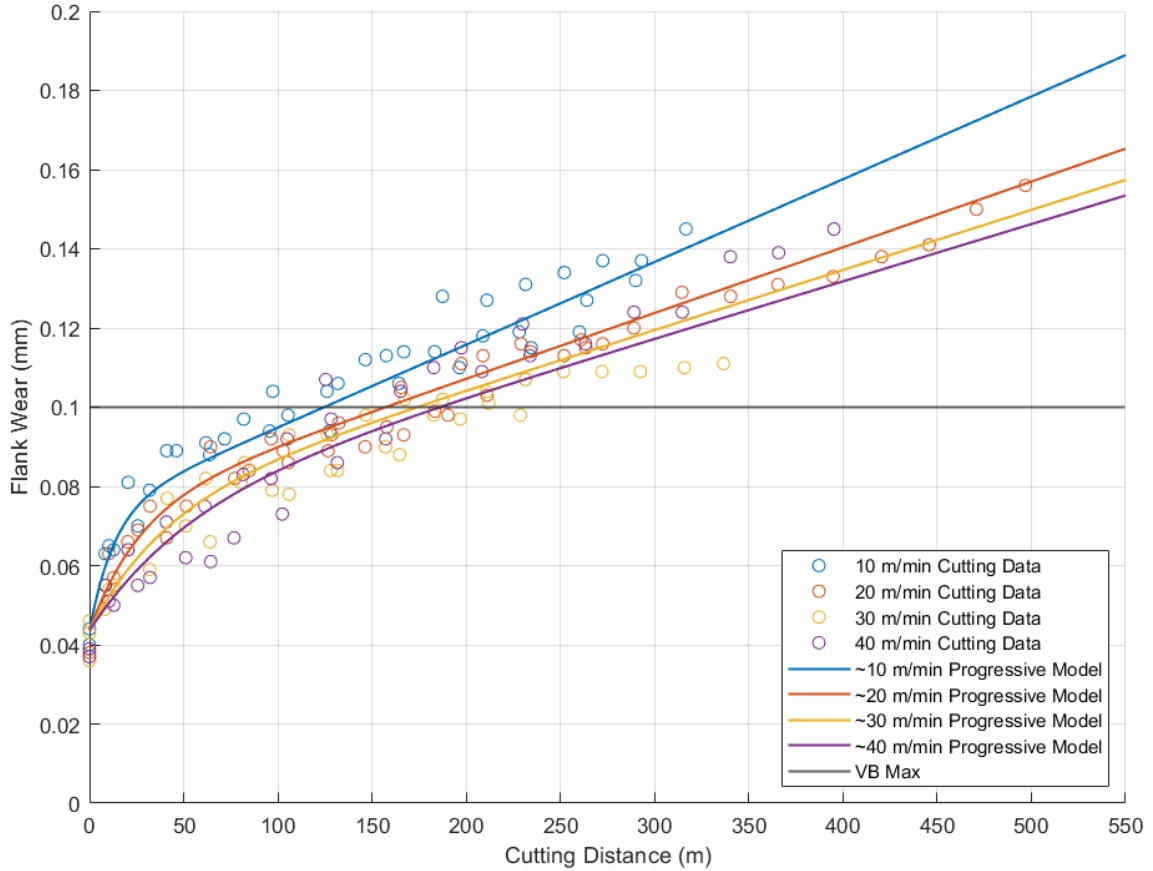


Figure 4.15: Comparison of the fitted progression-based model to the measured cutting data.

As shown in Figure 4.15, the progression-based wear model generally fits well to the measured cutting data over the length of the cutting experiments. Obviously, as the model is only an approximation to data with scatter, in certain regions the fit is better than in others, but nevertheless, the general trends are well-captured. The absolute and percentage of error in predicting the tool wear across all tests is: absolute error: maximum: 19.2 μm , standard deviation: 4.07 μm . Percentage of error (normalized by the measured tool wear for each test): maximum: 31.5 %, standard deviation: 5.77 %.

As the cutting speed increases, the cutting distance until the wear criterion also increases, although the tool life in terms of cutting time decreases (per Figure 4.13). This implies that while the tool wears out faster (as a function of time), a larger volume of material can be machined at the elevated cutting speed with the same cutter before requiring a tool change, indicating higher productivity potential (e.g., more gears cuts with the same shaping cutter). The physical reasons behind this observation should be investigated further in future research, looking at thermo-mechanical, tribological, and metallurgical

aspects. Also, it is advised that in future modelling, the predictions of the proposed progression-based model be augmented with their statistical uncertainty characterization, and larger data sets be used in calibrating the model.

4.6 Comparison of progression-based model with established tool life models

When proposed a new tool wear model, it is important to compare its prediction results with those of well-established tool wear models, like Taylor and Colding, in terms of replicating the experimental observations. For this purpose, in this section, a two-constant Taylor model (in Eq. (2.1)) and a five-constant Colding model (Eq. (2.6)) will also be fitted to the collected experimental data, based on a maximum wear criterion of $VB_{max} = 0.1$ mm. When compared to traditional cutting processes such as milling, turning, and drilling the chosen wear criterion of 0.1 is low with many processes continuing with tools at higher flank wear values. However, a lower wear limit may be preferred for shaping as the profile of the tool has a direct influence on the profile error of the produced workpieces. Should the developed flank wear progress to higher values and influence the cutting tooth profile, the produced workpieces may be negatively affected. In addition, during the cutting experiments it was found that the tools were failing prematurely during the testing due to chipping, so a lower value was preferred. The $VB_{max} = 0.1$ mm was chosen as a value that all test cases had exceeded. Traditionally, the wear criterion is chosen for a variety of reasons: depending on replacement cost of the tool, resharpening costs, a prescribed number of parts per tool, or if the tool wear is affecting the geometric accuracy of the finished workpiece. Further investigation may be undertaken to optimize the maximum wear value depending on the goals of the process planners.

Regardless of the model and wear limit chosen, the calibration workflow is the same. First, the model constants must be calculated using a selection of cutting data corresponding to the time needed to reach the wear criterion. For an experiment to be included, the final observed wear must have exceeded the chosen value. The cutting time (T) corresponding to the wear criterion can then be calculated from the dataset for each of the cutting parameter groups using linear interpolation. A least squares solver (e.g., using MATLAB) can then be used to calculate the model constants. The cutting time values recorded from the twelve experiments based on the $VB_{max} = 0.1$ mm criterion are summarized in Table 9.

Table 9: Tool life results from the analogy tests based on $VB_{max} = 0.1$ mm criterion. Cutting speed is the weighted average across all cuts based on the length of cut for each speed.

f ($\mu\text{m}/\text{rev}$)	v_c (m/min)	Measured Time (min)
40.6	10.6	13.8
40.6	20.8	7.21
40.6	28.7	8.17
40.6	37.3	3.86
50.8	9.89	8.98
50.8	20.8	8.91
50.8	30.9	6.53
50.8	39.9	4.22
63.5	9.78	11.5
63.5	19.4	10.2
63.5	32.2	4.88
63.5	44.0	2.63

4.6.1 Taylor's tool life model

Taylor's tool life models used for the analysis of the cutting data can be seen in Eq. (2.1) and Eq. (2.4) for the two and three constant models, respectively. To recap from Chapter 2, in the two constant model only the cutting speed (v_c) and cutting time (T) are considered, along with model constants m and C_T . In the three constant model, Woxen's equivalent chip thickness (h_e) and an additional constant p is introduced. The model coefficients were solved using the previously discussed linear least squares solver function **lsqr** in MATLAB. The **lsqr** solves a system of linear equations in the form of Eq. (4.10) solving for the coefficients arranged in matrix x using the known regressors in A matrix and the real (output) vector b . Using this linear structure, the models were rearranged into matrix-vector form seen in Eq. (4.11) and Eq. (4.12) for the two and three constant Taylor models.

$$A x \cong b \quad (4.10)$$

$$\begin{bmatrix} \log(T_1) & -1 \\ \log(T_2) & -1 \\ \vdots & \vdots \\ \log(T_N) & -1 \end{bmatrix} \begin{bmatrix} m \\ \log(C_T) \end{bmatrix} \cong \begin{bmatrix} -\log(v_{c1}) \\ -\log(v_{c2}) \\ \vdots \\ -\log(v_{cN}) \end{bmatrix} \quad (4.11)$$

$$\begin{bmatrix} \log(T_1) & \log(h_{e1}) & -1 \\ \log(T_2) & \log(h_{e2}) & -1 \\ \vdots & \vdots & \vdots \\ \log(T_N) & \log(h_{eN}) & -1 \end{bmatrix} \begin{bmatrix} m \\ p \\ \log(C_T) \end{bmatrix} \cong \begin{bmatrix} -\log(v_{c1}) \\ -\log(v_{c2}) \\ \vdots \\ -\log(v_{cN}) \end{bmatrix} \quad (4.12)$$

The calculated model constants for the two constant Taylor model can be seen in Table 10. As the two constant Taylor model does not include feed rate, three sets of model constants were calibrated using the three different feed rate groups. In addition, a fourth set of constants was found using the full data set. As can be seen there is variation between the four sets of constants, this can be attributed to the fact that each set is calibrated using four data points and is susceptible to changes in the data. Regardless of the variation, the overall wear trends are captured, correlating the cutting velocity (v_c) to the cutting time (i.e., tool life, T) as can be seen in Figure 4.16. Only one set of model constants was calculated for the three constant Taylor model as the model contains a chip thickness term. The calculated constants were: $m = 0.975$, $p = 0.327$, and $C_T = 55.2$. Using the calculated model constants, the curves for the Taylor tool model can be calculated and compared to the data points used to calibrate the models. These plots are shown in Figure 4.16 and Figure 4.17.

Table 10: Calculated constants for the two constant Taylor model.

Dataset	40.6 μm/rev	50.8 μm/rev	63.5 μm/rev	All wear profiles
n	0.939	1.415	0.878	0.955
Ct	146	342	114	141

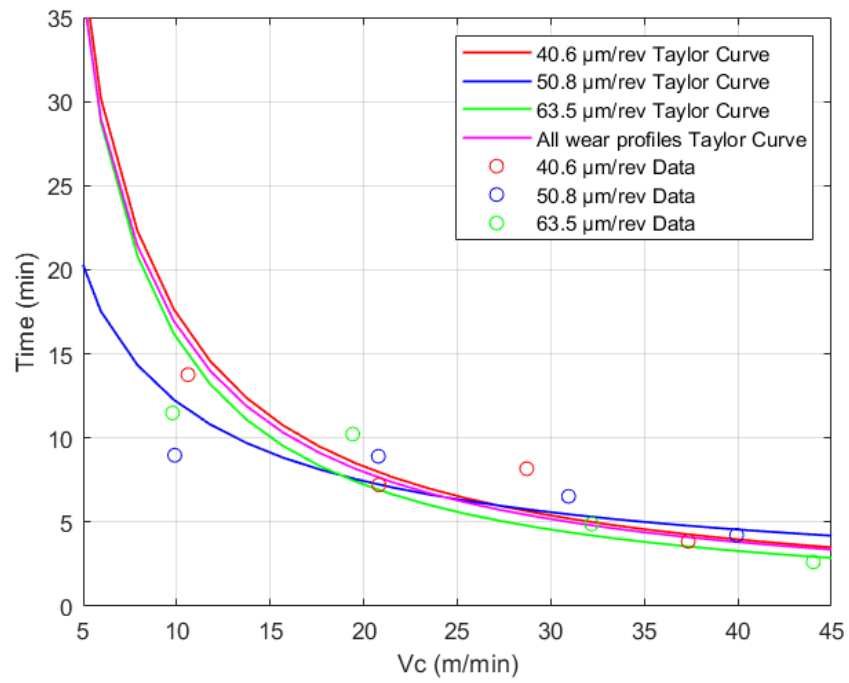


Figure 4.16: Calibrated 2 constant Taylor models (solid line) and the data used to calibrate them (points).

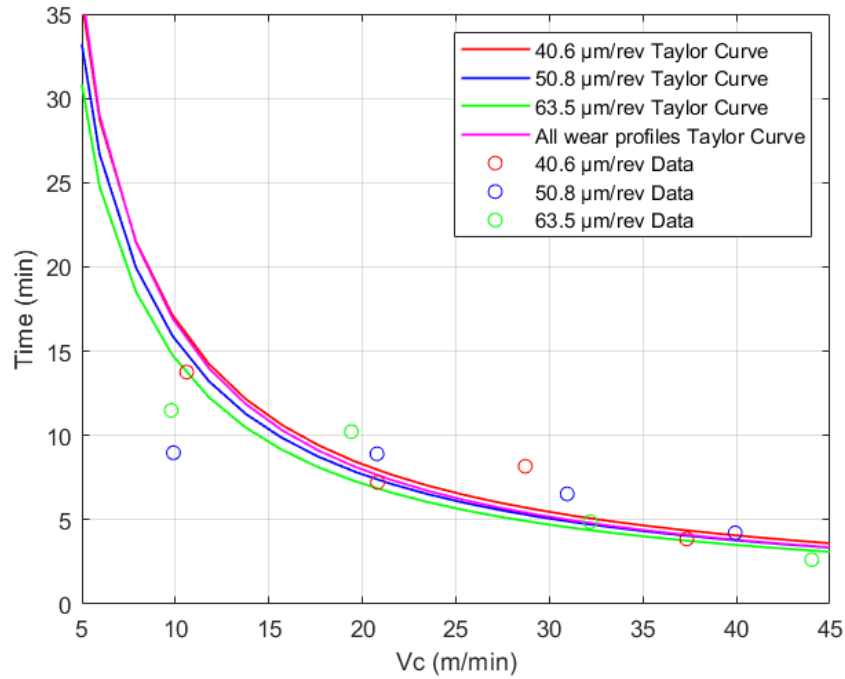


Figure 4.17 Calibrated 3 constant Taylor models (solid line) and the data used to calibrate them (points).

As can be seen in Figure 4.16 and Figure 4.17, while the Taylor model successfully captures the trends of the data, there is some deviation between the calculated curves and the data set. This indicates that the observed wear progression did not precisely follow the theoretical tool life predictions obtained with the Taylor model, and/or that a larger range or amount of datapoints is needed to further calibrate the model. Also, as presented in Section 4.6.3 - Table 13, the two and three parameter models, for the obtained data set, seem to produce comparable results.

4.6.2 Colding tool life model

The Colding tool life model is identified in the same way as the previously discussed Taylor model with the difference being the larger number of cutting constants. The Colding model uses Woxen's equivalent chip thickness (h_e), cutting speed (v_c) and cutting time (T), while also introducing the five model constants K, H, L, N_0 and M , as seen in Eq. (2.6). For the purposes of solving for the model constants using the least squares solver, the rearranged model shown in Eq. (2.5) was used and put into matrix form seen in Eq. (4.13). The equation seen in Eq. (2.7) introduces alternate constants α and m

in place of the Colding constants (refer to Appendix C for more information about the mathematical equivalence and transformation between two version of the Colding model).

$$\begin{bmatrix} \log(T_1) & \log(h_{e1})\log(T_1) & \log(h_{e1}) & \log(h_{e1})^2 & -1 \\ \log(T_2) & \log(h_{e2})\log(T_2) & \log(h_{e2}) & \log(h_{e2})^2 & -1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \log(T_N) & \log(h_{eN})\log(T_N) & \log(h_{eN}) & \log(h_{eN})^2 & -1 \end{bmatrix} \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ m_0 \\ m_1 \\ \log(C_T) \end{bmatrix} \cong \begin{bmatrix} -\log(v_{c1}) \\ -\log(v_{c2}) \\ \vdots \\ -\log(v_{cN}) \end{bmatrix} \quad (4.13)$$

Using the least squares solver, the constants were solved as summarized in Table 11. Using these, the cutting time across a range of cutting speeds was calculated and compared to the dataset, as shown in Figure 4.18.

Table 11: Calculated constants for the modified Colding equation.

α_0	α_1	m_0	m_1	C_T
0.292	-0.233	1.77	0.166	3.38

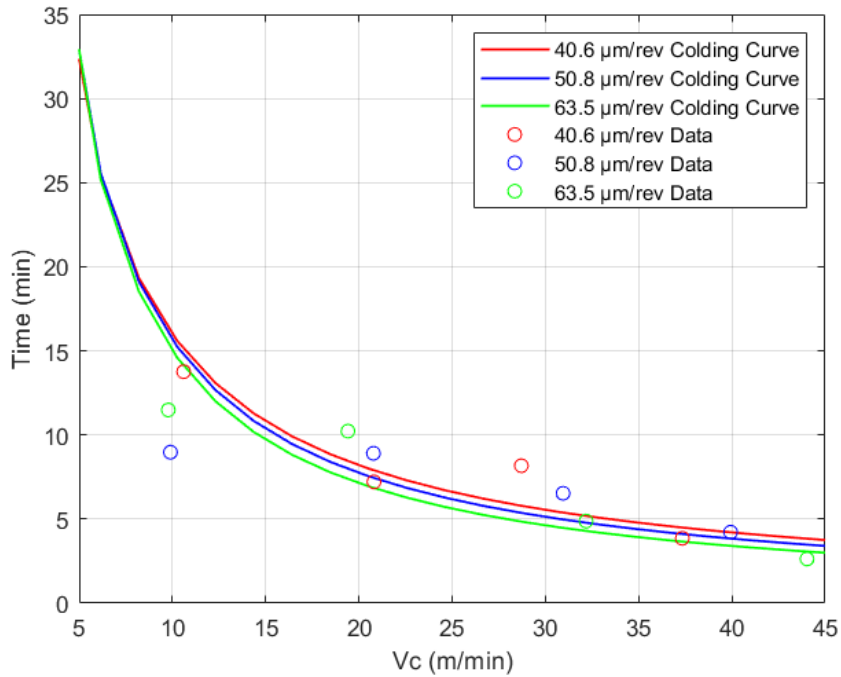


Figure 4.18: Calibrated Colding models (solid line) and the data used to calibrate them (points).

As can be seen in Figure 4.18 the calibrated Colding model generally produces a good fit to the measured wear data across all three feed rate groups. However, due to the low number of experiments the model may be overfit to outliers. Thus, should more cutting data be included the fit may be improved and any outliers that skew the data removed.

4.6.3 Benchmarking proposed progression-based model with Taylor and Colding wear models with the experimental data

The predictions of the progression-based wear model and the Taylor and Colding models were compared to the measured cutting data across all cutting data sets. The results are summarized in Table 12. Through this comparison, it was found that the tool life models aligned with the measured data with some cutting groups showing a better fit than others. The percent error between the predicted tool life and measured tool life can be seen in Table 13. It was found that the tool life models performed similarly with an average error of around 23%. Furthermore, the trials with the highest error were the same across the three models indicating those trials may be outliers. The progression-based model performed slightly better than the tool life models with a lower average error, and a smaller variance between the highest and lowest percent error across the trials. However, with such limited experimental data, it is early to jump to a conclusion on whether more accurate predictions can always be expected. The main affirming points about the proposed progression-based model are that:

- Tool life predictions obtained with this new model are consistent with those from Taylor and Colding structures
- The model can generalize to different flank wear limits without requiring re-fitting of the parameters, and most importantly,
- The model is highly suitable for integration into time-domain simulation of interrupted cutting operations, such as gear shaping.

Table 12: Measured and predicted tool life using the Colding, Taylor and progressive models.

Feed rate $f \left[\frac{\mu m}{rev} \right]$	Cutting speed $v_c \left[\frac{m}{min} \right]$	Tool Life (min)				
		Measured from Cutting Data	Two constant Taylor model	Three constant Taylor model	Modified Colding model	Progression-based wear model
40.6	10.6	13.8	15.0	15.9	15.2	12.0
40.6	20.8	7.21	7.41	7.96	7.92	7.63
40.6	28.7	8.17	5.29	5.72	5.81	6.00
40.6	37.3	3.86	4.02	4.37	4.51	4.90
50.8	9.89	8.98	16.2	15.8	15.9	12.5
50.8	20.8	8.91	7.43	7.40	7.48	7.64
50.8	30.9	6.53	4.89	4.92	4.99	5.66
50.8	39.9	4.22	3.75	3.79	3.86	4.66
63.5	9.78	11.5	16.4	14.9	15.4	12.6
63.5	19.4	10.2	7.97	7.35	7.40	8.03
63.5	32.2	4.88	4.70	4.38	4.31	5.49
63.5	44.0	2.63	3.38	3.18	3.08	4.32

Table 13: Percent difference between the applied models and the measured tool life.

Feed rate $f \left[\frac{\mu m}{rev} \right]$	Cutting speed $v_c \left[\frac{m}{min} \right]$	Tool Life (min)	Percent Error			
		Measured from Cutting Data	Two constant Taylor model	Three constant Taylor model	Modified Colding model	Progression-based wear model
40.6	10.6	13.8	9.15%	15.5%	10.2%	12.6%
40.6	20.8	7.21	2.82%	10.4%	9.84%	5.87%
40.6	28.7	8.17	35.2%	30.0%	28.9%	26.6%
40.6	37.3	3.86	4.19%	13.3%	16.9%	27.1%
50.8	9.89	8.98	80.0%	76.5%	76.8%	39.6%
50.8	20.8	8.91	16.6%	16.9%	16.1%	14.2%
50.8	30.9	6.53	25.1%	24.7%	23.6%	13.3%
50.8	39.9	4.22	11.2%	10.3%	8.68%	10.3%
63.5	9.78	11.5	42.4%	29.5%	34.2%	9.86%
63.5	19.4	10.2	22.0%	28.0%	27.7%	21.5%
63.5	32.2	4.88	3.74%	10.2%	11.7%	12.6%
63.5	44.0	2.63	28.6%	20.8%	17.0%	64.3%
Average Error:			23.4%	23.9%	23.5%	21.5%
Standard Deviation:			22.0%	18.2%	18.7%	16.5%

4.7 Conclusions

In this chapter, an analogy test for the gear shaping operation was designed and tested across a range of cutting parameters using interrupted turning tests. The wear results were evaluated and analyzed, and a new progression-based tool wear model was proposed. The progression-based model produced tool life predictions comparable to established tool life models, similar to Taylor and Colding and is believed to be suitable for simulating gradual development of tool wear inside interrupted cutting simulations, such as gear shaping.

The initial goal of this chapter was to compare the wear results of the gear shaping experiments performed in Chapter 3 to the developed analogy test. However, due to issues encountered, the wear results obtained could not be directly compared to the shaping results collected in Chapter 3. This is because in the shaping experiments, visible tool wear could not be induced (due to machine stiffness and capacity limitations) and in the analogy testing, similar HSS tooling material led to built-up edge development, which required a redesign of turning test. Nevertheless, a protocol for conducting future

interrupted cutting tests was developed and validated using different kind of (carbide) tooling and a novel progression-based tool wear model was proposed and evaluated.

The proposed analogy testing followed a method similar to the one discussed in Section 2.5.2. However, it has replaced the modified shaping tool with a more easily accessible turning tool with similar geometry to the cutting edge of a shaping tool. The major difference between the two tests is that the tool is fed axially along the workpiece instead of radially cutting tooth gaps. It is anticipated that the distance of material cut or cutting time can be compared to the shaping tests to model or predict flank wear values.

The modified workpiece holder enabled the analogy tests to be performed in an efficient manner with minimal amount of workpiece stock being required. The holding solution was developed considering the expected cutting parameters, but may require modifications should the required cutting parameters exceed those used in the safety calculations in Appendix B.

When testing the analogy method, cutting speeds ranging from 10 m/min to 40 m/min and feed rates ranging from 40.6 $\mu\text{m}/\text{rev}$ to 63.5 $\mu\text{m}/\text{rev}$ were tested, resulting in 12 cutting tests that were used for the wear analysis. During the testing, the tools would cut a specified length of material to ensure consistency and be photographed for wear at certain intervals. The wear was then measured following the ISO standard measurement guideline for single point lathe tooling. It was found during the cutting tests that the wear followed the first two zones of the traditional three phase flank wear progression. The third zone was not significantly observed before major chipping occurred. For the tested material (cold rolled 1020 steel) and tool pair (carbide) and cutting conditions, it was found that the major factor which affected the rate of the wear progression was the cutting speed, while the effect of feed rate was not discernable.

A new progression-based wear model was proposed, which is able to replicate the general trends observed in the test data. The model was also compared to the well-established Taylor and Colding tool life models for a flank wear criterion of 0.1 mm. The proposed model produced consistent tool life predictions with these models, and in some cases yields slightly more accurate results. However, the main advantages of the proposed model are its ability to be integrated inside digital time-domain simulation of interrupted cutting operations, like gear shaping, and its ability to predict different flank wear limits without requiring re-fitting of its parameters.

Some of the shortcomings of the current study were the limited number of experiments conducted. Obviously more data, and especially further repeats and broadening the range of testing parameters, could potentially produce a model with closer predictions than 16-21% range. Another interesting improvement to the model would be incorporating the ability to characterize the uncertainty of the predictions based, for example, on using methods like Bayesian parameter estimation.

Future studies, pending equipment availability, should focus on testing matching tool and workpiece materials and cutting conditions between gear shaping and interrupted turning analogy tests, and should also validate the tool wear progression in gear shaping operations using such a wear model estimated directly from lathe experiments. Future studies should also aim to characterize the physics of the tool wear phenomenon to better understand the reasons for discrepancy (or agreement) between the modeled and experimentally observed development of tool wear.

Finally, it is recommended to expand the model and research workflow to the machining of different kinds of metals with different types of tool substrates and coatings.

Chapter 5

Conclusions

5.1 Conclusions

This thesis investigated a framework for studying tool wear modeling in gear shaping, by conducting shaping experiments on a milling machine, developing a turning analogy test, and proposing a progression-based wear model which can be integrated inside digital machining simulation.

Gear shaping was performed using a five-axis milling machine through custom NC code to express the required motion between the tool and workpiece. The process kinematics were verified through a polygon subtraction simulation generating a sample workpiece that was compared to an ideal workpiece. Cutting experiments were then performed successfully, despite certain challenges stemming from the machine such as the thrust force limit, the potential for spindle rotational deflection, and the runout on the tools that were procured ($51\text{ }\mu\text{m}$). A total of 17 workpieces were cut gathering flank wear measurements between the workpieces. Unfortunately, due to the long process time of 90 minutes per part, further testing was not feasible. It was also found that the generated workpieces were of low-quality, showing a maximum profile error of $80\text{ }\mu\text{m}$ when measured with a coordinate measurement machine as well as burrs and rough flank faces. When analyzing the wear that had developed on the cutting tool it was found that very little wear had accumulated across the teeth, only showing wear at the tips and corners of the cutting teeth. When compared to digital simulations of the shaping process, that had been conducted the simulated ShapePro software, this coincided with the regions highest length of material cut as well as the highest average chip thicknesses. As only one tool and cutting speed was used during the shaping experiments, tool life models could not be calibrated using the shaping wear. Also, the amount of wear was not sufficient for validating a tool wear model at the current point in research. To accelerate the growth of wear and more easily calibrate a tool wear model, an analogy test was designed for interrupted turning on a lathe. This was to create cutting conditions specifically similar to those encountered in gear shaping. 12 different tests were performed considering four cutting speeds and three feed rates. Using the gathered data, an empirical progression-based wear model was proposed, as a new contribution. The two-component wear model, capturing the trends in the primary and secondary wear zones using an exponential and a linear function, was calibrated using the entire wear progression data. The advantage of this model, over traditional tool life models, like Taylor and Colding, is that:

- The model is not calibrated to only one fixed tool wear limit, and can be readily used (without re-calibration) for different tool wear limits
- The model is highly suitable for integration within a digital simulation environment, to keep track of and update the localized flank wear values, as a function of the cutting speeds encountered by each portion of the cutting edge. Tool life models, like Taylor and Colding cannot achieve this, as they are pre-calibrated for a set wear criterion.

The predictions of the proposed tool wear model were also compared to predictions from the Taylor and Colding models, by comparing the predicted tool life for a set flank wear criterion ($VB_{max} = 0.1 \text{ mm}$). Taylor and Colding models were able to predict the measured tool life with an average error 23-24%. The proposed progression-based model was able to predict the tool life with around 22% average error, indicating its comparability in prediction, while being more general and suitable for time-domain simulation (i.e., ‘digital machining’) applications.

5.2 Future Work

Future work for this project should focus on expanding the testing process to allow for comparisons between the gear shaping process and the designed analogy test while expanding the accuracy of the implemented tool life models. Due to practical considerations (time limits, machine limitations, etc.) the amount of testing performed during the gear shaping experiments was lacking. While the CNC machine was able to theoretically reproduce the shaping process, only a single set of cutting parameters could be tested. Furthermore, due to the machine limitations the tested parameters were not representative of parameters used in industrial shaping (higher cutting speeds, feed rates, and depths of cut). Should a dedicated gear shaping machine be used, a larger range of parameters can be tested while developing higher amounts of flank wear on the cutting tools in shorter time periods. Through more testing and subsequently more wear data, tool life models and the developed wear progression model can be calibrated and later used to predict varying tool life values for each node around the tool perimeter based on the in-process cutting conditions, such as chip thickness and cutting speed. Finally, the calculated tool life values can be implemented into ShapePro with the intention of allowing process planners further flexibility during optimization of the shaping process.

The analogy process was used in a range of tests varying both cutting speeds and feed rates while the collected wear data was used to calibrate the Taylor and Colding tool life models as well as the newly developed wear progression model. However, only a single test was performed at each cutting

parameter pair and was simply repeated if the test failed before reaching the wear criterion. Future work should perform multiple tests using the same cutting parameters to ascertain repeatability and variability of the analogy test and improve the consistency between the calibrated model and the measured wear observed during testing.

The implemented tool life models were calibrated using a least-squares fitting method isolating the $\log(v_c)$ term in the matrix form. A reduction in model error may be found if the model is rearranged isolating for the tool life ($\log(T)$) term instead. An example of this can be seen in Appendix D. Additional variations of the tool life models and methods to approximate the model constants should be performed to minimize the error between the calculated tool life values to the tool life found in the experimental cutting data.

While the tool wear model was curve-fit as an empirical mathematical function, future research should also target characterizing the uncertainty of the prediction, using methods like Bayesian parameter estimation [62]. Additionally, it is recommended to expand the progression-based wear model to the cutting of different kinds of metals, with tools of different kinds of substrates and coatings.

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Appendix A

Original tool selection for orthogonal analogy cutting experiments

This appendix describes the design and selection of the tooling that was originally intended for use in the orthogonal analogy experiments. The tool design consisted of a five-degree rake angle, consistent with typical rake angles seen on gear shaping tools. Additionally, a five-degree relief angle was introduced on both the front side of the tool and the flank face of the tool to avoid rubbing with the cut surfaces. The designed and produced tool can be seen in Figure A.1.

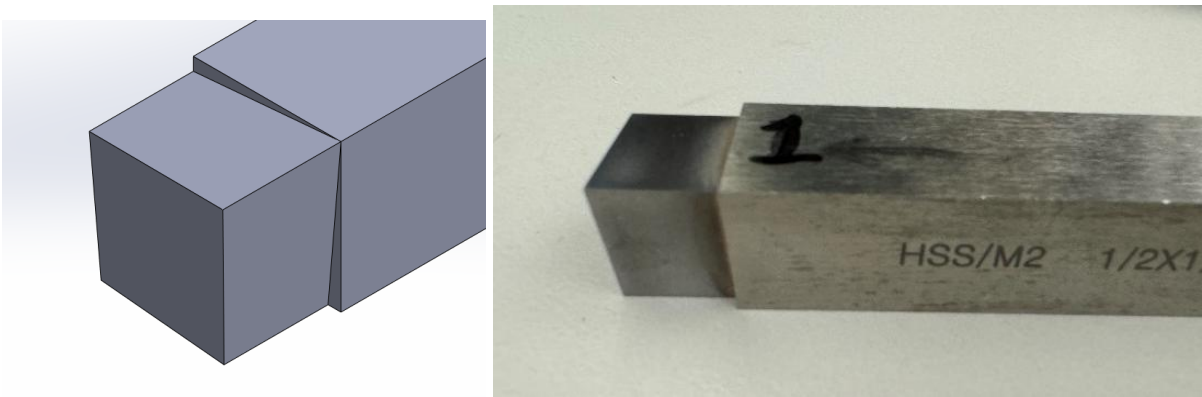


Figure A.1: Custom tooling produced for the orthogonal analogy cutting tests.

As the exact metallurgical composition of the shaping cutters was unknown from the supplier, a portable XRF (X-ray fluorescent) spectrometer was used to determine that the tools were most likely M2 tool steel, however there may have been some variance in exact composition as the carbon content could not be measured. The lathe tools were then produced using a wire EDM machine to cut M2 tool steel blanks sourced from McMaster-Carr. After cutting, the surfaces experienced oxidation leaving a layer of rust on the cut faces, as seen in Figure A.2. To clean the surfaces and improve image quality, the surfaces were honed using progressive grit honing stones. Once the rust was removed, surface pitting was found as an after effect of the EDM process. The honing process continued until a clean surface was revealed, free of any noticeable damage or imperfections. After honing it was found that burrs had been created on the tool corners and cutting edge. To remove the burrs the tool corners were slightly rounded with the honing stones. This process strengthened the cutting edge by reducing stress concentrations and matching the corner radius of 50 μm measured from the used shaping tools.

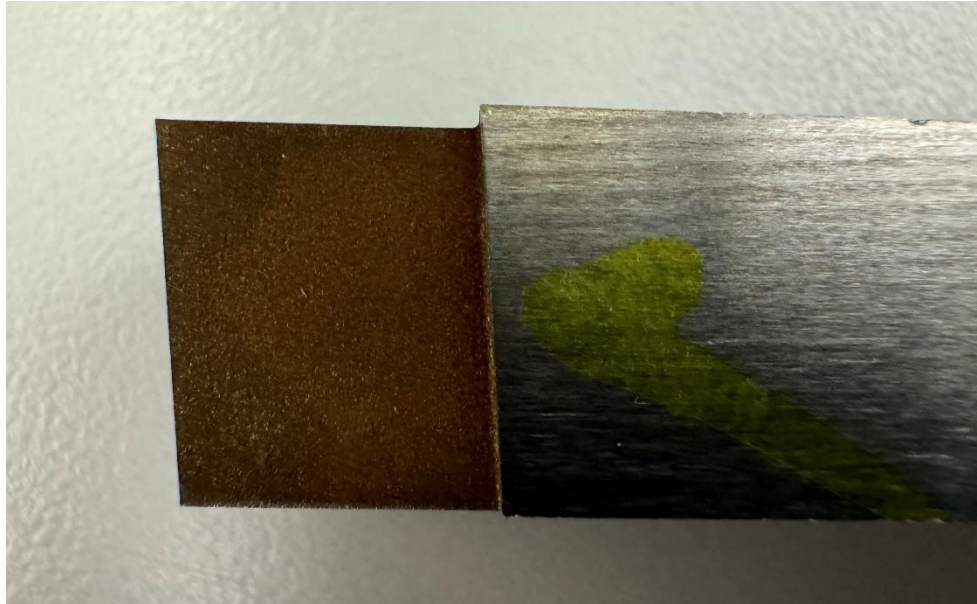


Figure A.2: Cutting tool showing rusted flank face.

When performing cutting tests with the chosen model parameters it was found that built up edge (BUE) was occurring on the cutting tool, as seen in Figure A.3, despite matching the cutting parameters used in the gear shaping tests where BUE was not observed. One possibility is that the built-up may be caused by the chip not being properly evacuated from the cut and instead sitting on the rake surface of the tool. Then the chip is welded to the rake face by repeated impacts caused by the interrupted cutting conditions. In contrast, the gear shaping ejects the chip below the workpiece falling away from the tool through gravity and there is no material on the top side of the workpiece when each cut begins. Additionally, the gear shaping process involves multi flank cutting wherein multiple flanks (left flank, tip, or right flank) are cutting simultaneously creating chip flow patterns that differ from the analogy testing. Chip sections created by the multi flank cutting may interact with each other and affect the chip flow.

Other possible sources of error were due to the unknown tool material used in the shaping tests. While efforts were made to match the tool and workpiece materials between the shaping and analogy tests, the materials originated from different sources and thus material composition, hardness, and microstructure may vary. Future research should include testing of the material compositions to ensure matching between the process conditions.

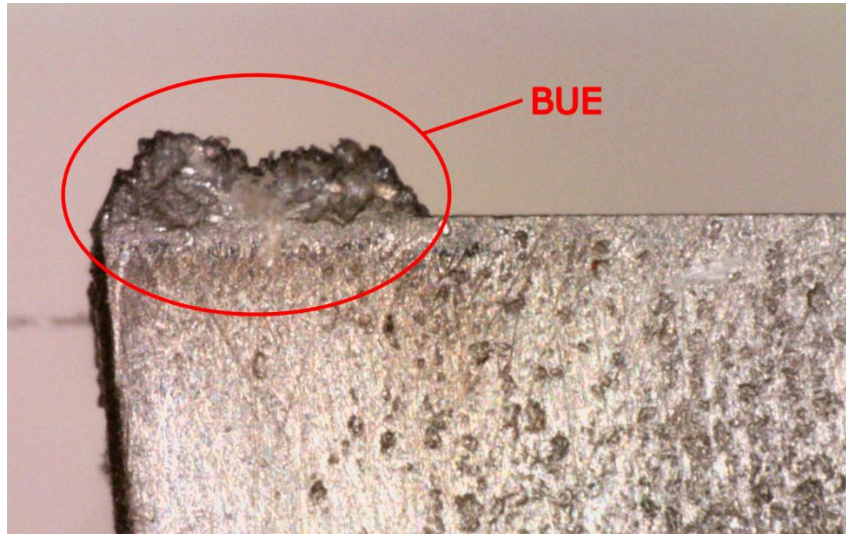


Figure A.3: Built up edge accumulating on the rake face of the HSS lathe cutting tool.

The appearance of BUE changed the wear mechanism from friction-based wear to chipping type wear that develops as material adheres to the tool and breaks off, removing the tool material with it. As this adhered material is on the top of the tool, it contributes to the development of crater wear by orienting the chip flow further into the rake face, while obscuring the development of flank wear as the built-up edge is performing the cutting action and not the tool's actual cutting edge.

Additional experiments were performed, modifying the cutting parameters to attempt to reduce the BUE. The modifications included changing the cutting speed, workpiece material, workpiece design, tool geometry, tool material and feed rate, as well as the quantity of cutting fluid being deposited on the workpiece. Longer material cut per interruption was also tested, hoping that a longer chip would better flow over the top of the tool and be pushed off the tool. While changing tool material and geometry showed some effectiveness, it only delayed the formation of the BUE but did not eliminate it.

Despite these changes, the HSS tooling always developed a BUE before any measurable flank wear was evident near the cutting edge. When testing varying tool materials, it was found that carbide cutting tools did not exhibit the growth of BUE but were more prone to chipping. Therefore, to continue with the analogy testing, carbide tools were chosen and used in the testing process, as has been elaborated in Chapter 4, and the data produced through interrupted cutting with carbide tools was used to parameterize the proposed progression-based tool wear model.

Appendix B

Safety calculations for orthogonal analogy testing workpiece holder

When designing the testing fixture for use in the orthogonal analogy cutting tests, safety of the operator was of utmost importance. While it was important for the fixture to work well and allow for faster experimentation, it could not be used if it was deemed unsafe. To ensure the designed fixture was safe and had no possibility of releasing the workpieces during operation, the design was evaluated to ensure the clamping force would not be overcome by the applied cutting forces or the centrifugal force acting upon the workpiece when spinning in the lathe. To ensure the design was safe, a factor of safety of five was used while applying a maximum rpm of 1050, far above the intended maximum rpm of approximately 150.

The basic design consists of a central holder where one end is held in the lathe chuck while the other side is supported by the tailstock and a live centre. Two milled slots were used to hold square bar stock. Four holes were drilled and tapped to allow for M6 setscrews that clamp the blanks in the slot.

A force balance diagram can be seen in Figure B.1 showing the forces applied to the workpiece during testing. The clamping force ($F_{clamping}$) generated by the four setscrews, produces a friction force ($F_{friction}$) on the back wall. The friction force prevents any movement that would be created by the centrifugal force ($F_{centrifugal}$) and cutting force (F_{feed}) that would otherwise pull the workpiece from the holder or shift the workpiece in the slot. A simplified force balance approach was used not considering additional factors, such as the setscrews physically retaining the workpiece. The setscrews physically retain the workpiece as they sit in the counterbores on the workpiece surface, shown in Figure B.2. The counterbores were added as a last resort safety feature to halt movement but are not the primary retaining method.

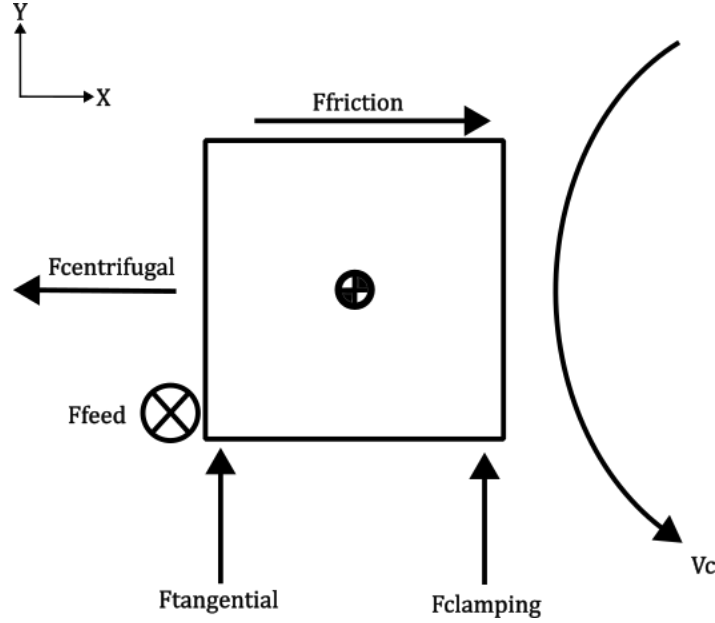


Figure B.1: Force balance diagram for the workpiece.

The clamping force of the mounting setscrews can be calculated using Eq. (B.1). Where the torque applied to the setscrew is represented by τ , the screw diameter by d_{screw} and finally the clamping constant (accounting for friction between threads) K . To avoid loosening due to vibrations from cutting, the setscrews were retained in the tapped hole using a second setscrew tightened behind the first one.

The friction force between the bar and the back wall can be calculated using Eq. (B.2). A friction coefficient (μ) of 0.1 was used as cutting oil will be applied during turning that may seep between the holder and the workpiece. The normal force is calculated using both the clamping force and the tangential cutting force.

The centrifugal force of the spinning bar can be calculated using Eq. (B.3). m_{wkp} represents the mass of the bar, v_c represents the linear velocity calculated using the rpm and r represents the radial distance from the centre of mass to the centre of rotation.

The applied cutting forces can be calculated by first finding the orthogonal cutting forces F_t and F_n (tangential and normal forces) seen Eq. (B.4) and Eq. (B.5). These forces are calculated using the cutting coefficients (K_{tc} , K_{te} , K_{fc} , and K_{fe}) as well as the chip dimensions b and h as seen in Figure 2.6. The cutting coefficients used were calculated in previous work [43] experimentally using the orthogonal to oblique cutting model. The tangential force applied during turning is equal to the

orthogonal tangential force while the applied feed force (F_f) can be calculated using Eq. (B.6). ψ represents the side edge cutting angle of the lathe tooling. While there is a radial force generated during cutting it is insignificant when compared to the other forces.

$$F_{clamping} = \frac{\tau}{K d_{screw}} \quad (B.1)$$

$$F_{friction} = \mu(F_{clamping} + F_{tangential}) \quad (B.2)$$

$$F_{centrifugal} = \frac{m_{wkp} v_c^2}{r} \quad (B.3)$$

$$F_t = K_{tc}bh + K_{te}b \quad (B.4)$$

$$F_n = K_{fc}bh + K_{fe}b \quad (B.5)$$

$$F_f = F_n \cos(\psi) \quad (B.6)$$

Using the free body diagram seen in Figure B.1, the calculated forces can be compared to ensure the forces restraining the workpiece ($F_{friction}$) are sufficient during operation and exceed the forces that may shift the workpiece ($F_{centrifugal}$ and F_f). The clamping force was found to be 3083 N for each m6 set screw when applying a torque of 3.7 Nm (half of the maximum torque) and using a friction coefficient of 0.2 (typical of steel-on-steel contact). Accounting for the four setscrews applied the total clamping force is 12333 N. The tangential cutting force F_t was found to be 174.5 N using a depth of cut (b) of 1 mm and chip thickness (h) of 0.0635 mm/rev. Using the calculated clamping force and tangential force the friction force $F_{friction}$ was found to be 1250.8 N.

The centrifugal force $F_{centrifugal}$ was found to be 215.7 N. The mass of each bar was found to be 0.644 kg for a five inch long one-inch square bar of 1020 cold rolled steel. The radius from the centre of rotation to the centre of mass was found to be 27.7 mm. While the highest rpm value used during cutting tests will be 140 rpm a value of 1050 rpm was used to calculate the centrifugal force to account for potential operator error such as incorrect selections on the lathe. This rpm value corresponds to a cutting speed (v_c) of 3.046 m/s. The orthogonal cutting normal force (F_n) was found to be 86.86 N. Using a side cutting edge angle (ψ) of five degrees the feed force (F_f) was found to be 86.5 N.

The resultant force between the feed force and the centrifugal force that seeks to remove the bar from the holder during operation was found to be 232.4 N applying Pythagorean theorem. Finally, the factor of safety between the frictional force restraining the bar and the resultant force was calculated to be 5.38.

Should the clamping of the setscrews fail, and the workpieces shift within the milled slot the force will be acting on the setscrews as a shear force. To ensure the setscrews will not fail the shear strength of the setscrews can be compared to the applied shear force. The shear force can be calculated using Eq. (B.7) applying the previously found resultant force of 232.4 N (F) and the stress area of the set screw A_s calculated in Eq. (B.8). d_2 represents the pitch diameter of the screw and d_3 represents the minor diameter. For the chosen m6 set screw the stress area was found to be 20.1 mm² creating a shear force of 11.54 MPa. The shear strength for a steel setscrew assuming the lowest property class of 8.8 is roughly 460 MPa. Comparing the shear strength and the applied shear a factor of safety of 39.9 can be found indicating that a single setscrew is able to resist the applied shear forces should the workpiece shift. As four set screws are applied to each workpiece the chances of failure are further reduced.

$$\tau_s = \frac{F}{A_s} \quad (B.7)$$

$$A_s = \frac{\pi}{4} \left(\frac{d_2 + d_3}{2} \right)^2 \quad (B.8)$$

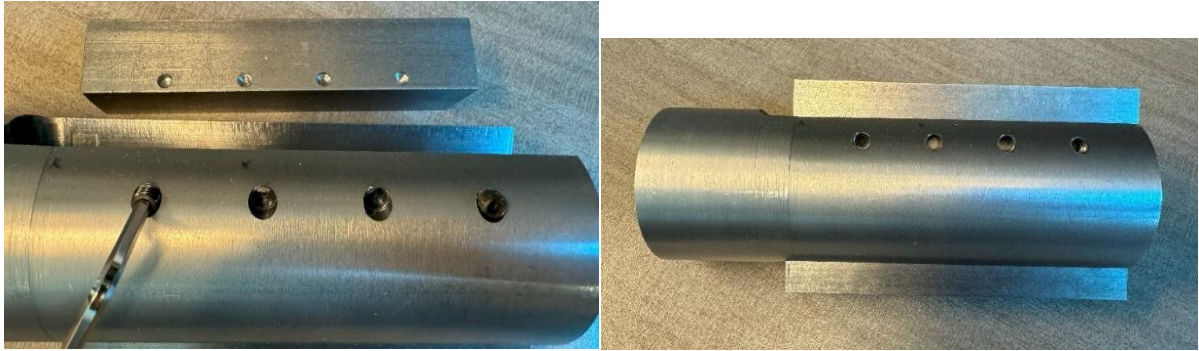


Figure B.2: Finalized workpiece holder. Left: the unassembled holder showing the holder and the workpiece. Right: the holder fully assembled.

Appendix C

Expansion of Colding function using modified Lindstrom constants

To show that the presented five constant Colding model seen in Eq. (2.6) [7] is in fact a special case of the Taylor tool life model and equivalent, the Colding model can be derived using the Taylor model. This derivation can be performed using the Taylor style model seen in Eq. (2.5) [30] substituting the linear equations presented by Lindstrom seen in Eq. (2.7) [31] for the model constants α and m . The constants C_0 , m_0 , m_1 , α_0 , and α_1 can then be substituted to the relationships presented by Lindstrom below.

$$\begin{aligned} C_0 &= \exp\left(K - \frac{H^2}{4M}\right) \\ m_0 &= -\frac{2H}{4M} \\ m_1 &= \frac{1}{4M} \\ \alpha_0 &= N_0 \\ \alpha_1 &= -L \end{aligned}$$

The derivation begins with the Taylor style model shown in Eq. (2.5) and rearranging to isolate for cutting speed v_c :

$$\begin{aligned} v_c T^{\alpha(h_e)} h_e^{m(h_e)} &= C_0 \\ v_c &= \frac{C_0}{T^{\alpha(h_e)} h_e^{m(h_e)}} \end{aligned}$$

To simplify the derivation, A is introduced in the form of: $v_c = e^A = \exp(A)$

The expression of A is determined as:

$$A = \ln\left(\frac{C_0}{T^{\alpha(h_e)} h_e^{m(h_e)}}\right)$$

$$A = \ln(C_0) - \alpha(h_e) \ln(T) - m(h_e) \ln(h_e)$$

Substituting the linear Lindstrom expressions for $\alpha(h_e)$ and $m(h_e)$ from Eq. (2.7):

$$A = \ln(C_0) - (\alpha_0 + \alpha_1 \ln(h_e)) \ln(T) - (m_0 + m_1 \ln(h_e)) \ln(h_e)$$

Further substituting relationships presented by Kantojärvi to introduce the Colding model constants K , M , N_0 , H , and L :

$$A = \ln \left(\exp \left(K - \frac{H^2}{4M} \right) \right) - [N_0 - L \ln(h_e)] \ln(T) - \left[-\frac{2H}{4M} + \frac{1}{4M} \ln(h_e) \right] \ln(h_e)$$

$$A = K - \frac{H^2}{4M} - \frac{\ln^2(h_e)}{4M} + \frac{2H \ln(h_e)}{4M} - [N_0 - L \ln(h_e)] \ln(T)$$

$$A = K - \frac{(\ln(h_e) - H)^2}{4M} - [N_0 - L \ln(h_e)] \ln(T)$$

Finally substituting A into the Taylor model that had been rearranged to isolate for v_c , the Colding model can be found below:

$$v_c = \exp \left[K - \frac{(\ln(h_e) - H)^2}{4M} - (N_0 - L \ln(h_e)) \ln(T) \right]$$

Through this derivation, the Colding model can be derived from the Taylor style model using the linear functions for α and m and introducing the relationships presented by Kantojärvi.

Appendix D

Variations in the Least Squares fitting of model constants for tool life models

Variations in the solving methods applied to the tool life models discussed in Chapter 4.6 may affect the accuracy of the model once calibrated. The two constant and three constant Taylor models as well as the five constant Colding model are rearranged into matrix form (for use in the MATLAB **lsqr** approximation) isolating the $\log(v_c)$ term. This form can be seen in Eq. (D.1) for the three constant Taylor model.

$$\begin{bmatrix} \log(T_1) & \log(h_{e1}) & -1 \\ \log(T_2) & \log(h_{e2}) & -1 \\ \vdots & \vdots & \vdots \\ \log(T_N) & \log(h_{eN}) & -1 \end{bmatrix} \begin{bmatrix} m \\ p \\ \log(C_T) \end{bmatrix} \cong \begin{bmatrix} -\log(v_{c1}) \\ -\log(v_{c2}) \\ \vdots \\ -\log(v_{cN}) \end{bmatrix} \quad (\text{D.1})$$

Applying the least squares solving method to the model in this form performs the regression on the v_c term. However the tool life T is the variable of interest. Thus, the model can be rearranged into the form seen in Eq. (D.2) isolating for the T term.

$$\begin{bmatrix} \log(v_{c1}) & \log(h_{e1}) & -1 \\ \log(v_{c2}) & \log(h_{e2}) & -1 \\ \vdots & \vdots & \vdots \\ \log(v_{cN}) & \log(h_{eN}) & -1 \end{bmatrix} \begin{bmatrix} 1/m \\ p/m \\ \log(C_T)/m \end{bmatrix} \cong \begin{bmatrix} -\log(T_1) \\ -\log(T_2) \\ \vdots \\ -\log(T_N) \end{bmatrix} \quad (\text{D.2})$$

When approximating the model constants using these two matrix forms, a variation can be found resulting in different model constant values seen in Table D.1.

Table D.1: Variation of the model constants found using the lsqr method depending on the applied matrix form.

	Original	Modified
m	0.975	1.29
p	0.327	0.455
C_t	55.2	68.8

Finally, the tool life estimations can be found for the two varying matrix forms and compared to the measured tool life values for each of the performed cutting experiments. This comparison can be seen in Table D.2 where a reduction in the average error of 4.57% is seen by conducting the regression directly on the tool life rather than cutting velocity. In addition to the reduction in error, a reduction in the standard deviation can be seen from 18.2% to 15.1%.

Table D.2: Tool life results comparing the original and modified matrix forms.

$f \left[\frac{\mu m}{rev} \right]$	$v_c \left[\frac{m}{min} \right]$	Tool life (min)			Percent error	
		Measured	Original	Modified	Original	Modified
40.64	10.6	13.8	15.9	13.2	15.5%	3.92%
40.64	20.8	7.21	7.96	7.84	10.4%	8.69%
40.64	28.7	8.17	5.72	6.11	30.0%	25.3%
40.64	37.3	3.86	4.37	4.98	13.3%	29.1%
50.8	9.89	8.98	15.8	12.9	76.5%	43.7%
50.8	20.8	8.91	7.40	7.25	16.9%	18.6%
50.8	30.9	6.53	4.92	5.32	24.7%	18.5%
50.8	39.9	4.22	3.79	4.37	10.3%	3.49%
63.5	9.78	11.5	14.9	12.0	29.5%	4.73%
63.5	19.4	10.2	7.36	7.07	28.0%	30.9%
63.5	32.2	4.88	4.38	4.77	10.2%	2.16%
63.5	44.0	2.63	3.18	3.74	20.8%	42.3%
Average Error:					23.9%	19.3%
Standard Deviation:					18.2%	15.1%

This comparison can be seen across a range of cutting speeds in Figure D.1., with the regression directly on tool life giving a better fit and reducing the outliers.

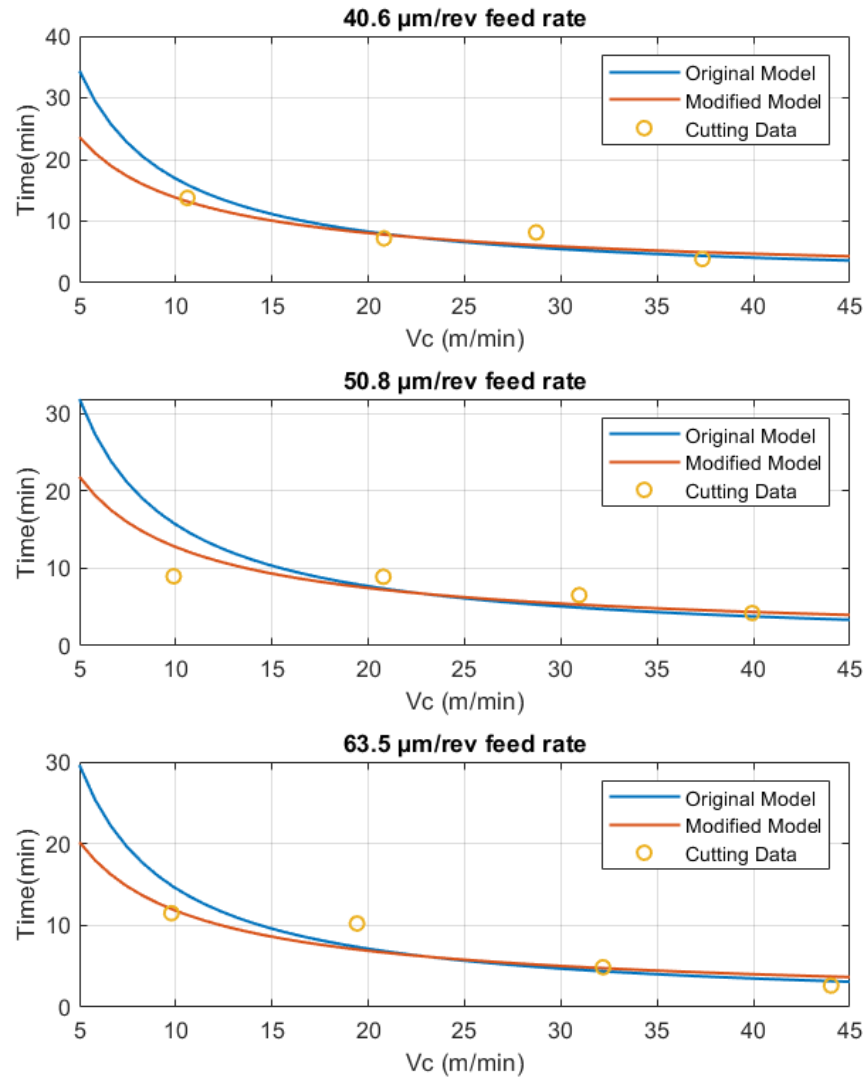


Figure D.1: Comparison of Taylor's tool life model fitting with experimental data considering regression on cutting velocity (v_c) versus tool life (T).